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Retrofitting of Reinforced Concrete Beam-Column Joints with Externally Bonded Fiber Laminates

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Abstract:** Reinforced concrete (RC) is one of the most widely used construction materials globally, but many RC structures deteriorate or become unsafe before reaching their design life due to factors such as earthquakes, corrosion, overloading, poor design, or faulty construction. In framed structures, beam-column joints are critical for transferring loads and moments; however, they are often inadequately designed, making them the most vulnerable components during extreme loading. Retrofitting is the process of strengthening a structure to achieve a predefined performance level, whether damaged or not. It differs from repair, which only restores partial strength, and rehabilitation, which aims to regain original strength. Retrofitting existing structures poses greater challenges than new construction and requires simple, durable, and economical techniques. Among various local retrofitting methods—such as injection, shotcreting, and plate bonding—the plate bonding technique is the most efficient. Common materials include ferrocement, FRP, PMC, and steel plates. Although FRP is effective, it is costly and requires skilled labor. Ferrocement jacketing, by contrast, offers advantages such as ease of application, low weight, durability, and cost-effectiveness. This study investigates the effect of ferrocement jacketing on the strength of RC beam-column joints, considering parameters like mesh layers, orientation, and initial stress levels. For comparison, some joints were retrofitted with two layers of CFRP at 45° orientation. Experimental results were validated using a 3D nonlinear finite element model developed in ATENA 3D, which showed good agreement (within ±10%). Retrofitting with ferrocement or CFRP significantly increased the load-carrying capacity and stiffness of stressed joints. Both methods restored full strength even at 85% of ultimate load, and failure shifted from the joint region to the beam ends, resulting in a safer weak-beam–strong-joint behavior. The findings confirm the effectiveness of ferrocement and CFRP jacketing for strengthening RC beam-column joints.
***Keywords:** Reinforced concrete, beam-column joint, retrofitting, ferrocement jacketing, CFRP, finite element analysis.*

I. INTRODUCTION

Reinforced concrete (RC) is one of the most widely used construction materials worldwide due to its strength, durability, and versatility. However, the performance of RC moment-resisting frames during recent earthquakes has highlighted the vulnerability of beam-column joints, which are the most critical zones in a structure. These joints play a vital role in transferring loads and moments between intersecting beams and columns, ensuring overall structural integrity. Despite their importance, beam-column joints are often inadequately designed or detailed, leading to severe damage or even collapse of structures during seismic events. Factors such as poor design, substandard construction quality, overloading, corrosion, and lack of ductility contribute to the premature deterioration of RC structures, even before the end of their service life.In many developing nations, including India, Pakistan, Turkey, and Iran, traditional construction practices and non-engineered methods are still prevalent, often ignoring codal provisions and seismic safety requirements. This makes buildings in earthquake-prone regions particularly susceptible to damage. In Indian design practice, for instance, beam-column joints have often been neglected in detailed analysis, with design codes mainly emphasizing anchorage rather than joint strength and ductility under dynamic loading. Historical earthquakes, such as those in Turkey (1999) and Taiwan (1999), demonstrated that inadequate joint detailing was a major cause of catastrophic structural failures.Under seismic loading, RC beam-column joints are subjected to large shear and bond stresses, and their response largely governs the global seismic performance of a structure. Brittle behavior of joints can result in the entire frame behaving in a brittle manner, while ductile joint behavior ensures resilience and energy dissipation. Therefore, proper design and detailing of beam-column joints are crucial for achieving the desired "strong-column, weak-beam" behavior in ductile moment-resisting frames, ensuring that damage occurs in beams rather than in joints, thus enhancing the overall safety and seismic resistance of RC structures

A. Aim

To investigate the effectiveness of ferrocement and CFRP jacketing techniques in enhancing the structural performance, load-carrying capacity, and failure behavior of reinforced concrete beam-column joints, through experimentally modeling.

