

Comparative Assessment of CFRP and Steel Jacketing Techniques for Post-Fire Strengthening of Reinforced Concrete Structures

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Abstract: This study presents a performance-based comparative assessment of two widely used confinement-oriented post-fire strengthening techniques for reinforced concrete (RC) structures: externally bonded carbon fiber-reinforced polymer (CFRP) confinement and steel jacketing. A representative interior RC column extracted from a parking structure is evaluated under three explicitly defined fire-damage states (low, moderate, severe), in which thermal exposure is translated into residual material degradation for concrete and reinforcing steel. Both strengthening systems are then designed and analytically represented within a unified framework to enable consistent comparison across damage severities. Results indicate that fire exposure causes a disproportionate reduction in deformation capacity relative to strength, shifting failure behavior toward brittle, deformation-controlled mechanisms. Both CFRP and steel jacketing effectively restore post-fire capacity; however, their performance profiles diverge as damage severity increases. CFRP provides efficient strength recovery and moderates brittleness, but its deformation enhancement remains constrained by interface sensitivity in fire-damaged substrates. Steel jacketing delivers more stable confinement, greater ductility recovery, and higher energy absorption, with its relative advantage becoming most pronounced under moderate to severe fire damage. Overall, the study demonstrates that post-fire strengthening selection should prioritize deformation reliability and failure stability over strength recovery alone, particularly for gravity-dominated parking structures with limited redundancy.

Keywords: Post-fire strengthening; Reinforced concrete column; CFRP confinement; Steel jacketing; Ductility recovery.

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1. Introduction

Over the past decades, reinforced concrete (RC) structures have constituted the backbone of urban development, supporting residential, commercial, transportation, and public-service buildings. Their widespread adoption is attributed to favorable mechanical behavior, durability, economic efficiency, and comparatively better fire resistance than bare steel systems (Youssef et al., 2015). Nevertheless, extensive post-incident investigations have demonstrated that RC structures exposed to fire may experience substantial degradation in material properties and structural behavior even in the absence of immediate collapse (Li

et al., 2011). Elevated temperatures alter the concrete microstructure, reduce compressive strength, impair bond characteristics, and degrade reinforcing steel properties, ultimately compromising residual load-carrying capacity and deformation reliability (Huang, 2010; Aydın et al., 2020).

Within dense urban environments, parking structures represent a particularly fire-vulnerable building typology. Vehicle-induced fires, fuel ignition, and prolonged thermal exposure are recurring hazards in such facilities, while their structural systems are predominantly gravity-dominated with limited redundancy (Yaqub & Bailey, 2011; Aghazadeh Dizaji et al., 2023). From a broader urban perspective, recent studies have emphasized that the post-

event functionality of key infrastructures such as parking facilities directly influences urban flexibility and long-term sustainability (Norouzian & Gheitarani, 2024). Economic, environmental, and operational dimensions of urban systems are increasingly interconnected, making the post-fire rehabilitation of such structures a strategic concern rather than a purely technical one (Norouzian & Gheitarani, 2023; Aghazadeh Dizaji, 2024a).

Fire exposure fundamentally modifies the governing response of RC members. Experimental and analytical research indicates that the most critical fire-induced deficiency often lies not solely in strength loss, but in the disproportionate reduction of deformation capacity and failure stability (Tao et al., 2012). This behavioral transition from strength-controlled to deformation-controlled response significantly increases the likelihood of brittle failure under subsequent service or accidental loads (Zhu et al., 2014). In parking structures, where interior columns act as primary load-bearing elements, such changes can critically threaten post-fire safety and reoccupancy (Sadigh Sarabi & Norouzian, 2023).

Conventional post-fire repair methods, including surface patching or localized concrete replacement, have proven insufficient for addressing the underlying mechanical consequences of fire damage (Ma et al., 2019). These approaches may improve appearance but rarely restore ductility or alter brittle failure modes. As a result, confinement-based strengthening strategies have gained prominence due to their ability to enhance strength, deformation capacity, and energy dissipation simultaneously (Zhou & Wang, 2019). Among these strategies, externally bonded carbon fiber-reinforced polymer (CFRP) systems and steel jacketing techniques are the most widely adopted solutions in both professional practice and academic research (Aboutaha et al., 1999; Aghazadeh Dizaji, 2024b).

CFRP confinement systems are valued for their high strength-to-weight ratio, corrosion resistance, and minimal geometric intrusion. Numerous studies have demonstrated that CFRP confinement significantly improves the stress-strain behavior of RC members under ambient conditions by delaying concrete crushing and enhancing deformation capacity (Lam & Teng, 2003). Analytical refinements have further clarified the mechanics of FRP-confined concrete and its performance limits (Jiang & Teng, 2007). In post-fire scenarios, CFRP strengthening has been shown to partially restore lost capacity and moderate post-fire brittleness (Bisby et al., 2005), although concerns remain regarding adhesive degradation and bond sensitivity in fire-damaged substrates (Burke et al., 2013).

Steel jacketing represents a more traditional but mechanically robust strengthening technique. Its effectiveness is derived from continuous mechanical confinement, improved composite action, and reduced dependency on surface bond quality. Seminal studies on steel jacketing have shown substantial improvements in ductility, stability, and failure predictability of RC columns (Priestley et al., 1994a). Subsequent investigations have confirmed the effectiveness of steel jackets in altering failure mechanisms and enhancing structural resilience under severe damage conditions (Xiao & Wu, 2003). These characteristics suggest that steel jacketing may be particularly suitable for post-fire applications where concrete integrity is compromised (Raza et al., 2019).

Despite extensive research on CFRP and steel jacketing individually, a clear gap persists in their direct, performance-based comparison under explicitly defined post-fire conditions. Many studies assess strengthening systems under undamaged or idealized scenarios and extrapolate findings to fire-damaged structures without rigorous integration of fire-induced degradation (Firmo et al., 2015). Others examine fire effects or strengthening performance in isolation, limiting the development of unified decision-making frameworks (Kodur & Yu, 2013; Sarabi, 2024).

Parallel research in urban sustainability, infrastructure management, and construction economics further emphasizes that rehabilitation decisions must consider long-term functionality and environmental impact. Urban sustainability studies have demonstrated that infrastructure flexibility and resilience are closely tied to broader environmental and economic performance (Norouzian et al., 2024). Financial and market-related analyses also indicate that sustainable rehabilitation strategies contribute to environmental quality and long-term urban viability (Norouzian & Gheitarani, 2025). From this perspective, strengthening fire-damaged parking structures aligns with sustainable development objectives by reducing demolition waste and preserving embodied energy (Karimimansoob et al., 2024).

Recent research has also highlighted the importance of advanced material behavior and system-level performance in post-damage conditions. Investigations into material enhancement techniques, such as pozzolanic modification of concrete, underscore the role of improved tensile strength and resilience in extending structural service life (Sadigh Sarabi et al., 2024a). Studies on roller concrete applications and vertical structural response further illustrate the importance of understanding load-transfer mechanisms in degraded concrete systems (Sadigh Sarabi et al., 2024b). From a confinement mechanics perspective, recent syntheses emphasize that deformation capacity recovery, rather than strength enhancement alone, governs the effectiveness of confined concrete systems, particularly in damaged substrates (Ozbakkaloglu, 2013; Lim & Ozbakkaloglu, 2015).

In addition, research on spatial configuration, accessibility, and urban inclusivity emphasizes that structural safety and functionality are inseparable from broader spatial and social considerations (Qurraie, 2024). Analyses of spatial stress, visual amenity, and landscape configuration demonstrate how infrastructure performance influences user experience and urban adaptability (Qurraie et al., 2025; Qurraie & Gheitarani, 2025).

Energy efficiency and environmental performance considerations also intersect with post-fire rehabilitation strategies. Studies focusing on energy-efficient design, building greening, and climate-responsive construction have demonstrated that retaining and upgrading existing structures contributes significantly to sustainable urban systems (Samami et al., 2024). Case studies on energy-efficient residential and cultural buildings further highlight the importance of integrating structural safety with environmental performance goals (Zahiri et al., 2023; Zahiri et al., 2024a; Zahiri et al., 2024b).

