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# STRUCTURAL BEHAVIOUR OF SEISMICALLY RETROFITTED RC BEAM-COLUMN JOINTS: A CRITICAL LITERATURE REVIEW

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**ABSTRACT**

Existing reinforced concrete beam-column joints of the pre-1970s remain very vulnerable to seismic damage because of inadequate reinforcement detailing, poor anchorage in joints, and insufficient confinement. This review paper evaluates a systematic review of three primary retrofitting techniques (i.e., Fiber-Reinforced Polymer wrapping, steel jacketing, and hybrid FRP-steel) based on an analysis of recent experimental and numerical studies of exterior beam-column joints. The results mainly explain the need for technique selection that balances strength gains, ductility, corrosion resistance, and material efficiency. Targeted X-shaped FRP strips gained 40% strength enhancement while using 30% less area than full wraps. Steel jacketing with 70mm batten spacing achieves a 67.1% enhancement in axial load capacity. The FRP-reinforced RC walls are strengthened by 48.9%, and hybrid-GFRP–steel bracing systems show an increment of 8% at maximum based shear resistance with improved ductility.

**Keywords:** seismic retrofitting, beam-column joints, fiber reinforced polymer wrapping, carbon fiber reinforced polymer, glass fiber reinforced polymer, steel jacketing, hybrid retrofitting.

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## 1. INTRODUCTION

Previous earthquake experiences like the El Asnam 1980, Mexico 1985, L'Aquila 2009, and Loma Prieta 1989 earthquakes had shown the vulnerability of RC frame structures (especially the beam-column joint) to various deterministic causes such as insufficient reinforcement ratio, inadequate anchorage length, and shear failure across the joint [3]. Figure-1 clearly provides a real time example of shear failure, especially in corner beam column joints, beams, and columns [16]. These vulnerabilities are more magnified in older buildings constructed without seismic design provisions.

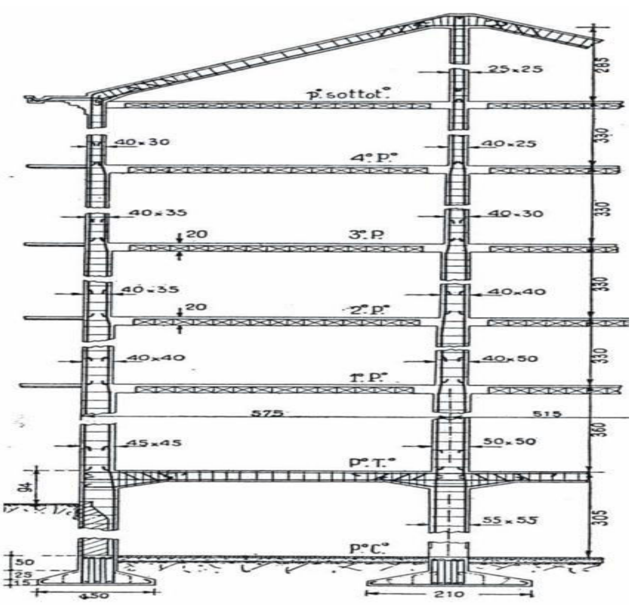

**Figure-1.** L'Aquila earthquake, 2009 [16].

To overcome this, some retrofitting methods have been studied. Among them, externally bonded fibre-reinforced polymers (FRPs) are in agreement among the most common systems because of their benefits such as high strength-to-weight ratio, corrosion resistance, and simple application [4]. It is found that the seismic performance of FRP retrofitted joints can be consistently improved based on experimental studies with respect to load capacity, ductility, and energy dissipation. However, certain drawbacks like premature debonding and anchorage failures initiated the evolution of sophisticated methods such as flange-bonded FRP and externally bonded reinforcement on grooves (EBROG) systems [5,6]. In parallel, finite element (FE) modelling has progressed, allowing better prediction of the in-service cyclic performance of retrofitted BCJs. Since bond development, material nonlinearity, and anchorage detailing are taken into account in such simulations, they provide results that can be compared with experimental observations in [7,8]. Research also indicates that using Carbon FRP (CFRP) bars as internal reinforcement enhances seismic resilience [9]. However, the lack of unified design guidelines and implementation challenges persist, particularly in developing nations.

