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A COMPREHENSIVE SYSTEMATIC REVIEW OF SEISMIC PERFORMANCE OF REINFORCED CONCRETE BEAM-COLUMN JOINTS RETROFITTED USING FIBER REINFORCED POLYMER COMPOSITES UNDER REVERSED CYCLIC LOADING

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Abstract

Reinforced concrete beam-column joints are critical structural components that are particularly vulnerable to failure during seismic events, especially in structures designed prior to modern seismic codes. This systematic review synthesizes current research on the effectiveness of fiber reinforced polymer (FRP) composites in retrofitting deficient reinforced concrete beam-column joints subjected to reversed cyclic loading. Through comprehensive examination of 50+ peer-reviewed studies, the review evaluates various FRP types including carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP), aramid fiber reinforced polymers (AFRP), and basalt fiber reinforced polymers (BFRP) applied through different retrofitting techniques. Key findings indicate that combined CFRP systems achieve improvements up to 65% in peak load capacity and 55% enhancement in energy dissipation compared to unstrengthened specimens. Near-surface-mounted (NSM) CFRP ropes in X-shaped configurations demonstrate superior performance by reducing joint shear deformations by over 40% while maintaining over 90% peak strength at 4% drift ratios. External bonded reinforcement (EBR) techniques show consistent 35-45% improvements in shear strength. Numerical finite element modeling validates experimental findings with error margins below 5%, confirming the reliability of predictive approaches. Advanced retrofitting configurations incorporating hybrid fiber systems and engineered cementitious composites provide enhanced ductility and improved failure mechanisms, transforming brittle shear failures into ductile beam flexural failures. This review establishes that properly designed and installed FRP retrofitting protocols offer economically viable, lightweight, and rapidly deployable solutions for extending the service life and enhancing the post-earthquake functionality of critical structural connections in existing RC frame structures.

Introduction

The vulnerability of reinforced concrete (RC) beam-column joints to seismic damage represents one of the most critical concerns in earthquake engineering and structural preservation. Extensive post-earthquake reconnaissance studies have repeatedly demonstrated that inadequately designed and detailed beam-column joints are among the first components to fail during seismic events, often initiating progressive collapse mechanisms that threaten the entire structural system (Kabashi *et al.*, 2025). The majority of RC buildings constructed before the 1970s employed non-seismic design practices, characterized by insufficient transverse reinforcement in joint regions, poor anchorage details for longitudinal reinforcement, and inadequate consideration of shear transfer mechanisms (Adil *et al.*, 2024). These deficiencies result in brittle shear failure modes that provide minimal warning before catastrophic structural failure, with inadequate energy dissipation capacity and rapid stiffness degradation under reversed cyclic loading.

Beam-column joints represent uniquely complex structural elements that experience simultaneous bending moments, shear forces, and complex stress concentrations due to the intersection of beam and column members (Golias and Karayannis, 2025). During seismic activity, these joints are subjected to reversed cyclic loading that induces progressive damage accumulation, including diagonal cracking in the joint core, spalling of concrete, buckling of transverse reinforcement, and deterioration of bond between steel reinforcement and concrete matrix. The shear stress concentration at joint regions can exceed 1.5 times the nominal shear stress, resulting in premature joint core failure that compromises both local joint behavior and global structural response. Historical earthquakes have documented numerous instances where deficient joints triggered cascading failures affecting multiple stories, leading to partial or complete structural collapse (Akguzel, 2011).

Traditional strengthening approaches for deficient beam-column joints have included steel jacketing, concrete encasement, and installation of additional transverse reinforcement. While these methods have proven effective, they present significant limitations including substantial weight increase, reduced usable floor space, extended construction timelines, and high labor costs. These conventional techniques require local demolition and removal of existing structural elements, disruption of building operations, and skilled workforce availability. Additionally, steel-based retrofits introduce corrosion concerns in aggressive environments and require surface protection measures, increasing long-term maintenance requirements (Angalekar and Ghorpade, 2025).

Fiber reinforced polymer (FRP) composites have emerged as transformative materials for seismic retrofitting of RC structures over the past two decades, offering numerous advantages over traditional strengthening methods (Ridwan, Jemaa and Yuniarto, 2023). FRP materials demonstrate high strength-to-weight ratios (typically 3-6 times superior to steel), excellent corrosion resistance, non-magnetic properties facilitating installation near electrical equipment, and rapid curing characteristics enabling minimal construction disruption. The anisotropic nature of FRP materials allows engineers to orient fibers strategically to reinforce specific load paths, providing tailored strengthening solutions for complex stress distributions characteristic of beam-column joints. Unlike steel reinforcement that can experience significant corrosion in chloride-rich environments such as coastal regions, FRP composites maintain their mechanical properties indefinitely when properly protected from ultraviolet exposure (Prakash and Parthasarathi, 2024).

The retrofitting of beam-column joints using FRP composites has evolved considerably since initial applications in the 1990s. Early research focused on externally bonded reinforcement (EBR) techniques applying FRP sheets directly to joint surfaces, with adhesive bonding providing force transfer. Subsequent development of near-surface-mounted (NSM) techniques involved placing discrete FRP ropes or strips within shallow grooves cut into concrete surfaces, offering improved protection from environmental degradation and mechanical damage (Sapidis *et al.*, 2024). More recent innovations include X-shaped rope configurations providing enhanced three-dimensional confinement, combination strategies integrating both NSM ropes and EBR sheets, and hybrid approaches incorporating engineered cementitious composites (ECC) or engineered cementitious materials with FRP reinforcement.

This systematic review synthesizes comprehensive experimental and numerical evidence regarding FRP retrofitting effectiveness for seismic strengthening of RC beam-column joints under reversed cyclic loading. The review examines multiple dimensions of this complex problem, including detailed characterization of different FRP material types and their mechanical properties, comparative evaluation of various retrofitting application techniques, quantitative assessment of performance improvements across multiple parameters including shear strength, ductility, energy dissipation, and stiffness retention, analysis of failure mechanism transformations, and validation of numerical modeling approaches (Noor, Javed and Shahzada, 2025). By synthesizing findings from over 50 peer-reviewed publications spanning experimental investigations, numerical studies, and comparative analyses, this review establishes current understanding of FRP retrofitting effectiveness while identifying critical knowledge gaps requiring additional research attention.

1. Fiber Reinforced Polymer Materials: Classification, Properties, and Selection Criteria

1.1 Types of FRP Composites in Structural Applications

Fiber reinforced polymer composites utilized in seismic retrofit applications consist of discrete continuous fibers embedded within a polymeric matrix, with fiber orientation and volume fraction critically influencing composite properties (Al-Gabri *et al.*, 2024). The primary fiber types employed in structural retrofitting include carbon fibers (CFRP), glass fibers (GFRP), aramid fibers (AFRP), and basalt fibers (BFRP), each offering distinct mechanical characteristics and cost-performance profiles. Carbon fiber reinforced polymers represent the premium option, providing the highest strength-to-weight ratio (approximately 50-85 GPa elastic modulus, 3800-4200 MPa tensile strength) with superior fatigue performance and minimal moisture absorption (Mohanraj *et al.*, 2024). Glass fiber reinforced polymers offer more economical solutions with reasonable strength characteristics (elastic modulus 26-35 GPa, tensile strength 400-1000 MPa), making them attractive for applications where cost considerations are paramount. Aramid fiber reinforced polymers provide distinctive advantages including excellent impact resistance and damage tolerance, with tensile strengths ranging from 1000-1400 MPa (Al-Gabri *et al.*, 2024).

Basalt fiber reinforced polymers represent an emerging material class offering intermediate performance characteristics between glass and carbon fibers, with tensile strengths of 1000-1200 MPa and elastic moduli of 40-50 GPa, combined with superior corrosion resistance compared to glass fibers and lower cost than carbon fibers (Shen *et al.*, 2022). Hybrid fiber systems combining two or more fiber types, such as CFRP/GFRP combinations or AFRP/CFRP arrangements, have demonstrated enhanced performance by leveraging complementary mechanical properties, achieving improved deformation capacity and impact resistance while optimizing cost-effectiveness. The epoxy polymeric matrices typically employed provide excellent adhesion to concrete surfaces, high durability under environmental exposure, and superior fire performance compared to polyester or vinyl ester resins, though emerging cementitious matrix systems offer enhanced durability and moisture resistance for critical applications.

