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An Overview of Retrofitting Strategies for Seismically Deficient RC Beam–Column Joints

ABSTRACT

Seismically deficient beam–column joints in reinforced concrete (RC) structures, particularly those built before the adoption of modern seismic codes, have long been identified as a critical weakness in structural systems. Numerous experimental and analytical investigations have confirmed that such joints are prone to brittle failure under seismic loading due to inadequate joint detailing. This paper presents an up-to-date review of retrofit strategies developed to improve the seismic performance of non-ductile RC beam–column joints. Emphasis is placed on three widely adopted categories of retrofit techniques: fiber reinforced polymer (FRP) systems, steel-based interventions, and embedded bar methods. FRP techniques involve externally bonded carbon or glass fiber sheets and wraps; steel-based methods include angle jacketing, prestressed bars, and haunch systems; while embedded bar systems use high-strength steel or FRP bars anchored in epoxy-filled holes within the joint core. Each technique is reviewed with particular focus on its application procedure, required labor, practical challenges, and observed structural performance. The comparative advantages, such as increased ductility, energy dissipation, and ease of installation, are highlighted alongside potential drawbacks like corrosion risk, debonding, or spatial limitations. The review concludes by identifying key gaps in the literature, particularly the lack of full-scale testing that considers the influence of floor slabs, transverse beams, and bidirectional loading. It highlights the need for further research that reflects real-world conditions to refine these retrofit strategies and enhance their broader applicability in seismic rehabilitation of RC structures.

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1. Introduction

Beam–column joints (BCJs) are fundamental to the structural integrity of reinforced concrete (RC) moment-resisting frames, as they ensure the effective transfer of shear and axial forces between beams and columns [1]. During seismic events, these joints experience high stress concentrations and can become critical points of failure if not properly detailed.

This vulnerability is especially common in structures built before the enforcement of modern seismic design codes, as demonstrated by widespread damage during recent events such as the 2023 Turkey–Syria earthquake. In these older buildings, poor detailing, including inadequate transverse reinforcement, insufficient bar anchorage, and lack of confinement, remains a primary concern and has been repeatedly linked to brittle joint failures that compromise the lateral load-resisting system, often resulting in soft-story collapse mechanisms [2]–[5]. Figure 1 shows typical deficient BCJ details, with 14 × 24 in. beams (2 #6 or 2 #8 bars, #3 stirrups at 5 in.) and 16 × 16 in. columns (1–2% reinforcement, #3 ties at 14–16 in.) [6].

Given the seismic risk posed by deficient joints in aging RC structures, there is a growing need for effective retrofitting solutions that can restore or enhance joint performance. This review explores current approaches aimed at improving the seismic behavior of non-ductile BCJs and evaluates their applicability in real-world scenarios.

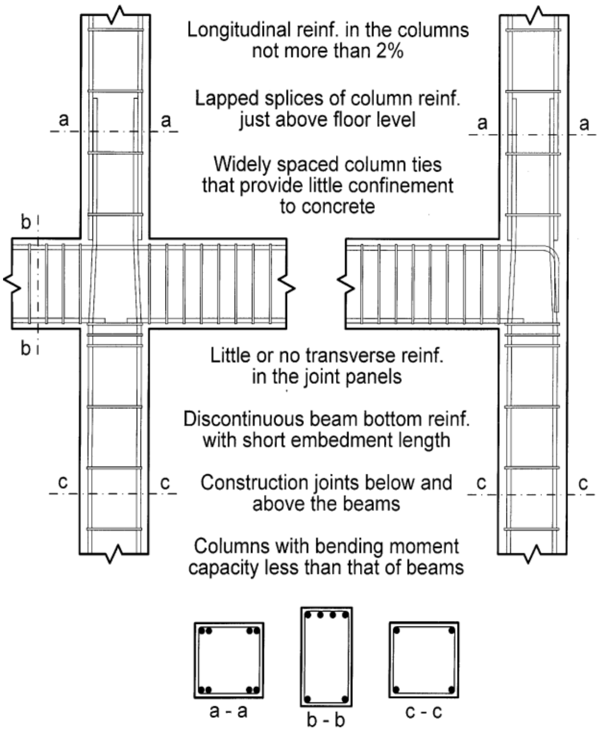

Figure 1. Common features of minimally reinforced concrete structures [6].