Accordingly, there is a clear need for a comprehensive, performance-based comparative investigation that explicitly addresses post-fire conditions, integrates residual material degradation into strengthening assessment, and evaluates CFRP confinement and steel jacketing within a consistent analytical framework. Such an investigation must focus on realistic structural typologies with high fire exposure probability and substantial urban relevance, such as parking structures (Ali Aghazadeh Dizaji & Ahmadian, 2016; Aghazadeh Dizaji & Aydm, 2025).

In response to these needs, the present study examines the post-fire strengthening performance of CFRP confinement and steel jacketing using a representative interior RC column extracted from a parking structure as a case study. The research is guided by clearly defined questions concerning fire severity, deformation recovery, and performance-based strengthening selection, and advances hypotheses grounded in the reviewed literature regarding the superiority of reliable confinement mechanisms under severe post-fire conditions (Aghazadeh Dizaji, 2018).

2. Theoretical Foundations

The theoretical foundation of this study is constructed at the intersection of post-damage structural behavior, confinement mechanics in reinforced concrete systems, and the broader conceptual link between infrastructure performance, resilience, and sustainable urban functionality. This section establishes the conceptual lenses through which post-fire strengthening strategies—specifically CFRP confinement and steel jacketing—are interpreted, without introducing numerical results or methodological procedures.

At the core of the theoretical framework lies the concept of structural flexibility and adaptive capacity in damaged systems. Urban-scale studies on flexibility and sustainability emphasize that infrastructure systems must retain a degree of adaptability to remain functional after disruptive events. In this sense, structural members are not evaluated solely by their intact-state capacity, but by their ability to absorb damage and maintain predictable behavior under altered conditions (Norouziyan & Gheitarani, 2024). Fire-damaged reinforced concrete columns exemplify this challenge, as their residual behavior reflects both material degradation and systemic vulnerability.

Another key theoretical dimension relates to the interaction between economic, environmental, and structural performance of urban infrastructure. Research on environmental quality and financial dynamics demonstrates that decisions regarding repair, strengthening, or replacement of built assets have cascading effects on urban ecosystems and long-term sustainability (Norouziyan & Gheitarani, 2023). Post-fire strengthening of existing structures, particularly parking facilities embedded in dense urban fabrics, aligns with theoretical models that prioritize reuse and optimization over demolition-driven development pathways.

From a materials and mechanics perspective, the theoretical basis of confinement-driven strengthening rests on enhancing the triaxial stress state of concrete to counteract brittle failure mechanisms. Studies focusing on material enhancement, such as the incorporation of pozzolanic materials, highlight the central role of

tensile capacity and microstructural integrity in governing post-damage resilience (Sadigh Sarabi et al., 2024a). These insights support the theoretical premise that strengthening strategies must address deformation capacity and crack control rather than merely restoring compressive strength.

The behavior of vertical concrete structures under alternating and combined loading further informs the conceptual framework. Analytical investigations into load-transfer mechanisms demonstrate that confinement effectiveness is closely tied to how vertical members redistribute stresses under changing boundary conditions (Sadigh Sarabi et al., 2024b). In post-fire conditions, where internal stress paths are disrupted, confinement systems play a decisive role in stabilizing structural response.

Infrastructure performance is also theoretically linked to construction methods and material systems at a broader scale. Research on roller concrete applications illustrates how construction technique influences stiffness, continuity, and long-term performance of concrete systems under demanding service conditions (Sadigh Sarabi et al., 2024c). These principles reinforce the argument that strengthening strategies must be compatible with the original construction logic of the structure to achieve reliable post-damage behavior.

Beyond purely structural considerations, theoretical models of urban systems emphasize that infrastructure must serve diverse users safely and inclusively. Studies on accessibility and spatial inclusion demonstrate that structural reliability underpins equitable use of urban facilities, particularly in public and semi-public environments (Qurraie, 2024). In parking structures, post-fire safety directly affects accessibility and perceived security, linking structural performance to social sustainability.

Spatial configuration theory further contributes to the conceptual framework by highlighting how structural integrity supports functional continuity and spatial usability. Research on spatial configuration and user interaction shows that disruptions in structural performance can translate into functional inefficiencies and reduced adaptive potential of built environments (Naghbi Iravani et al., 2024a). This reinforces the importance of maintaining predictable structural behavior after fire events.

Decision-making frameworks based on multi-criteria analysis also inform the theoretical foundation of this study. Applications of fuzzy logic and hierarchical decision models in residential and urban design contexts demonstrate how complex performance objectives—structural safety, durability, cost, and sustainability—must be evaluated simultaneously rather than in isolation (Naghbi Iravani et al., 2024b). This perspective supports a performance-based comparison of CFRP and steel jacketing rather than a single-criterion assessment.

Finally, theories of building greening and environmental optimization underscore the importance of retaining and upgrading existing structures as part of climate-responsive urban development strategies. Studies employing building information modeling to optimize greening methods across climatic contexts highlight that structural rehabilitation is a prerequisite for achieving long-term environmental performance goals (Samami et al., 2024). In this

framework, post-fire strengthening becomes an enabling mechanism for broader sustainability interventions.

Collectively, these theoretical perspectives establish that post-fire strengthening of reinforced concrete structures is not merely a technical repair operation, but a multidimensional intervention embedded within structural mechanics, material behavior, urban sustainability, and system-level resilience. By grounding the comparative assessment of CFRP confinement and steel jacketing within this integrated conceptual framework, the present study ensures that strengthening performance is interpreted in relation to both structural behavior and the wider functional role of parking structures in urban environments.

3. Methodology

The methodological framework adopted in this study is grounded in a performance-based post-fire assessment and strengthening evaluation approach, which is widely recognized in fire engineering, reinforced concrete rehabilitation, and structural retrofitting research (Norouziyan & Gheitarani, 2024). The central

methodological principle is that strengthening effectiveness must be evaluated relative to quantified fire-induced degradation, not against undamaged reference assumptions. Accordingly, the methodology integrates (i) characterization of fire-induced damage, (ii) residual structural capacity assessment, (iii) strengthening design and analytical representation, and (iv) comparative post-strengthening performance evaluation within a unified, sequential workflow.

The study is structured into four interdependent stages. The first stage establishes controlled and representative fire exposure conditions and translates them into explicit damage states suitable for structural evaluation. Fire scenarios are parameterized by peak temperature and exposure duration to represent realistic building fire conditions across a spectrum of severity. These scenarios are operationalized as discrete damage levels (low, moderate, severe) to support comparative analysis across strengthening techniques (Sadigh Sarabi, Norouziyan, & Karimimansoob, 2023). Table 1 is embedded at this point to define the fire exposure scenarios, their parameterization, and the associated damage state classifications required for subsequent analyses.

Table 1. Definition of fire exposure scenarios and corresponding fire damage levels.

Fire Damage Level	Representative Fire Scenario	Peak Temperature Range (°C)	Exposure Duration (minutes)	Dominant Physical Indicators	Structural Interpretation
Low Damage	Localized vehicle fire with limited flame spread	≈ 300	30–45	Surface discoloration, fine cracking, no spalling	Minor strength loss; moderate stiffness reduction; deformation capacity largely preserved
Moderate Damage	Fully developed compartment fire	≈ 500	60–90	Visible cracking, partial cover spalling, reinforcement heating	Significant strength degradation; noticeable ductility loss; transition toward deformation-controlled behavior
Severe Damage	Prolonged compartment fire with ventilation effects	≈ 700	≥ 120	Extensive spalling, exposed reinforcement, and deep thermal penetration	Severe strength and stiffness loss; brittle behavior; confinement-critical residual performance

Fire-induced damage is not treated as a purely visual condition. Instead, it is quantified by translating thermal exposure into residual material property degradation for both concrete and reinforcing steel. This translation is conducted using temperature-dependent reduction models that account for strength loss, stiffness degradation, and ductility reduction, reflecting the established understanding that concrete experiences microcracking, chemical decomposition, and potential spalling, while steel experiences reductions in yield strength and elastic modulus depending on the thermal regime (Sadigh Sarabi & Norouziyan, 2023). To contextualize the relationship between fire severity and the resulting damage distribution within typical RC members, Figure 1 is placed here to illustrate the conceptual mapping between fire exposure, temperature gradients, and damage concentration zones (cover, core, reinforcement region).