B. Objective

1) To investigate the effect of initial damage level and type of loading on strength characteristics of reinforced concrete orthogonal beam-column joints retrofitted using ferrocement jackets and fiber reinforced polymer plates.
2) To perform the effect of the number of wire mesh layers and their orientation on orthogonal beam-column joints retrofitted using ferrocement laminates.
3) To develop an experimental model for predicting the behavior of beam-column joints strengthened using ferrocement laminates.

II. LITERATUREREVIEW

Reinforced Concrete (RC) beam-column joints are vital components of moment-resisting frames, ensuring the effective transfer of loads and moments between beams and columns. However, inadequate design, poor detailing, aging, and material degradation often make these joints the weakest links under seismic or dynamic loading. To improve their performance and prevent brittle failure, retrofitting techniques using advanced composite materials such as Fiber Reinforced Polymers (FRPs) have gained significant attention in recent decades. FRPs, including Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP), offer advantages such as high tensile strength, corrosion resistance, and ease of installation, making them effective for enhancing the strength, stiffness, and ductility of RC joints.Lee et al. (2022) reported that CFRP retrofitting with proper anchorage significantly increased the shear resistance of joints, while unanchored laminates showed only minor improvement. Bousselham et al. (2022) reviewed 54 global experiments and found that FRP retrofitting improved strength, ductility, and energy dissipation, though stiffness slightly decreased. Sharma et al. (2025) observed that combined GFRP and CFRP retrofitting improved joint behavior but did not fully prevent failure due to surface debonding. Similarly, Li and Chua et al. (2025) found that FRP wrapping enhanced flexural strength and delayed shear failure, with CFRP strips proving effective in strong-column–weak-beam configurations.Ludovico et al. (2025) demonstrated the effectiveness of GFRP jacketing in reducing seismic damage, while Akguzel et al. (2025) highlighted the influence of axial load variation on joint performance. Mukherjee et al. (2025) and El-Amoury et al. (2025) confirmed that FRP retrofitting not only restored the original capacity of damaged joints but also improved ultimate strength and deformation capacity. Collectively, these studies affirm that FRP-based retrofitting significantly enhances the seismic resilience and load-carrying capacity of RC beam-column joints when properly designed and anchored.

III. METHODOLOGY

A. STUDY OF BEAM-COLUMN JOINTS

Beam-column joints form one of the most critical components of reinforced concrete (RC) moment-resisting frames. They are the zones where beams and columns intersect, transferring loads and moments between structural members. The portion of a column confined within the depth of the deepest beam framing into it is defined as the joint core. Depending on how many beams frame into a column, joints are classified as interior joints (beams on all four faces), exterior joints (two or three faces), and corner joints (two adjacent faces). These joints play a vital role in ensuring that the overall frame behaves effectively under various loading conditions. During seismic events, joints experience intense shear and bond stresses, and their performance largely dictates the ductility, energy dissipation, and overall safety of the structure. Poorly detailed joints tend to fail in a brittle manner, leading to catastrophic collapse.
Seismic design codes emphasize that structures must possess adequate stiffness, elasticity, and ductility under different earthquake intensities. During minor tremors, they should prevent non-structural damage; under moderate earthquakes, remain largely elastic; and during major earthquakes, undergo controlled inelastic deformation without collapsing. Since beam-column joints are difficult to repair or retrofit after failure, their design requires careful detailing and confinement. The ACI 352R-02 guidelines classify joints into Type-1 for non-seismic zones and Type-2 for seismic zones, recommending shear stress limits and reinforcement detailing to prevent premature joint failure. Research from the United States, Japan, and New Zealand has advanced understanding of shear mechanisms, with ACI and AIJ adopting a concrete arch model, while the New Zealand Standard incorporates both arch and truss mechanisms. Despite minor variations, all codes recognize that joint performance is influenced primarily by concrete strength, joint geometry, and reinforcement anchorage.
In Ductile Moment-Resisting Frames (DMRFs), the design follows the strong-column, weak-beam principle to ensure that energy dissipation occurs in the beams rather than in the columns or joints. Proper detailing ensures that plastic hinges form at a safe distance from the joint core, avoiding brittle shear failure. Inadequate reinforcement anchorage or insufficient transverse confinement often leads to diagonal cracking within the joint, compromising its load-carrying capacity. Therefore, improving ductility through joint confinement and efficient reinforcement layout remains a key focus of modern seismic design.