In light of these recurring failures, there is a critical need for effective and reliable retrofitting strategies for BCJs in existing RC frames. Retrofitting not only improves the overall seismic behavior of deficient structures but also enables a shift in the failure mechanism from brittle to more ductile modes. A wide range of retrofitting techniques and materials have been developed and applied, including both traditional and modern approaches. Traditional methods, such as concrete jacketing, steel jacketing, addition of shear walls, and epoxy injection, have been widely adopted and shown to be effective [7]. Concrete jacketing enhances joint performance by increasing cross-sectional dimensions and confinement through the addition of new longitudinal bars, ties, and a concrete layer. Steel jacketing involves encasing structural elements with steel plates, often filled with grout or epoxy, to improve both flexural and shear strength. However, these methods also present certain limitations, including increased weight and stiffness, larger member dimensions, and high labor intensity [8]. Thus, modern techniques have been devised in the endeavor to tackle these limitations while maintaining the highest efficacy possible. In this review, we shed the light on three techniques that are thought to be both effective and practical including: fiber-reinforced polymer (FRP) systems, including carbon (CFRP) and glass (GFRP) fiber-reinforced sheets and strips; steel-based methods, such as angle jacketing, post-tensioned bars, ferrocement overlays, and haunch retrofitting; and embedded bar systems.

2. Research Significance

This paper aims to gather current knowledge on the repair and strengthening of joints lacking seismic design, to support engineers and researchers in developing more effective seismic retrofitting solutions. It examines each technique in detail, highlighting its performance along with its advantages and limitations concerning implementation methods, labor intensity, and applicability.

3. Strengthening and Repair Solutions for Beam–Column Joints

Numerous retrofitting methods have been investigated to improve the seismic performance of BCJs, aiming to prevent brittle failures and encourage more ductile structural behavior. Among the most effective techniques are FRP applications, steel-based solutions, and embedded reinforcement systems. These approaches vary in terms of design complexity, labor demands, cost, and the degree to which they interfere with building operations. A key objective is to ensure a proper balance of strength between beams, columns, and joints, promoting controlled deformation in beams rather than failure in joints or columns. In structures originally designed for gravity loads, simply reinforcing the columns may not be adequate, as poorly detailed joints often remain vulnerable. Therefore, enhancing joint shear resistance and confinement is crucial. Modern retrofitting strategies continue to evolve, focusing on efficient and practical use of FRP wraps, steel jacketing methods such as angle sections, post-tensioned rods, ferrocement coatings, haunch additions, and embedded steel bars.

3.1. Fiber-Reinforced Polymer (FRP) Retrofitting Technique

More recently, modern retrofitting strategies have gained significant attention for their practicality and improved performance. Among the most widely researched are FRP systems, such as CFRP and GFRP sheets and strips. These materials offer high tensile strength, corrosion resistance, light weight, and ease of installation. In addition to their mechanical advantages, FRP systems can be applied rapidly and with minimal disruption to building occupancy, reducing downtime for commercial facilities and eliminating the need for relocation in residential settings. Experimental studies have demonstrated that well-anchored FRP wrapping can significantly enhance joint shear strength, ductility, and energy dissipation capacity [10–13]. However, FRP retrofits also suffer from certain limitations, including weak bond strength to concrete and low fire resistance, which can affect long-term performance and safety. To mitigate these drawbacks, hybrid retrofitting strategies have been developed, combining FRP with elements like steel anchor bolts, diagonal haunches, or reinforcement plates [14, 15]. Additionally, researchers are exploring solutions to improve fire resistance, such as applying intumescent coatings to FRP systems [16].

Antonopoulos and Triantafillou [9] conducted an experimental study to investigate the behavior of shear-critical exterior RC BCJs strengthened with FRP under simulated seismic loading. The study involved 18 2/3-scale RC joints that were poorly detailed to replicate typical deficiencies in older structures. Various FRP configurations were tested, including carbon and glass fibers applied as sheets and strips, with or without mechanical anchorage (illustrated in Figure 2). The results demonstrated that FRP significantly improved joint shear capacity, stiffness, and energy dissipation. CFRP sheets proved to be the most effective, increasing joint strength by up to 70%-80% and stiffness by 100% in some cases. The inclusion of mechanical anchorage was critical in preventing premature debonding of FRP, enhancing the effectiveness of the strengthening. Higher FRP area fractions correlated with increased strength and energy dissipation, though the gains were limited by debonding issues. The study also highlighted that axial loads positively influenced the performance of FRP-strengthened joints, contributing to increased shear capacity. Overall, the findings underlined the effectiveness of FRP in retrofitting deficient RC joints, provided that proper detailing, including anchorage, was employed to optimize the benefits of the strengthening system.