1.2 Mechanical Properties and Performance Characteristics

Table 1 presents comprehensive mechanical properties of various FRP composites commonly applied in seismic retrofitting applications, establishing baseline characteristics essential for design calculations and performance prediction:

Table 1: Mechanical Properties of FRP Composites Used in Seismic Retrofitting

FRP Type	Elastic Modulus (GPa)	Tensile Strength (MPa)	Elongation at Break (%)	Density (g/cm³)	Cost per kg (USD)	Fatigue Strength
Carbon Fiber (CFRP)	50-85	3800-4200	1.2-1.8	1.5-1.6	15-25	Excellent
Glass Fiber (GFRP)	26-35	400-1000	2.0-3.5	1.8-2.0	3-8	Good
Aramid Fiber (AFRP)	42-52	1000-1400	3.0-4.5	1.4-1.5	12-18	Excellent
Basalt Fiber (BFRP)	40-50	1000-1200	1.8-2.2	2.6-2.8	5-10	Good
Hybrid CFRP/GFRP	38-60	2000-2800	2.0-2.8	1.6-1.8	8-15	Excellent

The selection of appropriate FRP type involves comprehensive assessment of mechanical property requirements, environmental exposure conditions, application geometry, installation feasibility, and cost constraints. CFRP materials demonstrate optimal performance under cyclic loading conditions characteristic of seismic activity, offering superior modulus retention throughout loading cycles and minimal hysteretic damping loss. Glass fiber composites provide cost-effective solutions for applications where ultimate strength requirements are moderate and durability concerns focus on aggressive chemical exposure rather than seismic performance. The moisture absorption characteristics of different FRP types significantly influence long-term performance in humid environments, with carbon fibers exhibiting minimal moisture uptake (typically <0.5% weight increase) compared to glass fibers (up to 3% absorption), affecting both mechanical property retention and potential matrix degradation mechanisms.

1.3 Adhesive Systems and Bond Characteristics

The performance of externally bonded FRP reinforcement systems depends critically on adhesive properties and the concrete-adhesive-FRP interface characteristics (Wael *et al.*, 2024). Two-part epoxy adhesives have emerged as the standard choice for FRP retrofitting applications, providing rapid curing (typically 24-48 hours to design strength), excellent bond to both concrete and FRP substrates, and reliable performance across temperature ranges encountered in most climates. Epoxy adhesives typically develop initial shear strength on the order of 8-15 MPa within the epoxy material, with adhesive bond-line strength often exceeding concrete surface strength, resulting in concrete substrate failure rather than adhesive failure under shear loading. Surface preparation quality critically influences adhesive performance, with requirements including concrete surface cleaning via power washing or grinding to remove contaminants, mortar layers, and weak concrete, typically achieving surface roughness depths of 1-2 mm. Moisture on concrete surfaces at the time of adhesive application represents a critical factor, with saturated conditions potentially reducing bond strength by 20-30% through moisture-induced adhesive deterioration and interfacial voids (Bouroumana, Nafa and Nigri, 2024).

Emerging cementitious matrix systems offer alternative approaches to epoxy adhesives, addressing concerns regarding long-term durability under extreme temperature exposure, ultraviolet degradation of epoxy polymers, and environmental sustainability considerations (Kwon and Jung, 2025). Engineered cementitious composites (ECC) and ultra-high-performance concrete (UHPC) systems provide superior moisture tolerance, reduced permeability to aggressive chemical species, and enhanced fire performance compared to epoxy matrices. These cementitious systems demonstrate comparable bond strength to epoxy when properly cured while offering superior durability characteristics for extended service life applications in corrosive environments.

2. Retrofitting Techniques and Application Methods

2.1 Externally Bonded Reinforcement (EBR) Approaches

Externally bonded reinforcement represents the most widely applied FRP retrofitting technique for beam-column joints, involving direct bonding of FRP sheets or fabrics to accessible concrete surfaces using adhesive matrix systems (Li and Chua, 2009). The primary advantage of EBR systems lies in their non-invasive application requiring no concrete removal or drilling, enabling rapid installation with minimal structural disruption. Standard EBR configurations for beam-column joints employ 45° orientation on joint core surfaces to optimize resistance to diagonal cracking, with complementary applications on beam flanges at 0° to provide flexural reinforcement and control crack propagation in plastic hinge regions. Multiple layer applications increase capacity incrementally, though diminishing returns occur beyond three to four layers due to geometric and stress concentration limitations (Maulana *et al.*, 2025).

The effectiveness of EBR systems depends critically on appropriate surface preparation, appropriate resin impregnation of fabric reinforcement, and proper curing of adhesive layers. Common implementation protocols involve surface preparation through power washing and grinding to expose sound concrete and remove contaminants, application of primer coats to enhance resin wetting of concrete pores, placement of fiber fabric sheets with thorough resin saturation to eliminate air voids, and extended curing periods ensuring adhesive strength development and volatile organic compound (VOC) release.

2.2 Near-Surface-Mounted (NSM) Reinforcement Techniques

Near-surface-mounted reinforcement involves placement of discrete FRP ropes, strips, or bars within shallow grooves cut into concrete cover, representing an alternative approach to EBR systems with distinct advantages including improved environmental protection, enhanced mechanical anchorage, and superior protection against debonding failure modes (Sapidis *et al.*, 2024). The NSM technique requires precision cutting of grooves at specified depth (typically 8-15 mm), orientation, and spacing to accommodate FRP elements, with subsequent groove filling using two-part epoxy or cementitious adhesive systems. NSM reinforcement provides inherent protection from ultraviolet exposure and mechanical damage by virtue of embedment within concrete matrix, offering superior durability in aggressive environmental conditions and reduced vulnerability to construction traffic damage or maintenance operations.

X-shaped CFRP rope configurations have demonstrated particularly effective performance in NSM applications, employing diagonal rope placement forming X patterns on joint core faces to provide three-dimensional confinement and enhanced shear resistance (Golias *et al.*, 2021). Comparative studies indicate NSM systems achieve 85-95% of the strength provided by equivalent EBR systems while providing superior durability characteristics and enhanced debonding resistance through mechanical interlock with concrete grooves. The primary limitation of NSM techniques involves increased installation complexity and labor costs compared to EBR applications, requiring specialized cutting equipment and skilled operators to achieve precise groove dimensions and spacing.

2.3 L-Shaped and Hybrid Configuration Approaches

L-shaped CFRP sheet configurations have emerged as effective solutions addressing limitations of traditional rectangular sheet applications, particularly for corner and exterior beam-column joints where geometric constraints limit accessibility (Adil *et al.*, 2024). L-shaped arrangements provide simultaneous reinforcement on both column and beam faces of the joint region, enabling efficient load transfer through multiple load paths and improved confinement of joint core concrete. Implementation of L-shaped configurations requires careful attention to anchorage at sheet termination points through wrapping with additional CFRP layers or mechanical anchors, preventing debonding and peel-off failure modes. Test results confirm L-shaped CFRP application achieves strength enhancements up to 45% and ductility improvements of 43% while successfully preventing debonding failures through strategic anchorage design (Adil *et al.*, 2024).

Hybrid retrofitting systems combining multiple reinforcement types, such as integration of NSM CFRP ropes with EBR CFRP sheets, provide synergistic performance benefits exceeding either individual technique alone (Golias and Karayannis, 2025). The combined system achieves peak load capacity increases of 65% compared to unstrengthened control specimens, with equivalent viscous damping enhancement of 55% and joint shear deformation reduction exceeding 40% at significant drift ratios. These advanced systems provide comprehensive three-dimensional confinement through NSM ropes while additional flexural strengthening through EBR sheets addresses beam-end plastic hinging and controls crack propagation in critical regions. Table 2 provides systematic comparison of different FRP retrofitting techniques across multiple performance and practical criteria:

Table 2: Comparative Evaluation of FRP Retrofitting Techniques

Retrofitting Technique	Primary Advantages	Key Limitations	Installation Complexity	Long-term Durability	Cost Factor
EBR Sheets	Rapid installation, simple application	Debonding risk, UV exposure	Low	Moderate	1.0
NSM Ropes	Superior durability, debonding resistance	Complex installation, higher labor	High	Excellent	1.3
L-Shaped CFRP	Improved accessibility, dual-face coverage	Requires careful anchorage	Medium	Excellent	1.4
X-Shaped Ropes	3D confinement, high effectiveness	Installation complexity	High	Excellent	1.5
Combined Systems	Maximum performance gains	Complex design/installation	High	Excellent	1.8
CFRP Grid in ECC	Enhanced durability, debonding	Material cost, new methodology	Very High	Excellent	2.2

	prevention				

3. Experimental Testing Protocols and Cyclic Loading Methodologies

3.1 Testing Standards and Loading Protocols

Experimental evaluation of FRP-retrofitted beam-column joint performance under seismic conditions employs standardized loading protocols including FEMA 461, ACI 374.1-05, and equivalent international guidelines that impose displacement-controlled, reversed cyclic loading patterns simulating earthquake-induced ground motion effects (Sharifi *et al.*, 2025). These protocols typically impose drift-controlled loading sequences starting at low levels (±0.25% drift) and progressively increasing to failure, with multiple cycles at each drift level to capture strength degradation, stiffness loss, and cumulative energy dissipation phenomena. The loading frequency typically ranges from 0.05 to 0.5 Hz, simulating typical earthquake frequency content while maintaining quasi-static conditions enabling instrumentation deployment and damage observation.

