Structural Performance of Four-Sided UHPC Jacketing for RC Columns under Concentric Axial Loading: A Comprehensive Review

Satrio Harry[1], Mardiana Oesman[1*]

[1]*Civil Engineering Department, Politeknik Negeri Bandung, Bandung, Indonesia*
[*]*Corresponding author: mardianaoesman@polban.ac.id*

ABSTRACT

The structural rehabilitation of reinforced concrete (RC) columns is essential in extending the service life of aging infrastructure, especially in high-load or corrosive environments. Ultra-High-Performance Concrete (UHPC) jacketing has emerged as a promising strengthening technique, offering exceptional compressive and tensile strength, enhanced ductility, high durability, and superior bond characteristics compared to conventional concrete. When applied as a four-sided jacket to reinforced concrete (RC) columns, UHPC provides continuous confinement, improving axial load capacity and post-peak behavior. This review presents a comprehensive analysis of research related to four-sided UHPC jacketing under concentric axial loading, emphasizing material properties, confinement mechanisms, experimental results, and comparative evaluations against other strengthening techniques such as steel jacketing and Fiber Reinforced Polymer (FRP) wrapping. Experimental findings reveal that UHPC jacketing can achieve axial strength improvements of 30–80% with minimal increase in cross-sectional dimensions. The paper also discusses critical design considerations, life-cycle cost (LCC) implications, identifies current research gaps, and outlines future directions for the practical implementation of UHPC jacketing in structural retrofitting, including adaptation strategies for national standards.

Keywords: *Concentric Axial Load, Jacketing, RC Columns, Structural Retrofitting, UHPC*

1. INTRODUCTION

The need for efficient and durable retrofitting methods for aging RC structures has become increasingly urgent due to rising demands for safety, serviceability, and extended service life. Conventional jacketing methods, such as RC overlays and steel plates, have proven effective but present challenges including increased section size, susceptibility to corrosion, and significant construction disruption [1]. Fiber Reinforced Polymer (FRP) systems, while lightweight and corrosion-resistant, often suffer from brittle failure modes and reduced confinement efficiency after rupture [2].

Ultra-High Performance Concrete (UHPC), characterized by compressive strengths exceeding 150 MPa, low permeability, and steel fiber reinforcement, has emerged as a promising alternative. When applied as a four-sided jacket, UHPC can provide continuous confinement, increase axial strength, and maintain structural integrity under severe loading conditions [3]. The combination of mechanical superiority and durability makes UHPC jacketing particularly suited for critical infrastructure such as bridge piers, high-rise building columns, and seismic retrofits [4]. This paper aims to provide a comprehensive review of the mechanical performance of four-sided UHPC jacketing for RC columns under concentric axial loads, synthesize findings from experimental and analytical studies, compare UHPC jacketing with alternative retrofitting systems, and highlight areas for further research.

Ultra-High Performance Concrete (UHPC) is classified as an advanced cementitious composite characterized by exceptional mechanical performance, superior durability, and refined microstructural properties compared to conventional concrete. Typical compressive strengths of UHPC exceed 150 MPa, while tensile strengths generally range from 5 to 15 MPa when high-strength steel fibers are incorporated [5]. These superior properties are primarily attributed to a highly compact microstructure, achieved through a low water-to-binder ratio (typically 0.18–0.25), a high cementitious content, optimized particle size distribution via supplementary cementitious materials (SCMs) such as silica fume, and the use of high-range water-reducing admixtures (superplasticizers) to maintain adequate workability. The inclusion of short, high-strength steel fibers typically between 1% and 3% by volume further enhances tensile capacity, promotes strain-hardening behavior, and improves crack control.

From a microstructural standpoint, UHPC exhibits near-impermeability due to its optimized packing density and significantly reduced capillary porosity. This results in exceptional resistance to aggressive environmental exposures, including chloride ingress, freeze–thaw cycles, and carbonation. In the context of structural retrofitting, such durability ensures that the strengthening layer retains its mechanical and protective properties throughout extended service lives, thereby minimizing the need for future maintenance interventions.