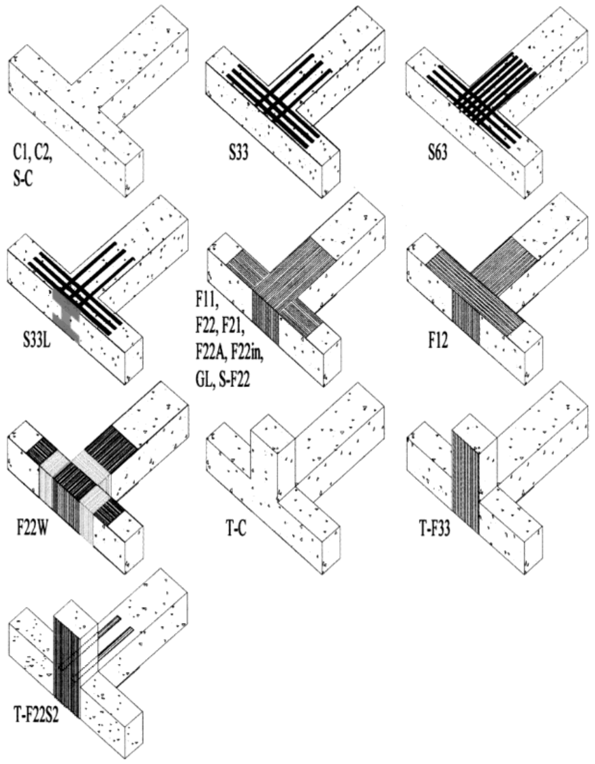

Figure 2. Various configurations of FRP layers [9].

Karayannis and Sirkelis [10] investigated the seismic retrofitting of RC BCJs lacking shear reinforcement using CFRP sheets and epoxy resin injections. The study tested 12 full-scale exterior joint specimens, divided into two groups: Group A with no joint shear reinforcement and Group B with adequate stirrups. CFRP sheets were applied as jacketing in various configurations, including U-shaped wraps extending along the beam and column critical regions to ensure confinement and anchorage, as seen in Figure 3. The layout of the CFRP sheets was carefully designed to cover the joint core and extend sufficiently along the adjoining members to avoid premature debonding or anchorage failure. Results demonstrated that CFRP significantly increased joint shear capacity, energy dissipation, and ductility. Specimens strengthened with CFRP from the beginning (A3 and B3) or repaired with CFRP and epoxy resin after initial damage (A2R and B2R) exhibited superior performance, with up to 186% higher load capacity and improved energy absorption compared to control specimens (A1 and A2). The CFRP layout shifted failure modes from brittle joint shear failure to ductile plastic hinge formation in the beam regions outside the wrapped areas, emphasizing the importance of proper anchorage detailing and CFRP application for effective retrofitting. These outcomes highlighted CFRP's potential as a retrofit solution for poorly detailed joints, provided proper detailing and anchorage were ensured.

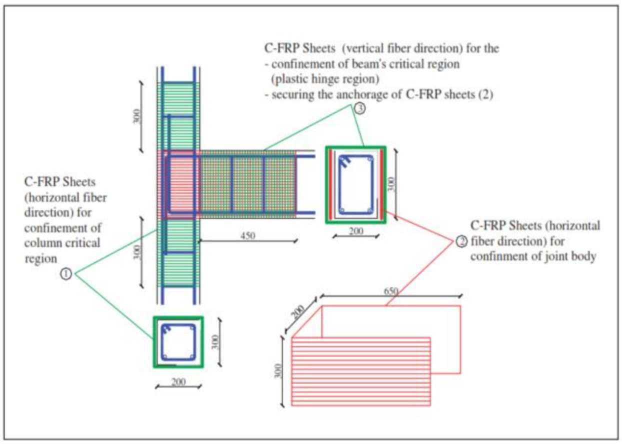

Figure 3. Details of the specimen: Reinforcement, dimensions, and arrangement of FRP [10], all dimensions in mm.

Le-Trung et al. [11] conducted an experimental study to evaluate the seismic performance of RC BCJs strengthened using CFRP composites. The study involved eight 1/3-scale exterior joint specimens, including two baseline specimens, one with non-seismic detailing and one with seismic detailing, and six retrofitted specimens with different CFRP configurations. The retrofitted configurations included T-shaped, L-shaped, and X-shaped CFRP sheets, as well as combinations of strips to improve joint confinement and anchorage(as indicated in Figure 4). The results demonstrated that CFRP retrofitting significantly enhanced lateral strength, ductility, and overall joint behavior. The X-shaped wrapping, aligned with principal stress directions, showed the best performance, increasing strength by up to 17.5% and ductility by over 5 times compared to non-retrofitted joints. Adding multiple layers of CFRP further improved performance, but economic and practical considerations were noted. The findings underscored the effectiveness of CFRP retrofitting, particularly with well-designed layouts, mitigating deficiencies in non-seismically detailed joints and improving seismic resilience.