## 2. COMMON WEAKNESSES OF BEAM-COLUMN JOINTS EVEN AFTER RETROFITTING

Beam-column joints, and in particular exterior ones, are likely to represent one of the weakest links in pre-1970's concrete frame systems [16]. They are considered the critical zones during seismic activity, particularly when they are exposed to lateral and/or cycled based seismic action. They are generally vulnerable in these cases, since those are based on construction before the contemporary seismic codes, and they have inadequate joint detail, inadequate reinforcement anchorage, and a lack of confinement. It results in brittle shear failures, causing the buildings to start to collapse during earthquakes. Figure-2 shows the rapid loss of load bearing capacity in columns, which leads to partial or total collapse of the structure.

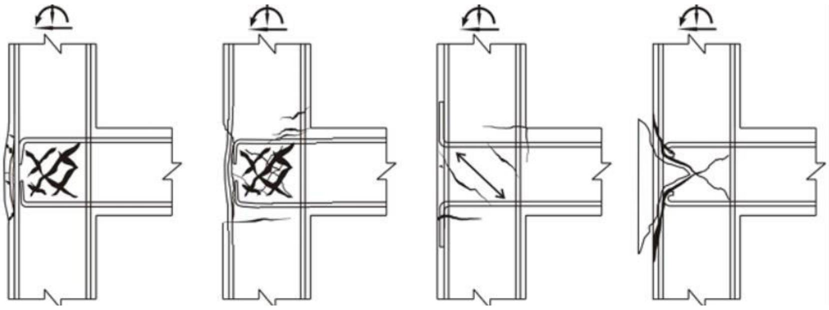

**Figure-2.** Failure mechanisms observed in the exterior BCJ's due to poor reinforcement detailing [16].

The lack of transverse reinforcement in the joint core is another common problem reported in experimental studies, which reduces the shear capacity and the ductility [3, 5, 6]. The pre-code joints are additionally deprived of the proper lapped splicing, beam bar anchorage, and corrosion over long-term loading [2, 5]. Diagonal cracks and an initial reduction of stiffness were observed in several studies, indicating a compromised load path through the joint [6]. Furthermore, external FRP layers debonding, especially for large displacement or poor anchorage, was observed to contribute significantly to the reduction in the efficacy of the retrofit [1, 3, 6]. For want of adequate anchorage details, FRP sheets tend to delaminate and peel off, thus constraining their share of the shear resistance and energy dissipation [3, 6]. Advanced FE models found evidence that failure usually initiates at the joint core, where stress concentrations build up rapidly under the effect of cyclic loading [1]. For precast concrete systems, and especially those using GFRP, failure modes are altered but continue to stem from connection detailing.

Pocketed joints showed early stiffness loss due to epoxy flexibility and stress concentration at column ends, compared to more robust bar/bolt-based pocketless connections [4]. Ultimately, these weaknesses, regardless of retrofit material, underscore the importance of confinement, anchorage integrity, and joint-core capacity as essential parameters in seismic performance enhancement.

## 3. RETROFITTING TECHNIQUES

The various retrofitting techniques have been discussed in this section.

### 3.1 Overview

Before the invention of the seismic code, the reinforced concrete BCJs were prone to major deficiencies. Retrofitting helps to enhance their load bearing capacity, ductility, strength, and energy dissipation. The most widely used retrofitting techniques are FRP wrapping techniques, steel jacketing, and hybrid techniques, which are the combination of FRP and steel jacketing. The selection of these retrofitting techniques depends on the failure mode, cost, and joint detailing.

### 3.2 FRP Wrapping Technique

There are different traditional retrofitting schemes, such as providing infill shear walls, providing external post-tensioning, and providing the bracings and steel plates for zones at tension, which are available [16]. Apart from all these schemes, FRP has many advantages, i.e., high strength to low weight ratio; this unique quality makes FRP a common retrofitting material. Use of FRP confinement has proved effective in seismically active zones [16]. FRPs can be bonded to the surface of the RC elements, such as beams, girders, and slabs, to help them carry more flexural load. This FRP is available in different forms like sheets, cables, laminates, and rebars; these are being used based on the requirements (wrapping, confinement, or flexure) [16].


**Figure-3.1.** Vertical FRP layer application on column.

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**Figure-3.2.** Application of U-shape horizontal laminate wrapped around the exterior column at the joint level.