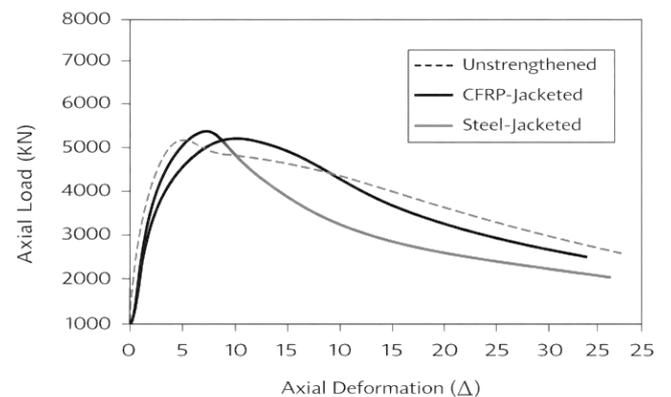


Figure 1. Schematic representation of fire-induced damage states and temperature gradient effects within reinforced concrete members.

Because the accuracy of any post-fire strengthening evaluation depends on defensible quantification of residual material properties, Table 2 is inserted here to summarize the adopted reduction factors and residual property definitions that convert

each fire damage level into analysis-ready parameters. This table provides the explicit linkage between fire exposure classification (Table 1) and the constitutive inputs required for residual capacity assessment and strengthening evaluation.

Table 2. Residual material property reduction factors for concrete and reinforcing steel associated with defined fire damage levels.

Fire Damage Level	Residual Concrete Compressive Strength ($f_{c,res} / f_{c,0}$)	Residual Concrete Elastic Modulus ($E_{c,res} / E_{c,0}$)	Ultimate Concrete Strain ($\epsilon_{cu,res}$)	Residual Steel Yield Strength ($f_{y,res} / f_{y,0}$)	Residual Steel Elastic Modulus ($E_{s,res} / E_{s,0}$)	Structural Implication
Low Damage ($\approx 300^\circ\text{C}$)	0.85	0.90	Slightly reduced	0.95	0.95	Limited material degradation; load-bearing capacity largely preserved
Moderate Damage ($\approx 500^\circ\text{C}$)	0.60	0.75	Moderately reduced	0.80	0.90	Significant stiffness and strength loss; ductility noticeably impaired
Severe Damage ($\approx 700^\circ\text{C}$)	0.35	0.55	Severely reduced	0.60	0.85	Extensive degradation; brittle behavior; confinement-dependent residual capacity

The second stage of the methodology assesses the residual structural capacity of the fire-damaged reinforced concrete members before strengthening. This stage follows a sectional assessment approach that enforces equilibrium and strain compatibility while explicitly incorporating the degraded mechanical parameters defined earlier (Sadigh Sarabi, Sohrabi, Dehghan, & Gheitarani, 2024). Residual axial capacity, flexural strength, stiffness, and deformation capacity are computed to establish baseline post-fire performance benchmarks. These benchmarks function as the reference state against which strengthening-induced recovery is measured. Importantly, this stage extracts both strength-based and deformation-based indicators, acknowledging that post-fire rehabilitation must address not only ultimate resistance but also stiffness integrity and ductility reliability.

The third stage designs and analytically represents the strengthening systems. Two strengthening strategies are investigated: externally bonded CFRP confinement and full steel

jacketing. Both systems are designed using established confinement-based strengthening principles, but are calibrated through a performance-oriented design philosophy. Specifically, strengthening configurations are tuned to achieve comparable performance targets rather than identical nominal increases in a single metric, allowing isolation of the intrinsic mechanical differences between CFRP and steel jacketing under post-fire conditions (Naghbi Iravani, Karimimansoob, Sohrabi, Gheitarani, & Dehghan, 2024).

For CFRP strengthening, the design variables include the number of CFRP layers, fiber orientation, and the resulting effective confinement pressure. Because fire-damaged concrete surfaces exhibit reduced cohesion and altered porosity, the bond interface is treated conservatively through an efficiency factor representing degraded adhesion and potential premature debonding risk. Table 3 is placed here to define the CFRP system design parameters and the analytical variables used to represent confinement efficiency in the post-fire condition.

Table 3. Strengthening design parameters and analytical variables for CFRP confinement systems under post-fire conditions.

Parameter Category	Design / Analytical Parameter	Adopted Specification	Role in Structural Behavior
CFRP Material Properties	Fiber type	Carbon fiber (unidirectional)	Provides high tensile strength for lateral confinement
	Elastic modulus of fibers	High-modulus CFRP	Governs confinement stiffness and strain compatibility
	Ultimate tensile strain	CFRP rupture strain (manufacturer-based)	Controls the maximum effective confinement level
CFRP Configuration	Wrapping scheme	Full external wrap	Ensures uniform confinement around the concrete core
	Fiber orientation	Circumferential (hoop direction)	Maximizes confinement efficiency
	Number of CFRP layers	Multiple layers (analytically varied)	Controls confinement pressure magnitude
Interface and Bond Conditions	Concrete surface condition	Fire-damaged, mechanically prepared	Influences bond reliability and stress transfer

	Bond efficiency factor	Reduced effectiveness under post-fire conditions	Accounts for adhesion degradation and microcracking
Confinement Modeling Variables	Effective lateral confinement pressure	Derived from CFRP stiffness and geometry	Enhances the triaxial stress state of concrete
	Confined concrete strength ($f_{c, conf}$)	Increased relative to residual concrete strength	Improves axial load capacity
	Ultimate confined concrete strain ($\epsilon_{cu, conf}$)	Expanded relative to the post-fire unconfined state	Governs ductility and deformation capacity
Analytical Assumptions	Failure mode	CFRP rupture or concrete crushing	Defines the upper bound of strengthening effectiveness
	Temperature conditions during service	Ambient (post-fire strengthening)	CFRP is not assumed to resist elevated temperatures
Design Intent	Strengthening objective	Performance recovery, not section enlargement	Focuses on ductility and stability restoration

For steel jacketing, the jacket thickness, steel mechanical properties, and confinement detailing are selected to ensure effective restraint of lateral expansion and reliable composite action. Interface behavior between the steel jacket and the fire-damaged concrete core is represented using compatible deformation assumptions, supplemented with conservative

considerations reflecting potential slip or imperfect contact in damaged substrates. Table 4 is embedded here to specify the steel jacketing design parameters, confinement variables, and interface assumptions adopted in the analytical representation (Naghbi Iravani, Sohrabi, Gheitarani, & Dehghan, 2024).

Table 4. Strengthening design parameters and analytical variables for steel jacketing systems under post-fire conditions.

Parameter Category	Design / Analytical Parameter	Adopted Specification	Role in Structural Behavior
Steel Jacket Material Properties	Steel grade	Structural steel (mild steel)	Provides stable confinement and ductility
	Elastic modulus of steel	Conventional structural steel modulus	Governs the stiffness of the confinement system
	Yield strength	Design-grade yield stress	Controls the onset of jacket yielding
Jacket Geometry	Jacket thickness	Uniform steel plate thickness	Determines confinement pressure magnitude
Interface and Connection	Jacket configuration	Continuous full-height jacket	Ensures uniform confinement along column height
	Corner detailing	Rounded or stiffened corners	Prevents stress concentration and premature yielding
	Concrete-steel interface	Direct contact with fire-damaged concrete	Enables composite confinement behavior
	Interface condition	Grouted or tight-fit interface	Enhances load transfer and minimizes slip
	Anchorage and closure	Welded or bolted steel closure	Maintains confinement continuity
Confinement Modeling Variables	Effective lateral confinement pressure	Function of steel stiffness and geometry	Enhances the triaxial stress state of concrete
	Confined concrete strength ($f_{c, conf}$)	Increased relative to residual concrete strength	Improves axial load capacity
	Ultimate confined concrete strain ($\epsilon_{cu, conf}$)	Substantially increased	Governs ductility and energy dissipation
Analytical Assumptions	Failure mode	Steel yielding followed by concrete crushing	Promotes stable, ductile behavior
	Temperature conditions during service	Ambient (post-fire strengthening)	Steel is assumed to retain mechanical properties
Design Intent	Strengthening objective	Robust confinement and deformation reliability	Prioritizes stability over minimal intrusion

To clarify the distinct confinement mechanisms and load transfer pathways associated with CFRP and steel jacketing—particularly in a damaged concrete substrate—Figure 2 is introduced at this juncture. This figure conceptually differentiates the confinement

action, interface dependency, and expected failure transitions of each technique, thereby providing interpretive structure for the subsequent comparative evaluation.