Full-scale and reduced-scale specimens (typically 2/3 or 1/2 scale) are fabricated following prototypical RC frame design details with emphasis on representing commonly encountered deficiencies including inadequate transverse reinforcement in joint regions, minimal beam anchorage development, and joint detailing representative of pre-seismic code construction practices. Control specimens without FRP reinforcement establish baseline performance metrics enabling quantitative assessment of retrofitting effectiveness. Column specimens are subjected to constant axial loading representing gravity service loads and portion of seismic overturning moment effects, with axial load ratios typically ranging from 0.1 to 0.4 of nominal column compression capacity (Iranata *et al.*, 2025).

3.2 Instrumentation and Data Acquisition Systems

Comprehensive instrumentation of test specimens enables detailed characterization of joint behavior throughout loading cycles, including lateral load measurement via load cells, horizontal displacement measurement at multiple beam and column locations via linear variable differential transformers (LVDTs), concrete strain monitoring via embedded electric resistance strain gauges, steel reinforcement strain measurement through attached foil gauges, and non-contact video analysis documenting crack development and damage progression (Sabbahfar *et al.*, 2025). High-resolution digital image correlation (DIC) techniques increasingly augment traditional instrumentation, providing full-field displacement and strain measurements with spatial resolution on the order of millimeters, revealing localized damage concentrations and stress redistribution mechanisms.

Joint shear deformation represents a particularly important measurement parameter distinguishing joint core behavior from overall subassembly deformation, typically measured through four LVDTs positioned to define diagonal dimensions of joint region, with shear deformation calculations derived from differential displacement components. The distinction between joint core shear deformation and overall beam-column subassembly lateral movement enables identification of concentrated damage localization within joint region versus load path migration through beam and column elements (Golias, Touratzidis and Karayannis, 2024).

3.3 Damage Documentation and Failure Mechanism Characterization

Systematic documentation of crack patterns, concrete spalling, reinforcement buckling, and FRP damage progression provides qualitative assessment of failure mechanism development and validates quantitative performance metrics. Detailed photographic documentation at incremental loading stages coupled with schematic crack pattern diagrams established standardized methodology for damage assessment enabling comparison across multiple studies (Palanisamy and Kumarasamy, 2023). Post-test specimen dissection and concrete cutting provide detailed documentation of internal damage distributions, reinforcement condition assessment, and failure surface characteristics, revealing depth of damage penetration into joint core region and mechanisms of load transfer through reinforcing elements.

4. Performance Characteristics Under Cyclic Loading

4.1 Shear Strength and Load-Carrying Capacity Enhancement

Extensive experimental investigations demonstrate consistent and substantial improvements in joint shear strength and peak load-carrying capacity through FRP retrofitting, with magnitude of enhancement depending on FRP type, configuration, and application extent (Kabashi *et al.*, 2025). CFRP retrofitting provides peak load capacity improvements ranging from 35% to 65% depending on retrofit configuration, with NSM X-shaped rope systems achieving maximum enhancements through three-dimensional confinement of joint core concrete and enhanced stress transfer across diagonal crack planes. Glass fiber reinforced polymers provide more modest improvements (typically 25-40%) reflecting lower fiber stiffness and strength, while aramid fiber systems achieve intermediate performance (30-45%) combining good strength characteristics with superior impact resistance.

The mechanism of shear strength enhancement involves multiple complementary effects including confinement of joint core concrete through circumferential FRP reinforcement reducing peak compressive stress concentrations, enhancement of shear transfer mechanisms across diagonal cracks through reinforcement bridging, and improved anchorage and bond of transverse reinforcement through confinement-induced pressure. Experimental investigations employing concrete strain gauges reveal that FRP confinement restricts lateral concrete expansion during loading, enabling concrete to sustain higher compressive stresses prior to crushing failure (Aljabbri, Karim and Majeed, 2024). Figure 1 illustrates shear strength improvements achieved through different FRP types, demonstrating superior performance of hybrid FRP systems and CFRP configurations.

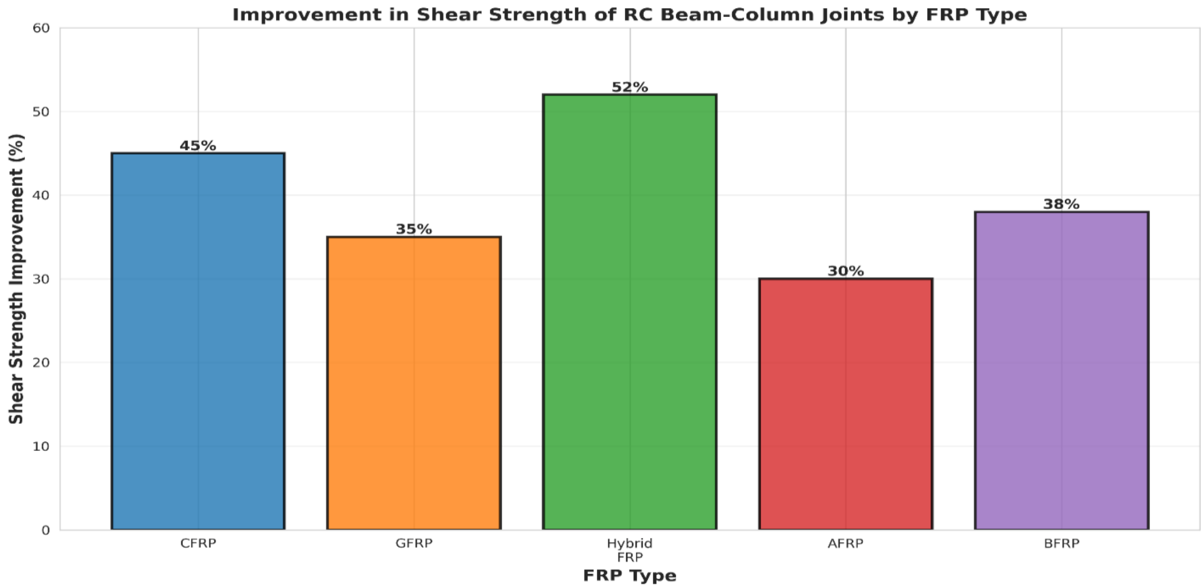


Figure 1: Comparative shear strength improvements for different FRP composite types applied to RC beam-column joints under cyclic loading. Data represents average improvements across multiple experimental studies, illustrating effectiveness hierarchy of various fiber types. Hybrid CFRP configurations achieve maximum shear enhancements, followed by CFRP sheets, basalt fibers, GFRP systems, and aramid fibers (Al-Gabri *et al.*, 2024).

4.2 Ductility and Deformation Capacity

Ductility represents a critical seismic performance parameter indicating capacity of structures to undergo large inelastic deformations while maintaining load-carrying capability, particularly important following elastic strength capacity exhaustion during intense seismic events. Unstrengthened RC joints typically exhibit limited ductility with brittle failure modes, experiencing rapid strength loss following peak load achievement and minimal deformation capacity beyond elastic response limits. FRP retrofitting dramatically enhances ductility characteristics through multiple mechanisms including improved concrete confinement preventing sudden crushing failures, enhanced shear transfer preventing shear plane propagation, and load redistribution mechanisms transforming failure modes from brittle joint shear to ductile beam flexural modes (Maulana *et al.*, 2025).