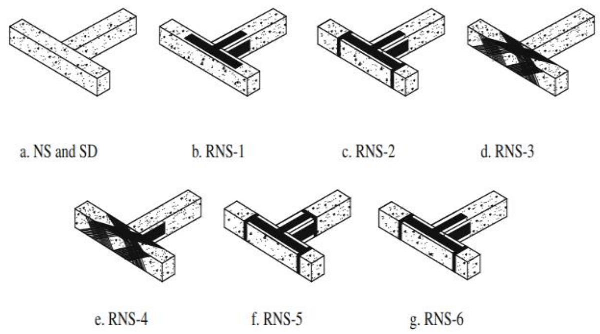

Figure 4. Details of the tested specimen [11].

Mahmoud et al. (2014) [2] conducted an experimental study to evaluate the effectiveness of strengthening defective RC BCJs using CFRP systems. The research involved testing 11 half-scale T-shaped BCJs divided into three groups, each representing a specific defect: absence of joint stirrups, insufficient bond length for beam reinforcement, and inadequately spliced columns. The CFRP strengthening schemes included externally bonded fabric sheets, strips, and near-surface mounted (NSM) CFRP plates, as indicated in Figure 5. Results showed that CFRP significantly improved the load-carrying capacity, stiffness, and ductility of the joints, with strengthened specimens outperforming unstrengthened controls. Specifically, diagonal overlaying CFRP sheets provided a 61% increase in capacity for joints lacking stirrups, while NSM plates demonstrated the best performance for spliced column defects. The study highlighted the importance of proper CFRP configuration and anchorage detailing in achieving effective strengthening. However, CFRP-strengthened joints exhibited reduced ductility compared to the control, underscoring the trade-off between strength and flexibility in retrofitting practices.

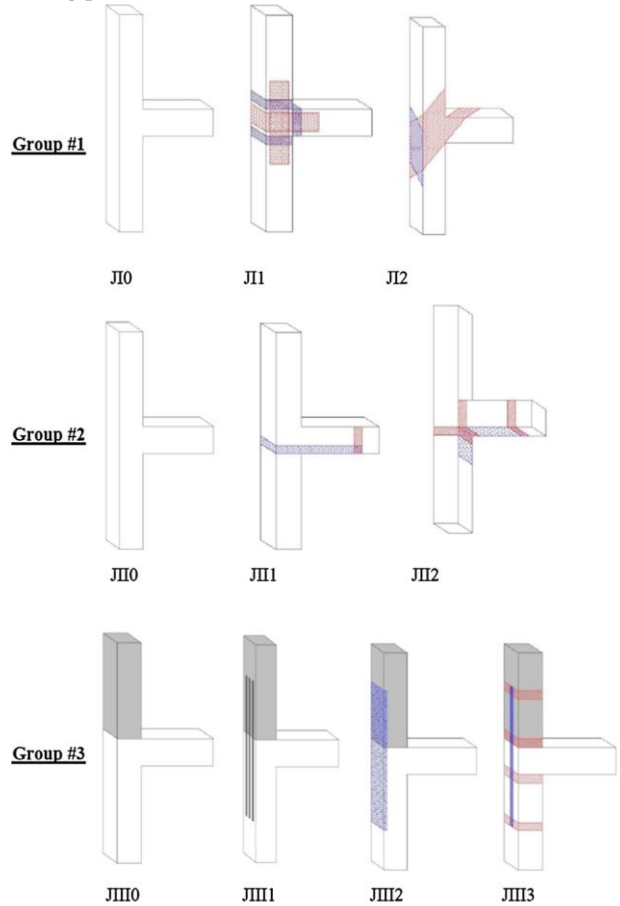

Figure 5. Illustrative layout of the three evaluated groups [2].

Wang et al. [12] conducted an experimental study on the seismic retrofitting of exterior BCJs using bonded CFRP reinforcement. The study involved six exterior RC BCJs, including one non-seismically designed joint, one seismically designed joint, and four retrofitted joints with different CFRP configurations, as seen in Figure 6. The retrofitting methods included externally bonded CFRP sheets and NSM CFRP strips. These methods were designed to enhance joint strength and ductility while relocating the plastic hinge away from the joint core. The results demonstrated that CFRP retrofitting significantly improved the seismic performance of deficient BCJs, with NSM CFRP strips being the most effective in preventing joint shear failure and promoting a ductile failure mode through beam flexural yielding. The study highlighted that proper CFRP detailing and anchorage were crucial for optimizing retrofit performance, as inadequate bonding or premature debonding could limit the effectiveness of the strengthening scheme. These findings reinforced the role of CFRP in improving the resilience of existing RC structures and provided valuable guidance for retrofitting strategies in seismic-prone regions.