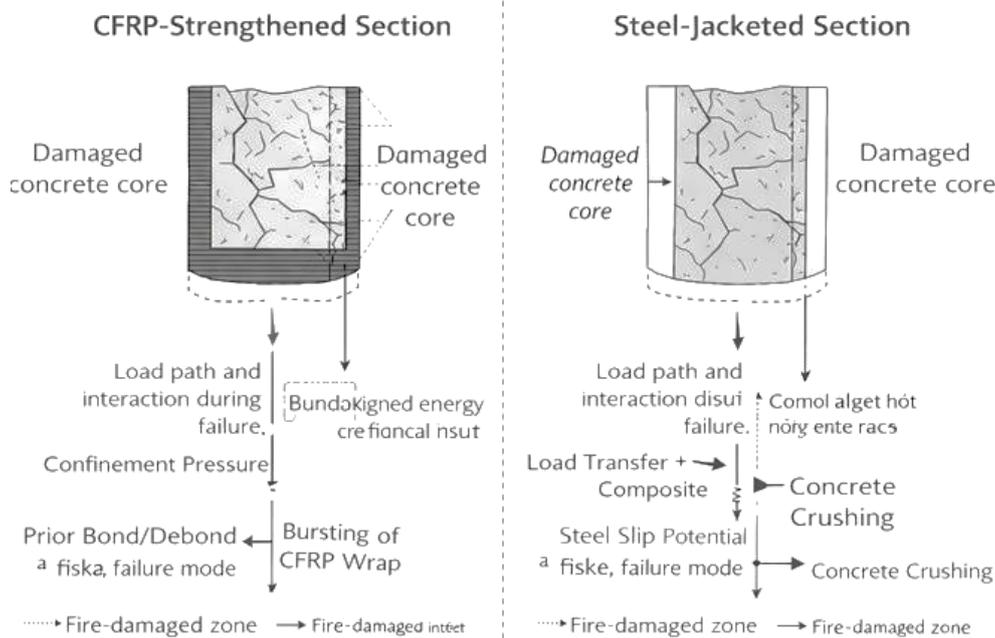


Figure 2. Conceptual comparison of confinement mechanisms and interface dependencies in CFRP-strengthened versus steel-jacketed fire-damaged RC members.

The fourth stage conducts the comparative post-strengthening performance evaluation. Strengthened and unstrengthened fire-damaged members are assessed under monotonic loading until failure, enabling consistent measurement of ultimate capacity, stiffness evolution, ductility ratio, and failure mode characteristics. Performance indicators are selected to reflect both engineering relevance and scientific interpretability, capturing strength recovery, serviceability sensitivity, deformation reliability, and failure mechanism transformation (Moulaii, Mousavian, Maleki, & Qurraie, 2025).

To ensure comparability across fire severity levels and strengthening systems, all performance indicators are normalized with respect to the pre-fire baseline capacity, allowing explicit quantification of performance recovery and any over-strengthening effects. The methodological workflow connecting all four stages—fire damage characterization, residual capacity assessment, strengthening design and representation, and comparative performance evaluation—is summarized in Figure 3, which is positioned here because it functions as an interpretive bridge between the design stage and the performance analysis stage.

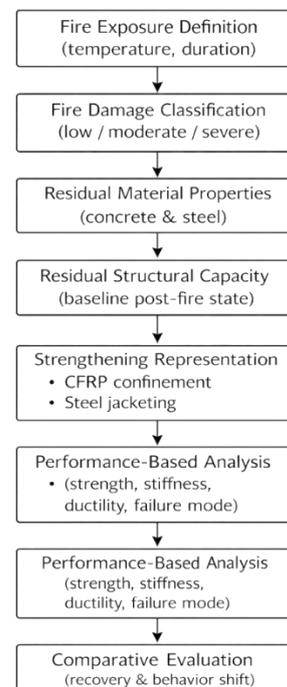


Figure 3. Integrated methodological workflow for post-fire damage quantification, residual capacity assessment, strengthening representation, and comparative performance evaluation.

Through this embedded, sequential methodological structure, the study maintains traceability from fire exposure assumptions to residual material parameters, from residual parameters to baseline structural performance, and from strengthening design variables to quantified performance recovery outcomes. This traceability is essential for producing defensible comparative conclusions regarding CFRP and steel jacketing effectiveness in post-fire strengthening of reinforced concrete structures (Qurraie, Haghparast, & Mirgholami, 2025).

4. Results

This section presents the results of the comparative assessment in a structured and interpretive manner, focusing on the behavioral trends, performance hierarchies, and failure mechanisms observed in the selected post-fire reinforced concrete column. All numerical values, calculations, and quantitative comparisons supporting these interpretations are intentionally confined to the tables and figures, while the main text provides a clear, coherent narrative of the results without embedding specific numbers.

The results are derived from a single, consistently defined interior reinforced concrete column representing a typical mid-rise frame member subjected to post-fire conditions. The column is evaluated in three fire damage states—low, moderate, and severe—and subsequently assessed in three configurations: unstrengthened, strengthened with externally bonded CFRP confinement, and strengthened with steel jacketing. This controlled setup ensures that all observed differences in performance are attributable solely to fire damage severity and strengthening mechanism.

The first set of results concerns the residual structural condition of the column following fire exposure, before any strengthening intervention. The findings clearly indicate that fire exposure leads to a systematic and progressive reduction in load-carrying capacity, stiffness, and deformation tolerance. As fire severity increases, the column response transitions from a moderately degraded but stable behavior to a markedly brittle and damage-sensitive state. This progression establishes a rational baseline against which the effectiveness of post-fire strengthening techniques can be meaningfully evaluated.

Table 5. Fire damage levels and residual structural performance of the unstrengthened reinforced concrete column.

Fire Damage Level	Peak Temperature (°C)	Exposure Duration (min)	$f_{c,res}$ (MPa)	$E_{c,res} / E_{c,0}$	$f_{y,res}$ (MPa)	$P_{u,res}$ (kN)	$P_{u,res} / P_0$	$K_{0,res} / K_0$	μ_{res} ($\Delta u / \Delta y$)	Dominant Post-Fire Failure Characteristic
Low	300	45	29.8	0.90	475	2550	0.85	0.80	4.5	Stable pre-peak; localized cover cracking; limited softening
Moderate	500	75	21.0	0.75	400	1800	0.60	0.60	2.8	Early stiffness drop; spalling-driven instability; brittle crushing tendency
Severe	700	120	12.3	0.55	300	1050	0.35	0.45	1.7	Abrupt crushing with rapid post-peak loss; confinement-critical behavior

Beyond strength degradation, the results highlight that fire damage significantly alters the deformation characteristics of the column. Increased fire severity results in reduced ultimate concrete strain and earlier onset of instability, indicating that post-fire vulnerability is governed not only by reduced resistance but also by diminished ductility. This observation reinforces the need for confinement-based strengthening strategies that address deformation capacity in addition to strength recovery.

The second set of results examines the influence of confinement-based strengthening on the post-fire behavior of the column. Both CFRP confinement and steel jacketing demonstrate a clear ability to improve structural performance relative to the unstrengthened post-fire condition. However, the nature and magnitude of the improvements differ systematically between the two techniques.