B. BEHAVIOUR OF BEAM-COLUMN JOINTS

Understanding the shear transfer mechanism within a beam-column joint is essential for assessing its seismic performance and selecting effective retrofitting techniques. Under gravity loads, compression and tension forces from beams and axial loads from columns are transmitted directly through the joint. However, under lateral or seismic loading, diagonal tensile and compressive stresses develop within the joint core, leading to the formation of diagonal cracks. These cracks typically initiate at beam faces and propagate through the joint region. Concrete resists compression but is weak in tension, so transverse reinforcement is placed strategically to resist diagonal tensile stresses, enhance confinement, and prevent brittle failure.

In exterior joints, where beams frame into only one or two faces, shear stresses are particularly severe. Studies show that beam bar anchorage has a profound effect on joint performance: if beam bars are bent away from the joint, strength may drop to 25–40% of the expected value, while proper anchorage through the joint core can achieve 85–100% efficiency. Adequate stirrups and confinement reinforcement help maintain integrity under cyclic loading, allowing the joint to sustain repeated stress reversals without degradation. Hence, appropriate detailing of both longitudinal and transverse reinforcement is critical to ensuring ductility, strength, and energy dissipation capacity during earthquakes.

C. RETROFITTING OF BEAM-COLUMN JOINTS

Many existing buildings in India and elsewhere were designed using outdated codes that did not fully address seismic performance. With the revision of IS 1893:2002 and the reclassification of several regions into higher seismic zones, the vulnerability of older structures became evident. Retrofitting—the process of strengthening and upgrading existing structures to meet current performance standards—has therefore become essential. Unlike repair or rehabilitation, which merely restore original strength, retrofitting enhances the structural capacity, ductility, and resilience of buildings, enabling them to resist future earthquakes more effectively.

The main objectives of retrofitting are to improve load-carrying capacity, stiffness, and energy dissipation while eliminating weak points. The retrofitting process generally includes four key steps:

1) Assessment: The structural condition is evaluated through inspection, testing, and analysis based on current codes. If the structure fails to meet target performance levels, retrofitting becomes necessary.
2) Retrofit Scheme: Depending on the identified deficiencies, suitable strengthening schemes are proposed for specific members.
3) Selection of Retrofit Technique: The method is chosen based on the structural analysis, expected failure modes, and cost-effectiveness.
4) Construction and Monitoring: The retrofitting work is executed carefully, and the performance is monitored to ensure the desired improvement in behavior.

Retrofitting strategies are broadly classified as global or local. Global retrofitting targets the overall structure—by adding shear walls, braced frames, or reducing irregularities—to improve overall stiffness and stability. Local retrofitting focuses on individual components such as beams, columns, or joints, where deficiencies are identified. In addition, base isolation and energy dissipation devices such as dampers and tuned mass systems are sometimes employed to reduce seismic forces transmitted to the superstructure.

D. RETROFITTING TECHNIQUES

Several techniques are available to restore or enhance the performance of damaged or deficient RC beam-column joints:

1) Epoxy Injection Technique: High-strength epoxy is injected under pressure into fine or moderate cracks to bond separated concrete surfaces and restore continuity.
2) Mortar Injection Technique: Pre-mixed mortar or grout is injected to fill voids and cavities, particularly in older masonry or concrete structures where concrete replacement is difficult.
3) Epoxy Mortar Filling: A mixture of epoxy resin and fine aggregate is used to fill larger voids, providing superior adhesion and strength compared to conventional concrete.
4) Shotcreting: Concrete or mortar is pneumatically applied onto prepared surfaces to restore damaged regions or provide an additional confining layer. The process may employ steel or synthetic fibers for added ductility.
5) Removal and Replacement: Severely deteriorated concrete is cut out and replaced with new concrete, often supplemented with welded steel reinforcement for added strength.
6) Steel Fibrous Concrete: Recasting damaged regions with steel-fiber-reinforced concrete improves stiffness, ductility, and crack control.