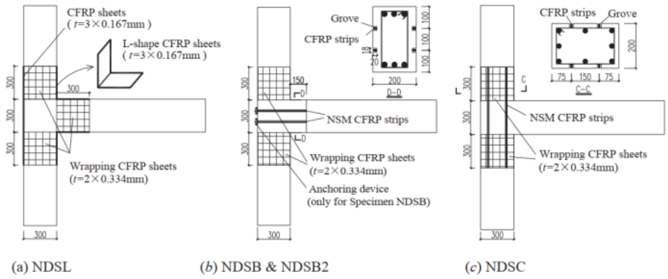

Figure 6. Failure of CFRP retrofitted specimens [12], all dimensions in mm.

Saad et al. [13] investigated the effectiveness of retrofitting non-seismically designed RC BCJs using CFRP sheets. The study involved testing multiple BCJ specimens, including control specimens with deficient joint detailing and retrofitted specimens strengthened using CFRP U-jacketing, as seen in Figure 7. The control specimens represented existing RC joints lacking sufficient joint shear reinforcement, leading to brittle failure modes under loading. The retrofitted specimens were strengthened using CFRP U-jackets applied around the joint region with different anchorage configurations to enhance shear strength and prevent premature debonding. The test results demonstrated that the control specimens exhibited significant stiffness and strength degradation due to brittle joint shear failure. In contrast, the CFRP-retrofitted specimens showed improved shear strength, energy dissipation, and ductility, with failure modes shifting from brittle joint failure to more ductile beam flexural hinging. However, the study also highlighted that improper CFRP anchorage could lead to premature debonding, limiting the effectiveness of the retrofit. The results demonstrated that CFRP U-jacketing was an effective method for strengthening deficient BCJs, provided that proper detailing and anchorage techniques were employed to maximize structural performance.

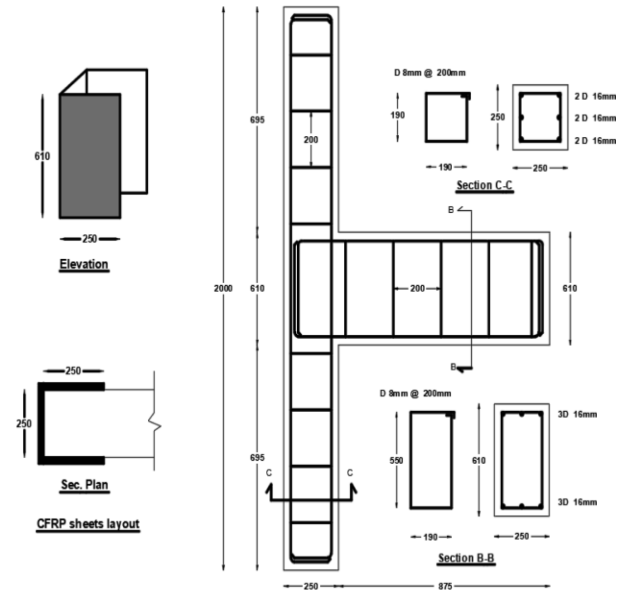

Figure 7. Details of the specimen: Reinforcement, dimensions, and arrangement of CFRP [13], all dimensions in mm.

Cao et al. [14] investigated the monotonic and cyclic behavior of postfire RC beam-column joints with and without CFRP retrofitting. A total of nine joints were tested, including a control specimen, and joints exposed to 45-minute and 75-minute fires, both retrofitted and un-retrofitted. Fire exposure significantly reduced the mechanical performance of joints, with ultimate load and stiffness decreasing by up to 25%, and ductility dropping to low levels under cyclic loading. CFRP retrofitting involved applying flexural and confinement CFRP wraps at the ends of beams and columns, excluding the joint core due to practical limitations, as seen in Figure 8. The retrofitted joints exhibited improved load-carrying capacity, with ultimate loads increasing by up to 15% and stiffness nearly fully recovered compared to the control specimen. Failure modes shifted from brittle joint shear in un-retrofitted specimens to more ductile mechanisms, such as flexural hinging at the beam ends. Under cyclic loading, CFRP-retrofitted joints absorbed more energy and maintained better performance than un-retrofitted ones, although damage still concentrated at the joint center where CFRP was not applied. Some CFRP rupture was observed at large displacements near the beam-column intersections. The study concluded that CFRP retrofitting is an effective technique for strengthening postfire RC joints, especially under monotonic loading. However, under combined fire and cyclic loading, its effectiveness was reduced, highlighting the need for improved detailing and possibly core-joint strengthening.