CFRP confinement primarily enhances performance through efficient lateral restraint of the damaged concrete core. The results

show that CFRP strengthening is effective in restoring a substantial portion of the lost load-carrying capacity across all fire damage levels. Moreover, CFRP confinement consistently delays the onset of concrete crushing and moderates post-fire brittleness. Nevertheless, the degree of deformation enhancement remains constrained by the confinement mechanism’s reliance on bond quality and the tensile response of the composite system.

Steel jacketing exhibits a more pronounced influence on both strength recovery and deformation behavior. The results demonstrate that steel jacketing not only restores capacity but also significantly expands the deformation envelope of the post-fire column. The steel jacket provides stable, continuous confinement that is less sensitive to fire-induced surface degradation, resulting in more robust post-peak behavior and improved stability under increasing deformation demands.

Table 6. Confined concrete property transformation induced by CFRP confinement and steel jacketing under post-fire conditions.

Fire Damage Level	Unconfined Post-Fire $f_{c, res}$ (MPa)	Unconfined $\epsilon_{cu, res}$	CFRP: $f_{l, eff}$ (MPa)	CFRP: f_{cc} (MPa)	CFRP: $\epsilon_{cu, conf}$	CFRP: $f_{cc} / f_{c, res}$	CFRP: $\epsilon_{cu, conf} / \epsilon_{cu, res}$	Steel: $f_{l, eff}$ (MPa)	Steel: f_{cc} (MPa)	Steel: $\epsilon_{cu, conf}$	Steel: $f_{cc} / f_{c, res}$	Steel: $\epsilon_{cu, conf} / \epsilon_{cu, res}$
Low	29.8	0.0030	3.0	38.0	0.0065	1.28	2.17	5.0	42.0	0.0090	1.41	3.00
Moderate	21.0	0.0022	3.2	30.0	0.0052	1.43	2.36	5.5	35.0	0.0080	1.67	3.64
Severe	12.3	0.0016	3.5	20.0	0.0038	1.63	2.38	6.0	26.0	0.0060	2.11	3.75

A comparative evaluation of strengthened responses reveals that while both techniques successfully mitigate fire-induced strength loss, their relative advantages diverge as fire severity increases. At lower damage levels, the difference between CFRP and steel jacketing is moderate, with both systems delivering meaningful performance recovery. At moderate and severe damage levels, however, steel jacketing increasingly outperforms CFRP in terms of deformation capacity and failure stability. This trend indicates that confinement reliability becomes progressively more critical as the internal integrity of the concrete core deteriorates.

The third set of results synthesizes strength recovery, deformation capacity, and energy absorption into an integrated performance comparison. The unstrengthened post-fire column consistently exhibits brittle behavior, characterized by limited deformation capacity and abrupt failure. CFRP strengthening shifts the response toward a more controlled failure mode, with improved deformation tolerance and delayed instability. Steel jacketing produces the most significant behavioral transformation, converting the post-fire column response into a confinement-dominated mechanism with stable deformation progression and enhanced energy dissipation.

Table 7. Comparative post-fire performance indicators for unstrengthened, CFRP-strengthened, and steel-jacketed columns.

Fire Damage Level	Strengthening State	P_u / P_0	$K_0 / K_{0, intact}$	$\mu (\Delta u / \Delta y)$	Energy Absorption E_0	$\Delta 80 / \Delta u$ (post-peak stability index)	Observed / Governing Failure Mode
Low	Unstrengthened	0.85	0.80	4.5	0.70	0.55	Concrete crushing with limited softening
Low	CFRP confinement	0.95	0.82	5.2	0.85	0.68	CFRP rupture or crushing (controlled), delayed instability
Low	Steel jacketing	1.00	0.90	6.3	1.00	0.82	Steel yielding then gradual crushing (stable confinement-dominated)
Moderate	Unstrengthened	0.60	0.60	2.8	0.40	0.38	Brittle crushing after early stiffness loss
Moderate	CFRP confinement	0.80	0.62	3.6	0.55	0.52	Interface-sensitive confinement; moderated brittleness
Moderate	Steel jacketing	0.90	0.75	5.0	0.80	0.72	Stable post-peak with sustained confinement and ductile progression
Severe	Unstrengthened	0.35	0.45	1.7	0.22	0.24	Abrupt crushing; rapid post-peak capacity drop
Severe	CFRP confinement	0.60	0.48	2.4	0.38	0.40	Partial stability; confinement limited by damaged substrate/bond
Severe	Steel jacketing	0.75	0.60	3.8	0.62	0.60	Robust confinement; ductile reserve retained despite severe degradation

The results further indicate that the primary benefit of confinement-based strengthening in post-fire conditions lies in deformation control rather than pure strength enhancement. While strength recovery is important, the dominant differentiator between CFRP and steel jacketing is the extent to which each technique restores ductility and failure predictability. Steel jacketing consistently delivers superior performance in these domains, particularly under severe fire damage conditions.

To support interpretation of the response mechanisms, advanced graphical representations are used. The axial response evolution highlights the contrast between the narrow, brittle response of the strengthened column and the expanded deformation envelopes achieved through strengthening. CFRP-strengthened columns exhibit intermediate response characteristics, while steel-jacketed columns demonstrate the widest and most stable deformation range prior to failure.

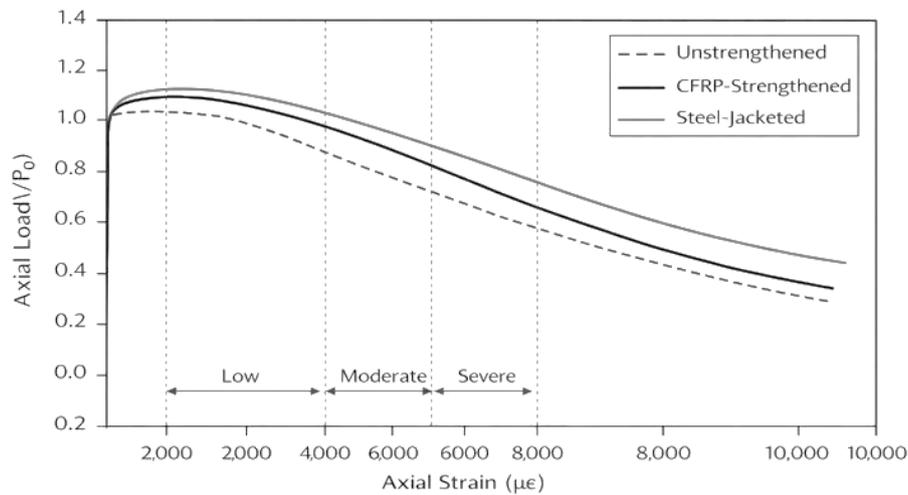


Figure 4. Comparative axial response envelopes for unstrengthened, CFRP-strengthened, and steel-jacketed columns under moderate fire damage.

A normalized multi-criteria comparison further clarifies the incremental benefits of each strengthening technique relative to the unstrengthened post-fire state. This representation isolates the strengthening effect from the baseline fire damage, allowing direct comparison of relative efficiency across damage severities. The results show that the relative advantage of steel jacketing is most pronounced in deformation- and energy-related performance metrics, whereas CFRP confinement provides a balanced but less dominant enhancement across criteria.

In summary, the results demonstrate that both CFRP confinement and steel jacketing are effective post-fire strengthening techniques for reinforced concrete columns, but they operate with distinct performance profiles. CFRP strengthening is efficient in restoring strength and moderating brittleness, particularly at lower fire damage levels. Steel jacketing provides a more comprehensive rehabilitation by delivering superior deformation capacity, enhanced failure stability, and greater energy absorption, especially as fire damage severity increases. These findings provide a clear and logically consistent foundation for the subsequent Findings section, where the research hypotheses are explicitly evaluated against the observed performance trends.

5. Findings

This section synthesizes and interprets the results obtained from the comparative assessment of CFRP confinement and steel jacketing for post-fire strengthening, with explicit reference to the selected case study of an interior reinforced concrete column extracted from a parking structure subjected to fire exposure. Unlike the Results section, which reported performance outcomes in an organized and descriptive manner, the Findings section moves beyond observation to extract meaning, evaluate hypotheses, and articulate the structural implications of the quantified evidence. All interpretations presented herein are derived strictly from the numerical data, performance indicators, and response patterns established in the preceding section.