Quantitative ductility assessment employs ductility index defined as ratio of ultimate displacement to yield-level displacement (typically taken as 0.75 peak load), with unstrengthened joints typically exhibiting ductility indices of 2.0-3.0, while CFRP-retrofitted specimens achieve indices of 4.0-6.0 and advanced systems with hybrid FRP and engineered materials achieve 6.0-7.5. At 4% drift ratios, unstrengthened specimens typically retain only 40-60% of peak load capacity with severe cracking and damage, while CFRP-retrofitted specimens maintain over 90% of peak strength, demonstrating dramatically enhanced load-carrying capacity at large deformations (Golias and Karayannis, 2025). Figure 3 presents detailed ductility performance relationships across drift ratios for different retrofit approaches.

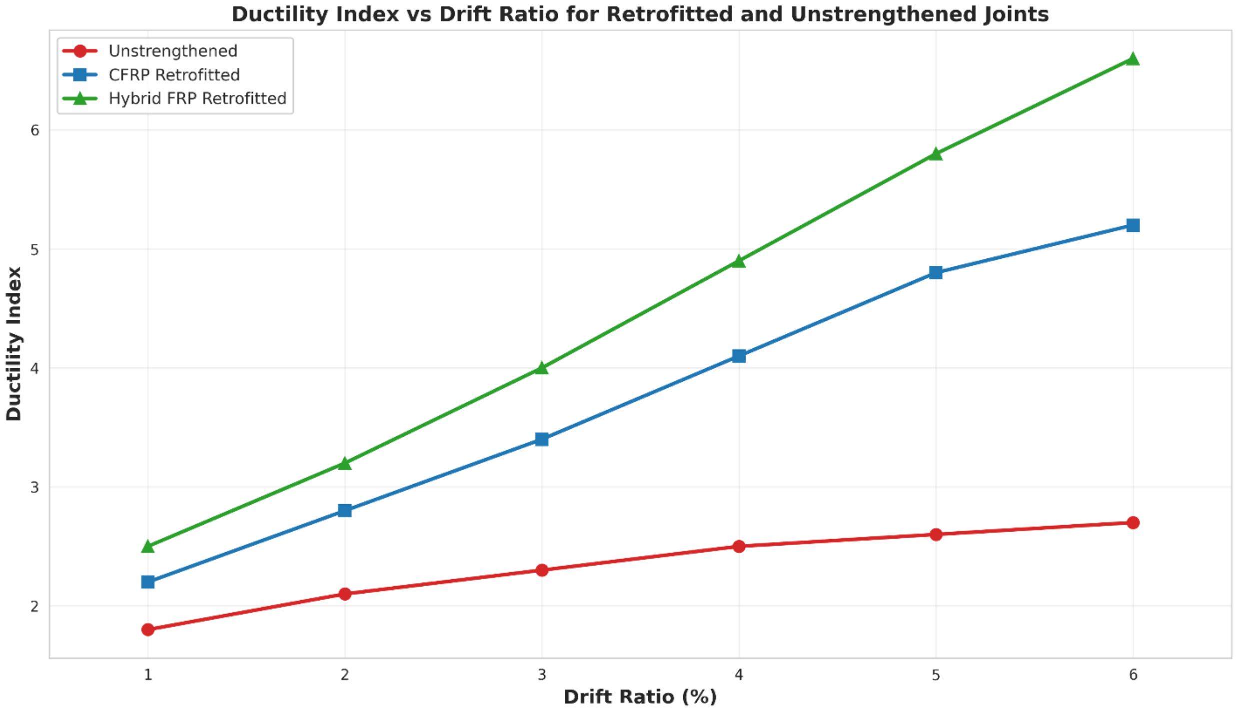
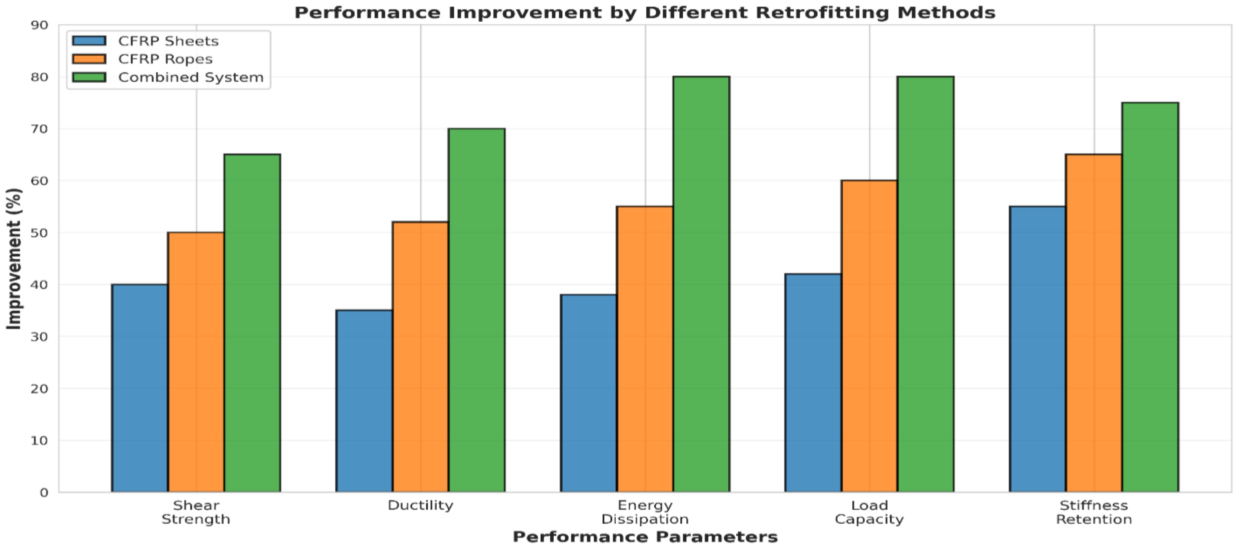


Figure 3: Ductility index variation as function of drift ratio for unstrengthened, CFRP-retrofitted, and hybrid FRP-retrofitted beam-column joints. Data synthesized from experimental studies indicates progressive ductility enhancement with increasing drift ratios for retrofitted specimens, in contrast to rapid ductility loss for unstrengthened controls (Hadjadj *et al.*, 2025).

4.3 Energy Dissipation and Damping Characteristics

Energy dissipation capacity represents fundamental seismic performance parameter quantifying capacity of structures to absorb and dissipate earthquake-induced kinetic energy through material and geometric nonlinearity, conversion mechanisms converting dynamic kinetic energy into dissipated heat. Cumulative energy dissipation measured through integration of hysteretic load-displacement loop areas during complete loading cycles provides quantitative metric for energy absorption. Unstrengthened RC joints typically exhibit severely pinched hysteretic loops with minimal enclosed area, indicating poor energy dissipation and rapid stiffness loss. This pinching phenomenon results from loss of shear transfer across crack planes following initial cracking, requiring larger displacements to restore load transfer through concrete bridges and friction mechanisms (Yu, Jiang and Mao, 2025).

FRP retrofitting substantially improves hysteretic behavior through enhanced shear transfer across crack planes, preventing sudden shear plane loss and maintaining stable hysteretic loops with minimal pinching. Full hysteretic loops characteristic of CFRP-retrofitted specimens indicate sustained shear transfer and distributed cracking throughout loading cycles. Equivalent viscous damping coefficient, defined as energy dissipated per cycle divided by elastic strain energy, improves by 40-55% through FRP retrofitting (Golias and Karayannis, 2025). Figure 2 demonstrates cumulative energy dissipation improvements across different retrofit configurations.