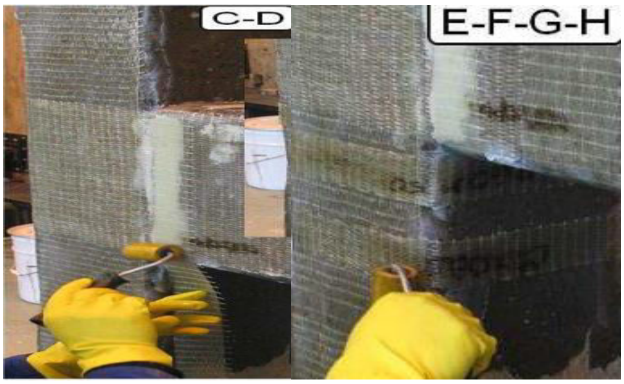


**Figure-3.3.** The additional smaller strips were also used to provide better anchorage to the main FRP laminates in the beam and column.

**Figure-3.** Application of FRPs to the beam-column joints [16].

Among the various types of FRPs, the two most widely used techniques are CFRP (Carbon Fiber reinforced polymer) and GFRP (Glass Fiber reinforced polymer).

### 3.2.1 Carbon fibre reinforced polymer (CFRP)

Carbon Fiber reinforced polymer (CFRP) is made by combining high-strength carbon fibres and strong resin. Its mechanical properties, such as extremely high tensile strength (better than steel), lighter weight, and corrosion resistance, made it an ideal choice for retrofitting the deficient structural elements. One of the key advantages of using CFRP is that it doesn't increase the thickness or weight of the structural member, making it highly suitable for strengthening existing buildings without increasing the weight. CFRP helps in increasing the joint's ability to withstand cyclic loading. These are available in different forms and have been used based on the requirement.

### 3.2.2 Glass fibre reinforced polymer (GFRP)

Glass Fiber reinforced polymer (GFRP), which is another useful material in retrofitting. Compared to CFRP, GFRP is a more affordable retrofitting technique. These are made up of glass fibres embedded in polymer resins. The advantages, like ease of application and economic benefits, make it a valuable option, mainly when we are retrofitting the multiple BCJ's of older buildings. Even though it offers slightly lesser mechanical properties when compared to the CFRP, it helps in extending the life, strength, and safety of the building.

### 3.3 Steel Jacketing

Steel jacketing is an older but very effective retrofitting method used for increasing the strength of RC structures, mainly for beam-column joints. It involves wrapping steel plates or angles around the concrete to improve the ductility, strength, and stiffness. This method is mainly helpful during earthquakes. However, it has some disadvantages, such as adding weight to the building, installation duration, and corrosion risk. Because of these downsides, the FRP retrofitting technique is mostly preferred in many cases. Still, steel jacketing remains a good choice for heavily damaged structures and highly risky areas. As noted by Hadigheh *et al*. [4], steel and concrete jacketing have long been used to improve the strength of older RC buildings.

### 3.4 Hybrid Methods

Hybrid retrofitting techniques offer a compelling way to strengthen reinforced concrete columns by combining materials like GFRP and steel. The core idea is to use a Glass-Fiber-Reinforced plastic for the outside with excellent resistance against corrosion, while installing a steel reinforcement on the inside that provides essential ductility as well as rigidity. This blend successfully delivers both seismic design strength and long-term corrosion protection better than does a material combination technique [20].

## 4. LITERATURE

To establish a comprehensive perspective on existing research, this review synthesizes a few recent studies by categorizing them based on the retrofitting strategy studied, such as Fiber-Reinforced Polymer (FRP) wrapping, conventional steel jacketing, hybrid strengthening methods, and direct comparative analyses.

### 4.1 Performance of Fiber-Reinforced Polymer (FRP) Wrapping

FRP wrapping technique is a widely studied technique due to its high strength-to-weight ratio and ease of application. Shokrzadeh *et al.* (2024) performed a numerical analysis for the low-cost FRP strengthening of RC beam-column joints based on ABAQUS. Their findings indicated that while a full FRP wrap (referred to as the first specimen) achieved the maximum strength enhancement of 48.9%, a more targeted approach, specifically an X-shape and orthogonal FRP strip arrangement (like Specimen 4, shown in the below Figure-4), achieved a similar load bearing ability, where the

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strength was increased by 40%. This result is of particular interest as the strip-type arrangement provided a significant 30% reduction in material usage compared to a complete wrap, providing a more cost-effective and practical retrofit solution [17]. Their numerical predictions had errors of less than 5% when compared to measurements (Figure-5). Similarly, it was also found that another research showed an improvement of shear capacity by the addition of FRP, and re-orientation of crack paths as increasing the thickness of strips is more strength-effective than widening them [17].