Among advanced techniques, plate bonding methods have gained wide acceptance. These involve attaching high-strength plates to structural elements using adhesives, cementitious slurry, or mechanical connectors to enhance flexural and shear strength. The most commonly used plate materials include:

- Ferrocement plates: Thin reinforced mortar panels with wire mesh reinforcement, offering good tensile strength, corrosion resistance, and low cost.
- Fiber-Reinforced Polymer (FRP) plates: Made from carbon, glass, or aramid fibers embedded in resin, FRPs exhibit high tensile strength, light weight, and corrosion resistance, though they are expensive and sensitive to heat and moisture.
- Polymer-Modified Concrete or Mortar (PMC/PMM): Combines polymer latexes with cement to improve bonding, workability, and impermeability.
- Steel plates: Bonded or bolted plates significantly enhance strength and stiffness but require protection against corrosion.

Among these, FRP and ferrocement jacketing are especially effective for beam-column joints. FRP jackets offer high strength-to-weight ratio and superior confinement, while ferrocement jacketing provides an economical alternative that can be executed using semi-skilled labor. Owing to its low cost, durability, and ease of application, ferrocement is particularly suited for developing regions and has shown excellent results in improving ductility and load capacity of RC joints.

IV. RESULTS AND DISCUSSION

This chapter presents and analyzes the experimental results of beam-column joints retrofitted with ferrocement jackets reinforced using galvanized iron (GI) woven wire mesh. The objective of the study was to evaluate how varying the number of mesh layers and stress levels influenced the strength, stiffness, and deformation behavior of the joints.Introduction

This chapter presents and analyzes the experimental results obtained from testing reinforced concrete beam-column joints retrofitted with ferrocement jackets. The main objective of the study was to evaluate how varying the number of galvanized iron (GI) woven wire mesh layers and the level of pre-loading before retrofitting affect the structural performance of these joints. Key parameters examined include ultimate load capacity, yield strength, deflection, ductility, stiffness, and crack patterns. The investigation aimed to assess the effectiveness of ferrocement jacketing as a strengthening and rehabilitation technique for damaged or underperforming joints.The experimental work was carried out in two phases. In the first phase, the specimens were tested to determine their ultimate load capacity. Three different stress levels were selected to simulate varying degrees of pre-damage before retrofitting: Stress Level-1 (100% of ultimate load), Stress Level-2 (85%), and Stress Level-3 (50%).

In the second phase, the damaged joints were retrofitted using ferrocement jackets reinforced with two, four, and six layers of GI woven wire mesh. The mesh was placed in an L-shape at 45° to the beam axis, and a cement slurry was used to ensure proper bonding between the ferrocement jacket and the concrete surface.

A total of 27 beam-column joints were cast and tested, divided into three groups based on the number of wire mesh layers. Each group of nine specimens was further divided into three subgroups corresponding to the three stress levels. Both control and retrofitted joints were tested to compare improvements in structural behavior, and load-deflection data were recorded for analysis. The curves obtained were idealized into trilinear forms to calculate stiffness, ductility, and energy absorption.

The test results showed that ferrocement jacketing significantly enhanced the strength and stiffness of the beam-column joints. The increase in load capacity was primarily due to the confinement effect provided by the mesh layers, which restricted crack propagation and delayed failure. Retrofitted specimens exhibited finer, well-distributed cracks, while control specimens showed wider cracks at lower loads.

The stiffness of the joints increased with the number of mesh layers, but ductility and energy absorption decreased slightly, suggesting that the retrofitted joints became stronger but somewhat more brittle. Overall, ferrocement jacketing was highly effective in improving joint performance and restoring strength.

(a) Two-Layer GI Mesh Joints retrofitted with two layers of wire mesh showed moderate improvement. The ultimate load increased by 17–22%, and deflection at ultimate load reduced by 34–46%. The yield load improved by around 30%, indicating a stronger elastic phase before yielding. The stiffness increase was most notable at Stress Level-2 (85%), reaching up to 110%, suggesting this pre-loading condition provided the best confinement. However, ductility and energy absorption decreased slightly due to the stiffer behavior introduced by the jacket.