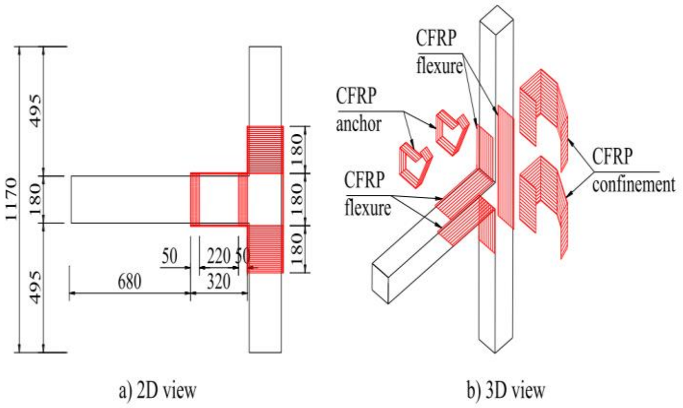

Figure 8. CFRP wrapping scheme [14], all dimensions in mm.

3.2. Steel-based Retrofitting Technique

In parallel, steel-based retrofits, including angle jacketing, post-tensioned bars, ferrocement overlays, and haunch retrofitting, have shown strong performance, especially in joints with plain bars or lacking transverse reinforcement. These techniques are particularly valuable where minimal architectural disruption is desired [15]–[18]. However, they have notable disadvantages, including the risk of corrosion, which can affect long-term durability. They may also be challenging to apply in tight or confined spaces, potentially leading to difficulties in installation. Additionally, these methods can result in aesthetic concerns, as the external steel elements may be visually unappealing [8].

Ghobarah et al. [19] introduced a technique to enhance the seismic resistance of existing RC structures by reinforcing deficient connections with corrugated steel jackets, as depicted in Figure 9. The study involved the construction and testing of four RC BCJs. Three specimens were designed to replicate joints with inadequate transverse reinforcement, while the fourth was properly detailed. Two of the deficient specimens were strengthened using 2.8 mm thick corrugated steel jackets; one enclosing both the beam and column, and the other surrounding only the column. The specimens were subjected to quasi-static loading applied at the beam tip, while a constant axial load equivalent to 0.08 of the column's capacity was maintained. Test results demonstrated a rapid reduction in stiffness and strength in the deficient specimen due to brittle shear failure in the joint. Findings indicated that the retrofitted joints exhibited slightly better performance than the specimen designed according to code requirements. Beam jacketing successfully prevented shear failure in the beam, allowing a flexural hinge to develop, whereas column jacketing alone resulted in shear failure in the beam.

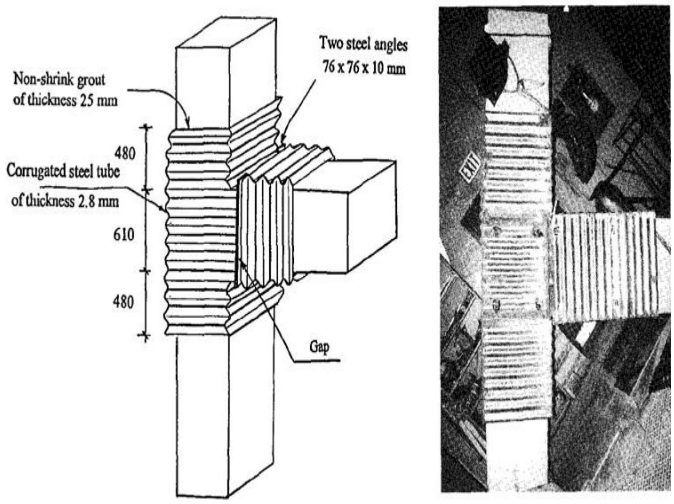

Figure 9. Retrofitting technique by Ghobarah et al. [19], all dimensions in mm.

Kam and Pampanin [20] introduced a retrofit technique known as "selective weakening" to enhance the performance of exterior non-ductile BCJs constructed before the 1970s. This method involved selectively reducing the beam’s strength to protect the joint from damage or reinforcing the joint through external prestressing, or a combination of both approaches. The study demonstrated that the beam’s flexural capacity could be reduced by cutting 50% of the bottom longitudinal reinforcement using a plate grinder (Figure 10), ensuring that plastic hinging occurred in the beam rather than in the column or the joint. Four specimens were tested, revealing that the non-retrofitted specimen developed diagonal shear cracks, while the specimen retrofitted solely with post-tensioning exhibited beam and column hinging failure. In contrast, specimens subjected to both beam weakening and post-tensioning demonstrated ductile behavior and controlled beam hinging. The combination of post-tensioning and selective weakening significantly improved the joint’s energy dissipation capacity and effectively prevented shear failure, which was observed in the non-retrofitted specimen.