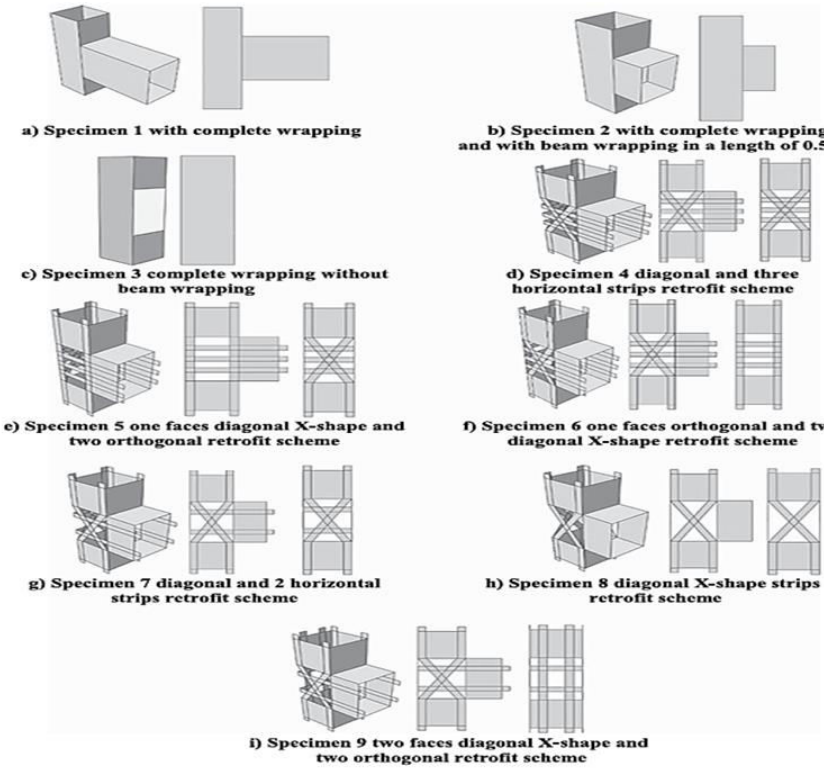


**Figure-4.** FRP arrangements in the specimens under consideration [17].

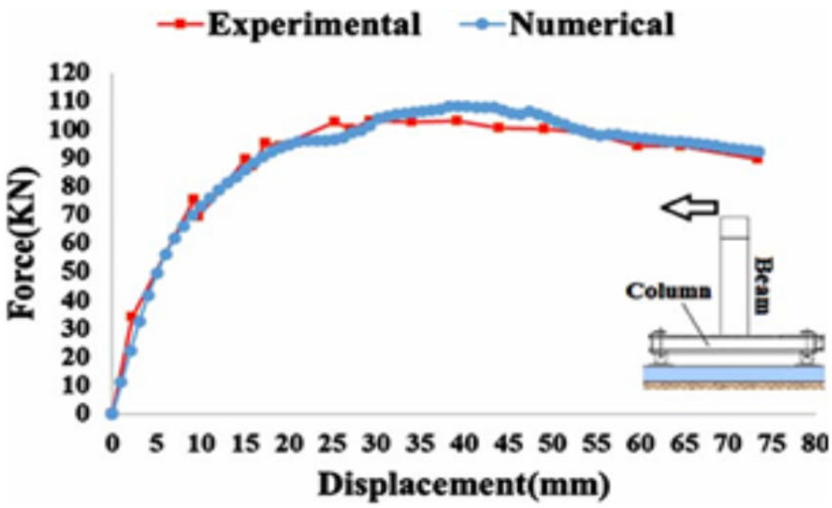


**Figure-5.** Force-displacement curve obtained from experimental results in compared with the results of numerical analysis [17].

Kabashi *et al*. (2025) conducted research to examine the contribution of advanced Fiber-Reinforced Polymer (FRP) retrofitting techniques to improve seismic performance in RC structures, with particular reference to

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beam-column joints, which are frequently deficient due to poor concrete quality or lack of proper detailing. They used ATENA software with GiD for elaborate joint analysis and FEM (Seismo Build) for overall building behaviour after calibrating models on the real Albanian earthquake damage. The results showed that seismic performance was largely enhanced with FRP. Joints saw a 25% increase in peak shear force and a 20% rise in displacement capacity, as illustrated in Figure-6 [18].