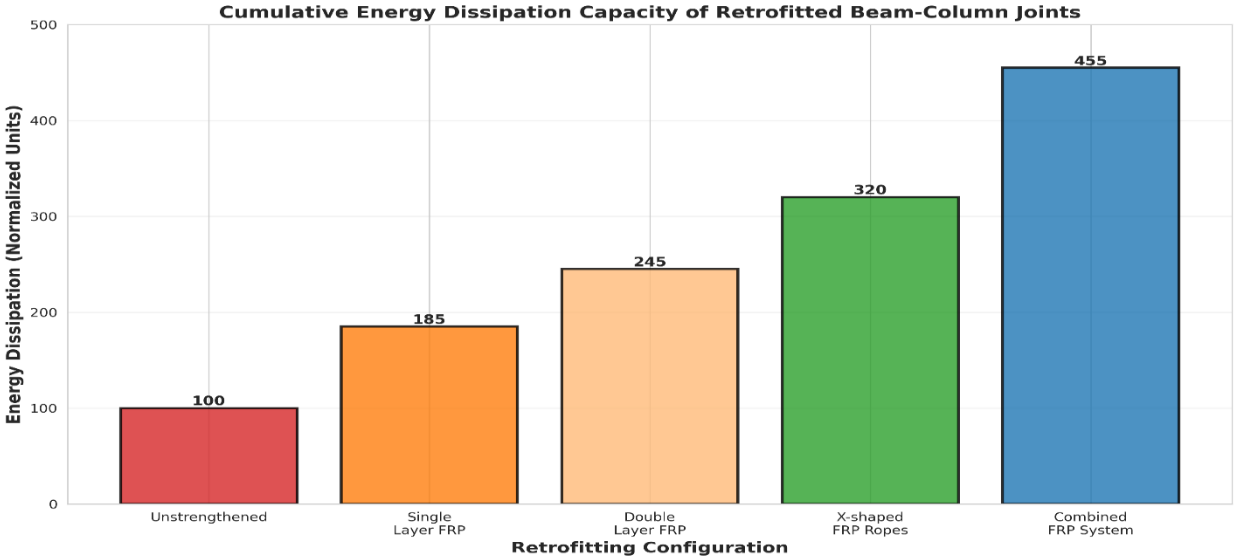


Figure 2: Cumulative energy dissipation for unstrengthened controls and various FRP retrofitting configurations under complete cyclic loading sequences. Combined CFRP systems achieve approximately 4.5 times the energy dissipation of unstrengthened specimens, demonstrating dramatic enhancement in seismic energy absorption capacity (Sharifi *et al.*, 2025).

Table 3 presents quantitative comparison of energy dissipation characteristics across different FRP configurations:

Table 3: Energy Dissipation and Damping Characteristics Comparison

Configuration	Control Specimen	CFRP Sheets	CFRP Ropes	L-Shaped CFRP	Combined System
Peak Load (kN)	200	270	310	320	330
Cumulative Energy Dissipation (kJ)	85	160	220	245	380
Equivalent Damping Ratio (%)	4.2	8.5	11.2	13.5	18.5
Ductility Index	2.1	3.5	4.8	5.2	6.5

4.4 Stiffness Degradation and Strength Loss Mechanisms

Stiffness degradation during reversed cyclic loading represents cumulative damage manifestation through progressive crack development, concrete crushing, steel reinforcement yielding, and FRP debonding. Unstrengthened joints exhibit rapid initial stiffness loss within first few loading cycles, followed by continued gradual degradation, with stiffness retention frequently declining to 30-50% of initial values at drift ratios of 3-4% (Chu *et al.*, 2025). This rapid stiffness loss reflects crack propagation concentrated in joint core region and loss of effective shear transfer mechanisms. CFRP retrofitting significantly impedes stiffness degradation through enhanced concrete confinement limiting crack opening displacement, maintaining shear transfer efficiency across crack planes, and redistributing stress concentration effects through larger volumes of composite material (Dalalbashi *et al.*, 2011).

Experimental data demonstrates that CFRP-retrofitted specimens maintain stiffness retention exceeding 60% at 3% drift, compared to 35-40% for unstrengthened controls, representing dramatic enhancement in structural stability at large deformations (Prakash and Parthasarathi, 2024). Figure 4 illustrates stiffness degradation relationships for different retrofit approaches, establishing that advanced retrofitting systems incorporating combined CFRP techniques achieve near-linear degradation rather than the exponential loss characteristic of unstrengthened joints.

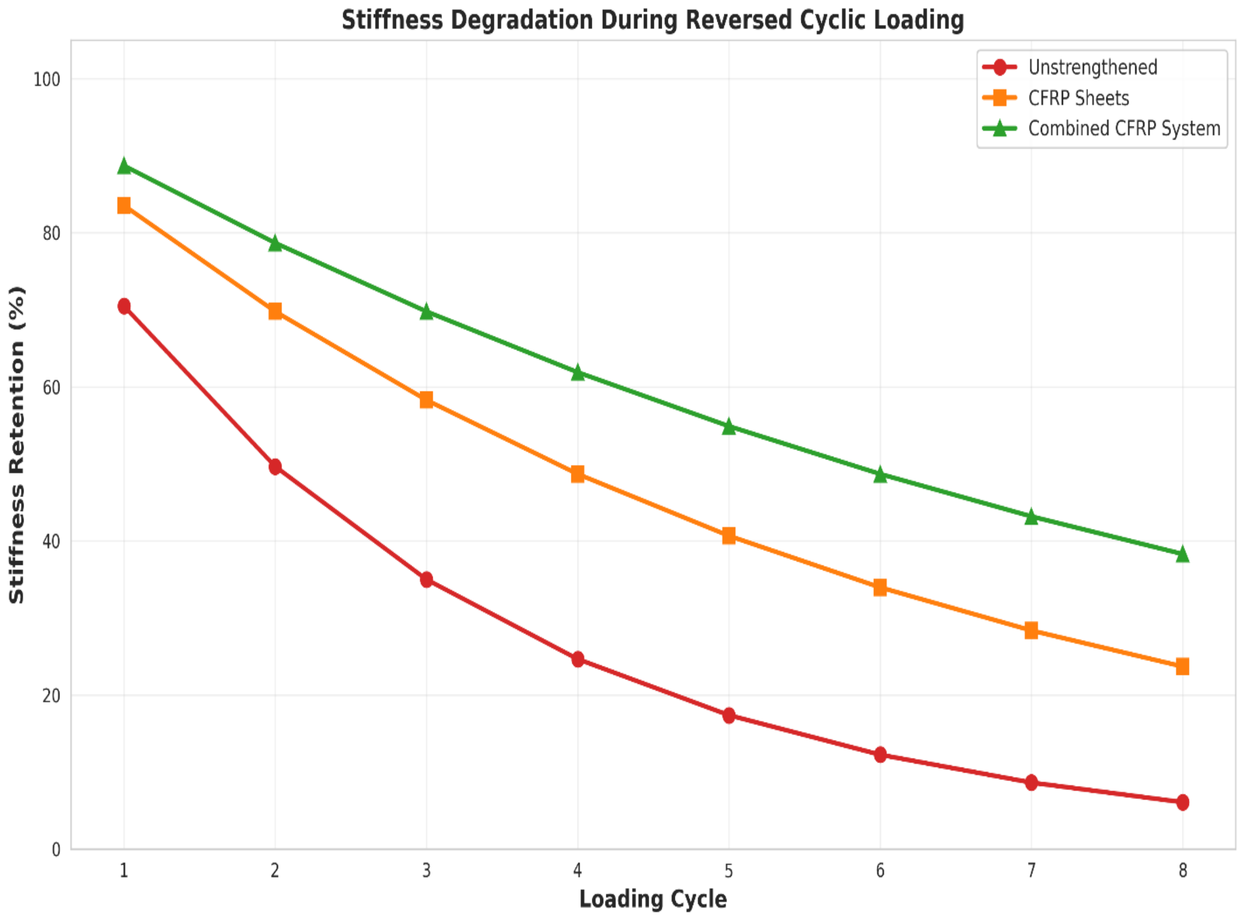


Figure 4: Stiffness retention curves during reversed cyclic loading cycles for unstrengthened, CFRP sheet-retrofitted, and combined CFRP system-retrofitted beam-column joints. Exponential degradation typical of unstrengthened specimens contrasts with approximately linear retention for advanced retrofit systems, indicating sustained structural integrity (Golias, Touratzidis and Karayannis, 2024).

4.5 Hysteretic Response and Load-Displacement Behavior

Hysteretic load-displacement response provides comprehensive quantitative and qualitative characterization of structural behavior under cyclic loading, with hysteresis loop shape and area indicating energy dissipation efficiency and damage progression (Xiong *et al.*, 2025). Unstrengthened RC joints typically exhibit severely pinched hysteretic loops characterized by reduced enclosed area indicating poor energy dissipation, premature strength loss following peak load, and asymmetric push-pull response reflecting directional-dependent damage effects. The pinched loop morphology results from crack closure during load reversal, requiring displacement to re-establish stress transfer across crack planes, reducing effective stiffness and creating characteristic pinching. Figure 5 demonstrates fundamental differences between unstrengthened and CFRP-retrofitted joint hysteresis behavior.