Figure 10. Retrofitting approach (post-tensioning and partial removal of bottom reinforcement) [20].

Etman et al. [21] explored the effectiveness of external pre-stressed bars in retrofitting and strengthening RC BCJs. The study involved subjecting the joints to incremental monotonic static loading at the beam tip while maintaining a constant axial load on the column. The specimens were divided into two groups: the first group was initially loaded up to 80% of the ultimate capacity of the control (non-retrofitted) specimen, then retrofitted with external pre-stressed bars of varying diameters and prestressing levels and finally tested to failure. The second group was directly strengthened using the same technique without prior loading and then tested to failure. The results indicated that varying the number of pre-stressing bars had no significant impact on the strength enhancement, with strength increases ranging between 26% and 42% across all specimens. Notably, the ultimate capacity improvement was consistent regardless of the number of pre-stressing bars used. The failure patterns observed in the specimens highlighted the effectiveness of the retrofitting technique in enhancing joint performance, as shown in Figure 11.

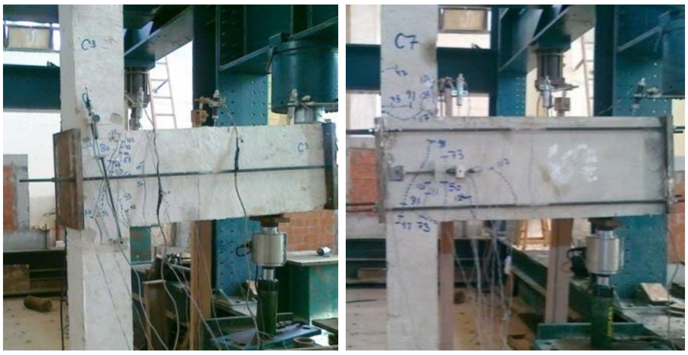

Figure 11. Failure patterns of selected specimens [21].

Shafaei et al. [22] investigated a novel seismic retrofitting technique for non-seismically detailed RC exterior BCJs using prestressed steel angles. The study involved testing seven half-scale BCJs under cyclic lateral loading, including three control specimens and four retrofitted specimens, as seen in Figure 12. The control specimens comprised one seismically detailed joint (C1) designed according to modern code provisions, while the other two (C2 and C3) lacked joint transverse reinforcement and sufficient anchorage for beam bars, representing pre-1970s construction deficiencies. The retrofitting scheme consisted of a two-dimensional joint enlargement using stiffened steel angles installed at the beam-column intersection and held in place with prestressed high-strength steel bars. Two different retrofitting configurations were applied, varying the size of the steel angles and the length of the prestressed bars. Test results showed that the control specimens lacking shear reinforcement exhibited joint shear failure, leading to rapid stiffness degradation and reduced load-carrying capacity. The retrofitted specimens, however, demonstrated significant improvements in strength, stiffness, ductility, and energy dissipation. The enlargement of the joint region effectively redistributed shear forces, preventing brittle joint failure and ensuring beam flexural yielding instead. The study concluded that the proposed retrofitting method was a practical and effective solution for strengthening deficient BCJs, offering enhanced seismic resilience while minimizing architectural disruptions.

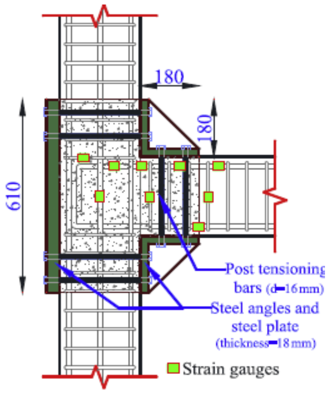

Figure 12. Schematic view of retrofitted specimens [22], all dimensions in mm.