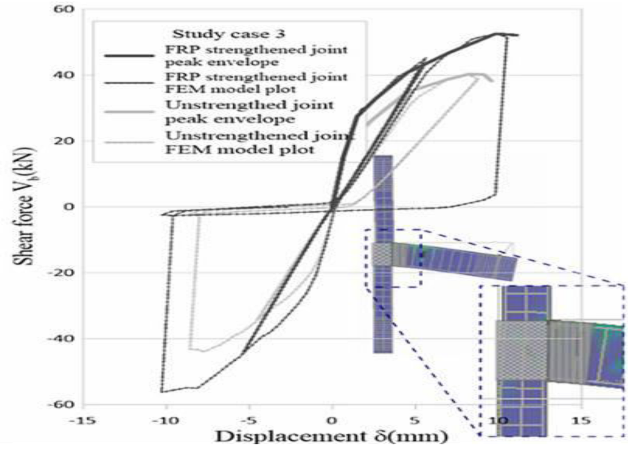


**Figure-6.** FRP strengthened vs. non strengthened joint [18].

Similarly, Ilki *et al*. (2008) performed some experimental tests on the behavior of weak concrete joints of older reinforced concrete structures. They tested four life-sized corner joints using low-quality concrete and plain, poorly detailed rebar. The study aimed to compare the reference specimens with retrofitted specimens using diagonally applied CFRP sheets. They also investigated the influence of including a transverse beam and slab. The reference specimens demonstrated limited strength, primarily due to the slippage of the plain beam bars. However, this spillage mechanism unintentionally provided some pseudo-ductility, allowing the joint to withstand drift ratios up to 4%. The CFRP retrofitting significantly enhanced the joints' performance. It increased the joint shear strength (from approx. $0.42\sqrt{f'c}$ - $0.52\sqrt{f'c}$ to $0.70\sqrt{f'c}$) and improved energy dissipation. The CFRP application method varies by two plies that were applied to the exterior face when the transverse beam/slab was present in Figure-7, whereas simpler T-joints had one ply wrapped on two faces. The key finding was that the failure mode shifted in the retrofitted specimens. They failed due to the rupture of the FRP sheets under diagonal tension, which indicated that the strengthened joints were able to develop the full theoretical flexural capacity of the connecting beams [21].

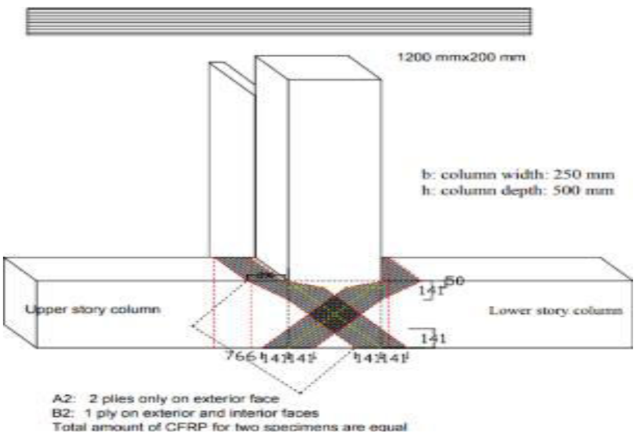


**Figure-7.** Retrofitting scheme of a specimen A2 (dimensions in mm) [21].

### 4.2 Performance of Steel Jacketing

Ghoneim *et al*. (2023) conducted an experimental study and investigated how steel jacketing strengthens reinforced concrete (RC) columns under static axial loads to increase the load capacity and ductility. They experimented on ten rectangular columns, varying cross-sectional aspect ratio, steel batten plate width, and spacing. Their experimental results confirmed that steel jacketing is a highly effective technique. A key finding was the transition from brittle to much more ductile failure in the RC specimens. Reducing steel batten plate spacing clearly showed the increase in compressive strength, with a 70mm spacing resulting in a 67.10% increase in load capacity. Similarly, increasing the width of a batten plate improved the capacity, with 60mm wide plates achieving a 56.81% increase. At 49%, square columns generally showed the greatest strength growth. Detailed failure of load measurements (Table-2 in their publication) and load-strain curves, which showed improved load-bearing capability and ductility, consistently corroborated these findings. Figure-7, which shows the load-strain response for reinforced specimens, provides an illustration of this improved behavior [19].