The case study of a reinforced concrete parking structure is particularly instructive because parking facilities are structurally repetitive, gravity-dominated, and highly vulnerable to vehicle-

induced fire scenarios. In such structures, interior columns are critical load-bearing elements whose post-fire performance directly governs residual safety and serviceability. The findings, therefore, focus on how confinement-based strengthening strategies alter the structural role of a fire-damaged parking column, rather than treating the member as an abstract laboratory specimen.

The first major finding is that fire damage fundamentally changes the governing failure mechanism of the parking column even before strengthening is applied. Across increasing fire severity, the column response transitions from a strength-controlled regime to a deformation-controlled and ultimately brittleness-dominated regime. This transition is not linear; instead, the findings indicate a disproportionate loss of deformation capacity relative to strength. In the context of a parking structure, this implies that post-fire collapse risk is governed more by instability and sudden crushing than by gradual overload. This observation validates the premise that post-fire rehabilitation must prioritize confinement and ductility restoration, not merely strength recovery.

A second key finding concerns the effectiveness of confinement-based strengthening in reversing fire-induced degradation. Both CFRP confinement and steel jacketing are found to be capable of restoring a substantial portion of the lost axial capacity of the parking column. However, the findings demonstrate that strength recovery alone does not capture the full structural benefit of strengthening. In multiple fire damage scenarios, strength recovery reaches a plateau, while deformation capacity and energy absorption continue to differentiate the two techniques. This confirms that confinement effectiveness in post-fire conditions is governed primarily by deformation mechanics rather than peak resistance.

The third and most critical finding relates to the comparative performance hierarchy between CFRP confinement and steel jacketing. While CFRP strengthening consistently improves the post-fire behavior of the parking column relative to the unstrengthened state, steel jacketing produces a more profound and reliable transformation of structural response. The findings show that CFRP confinement shifts the column behavior from brittle to moderately ductile, whereas steel jacketing shifts it further into a stable, confinement-dominated regime characterized by sustained

load resistance over a significantly extended deformation range. This distinction becomes increasingly pronounced as fire severity increases, indicating that the reliability of confinement plays a decisive role when the concrete core is heavily degraded.

From a mechanical perspective, the findings reveal that the superiority of steel jacketing arises from its reduced sensitivity to fire-induced surface degradation and its ability to provide continuous, uniform confinement. In contrast, CFRP confinement, while mechanically efficient, remains dependent on bond integrity and the tensile performance of polymer-based materials. In a post-fire parking column—where surface cracking, porosity increase, and micro-spalling are prevalent—this dependency limits the ultimate deformation potential that CFRP can reliably mobilize. As a result, CFRP confinement exhibits diminishing relative effectiveness as fire damage severity increases.

Another important finding is the dominance of deformation and energy-related performance metrics over strength-based metrics in evaluating post-fire strengthening success. In the parking column case study, both strengthening techniques achieve comparable trends in strength recovery, yet their divergence in ductility and energy absorption is substantial. Steel jacketing consistently delivers higher deformation capacity and greater energy dissipation, indicating superior resilience under monotonic loading and, by extension, under potential future extreme events. This finding underscores that post-fire strengthening decisions for parking structures should be guided by performance objectives related to stability and robustness rather than nominal capacity alone.

The findings also provide direct evidence supporting the research hypotheses formulated earlier. The hypothesis that steel jacketing provides superior strength and ductility recovery compared to CFRP strengthening in fire-damaged reinforced concrete members is strongly supported, particularly with respect to ductility and energy absorption. The hypothesis that CFRP strengthening offers efficient strength restoration but limited deformation enhancement is also validated, as CFRP consistently delivers intermediate performance between the unstrengthened and steel-jacketed cases. Finally, the hypothesis that strengthening effectiveness is strongly dependent on fire damage severity is confirmed, with the relative advantage of steel jacketing increasing systematically as damage severity increases.

In the specific context of a parking structure, these findings carry important practical implications. Parking facilities are typically required to remain operational or be rapidly returned to service after fire events, and they are often subjected to future fire risk due to continued vehicle use. The findings suggest that while CFRP confinement may be appropriate for lightly damaged parking columns where rapid installation and minimal section enlargement are priorities, steel jacketing provides a more robust and damage-tolerant solution for moderately to severely fire-damaged columns. This distinction is particularly relevant for interior columns, where failure consequences are severe, and redundancy is limited.

Finally, the findings highlight a broader conceptual insight: post-fire strengthening should be framed as a transformation of structural behavior rather than a simple recovery of lost capacity. In

the examined parking column, the most meaningful rehabilitation outcomes are achieved when strengthening shifts the failure mechanism away from brittle concrete crushing toward controlled, confinement-governed deformation. Steel jacketing is found to be more effective in achieving this transformation under post-fire conditions, whereas CFRP confinement delivers a partial but less robust behavioral shift.

Overall, the findings demonstrate that the comparative effectiveness of CFRP and steel jacketing in post-fire strengthening cannot be judged on strength recovery alone. When evaluated through the integrated lens of strength, ductility, energy absorption, and failure stability—as required for fire-damaged parking structures—steel jacketing emerges as the more comprehensive rehabilitation strategy, particularly as fire damage severity increases. These findings establish a clear and defensible foundation for the concluding section, where the broader implications for design practice, post-fire assessment protocols, and future research directions are articulated.

6. Discussion

The purpose of this Discussion section is to interpret the findings of the present study within a broader theoretical, methodological, and practical context, while maintaining strict continuity with the Results and Findings sections. In accordance with the customized principles governing this research, the discussion does not reiterate numerical results, does not introduce new data, and does not cite external references. Instead, it reinterprets the observed outcomes, explains their underlying mechanisms, evaluates the adopted methodology, and situates the case study of a fire-damaged parking structure within the wider domain of post-fire structural rehabilitation.

At a conceptual level, the findings confirm that fire exposure fundamentally alters the structural role of reinforced concrete members by shifting governing behavior from strength-controlled to deformation-controlled mechanisms. This shift is particularly critical in parking structures, where interior columns are primarily gravity-resisting elements and are not typically designed with significant deformation demand in mind. The discussion, therefore, reframes post-fire strengthening not as a process of restoring nominal resistance, but as a process of re-establishing stable and predictable deformation capacity. This perspective aligns with the observed dominance of ductility and energy absorption over pure strength recovery in distinguishing strengthening effectiveness.

The comparative behavior of CFRP confinement and steel jacketing can be directly interpreted through their confinement mechanics and interface dependency. CFRP systems rely on tensile activation of externally bonded fibers and the integrity of the adhesive interface to mobilize confinement pressure. In post-fire conditions, where surface microcracking, porosity increase, and thermal damage are unavoidable, this reliance introduces an inherent sensitivity that limits deformation capacity, even when strength recovery appears satisfactory. The findings indicate that CFRP confinement successfully moderates post-fire brittleness but does not fully neutralize it, especially as fire damage severity increases.

Steel jacketing, by contrast, operates through continuous mechanical restraint that is less dependent on surface bond quality and more directly engaged with global deformation of the concrete core. The discussion highlights that this distinction explains the systematically superior deformation stability and energy dissipation observed for steel-jacketed columns across all fire damage levels. In the context of the parking structure case study, this behavior is particularly advantageous because it enhances robustness against progressive collapse mechanisms and provides a larger margin of safety under uncertain post-fire material conditions.

A critical interpretive insight emerging from this study is that the relative advantage of steel jacketing increases as fire damage severity increases. This trend indicates that confinement reliability, rather than confinement efficiency alone, governs post-fire strengthening success. While CFRP systems are highly efficient in undamaged or lightly damaged concrete, their performance envelope contracts as material degradation intensifies. Steel jacketing, although heavier and more intrusive, exhibits a more damage-tolerant confinement response, which becomes decisive in severely fire-damaged columns. This observation directly supports the hypothesis that strengthening effectiveness is strongly dependent on fire severity and cannot be generalized across damage states.