2. MATERIAL PROPERTIES OF UHPC

Ultra-High Performance Concrete (UHPC) is classified as an advanced cementitious composite characterized by exceptional mechanical performance, superior durability, and refined microstructural properties compared to conventional concrete. Typical compressive strengths of UHPC exceed 150 MPa, while tensile strengths generally range from 5 to 15 MPa when high-strength steel fibers are incorporated [5]. These superior properties are primarily attributed to a highly compact microstructure, achieved through a low water-to-binder ratio (typically 0.18–0.25), a high cementitious content, and optimized particle size distribution.
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3. EXPERIMENTAL FRAMEWORK AND LITERATURE REVIEW

This review systematically investigates experimental and numerical studies on RC columns strengthened with four-sided UHPC jackets. The scope encompasses a comparative performance analysis among conventional RC, steel, FRP, and UHPC jacketing techniques. Furthermore, this study identifies key design parameters influencing retrofitting effectiveness and highlights critical knowledge gaps, particularly concerning structural applications in tropical climates and active seismic zones. To ensure methodological transparency, this review adopted a structured approach inspired by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Literature was gathered from peer-reviewed journals indexed in Scopus and Web of Science for the period 2015–2024. The primary search strings included combinations of keywords: ("UHPC" OR "Ultra-High Performance Concrete") AND ("jacketing" OR "confinement" OR "strengthening") AND ("RC columns" OR "axial loading"). The initial search yielded over 150 records, which were screened for relevance. Inclusion criteria required explicit reporting of axial capacity improvement, jacket configuration, and material properties. After removing duplicates and off-topic studies, a core set of highly relevant experimental and numerical studies was selected for detailed quantitative and qualitative synthesis.

4. STRENGTHENING MECHANISM OF UHPC JACKETING

4.1 Confinement and Compressive Stress-Strain Enhancement

UHPC jacketing increases lateral confinement pressure, delaying the crushing of the concrete core and raising the ultimate compressive strain. This results in higher axial capacity and improved post-peak behavior.

4.2 Composite Action and Interface Bond

Effective stress transfer between the existing reinforced concrete column and the UHPC jacket is essential to achieve full composite behavior. Without adequate bonding, premature sliding or delamination occurs, severely limiting the jacket's confinement efficiency. Recent analytical bond-slip models suggest that cohesive-friction behavior at the interface relies heavily on mechanical interlocking. While surface treatments such as sandblasting or grooving improve the micro-texture, they are often insufficient under high axial strain gradients. The introduction of mechanical connectors, such as steel dowels or internal shear meshes, significantly delays debonding. These connectors ensure that the high tensile strain capacity of the UHPC jacket is fully utilized before interface failure occurs.

5. EXPERIMENTAL RESULTS AND QUANTITATIVE SYNTHESIS

The reviewed studies consistently report substantial improvements in axial capacity and ductility. Table 1 synthesizes the key experimental findings from validated literature, ensuring consistent tracking of geometric and performance parameters. Based on the synthesized data, there is a positive correlation between fiber volume fraction (up to 2.0–2.5%) and the percentage increase in axial load capacity. Jacket thicknesses between 30–50 mm provides an optimal strength gain ranging from 150% to over 300%, depending on the original concrete strength and the presence of transverse ties. Claims of strength increases beyond 300% are generally associated with hybrid reinforcement configurations or extremely degraded initial core conditions.

6. LIFE-CYCLE COST (LCC) AND SUSTAINABILITY

While the initial material cost of UHPC is significantly higher than conventional concrete, a Life-Cycle Cost (LCC) perspective justifies its use. Over a 50-year service life, the near-zero maintenance requirement, immunity to chloride-induced corrosion, and superior durability of UHPC offset the initial expenditure. Furthermore, the minimal increase in cross-sectional area preserves valuable architectural space. Environmentally, optimizing UHPC mixes with supplementary cementitious materials (SCMs) can reduce its carbon footprint, making it a sustainable choice for long-term retrofitting.