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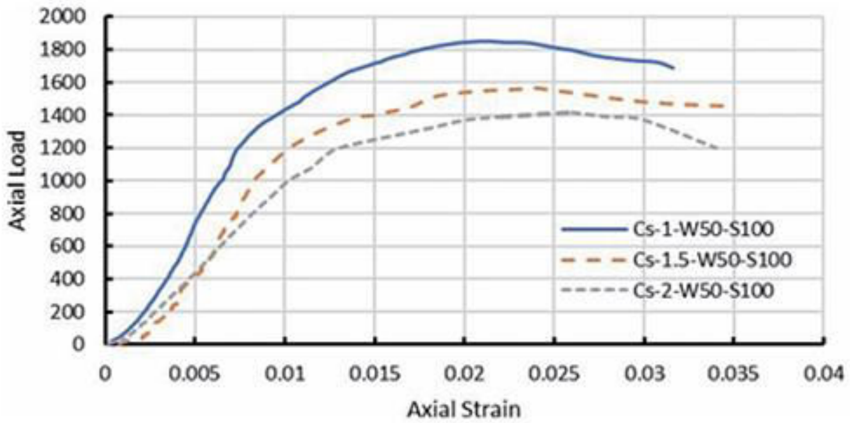


**Figure-8.** Load-strain response for strengthened specimens [19].

Addressing multiple issues at once, Osman et al. (2023) performed an investigation to improve simultaneously the seismic performance and corrosion resistance of reinforced concrete (RC) bridge columns simultaneously. They proposed a combination of GFRP and steel to reinforce structures where the external 67 CFRP bar was used for corrosion resistance and the internal traditional Steel bar was employed to ensure stiffness and ductility. They developed and tested a sophisticated numerical model to locate the seismic behavior of these hybrid columns and produced useful design tools [20]. Significant findings from the study demonstrated that this hybrid system successfully achieved the objectives of seismic performance and corrosion resistance. As shown in Figure-9 [20].

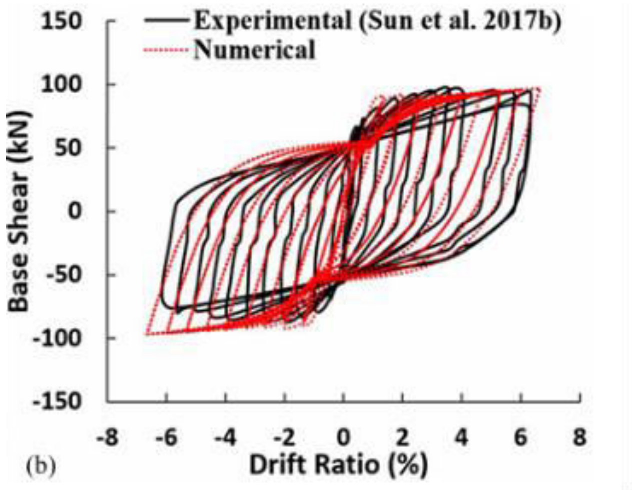


**Figure-9.** Validation of hybrid column load-drift response [20].

An increased GFRP reinforcement ratio improved resistance to lateral forces and extended elastic behavior. In order to optimize seismic capability and energy absorption, the optimal range for steel reinforcement was found to be between 39% and 66%. Simplified design charts were developed to assess the stiffness of fractured hybrid sections for practical usage, as shown in Figure-9 [20].

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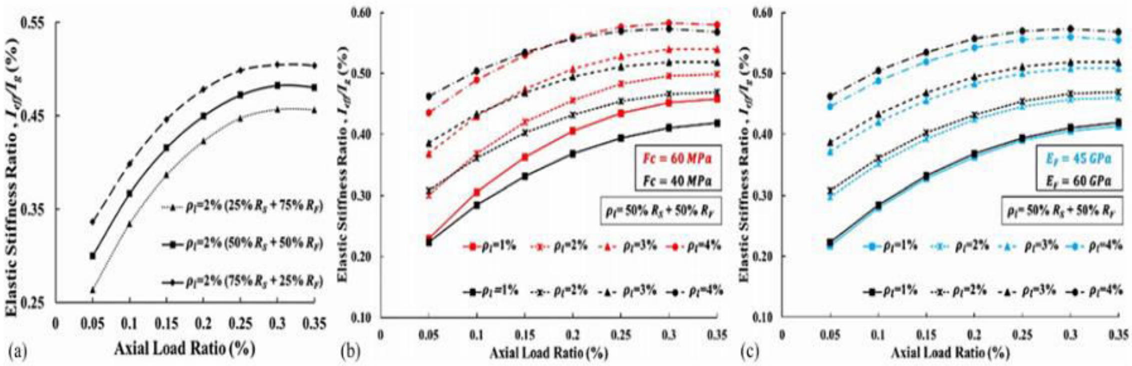


**Figure-10.** Design charts for hybrid section stiffness [20].

In the end, their hybrid design outperformed conventional columns, obtaining an 8% greater maximum base shear and offering crucial corrosion resistance. Figure-11 provides a clear illustration of this comparative advantage [20].