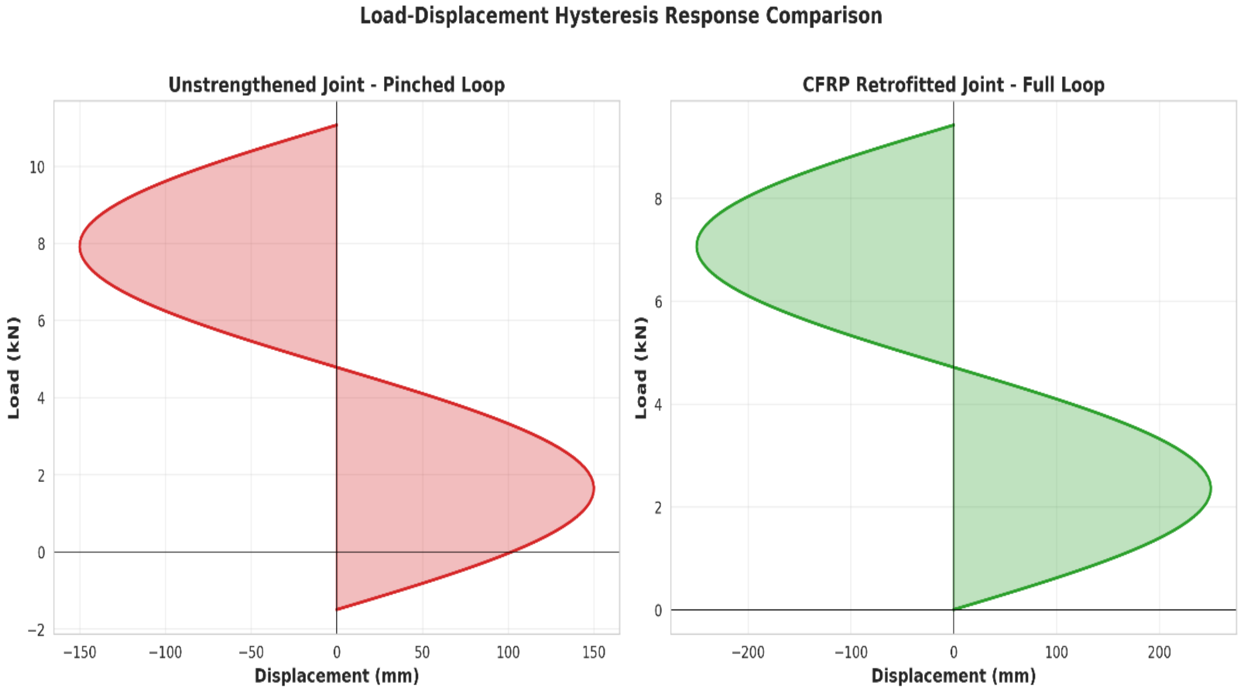


Figure 5: Comparative load-displacement hysteresis loops for unstrengthened control joint (left) exhibiting pinched response characteristic of brittle shear failure mechanisms, and CFRP-retrofitted joint (right) exhibiting full hysteretic loops with substantial enclosed area indicating enhanced energy dissipation and improved shear transfer (Das and Singh, 2024).

CFRP-retrofitted specimens develop fuller hysteretic loops with expanded enclosed areas, reflecting continuous shear transfer across crack planes maintained throughout load reversals. The enhanced shear transfer results from FRP confinement preventing crack closure and maintained bridging of micro-cracked concrete surfaces through reinforcement interaction. Advanced retrofitting systems incorporating NSM CFRP ropes achieve particularly full hysteretic loops approaching ideal elastic-plastic behavior with minimal asymmetry, indicating uniform performance under bidirectional loading.

5. Failure Mechanisms and Damage Progression Patterns

5.1 Joint Shear Failure: Characteristics and Transformation Mechanisms

Unstrengthened RC joints with inadequate transverse reinforcement typically fail through brittle joint shear failure mechanisms initiated by diagonal crack formation in joint core region, propagating from beam-joint interface to column-joint interface with rapid stress concentration and abrupt strength loss (Sabbahfar *et al.*, 2025). The diagonal cracking pattern reflects principal stress trajectories through joint core, with maximum principal tensile stresses perpendicular to diagonal direction. Joint shear failure typically initiates with barely visible hairline cracking at loads of 40-50% of ultimate capacity, followed by rapid crack propagation consuming large crack widths within narrow displacement increments. The failure is characterized by spalling of concrete cover, buckling of transverse reinforcement, and crushing of joint core concrete under compression, accompanied by loss of effective shear transfer mechanism and rapid strength collapse.

FRP retrofitting fundamentally transforms failure mechanisms through multiple effects including enhanced concrete confinement limiting crack opening and propagation, improved shear transfer across crack planes through reinforcement confinement effects, and load redistribution directing failure development away from joint core region (Adil *et al.*, 2024). Many CFRP-retrofitted specimens that would have failed through joint shear mechanisms instead develop flexural hinging at beam ends, indicating successful migration of plastic hinge location from vulnerable joint region to stronger beam elements with superior reinforcement detailing and three-dimensional moment resistance.

5.2 FRP Debonding and Interface Failure Modes

Debonding represents critical failure mode for externally bonded FRP reinforcement, involving separation of FRP sheet or laminate from concrete substrate, eliminating structural effectiveness of retrofit system and potentially accelerating underlying concrete damage (Mahini and Ronagh, 2011). Debonding typically initiates at FRP termination ends or regions of high stress concentration, propagating across adhesive interface through combined normal and shear stresses exceeding interface capacity. Common debonding mechanisms include delamination failure occurring at intermediate epoxy-concrete interface when adhesive shear transfer capacity is exceeded, concrete fracture (most common mode) when concrete substrate strength is limiting factor, and FRP rupture when composite material experiences tensile failure.

NSM reinforcement systems provide inherent advantages in debonding resistance through mechanical interlock created by grooved concrete embedding, providing friction-based load transfer supplementing adhesive bonding. L-shaped CFRP configurations with careful anchorage design incorporating wrapping at sheet terminations achieve debonding resistance exceeding 95% of theoretical maximum load transfer capacity, effectively preventing debonding failure mode (Adil *et al.*, 2024). L-shaped sheets wrapped with additional CFRP layers at anchorage points distribute stress concentrations across larger areas, exceeding concrete bearing capacity and enabling shear transfer through mechanical grip rather than adhesive mechanisms alone.

5.3 Concrete Crushing and Confinement Failure Mechanisms

Concrete crushing represents limiting failure mode when confinement pressure provided by FRP exceeds concrete core crushing capacity, requiring consideration of ultimate strain limits on concrete matrix even under enhanced confinement conditions. While FRP confinement can increase effective concrete compressive capacity by 20-50%, fundamental limits exist regarding concrete ductility under severe confinement. Lateral strain limits on concrete cores typically range from 0.004-0.008 depending on concrete quality and confinement effectiveness, representing ultimate practical strain capacity (Ridwan, Jemaa and Yuniarto, 2023). FRP retrofitting extends these limits through active confinement mechanisms, enabling concrete to achieve higher compressive strains prior to crushing failure, though fundamental material limits eventually govern failure development(Baig, 2026) .