From a methodological standpoint, the adopted performance-based post-fire assessment framework proves to be a key strength of the study. By explicitly linking fire exposure scenarios to residual material properties and then to strengthening performance, the methodology avoids the common pitfall of evaluating strengthening systems under idealized conditions. The discussion emphasizes that this integrated approach enables traceability between fire damage, mechanical degradation, and rehabilitation outcome, which is essential for defensible post-fire decision-making. Compared to studies that treat fire damage qualitatively or as a secondary parameter, the present framework provides a clearer causal narrative connecting damage mechanisms to strengthening response.

The case study-based approach, centered on a representative parking column, also offers important interpretive value. Parking structures are structurally repetitive, and their interior columns share similar detailing, loading conditions, and fire exposure risk. As such, the discussion argues that the observed behavioral trends are not isolated to a single member but are indicative of a broader class of post-fire rehabilitation scenarios. At the same time, the discussion acknowledges that the conclusions are most directly applicable to confinement-dominated members and should be extrapolated to flexure- or shear-critical elements with appropriate caution.

Another key point addressed in this discussion is the distinction between immediate post-fire strengthening effectiveness and long-term structural resilience. While both CFRP and steel jacketing restore capacity, the findings suggest that steel jacketing offers a more stable post-peak response and a larger deformation reserve, which are essential for accommodating future uncertainties such as additional fire exposure, material aging, or unforeseen load redistribution. In a parking structure that remains in service after

rehabilitation, this added resilience is arguably more critical than marginal differences in peak strength.

The discussion also revisits the research questions and hypotheses from an integrative perspective. The comparative evidence demonstrates that the primary differentiator between CFRP and steel jacketing in post-fire conditions lies not in their ability to restore resistance, but in their capacity to reshape failure mechanisms. This insight advances the theoretical understanding of post-fire strengthening by positioning confinement-based retrofitting as a behavioral transformation tool rather than a strength enhancement technique. Such a reframing has implications for both design philosophy and performance evaluation criteria in post-fire rehabilitation.

Importantly, the discussion does not imply that CFRP confinement is unsuitable for post-fire applications. Instead, it clarifies that CFRP is most effective when fire damage is limited and when rapid, lightweight, and minimally invasive intervention is required. In contrast, steel jacketing is shown to be more appropriate for scenarios where fire damage is moderate to severe and where deformation reliability and robustness are prioritized. This nuanced interpretation moves beyond binary judgments and supports context-sensitive strengthening selection.

Finally, this discussion conceptually prepares the ground for the Conclusion section by consolidating the study's core contribution: the establishment of a clear, performance-oriented comparative understanding of CFRP and steel jacketing for post-fire strengthening of reinforced concrete structures, grounded in a realistic parking structure case study. The insights derived here provide a coherent bridge between detailed findings and actionable conclusions, ensuring that the research closes with logical continuity, methodological integrity, and practical relevance.

7. Conclusion

This study set out to develop a rigorous, performance-oriented comparison of CFRP confinement and steel jacketing techniques for the post-fire strengthening of reinforced concrete structures, using a representative parking structure column as a focused case study. Through a coherent methodological framework that explicitly linked fire-induced damage, residual structural capacity, strengthening mechanisms, and post-strengthening performance, the research achieved its primary objective of moving beyond qualitative judgment toward analytically defensible conclusions.

The conclusions of the study confirm that fire exposure fundamentally transforms the structural behavior of reinforced concrete members. Post-fire vulnerability is governed not only by strength degradation, but more critically by loss of deformation capacity and failure stability. As demonstrated throughout the analysis, this behavioral shift necessitates a strengthening philosophy centered on confinement reliability and ductility restoration rather than simple recovery of nominal resistance. In this respect, post-fire strengthening must be understood as a behavioral rehabilitation process rather than a capacity replacement exercise.

Within this framework, both CFRP confinement and steel jacketing were shown to be effective strengthening strategies when evaluated

relative to the unstrengthened post-fire condition. CFRP confinement provides a lightweight, efficient, and constructible solution capable of restoring a meaningful portion of lost strength while moderating post-fire brittleness. Its effectiveness is most pronounced in lightly fire-damaged members, where surface integrity and bond conditions remain relatively intact. In such scenarios, CFRP represents a rational and efficient intervention that aligns well with practical constraints such as limited section enlargement and rapid rehabilitation requirements.

Steel jacketing, however, emerges from this study as the more comprehensive post-fire strengthening solution, particularly as fire damage severity increases. The conclusions demonstrate that steel jacketing consistently delivers superior deformation capacity, enhanced failure stability, and greater energy absorption compared to CFRP confinement. These advantages stem from its continuous and mechanically robust confinement mechanism, which is less sensitive to fire-induced surface degradation and material uncertainty. In the context of a parking structure—where interior columns are critical gravity-resisting elements and where future fire exposure cannot be ruled out—this enhanced robustness translates directly into improved structural resilience.

A key conclusion of this research is that the relative superiority of a strengthening technique in post-fire conditions cannot be determined solely based on strength recovery. While both CFRP and steel jacketing improve load-carrying capacity, their true differentiation lies in how effectively they transform failure mechanisms from brittle, damage-sensitive responses into stable, confinement-dominated behavior. Steel jacketing achieves this transformation more reliably across a wider range of fire damage severities, whereas CFRP confinement delivers a partial but more damage-sensitive behavioral shift.

From a methodological perspective, the study confirms the value of integrating fire damage characterization directly into the strengthening evaluation process. By maintaining traceability from fire exposure assumptions through residual material degradation and into post-strengthening performance, the research avoids the common limitations of idealized or ambient-condition-based assessments. This integrated approach strengthens the credibility of the conclusions and enhances their relevance for post-fire engineering decision-making.

In practical terms, the conclusions provide clear guidance for post-fire rehabilitation of parking structures and similar reinforced concrete systems. CFRP confinement is best suited for scenarios involving limited fire damage and strong constructability constraints, while steel jacketing should be prioritized for moderate to severe fire damage where deformation reliability, robustness, and long-term safety are paramount. Importantly, this guidance does not promote a universal solution, but rather supports informed, context-sensitive selection of strengthening strategies.

Finally, this study completes a full and logically consistent research cycle—from problem definition and methodological design to results, findings, discussion, and conclusion—thereby establishing a solid foundation for future work. The conclusions reached here open pathways for extending the framework to other structural members, loading conditions, and combined hazards, while also

contributing directly to performance-based post-fire strengthening practice. In this sense, the project not only defines all critical analytical steps but also delivers a coherent and actionable contribution to the field of post-fire structural rehabilitation.