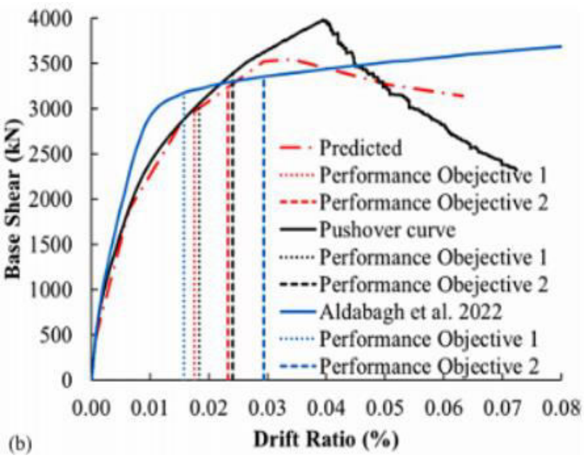


**Figure-11.** Comparative seismic performance of hybrid and conventional columns [20].

### 4.3 Comparative Analysis of Retrofitting Techniques

Directly comparing methods, Ahmed et al. (2025) conducted a numerical study utilizing validated finite element (FE) models to systematically compare three retrofitting techniques for substandard exterior RC beam-column joints: embedded U-shaped steel bars, steel angles with pretension bolts, and CFRP wrapping. For every method, a parametric study optimized important design variables. The comparison (Table-1) revealed that steel angles secured with pretension bolts provided the highest enhancement in ultimate load capacity (148.5% increase over the control joint) and ductility (DI = 3.20), effectively relocating the failure mode to a ductile flexural hinge in the beam. CFRP wrapping also significantly increased strength (103.9% increase) but resulted in a mixed beam-joint failure and lower ductility (DI = 1.76). The embedded U-shaped bars offered a moderate strength increase (43.6%) and ductility (DI = 2.25), also showing a mixed beam-joint failure mode (Figure-32 in their paper shows stress distributions). The study concluded that while all methods improved performance, the steel angle technique was the most robust in enhancing both strength and ductility while achieving the desired failure mode of relocation [22].

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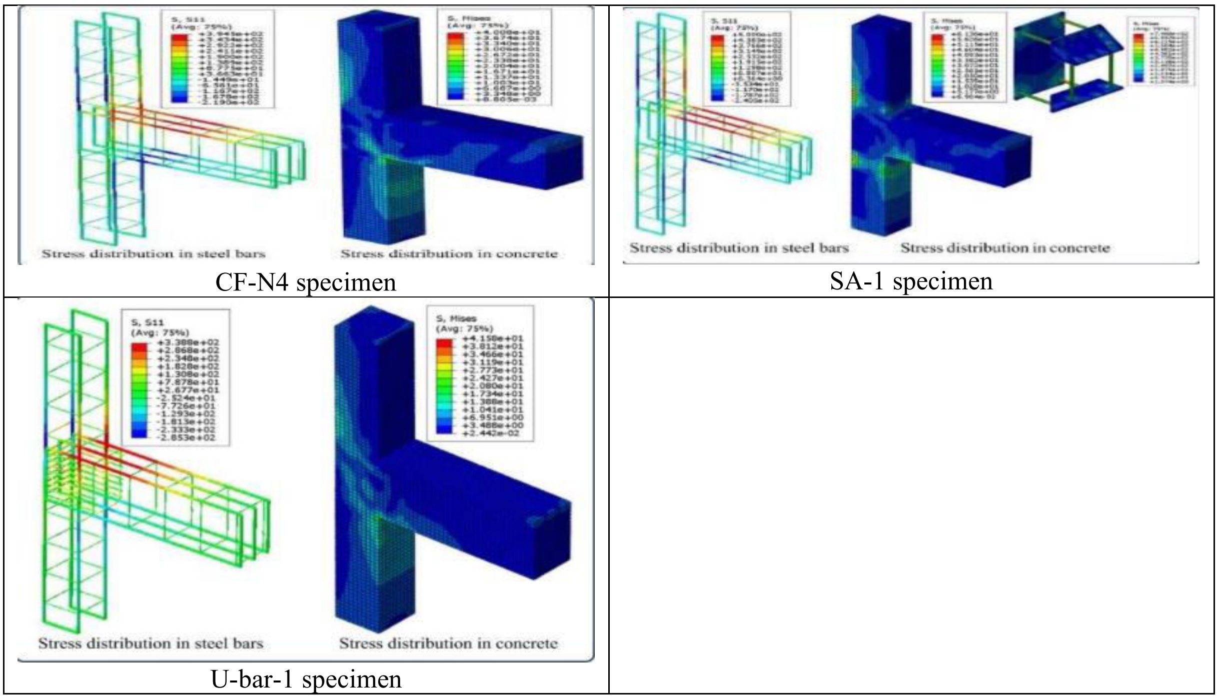