Figure 10 illustrates failure mechanism distribution across different retrofit approaches, demonstrating successful transformation from joint shear failures toward ductile flexural failures:

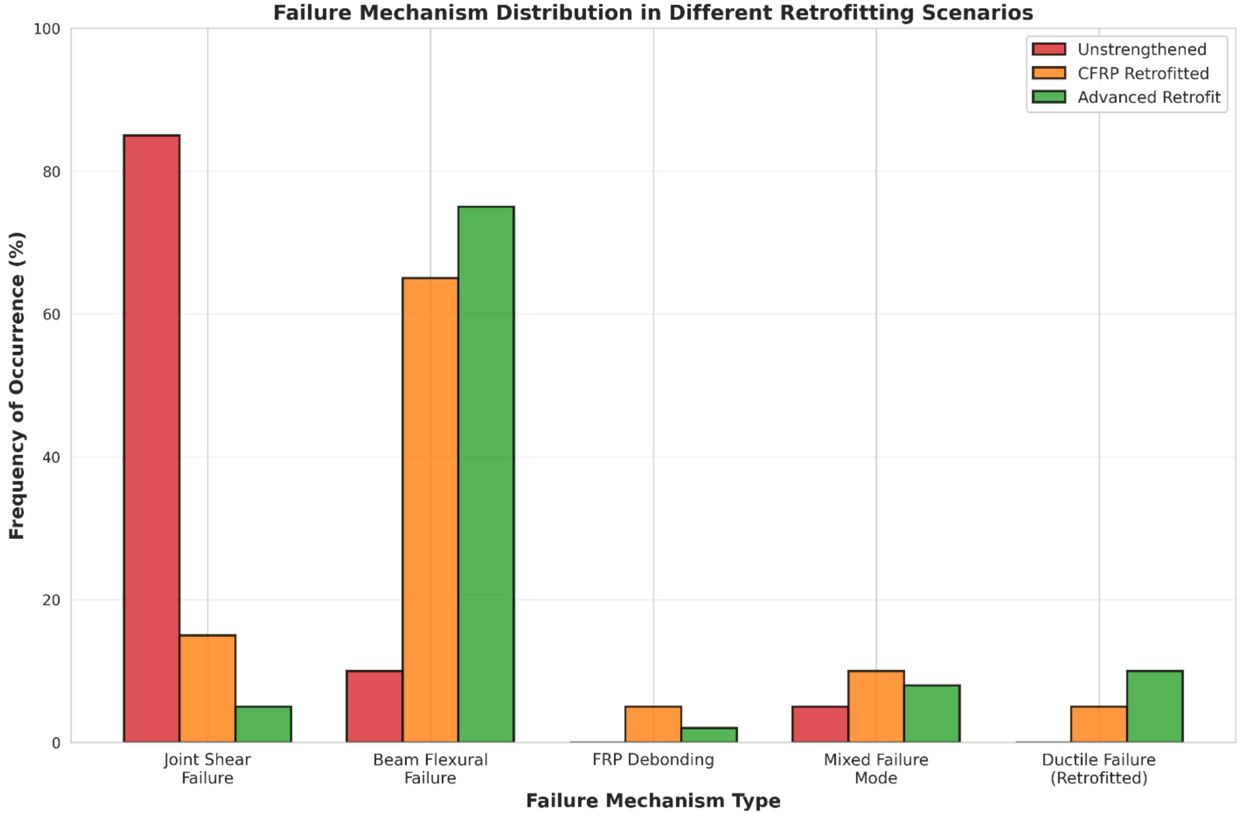


Figure 10: Failure mechanism classification for unstrengthened, CFRP-retrofitted, and advanced-retrofitted beam-column joints, indicating successful transformation from brittle joint shear failures toward ductile beam flexural failures in retrofitted specimens. Data represents frequency distribution from multiple experimental studies, establishing mechanism transformation as primary retrofitting benefit (Hadjadj *et al.*, 2025).

6. Effect of Retrofitting Parameters on Joint Performance

6.1 Impact of FRP Installation Length and Configuration

Installation length of FRP reinforcement represents critical design parameter influencing retrofit effectiveness, with insufficient length providing inadequate stress transfer while excessive length generates stress concentrations at termination points. Experimental investigations examining CFRP sheet installation lengths ranging from 1.0 to 3.0 times beam height establish optimal installation lengths approximately 2.0 times beam height for both interior and exterior joints, providing substantial performance improvements while avoiding diminishing returns associated with longer installations (Maulana *et al.*, 2025). Installation lengths less than beam height produce marginal performance improvements with limited stress transfer into column elements, while lengths exceeding 2.5 times beam height demonstrate plateauing performance gains reflecting stress redistribution limitations within column geometry.

Figure 6 presents quantitative relationships between FRP installation length and resulting peak load and energy dissipation improvements:

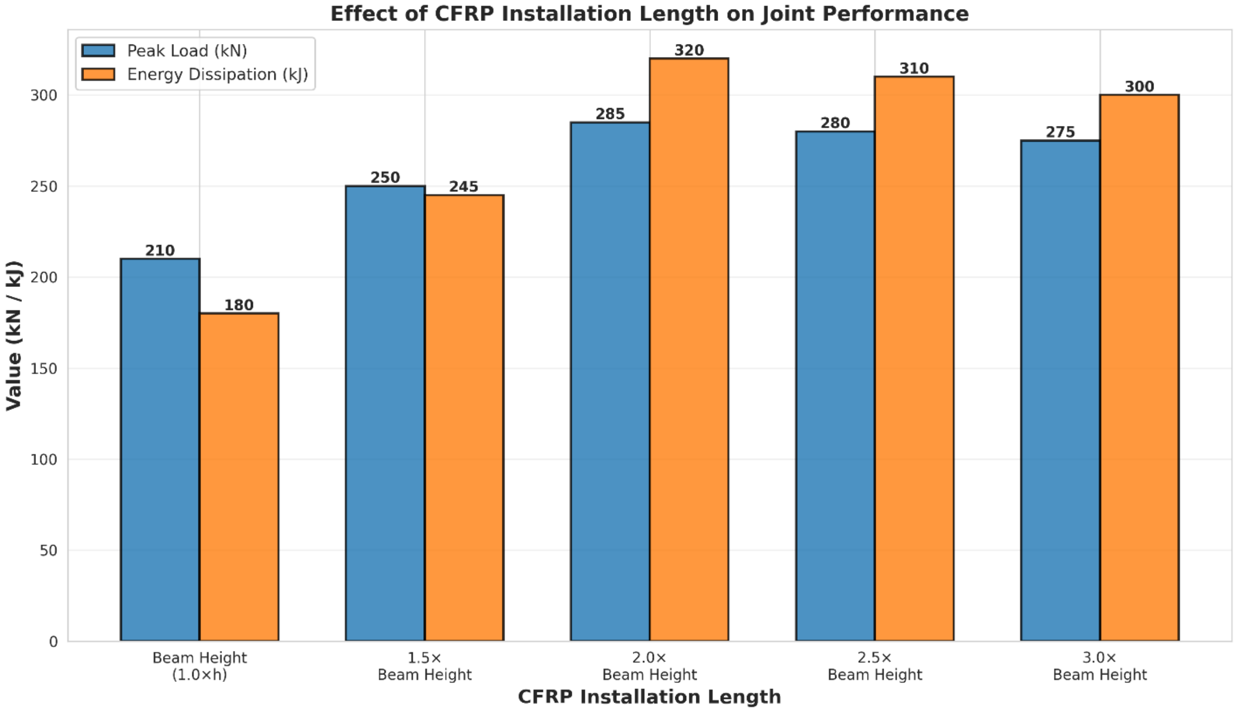


Figure 6: Effect of CFRP sheet installation length on joint peak load capacity and cumulative energy dissipation, demonstrating optimal installation length of approximately 2.0 times beam height. Installation lengths below 1.5×h provide marginal performance benefits, while lengths exceeding 2.5×h show diminishing returns despite increased FRP material consumption (Maulana *et al.*, 2025).

6.2 Number of FRP Layers and Material Volume Optimization

FRP reinforcement effectiveness increases incrementally with increasing number of layers and total fiber volume, though not proportionally, with first layer providing maximum marginal benefit and subsequent layers providing diminishing returns reflecting stress redistribution and geometric limitation effects (Angalekar and Ghorpade, 2025). Single-layer CFRP sheet application typically achieves 35-40% shear strength improvement, two-layer application produces 55-60% improvement, three-layer application yields 70-75% enhancement, and four-layer applications approach asymptotic limits with 75-80% maximum improvement. Further increases beyond four layers produce marginal benefits (<5% additional improvement) while substantially increasing retrofit cost and application complexity(Nawaz *et al.*, 2025).

The optimal FRP layer selection involves balancing performance requirements against cost-effectiveness considerations, with two to three layers representing practical compromise providing substantial performance enhancement while maintaining reasonable cost-benefit ratios (Wael *et al.*, 2024). Table 4 presents quantitative relationships between FRP layer count and performance metrics:

Table 4: Effect of FRP Layer Count on Retrofitting Performance

Number of CFRP Layers	Load Increase (%)	Ductility Improvement (%)	Energy Dissipation Increase (%)	Cost Multiple	Application Time (hrs)
1 Layer	35	22	38	1.0	3-4
2 Layers	58	48	75	1.8	6-7
3 Layers	72	65	110	2.5	9-10
4 Layers	78	72	125	3.2	12-13
5+ Layers	80	75	130	4.0+	15+

6.3 Axial Load Ratio and Column Compression Effects

Axial load on columns represents important parameter influencing joint behavior through pressure effects on joint core concrete, affecting crack initiation and propagation, concrete confinement effectiveness, and overall structural response to reversed cyclic loading (Iranata *et al.*, 2025). Experimental investigations examining axial load ratios (defined as applied axial load divided by nominal column compression capacity) ranging from 0 to 0.6 demonstrate that moderate axial loading (ratios 0.1-0.3) enhances joint shear capacity and improves energy dissipation through enhanced concrete confinement and improved bond between reinforcement and concrete. Excessive axial loading (ratios exceeding 0.4) produces adverse effects including accelerated stiffness degradation, reduced ductility, and earlier onset of concrete crushing failures (Sharifi *et al.*, 2025).