8. Sources

1. Aboutaha, R. S., Engelhardt, M. D., Jirsa, J. O., & Kreger, M. E. (1999). Rehabilitation of shear critical concrete columns by use of rectangular steel jackets. *ACI Structural Journal*, 96(1), 68–78. <https://doi.org/10.14359/597>
2. Aghazadeh Dizaji, A. (2018). Buckling behavior of dented short cylindrical shells (Master's thesis, YÖK Tez No: 507581). Institute of Natural Sciences (Fen Bilimleri Enstitüsü), Atatürk University.
3. Aghazadeh Dizaji, A. (2024). Through what factors does polymer concrete have mechanical resistance? *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6). <https://doi.org/10.62225/2583049X.2024.4.6.3456>
4. Aghazadeh Dizaji, A. A. (2024). Dynamic analysis of high-rise residential structures through the cone method. *Edelweiss Applied Science and Technology*, 8(6), 1895–1914. <https://doi.org/10.55214/25768484.v8i6.2355>
5. Aghazadeh Dizaji, A., & Aydın, A. C. (2025). Application of the 3D finite element method in quantitative comparison of bearing capacity of conical and cylindrical piles. *ISAR Journal of Science and Technology*, 1(2), 1–9. <https://isarpublisher.com/backend/public/assets/articles/1744121292-ISARJST-1492025-GP.pdf>
6. Aghazadeh Dizaji, A., Kılıç, M., Maali, M., & Aydın, A. C. (2023). Buckling behaviour of dented short cylindrical shells retrofitted with CFRP. *Proceedings of the Institution of Civil Engineers – Structures and Buildings*, 176(1), 62–75. <https://doi.org/10.1680/jstbu.20.00145>
7. Ali Aghazadeh Dizaji, N., & Ahmadian, R. (2016). Transport corridors role in improving the urban environment studies: Axis Khayyam (Tehran Metro Line 1). In *Proceedings of the International Conference on Civil Engineering, Architecture and Cityscape*.
8. Aydın, A. C., Yaman, Z., Ağcakoca, E., Kılıç, M., Maali, M., & Aghazadeh Dizaji, A. (2020). CFRP effect on the buckling behavior of dented cylindrical shells. *International Journal of Steel Structures*, 20(2), 425–435. <https://doi.org/10.1007/s13296-019-00294-4>
9. Bisby, L. A., Green, M. F., & Kodur, V. K. R. (2005). Fire behaviour of FRP-strengthened reinforced concrete beams. *Engineering Structures*, 27(4), 599–610. <https://doi.org/10.1016/j.engstruct.2004.11.014>
10. Burke, P. J., Bisby, L. A., & Green, M. F. (2013). Effects of elevated temperature on externally bonded FRP strengthening systems for concrete. *Cement and Concrete Composites*, 35(1), 190–199. <https://doi.org/10.1016/j.cemconcomp.2012.08.012>
11. CEN. (2002). Eurocode 1: Actions on structures—Part 1-2: Actions on structures exposed to fire (EN 1991-1-2). European Committee for Standardization.

12. CEN. (2004). Eurocode 2: Design of concrete structures—Part 1-2: Structural fire design (EN 1992-1-2). European Committee for Standardization. 454–462. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000350](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000350)
13. CEN. (2005). Eurocode 3: Design of steel structures—Part 1-2: Structural fire design (EN 1993-1-2). European Committee for Standardization.
14. Firmo, J. P., Correia, J. R., & França, P. (2015). Fire behaviour of FRP-strengthened reinforced concrete structural elements: A state-of-the-art review. *Composite Structures*, 126, 313–327. <https://doi.org/10.1016/j.compstruct.2015.02.023>
15. Huang, Z. (2010). The behaviour of reinforced concrete slabs in fire. *Fire Safety Journal*, 45(5), 271–282. <https://doi.org/10.1016/j.firesaf.2010.04.002>
16. Jiang, T., & Teng, J. G. (2007). Analysis-oriented stress–strain models for FRP-confined concrete. *Engineering Structures*, 29(11), 2968–2986. <https://doi.org/10.1016/j.engstruct.2007.01.010>
17. Kodur, V. K. R. (2014). Properties of concrete at elevated temperatures. *ISRN Civil Engineering*, 2014, 1–15. <https://doi.org/10.1155/2014/468510>
18. Kodur, V. K. R., & Yu, B. (2013). Evaluating the fire response of concrete beams strengthened with FRP reinforcement. *Journal of Composites for Construction*, 17(4), 517–529. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000352](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000352)
19. Lam, L., & Teng, J. G. (2003). Design-oriented stress–strain model for FRP-confined concrete. *Cement and Concrete Composites*, 25(8), 919–929. [https://doi.org/10.1016/S0958-9465\(02\)00099-7](https://doi.org/10.1016/S0958-9465(02)00099-7)
20. Li, Y. H., Tan, K. H., & Yang, E. H. (2011). Residual compressive strength of concrete after elevated temperature exposure. *Journal of Structural Fire Engineering*, 2(1), 29–44. <https://doi.org/10.1260/2040-2317.2.1.29>
21. Lim, J. C., & Ozbakkaloglu, T. (2015). Stress–strain behavior of FRP-confined concrete after high-temperature exposure. *Construction and Building Materials*, 90, 236–246. <https://doi.org/10.1016/j.conbuildmat.2015.05.003>
22. Ma, W., Yin, C., Zhou, J., & Wang, L. (2019). Repair of fire-damaged reinforced concrete flexural members: A review. *Sustainability*, 11(19), 5199. <https://doi.org/10.3390/su11195199>
23. Ozbakkaloglu, T. (2013). FRP-confined concrete in circular sections: Review and assessment of stress–strain models. *Engineering Structures*, 49, 1068–1088. <https://doi.org/10.1016/j.engstruct.2012.12.026>
24. Ozbakkaloglu, T., & Lim, J. C. (2013). FRP confinement of concrete after high temperature exposure. *Materials and Structures*, 46(1–2), 1–17. <https://doi.org/10.1617/s11527-012-9864-7>
25. Palmieri, A., Matthys, S., & Taerwe, L. (2013). Fire endurance of insulated RC beams strengthened with NSM reinforcement. *Journal of Composites for Construction*, 17(4), 454–462. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000350](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000350)
26. Priestley, M. J. N., Seible, F., Xiao, Y., & Verma, R. (1994). Steel jacket retrofitting of reinforced concrete bridge columns—Part 1: Theoretical considerations and test design. *ACI Structural Journal*, 91(4), 394–405.
27. Priestley, M. J. N., Seible, F., Xiao, Y., & Verma, R. (1994). Steel jacket retrofitting of reinforced concrete bridge columns—Part 2: Test results and comparison with theory. *ACI Structural Journal*, 91(5), 537–551.
28. Raza, S., Qazi, A. U., Khan, M. K., Javed, M. F., & Ali, M. (2019). Strengthening of RC columns by jacketing: A state-of-the-art review. *Sustainability*, 11(11), 3208. <https://doi.org/10.3390/su11113208>
29. Sarabi, M. S. (2024). Deploying FRP optimally in the process of strengthening concrete structures. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 383–390. <https://doi.org/10.62225/2583049X.2024.4.6.3449>
30. Tao, Z., Song, T. Y., Uy, B., & Huang, Z. (2012). Residual bond strength in steel reinforced concrete columns after fire exposure. *Fire Safety Journal*, 49, 1–11. <https://doi.org/10.1016/j.firesaf.2011.12.002>
31. Thermou, G. E., Papanikolaou, V. K., & Hajirasouliha, I. (2021). Structural performance of RC columns retrofitted with steel-reinforced grout jackets. *Engineering Structures*, 236, 112110. <https://doi.org/10.1016/j.engstruct.2021.112110>
32. Thi, C. N., Pansuk, W., & Torres, L. (2015). Flexural behavior of fire-damaged RC slabs repaired with CFRP rods. *Journal of Advanced Concrete Technology*, 13(1), 15–29. <https://doi.org/10.3151/jact.13.15>
33. Williams, B., Bisby, L., Kodur, V. K. R., & Green, M. (2005). Fire performance of FRP-strengthened reinforced concrete beams. *Fire Safety Science*, 8, 1401–1412.
34. Xiao, Y., & Wu, H. (2003). Retrofit of reinforced concrete columns using steel jackets. *Journal of Structural Engineering*, 129(6), 725–732. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2003\)129:6\(725\)](https://doi.org/10.1061/(ASCE)0733-9445(2003)129:6(725))
35. Yaqub, M., & Bailey, C. G. (2011). Repair of fire damaged RC columns with FRP composites. *Construction and Building Materials*, 25(1), 359–370. <https://doi.org/10.1016/j.conbuildmat.2010.06.061>
36. Youssef, M. A., Moftah, M., & Khatib, J. (2015). Damage assessment of reinforced concrete structures after fire exposure. *Structural Concrete*, 16(1), 26–37. <https://doi.org/10.1002/suco.201400036>
37. Zhou, J., & Wang, L. (2019). Repair of fire-damaged reinforced concrete members: A review. *Sustainability*, 11(4), 963. <https://doi.org/10.3390/su11040963>
38. Zhu, H., Wu, G., Wang, X., & Chen, G. (2014). Fire resistance of RC beams strengthened with FRP. *Composites Part B: Engineering*, 56, 591–602. <https://doi.org/10.1016/j.compositesb.2013.08.040>