**Figure-12.** Stress distribution comparison in steel bars and concrete for optimized retrofitting techniques: Steel Angles (SA-1), CFRP (CF-N4), and U-shaped bars (U-bar-1) [22].

**Table-1.** An overview of the test specimens' structural performance metrics [22].

| BCJ specimen | Ultimate load $P_u$ (kN) | Δy (mm) | Δ*u* (mm) | Ductility Index (*DI*) | $P_u$ (Enhancement ratio, %) | Failure mode |
|---|---|---|---|---|---|---|
| SA-2 | 165.00 | 6.00 | 19.20 | 3.20 | 148.50 | B[a] |
| CF-N4 | 135.41 | 7.00 | 12.35 | 1.76 | 103.93 | BJ[b] |
| U-bar-1 | 95.32 | 5.70 | 12.80 | 2.25 | 43.55 | BJ |

[a]B refers to a flexural failure occurring at the beam
[b]BJ refers to a failure occurring at the beam-joint

**Table-2.** Comparison of retrofitting techniques.

| Retrofitting Technique | Advantages | Disadvantages | Best Application |
|---|---|---|---|
| FRP Wrapping | Light Weight, No Corrosion | Debonding Risk | Moderate Damage |
| Steel Jacketing | Maximum strength (67-148%) | Heavy And Rusts | Severe Damage |
| Hybrid | Corrosion + Ductility | Complex Installation | Bridges And Coastal |

## CONCLUSIONS

The examination of retrofitting methods for reinforced concrete beam column connections emphasizes how important it is to use suitable strengthening procedures that successfully reduce the systemic vulnerabilities of current structures. Research on FRP wrapping demonstrates that full surface application of FRP is not always necessary for maximum performance. Strategic partial wrapping, particularly with X-shaped and orthogonal strip configurations, can result in load bearing capacities that are 30% less material-intensive than full wraps. Following FRP treatments, the seismic characteristics significantly increase, with a 20% increase in displacement capacity and a 25% increase in peak shear force. The shift in failure mode from brittle bar spilling to ductile FRP rupture, which enables the joint to achieve the full theoretical flexural strength, is one significant result of this method.

According to the research, steel jacketing is a useful strategy for changing the behavior of a structure from brittle to ductile. The technique's performance is extremely sensitive to geometric parameters, and reducing the steel batten plate spacing to 70mm increased load capacity by more than 67%. This and other findings support the importance of confinement pressure in improving the axial loading load carrying capacity and energy dissipation of square and rectangular columns.

Different performance hierarchies can be seen when retrofitting strategies are directly compared. In contrast to the 103.9% increase observed with the CFRP wrapping method, the mechanical solutions, particularly the steel angles with pretension bolts, demonstrated superior strengthening potential by increasing the ultimate road carrying capacity by 148.5%. Additionally, relocating the plastic hinge away from the joint location and into the beam for a preferred ductile failure mechanism has proven to be the most successful application of this steel angle approach.

Hybrid retrofitting techniques, which combine internal steel reinforcement with external GFRP bars, are fairly successful in addressing both seismic performance and environmental durability. In particular, they achieved an 8% higher maximum base shear than standard columns. However, it comes to realization that while these reviewed methods improve structural performance, the technique selection must strike a compromise between the need for load augmentation, ductility objectives, and environmental limitations.

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