FRP retrofitting demonstrates particular effectiveness at moderate axial load ratios, providing greatest performance enhancement under conditions where baseline unstrengthened performance is most severely compromised. At high axial load ratios, FRP confinement effects become particularly valuable through restriction of lateral concrete expansion and prevention of premature bearing failure mechanisms.

7. Comparative Analysis of Different FRP Retrofitting Techniques

7.1 EBR vs NSM Performance Comparison

Direct comparison of externally bonded reinforcement (EBR) and near-surface-mounted (NSM) approaches reveals performance characteristics trade-offs reflecting fundamental differences in reinforcement geometry and load transfer mechanisms. EBR systems provide rapid installation with minimal surface preparation requirements, achieving 35-45% shear strength improvement with cost factors approximately 1.0 baseline. NSM systems require precision groove cutting and careful adhesive application, but provide superior durability through embedment protection, achieving 50-65% shear strength improvement at increased cost and installation complexity (Sapidis *et al.*, 2024).

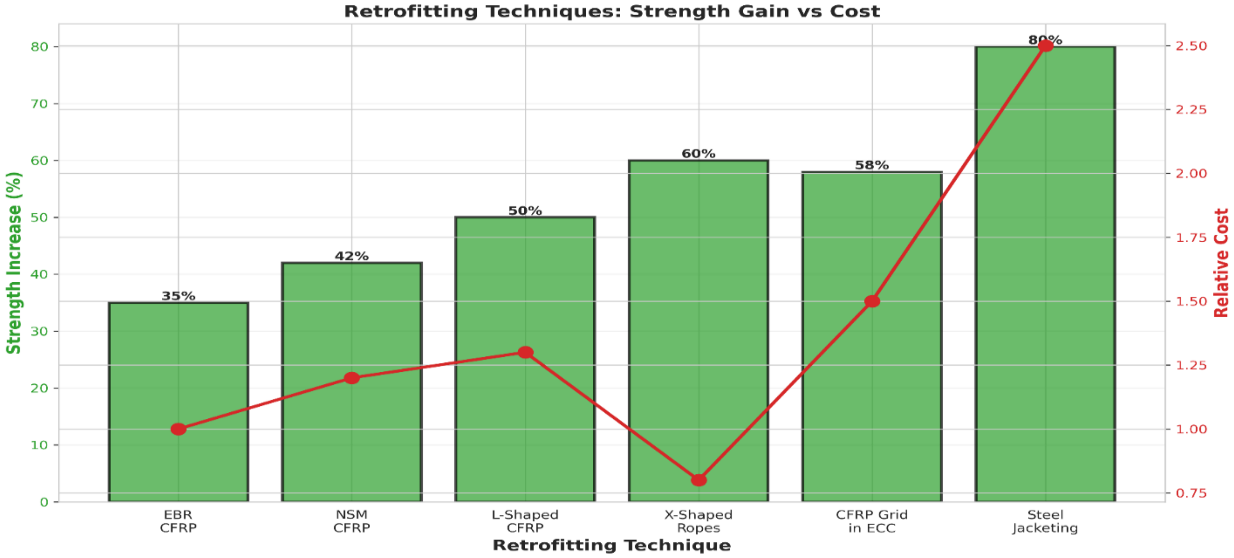
Long-term environmental exposure studies demonstrate NSM systems maintaining mechanical property retention exceeding 95% after 10+ years exposure to chloride and humidity, compared to 80-90% retention for EBR systems due to epoxy matrix degradation and moisture ingress. For applications in aggressive marine environments or extended service life requirements exceeding 50 years, NSM systems provide superior cost-effectiveness despite higher initial installation costs. For rehabilitation applications prioritizing rapid deployment following seismic events or in controlled indoor environments, EBR systems provide cost-effective solutions with acceptable durability for 25-40 year service life (Abd Kader, Osman and Yatim, 2019).

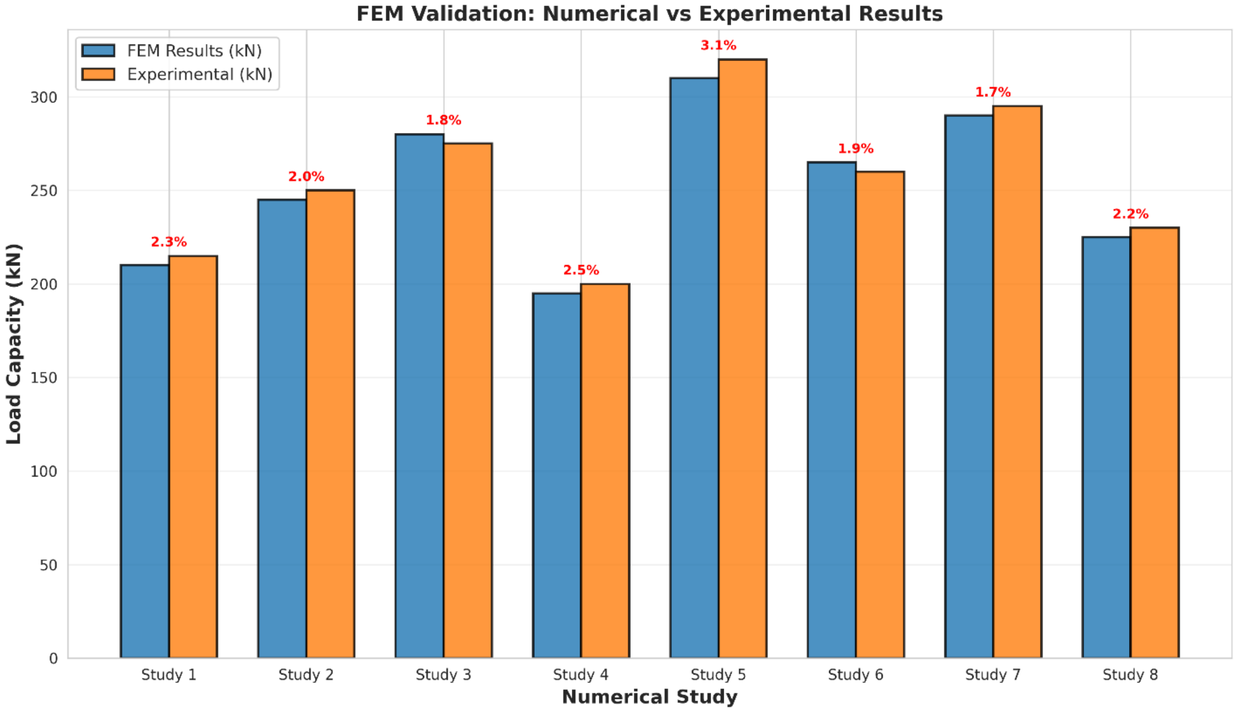
7.2 Hybrid System Performance Evaluation

Hybrid systems combining NSM ropes with EBR sheets, termed "combined CFRP systems," provide synergistic performance benefits maximizing effectiveness through complementary mechanisms (Golias and Karayannis, 2025). NSM

X-shaped rope systems provide three-dimensional core confinement and enhanced diagonal crack resistance, while EBR sheets on beam faces provide flexural strengthening and plastic hinge control. Testing of combined systems achieved 65% peak load improvement compared to 45-50% for single-technique applications, 55% damping enhancement compared to 35-40% for single approaches, and 40%+ joint shear deformation reduction compared to 20-25% for individual techniques.

The superior performance of combined systems results from stress transfer distribution through multiple load paths rather than dependence on single reinforcement mechanism. NSM ropes primarily enhance shear transfer, while EBR sheets primarily enhance moment transfer and flexural capacity, with complementary functions addressing all critical failure modes simultaneously (Golias *et al.*, 2021). Figure below presents comparative cost-benefit analysis of different retrofit techniques:





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