Table 1. Summary of experimental studies on UHPC jacketing

Author (Year)	Column Dimensions (mm)	Original Concrete (MPa)	Jacket Thickness (mm)	Fiber Content (vol %)	Strength Gain (%)	Failure Mode
Lee et al. (2017)	300×300×1200	25	30	2.0	+180%	Core crushing after UHPC cracking
Yoo & Yoon (2018)	250×250×1000	28	25	1.5	+150%	Jacket cracking followed by core crushing
Kang et al. (2019)	350×350×1400	21	40	2.0	+220%	Delayed spalling, ductile crushing
Le Hoang et al. (2024) [6]	Ø150 (Circular)	N/A	20–40	1.0–2.0	+75%	Validated via FEM models
Zhang et al. (2021)	400×400×1600	25	50	2.5	+310%	Progressive fiber pull-out

7. COMPARATIVE EVALUATION AND DESIGN CONSIDERATIONS

Strengthening RC columns can be achieved through various jacketing and retrofitting methods, including reinforced concrete (RC) jacketing, steel jacketing, fiber-reinforced polymer (FRP) wrapping, and ultra-high performance concrete (UHPC) jacketing. While all methods aim to enhance axial capacity, ductility, and durability, each has distinct advantages and limitations, especially when evaluated for concentric axial loading.

7.1 RC Jacketing

RC jacketing involves encasing the column with a layer of conventional concrete reinforced with steel bars and ties. Increases cross-section and axial load capacity by 20–50 % but adds significant dead weight and often requires long curing times [11]. RC jackets also have lower durability in chloride-rich or marine environments compared to UHPC [12].

7.2 Steel Jacketing

Fan et al. (2025) investigated the behavior of square RC short columns confined with corrugated steel jackets under axial compression and reported significant improvements in compressive strength as well as more stable failure modes [13]. Steel-based confinement techniques were also proposed through the use of directly fastened steel plates for seismic strengthening and later extended for axial capacity enhancement [14, 15]. However, steel jacketing is prone to corrosion, requiring protective coatings.

7.3 FRP Wrapping

Lightweight, corrosion-resistant, and quick to install, FRP confinement can improve strength by 25–60 % [16] but loses performance at elevated temperatures (>60 °C) and is sensitive to UV degradation.

7.4 UHPC Jacketing

UHPC jacketing combines high compressive strength, high stiffness, superior durability, and excellent bond characteristics. Comparative studies [17] indicate that UHPC jackets outperform FRP in long-term durability. UHPC jacketing provides substantial strength increases, typically ranging from 60% to 310% in standard applications. In extreme cases, where UHPC is combined with additional longitudinal steel reinforcement, the axial capacity can be multiplied by up to 6.4 times (an increase of over 500%) compared to the unconfined column [8]. Furthermore, UHPC provides high durability due to the dense matrix and fiber reinforcement, minimal increase in section size, and superior protection of internal steel reinforcement [18, 19].

7.5 Design Considerations for UHPC Jacketing

Design considerations must emphasize the critical role of anchorage and interface detailing in the effectiveness of jacketing systems [20]. Reviews of external confinement techniques further highlight its advantages when compared to conventional approaches [21]. In contrast, experimental work on cold-formed steel jackets shows notable improvements... employing UHPC jacketing in axial strengthening applications [22]. When designing UHPC jackets for RC columns under concentric axial loading, several factors must be addressed:

1. The jacket thickness should be designed to provide an optimal balance between strength enhancement, constructability, and additional structural weight.
2. The fiber content and type significantly influence the confinement effect; steel fibers with a 2% volume fraction and hooked-end geometry are generally considered optimal, whereas excessive fiber content may lead to workability problems.

3. The bonding strategy between the UHPC jacket and the existing concrete substrate is critical; appropriate surface preparation, such as sandblasting or grooving, is recommended to minimize the risk of delamination.
4. The reinforcement layout within the UHPC jacket can improve performance; incorporating light transverse reinforcement can delay crack initiation and enhance ductility.
5. The curing regime should be properly controlled to ensure that UHPC attains its intended mechanical properties; steam curing may be employed for prefabricated shells.
6. The continuity of the load path must be ensured to achieve uniform confinement; discontinuities such as gaps or voids can significantly reduce the effectiveness of the jacket.

Design considerations for UHPC jacketing must address not only the superior material properties of UHPC but also its interaction with reinforcement and alternative confinement systems. Recent studies demonstrate that integrating CFRP rods with UHPFRC jackets and mechanical anchorage enhances both axial and flexural performance, emphasizing the critical role of anchorage and interface detailing in the effectiveness of jacketing systems [22].