(b) Four-Layer GI Mesh With four layers of mesh, the performance improved further. The ultimate load rose by 25–33%, and deflection decreased by nearly 55%. Rotation also reduced by 60%, showing enhanced rigidity and reduced deformation. The yield load increased by up to 40%, and cracks were finer and more uniformly distributed.

Although there was a slight reduction in ductility, the joints demonstrated a balanced combination of strength and stiffness, indicating effective confinement by the thicker ferrocement layer.

(c) Six-Layer GI Mesh The best results were obtained with six layers of mesh. The ultimate load capacity increased by 33–41%, and yield load rose by as much as 50%. Deflection and rotation reduced sharply, while stiffness improved by 70–120% depending on the stress level. The joints became highly rigid, with fine crack distribution and minimal deformation. However, the ductility and energy absorption decreased slightly, indicating a tendency toward brittle failure after yielding. Despite this, the six-layer jacket provided the highest strength and best crack control.

Across all configurations, the stress level before retrofitting influenced the improvement achieved. Specimens retrofitted after being stressed to 85% of their ultimate load (Stress Level-2) consistently exhibited the best overall results. At this level, internal damage was moderate, allowing the ferrocement jacket to bond effectively and enhance confinement. Specimens retrofitted at 100% stress level showed slightly lower gains due to prior cracking, while those at 50% stress level displayed smaller improvements because the initial stress was insufficient to activate full confinement.

Overall, ferrocement jacketing using GI woven wire mesh proved to be an effective and economical technique for strengthening beam-column joints, significantly improving load capacity, stiffness, and crack resistance, particularly at intermediate stress levels.

V. CONCLUSIONS

The experimental investigation on reinforced concrete (RC) beam-column joints retrofitted with ferrocement jackets using four and six layers of GI woven wire mesh has led to the following conclusions: • Retrofitting considerably enhanced the load-carrying capacity of all beam-column joints. The ultimate load increased by 25–41%, with higher gains observed in specimens retrofitted with six layers compared to those with four layers of wire mesh. • The yield load increased by 35–50%, indicating that the retrofitted joints could sustain higher loads before yielding. This confirms the efficiency of ferrocement jackets in restoring and strengthening damaged joint zones. • The deflection at ultimate load decreased by 17–55%, while rotation reduced by nearly 40–60% in all retrofitted specimens. This demonstrates improved stiffness and better confinement due to the ferrocement layers. • The stiffness of the beam-column joints increased significantly — by 110–180% for four-layer and 70–120% for six-layer ferrocement jackets. This improvement reflects higher rigidity and improved load transfer capacity after retrofitting. • Despite the strength gain, the deflection ductility ratio and energy absorption decreased for all retrofitted specimens. This reduction is attributed to the load-controlled testing conditions and the increased confinement, which led to more brittle post-yield behavior. • Comparing the two retrofitting configurations, six-layer jackets showed higher load capacity and stiffness, whereas four-layer jackets exhibited slightly better ductility. Therefore, the selection of mesh layers should balance between strength enhancement and ductility retention based on performance needs. Retrofitting RC beam-column joints with ferrocement jackets reinforced with GI woven wire mesh is an effective and economical technique to enhance the strength, stiffness, and loadcarrying capacity of damaged or underperforming joints. However, care should be taken to control the brittleness induced by excessive confinement, particularly when increasing the number of wire mesh layers.

VI. FUTURE SCOPE

Optimized Layer Configuration: Further studies can focus on identifying the optimum number of wire mesh layers and thickness of the ferrocement jacket to achieve a balance between strength enhancement and ductility retention. Alternative Mesh and Mortar Types: The use of different mesh materials (such as stainless steel, carbon, or polymer mesh) and highperformance mortars (UHPFRC, GGBS, silica fume mixes) can be explored to enhance durability and bond characteristics. Dynamic and Cyclic Load Studies: Extending the experimental work to cyclic, impact, and seismic loading conditions would provide better insight into the energy dissipation and fatigue performance of retrofitted joints under real-life earthquake scenarios.

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