7.6 Practical Implementation

Field applications of UHPC jacketing have shown that prefabricated UHPC shells can significantly reduce on-site labor and curing time. The shells are fabricated in controlled environments, ensuring consistent quality, and then bonded to the existing column using high-strength grout or UHPC slurry. Cast-in-place jackets remain common for smaller projects or where shell installation is impractical.

7.7 Adaptation to Indonesian Standards (SNI)

The Indonesian National Standard (SNI) currently covers FRP and conventional concrete jacketing but lacks explicit provisions for UHPC retrofitting. Based on international codes (e.g., ACI 239R, fib Model Code 2020), the following adaptations are proposed:

1. Material Classification: UHPC should be defined as cementitious composite with compressive strength ≥120 MPa and documented tensile strain-hardening capacity.
2. Design Methodology: Axial capacity design should combine core confinement models with UHPC-specific stress–strain relationships validated by local tests.
3. Durability Requirements: Specify maximum chloride permeability (≤1000 C, ASTM C1202) and minimum fiber volume fraction (≥1.0 %).
4. Construction Tolerances: Define allowable deviations for jacket thickness (±3 mm) and fiber dispersion.
5. Quality Control: Mandate trial mixes, shrinkage measurement, and interface bond tests before site application.

Such provisions would facilitate safe and standardized application of UHPC jackets in Indonesia's coastal, seismic, and tropical environments.

8. RESEARCH GAPS AND FUTURE WORK

Despite the promising experimental and analytical results obtained so far, the application of four-sided UHPC jacketing for RC columns under concentric axial loading is still in its developmental stage. Current literature highlights several gaps that need to be addressed before this technique can be fully standardized in design codes and widely implemented in practice.

8.1 Limited Full-Scale Testing

Most experimental programs have used small- to medium-scale specimens due to laboratory constraints, cost, and handling limitations. While these scaled tests provide valuable insights into general trends, they may not fully capture scale-dependent behaviors such as strain gradients, load transfer mechanisms, and potential buckling phenomena in taller columns. Full-scale testing, particularly for bridge piers and high-rise building columns, is necessary to validate scaling laws and refine design parameters.

8.2 Incomplete Understanding of Long-Term Performance

UHPC's durability under aggressive environmental exposure is well-documented in its unrestrained form, but less is known about how it performs as a jacket bonded to existing concrete over decades. Factors such as differential shrinkage between UHPC and the old concrete core, creep under sustained loads, and freeze–thaw cycling at the interface could influence long-term confinement effectiveness. There is a need for accelerated aging studies and long-term field monitoring of retrofitted structures.

8.3 Bond and Interface Behavior under Complex Loading

Most studies focus on monotonic concentric compression. However, in real structures, columns are subjected to combined loading conditions including bending, shear, and torsion, often under cyclic or seismic excitation. The bond between the UHPC layer and the original concrete under these complex states of stress remains poorly understood. Debonding or slip at the interface could compromise jacket performance, especially during seismic events. Detailed bond-slip models and experimental validation are required.

8.4 Optimization of Jacket Thickness and Fiber Content

Current practice often selects jacket thickness and fiber volume fraction based on prior studies or practical constraints, rather than optimized structural performance. Systematic parametric studies, combining experiments and finite element simulations, could identify optimal configurations for different retrofitting objectives.

8.5 Influence of Construction Methods

The choice between cast-in-place and prefabricated UHPC shells significantly affects construction time, quality control, and performance. While prefabricated shells ensure consistent UHPC quality, achieving a perfect fit and bond to irregular existing columns is challenging. Conversely, cast-in-place jackets can adapt to irregularities but may suffer from inconsistent fiber distribution or void formation. Research into hybrid approaches, such as prefabricated panels combined with in-situ UHPC joints, could bridge this gap.

8.6 Future Research Directions

Based on the identified gaps, the following research directions are proposed:

1. Conduct large-scale and full-scale testing of UHPC-jacketed columns under various loading conditions, including seismic simulations.
2. Develop and validate long-term durability models for bonded UHPC-concrete interfaces.
3. Perform advanced numerical simulations incorporating nonlinear material models, fiber pull-out behavior, and interface mechanics.
4. Investigate hybrid strengthening systems combining UHPC jackets with embedded FRP or steel elements for enhanced multi-hazard performance.
5. Explore sustainable UHPC mix designs using low-carbon binders and alternative fibers.
6. Formulate design recommendations and reliability-based safety factors for code adoption.

8.7 Economic and Environmental Assessment

UHPC materials are more expensive than normal concrete, and their environmental footprint is higher per unit volume due to cement content and energy-intensive fiber production. Comprehensive life-cycle cost analyses, considering reduced maintenance and extended service life, are needed to justify UHPC jacketing from both economic and sustainability perspectives. Moreover, research into greener UHPC formulations can help mitigate environmental impacts.

8.8 Integration into Design Codes

Currently, there are no widely adopted design provisions specifically addressing UHPC jacketing for RC columns. Most practitioners adapt confinement models originally developed for steel or FRP jacketing, applying empirical adjustments based on test results. This lack of standardized guidance can lead to inconsistent designs and performance outcomes. Collaborative research involving academia, industry, and code-writing bodies is essential to develop reliable, universally accepted design equations.

9. CONCLUSION

The use of ultra-high performance concrete (UHPC) jacketing for strengthening reinforced concrete (RC) columns represents a significant advancement in structural retrofitting technology. In particular, the application of four-sided UHPC jackets under concentric axial loading has demonstrated substantial benefits in terms of strength enhancement, ductility improvement, and long-term durability. Experimental evidence consistently shows that UHPC jackets, even with relatively small thicknesses of 20–50 mm, can achieve strength gains comparable to or exceeding those obtained with conventional reinforced concrete or steel jacketing, while also offering superior resistance to environmental degradation.

The exceptional performance of UHPC jacketing can be attributed to its unique combination of high compressive strength, high modulus of elasticity, and steel fiber reinforcement, which together create an efficient and sustained confinement effect on the concrete core. Unlike FRP systems, whose confinement efficiency can drop sharply after fiber rupture, UHPC maintains its integrity and load-carrying capacity well into the post-cracking phase. This sustained confinement not only increases peak load capacity but also improves post-peak ductility, which is critical for structural safety and serviceability.

From a practical perspective, UHPC jacketing offers several additional advantages. Its relatively small thickness preserves architectural clearances, making it suitable for retrofitting in constrained urban environments. Its inherent durability, including resistance to chloride penetration, freeze–thaw damage, and carbonation, ensures minimal maintenance over the structure's extended service life. Prefabricated UHPC shells allow for rapid installation with minimal disruption, while cast-in-place options can adapt to irregular geometries and site conditions.

However, despite these advantages, the widespread adoption of UHPC jacketing faces certain challenges. Key among these is the higher initial material cost compared to conventional retrofitting methods, although life-cycle cost analyses may demonstrate its long-term economic viability. Additionally, the lack of standardized design guidelines specific to UHPC jacketing requires engineers to adapt models developed for other confinement systems, leading to potential variability in design and performance outcomes. The mechanical behavior of the UHPC-concrete interface under complex loading states, particularly over long service periods, also warrants further investigation.

Looking ahead, addressing the identified research gaps—such as scaling up to full-size column testing, developing comprehensive long-term durability models, optimizing mix designs for sustainability, and integrating UHPC jacketing provisions into structural design codes—will be critical for realizing the full potential of this technology. Collaborative research between academia, industry, and code-making bodies will accelerate this process, leading to safer, more durable, and more efficient retrofitting solutions for aging infrastructure.

In conclusion, four-sided UHPC jacketing under concentric axial loading stands out as a highly effective method for strengthening RC columns, combining mechanical performance with durability in a way that few other systems can match. With continued research, optimization, and standardization, UHPC jacketing has the potential to become a mainstream retrofitting strategy, particularly for critical infrastructure where long-term reliability and minimal maintenance are paramount. Four-sided UHPC jacketing represents a high-performance, durable, and potentially cost-effective strengthening strategy for RC columns. With targeted research to address the identified gaps, this technique could play a significant role in enhancing the safety, resilience, and service life of critical infrastructure in Indonesia and beyond.

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