Yurdakul and Avşar [23] conducted an experimental study to assess the seismic retrofitting of substandard RC BCJs using external post-tension rods. The study involved five full-scale specimens, all constructed with low-strength concrete, plain round bars, and no transverse reinforcement in the joint region. The specimens were designed to simulate common deficiencies in RC buildings, such as poor material properties and inadequate reinforcement detailing. Four retrofitted specimens were strengthened with post-tension rods mounted diagonally on each side of the joint, as shown in Figure 13, while the reference specimen (EJ-R) remained unretrofitted. One of the specimens (EJB-P-3) was equipped with a transverse beam to evaluate the effect of this additional confinement on joint performance. The specimens were subjected to cyclic quasi-static loading up to an 8% drift ratio to assess their response under seismic-like conditions. The test results demonstrated that the retrofitted specimens showed significant improvements in strength, stiffness, and energy dissipation compared to the reference specimen. The specimen with the transverse beam (EJB-P-3) exhibited the best performance, with enhanced joint shear strength and a more ductile failure mode. In contrast, specimens without the transverse beam, though showing strength improvements, still experienced brittle joint shear failure under higher drift levels. The study concluded that the proposed post-tension rod retrofitting method was an effective and practical solution for strengthening substandard RC BCJs, offering significant enhancements in seismic performance without introducing additional force demands on other structural elements.

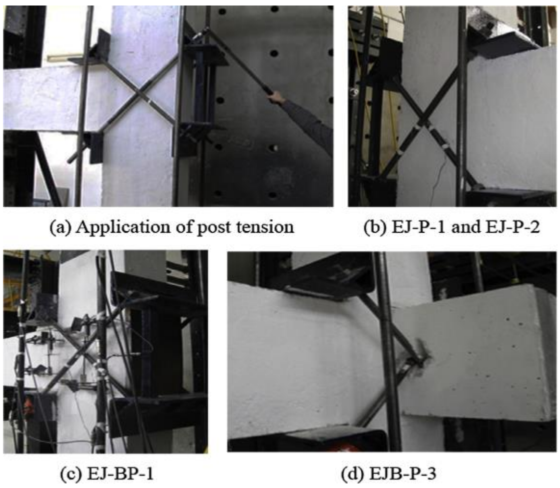

Figure 13. Details of retrofitted specimens [23].

Adibi et al. [24] investigated a seismic retrofitting technique for external RC BCJs reinforced with plain bars, employing steel angles prestressed with cross ties. The experimental program consisted of five half-scale specimens, including two control specimens (SC1 and SC2) and three retrofitted specimens (SR1, SR2, and SR3). The control specimens were reinforced with plain bars without any seismic detailing, whereas the retrofitted specimens were strengthened using steel angles and prestressed cross ties, as illustrated in Figure 14. The test results confirmed that the retrofitting approach effectively mitigated the sliding of plain bars, a prevalent failure mode in these joints, and successfully relocated the damage zone away from the joint region. The retrofitted specimens demonstrated notable improvements, particularly in terms of enhanced ductility, reduced pinching effects in the hysteresis response, and improved energy dissipation. Among them, SR1, which featured steel angles with a higher prestressing rate, exhibited the most favorable performance, showing moderate strength enhancement and a more stable response compared to the control specimens. Furthermore, even the minimally retrofitted specimen (SR3) achieved satisfactory results, highlighting the cost-effectiveness and practicality of this retrofitting method for strengthening deficient RC joints.

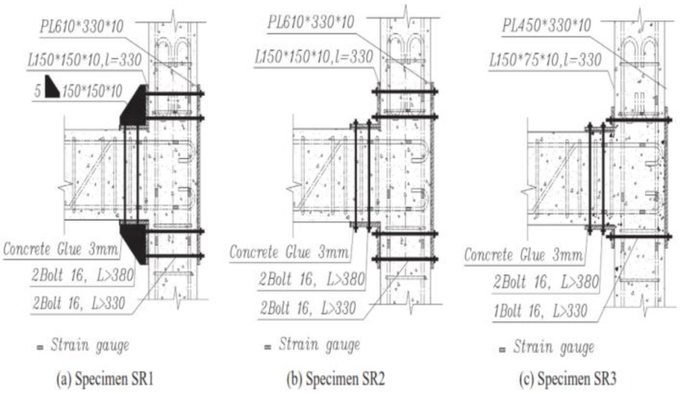

Figure 14. . Details of retrofitted specimens [24], all dimensions in mm.

Khodaei et al. [25] extended previous research by Shafaei et al. [22] and Adibi et al. [24] by investigating the effectiveness of prestressed steel angles and post-tensioned bars in retrofitting deficient RC BCJs, considering the impact of slabs and transverse beams. Seven half-scale BCJs were tested under cyclic lateral loading, including four control specimens and three retrofitted specimens. One control specimen (SJ0) followed modern seismic code requirements, while the others (SJ1, SJ2, and SJ3) represented older, seismically deficient designs lacking transverse reinforcement and proper bar anchorage. The retrofitting approach involved joint enlargement using prestressed steel angles and post-tensioned bars to enhance confinement and relocate plastic hinges outside the joint core, as depicted in Figure 15. The retrofitted specimens (RSJ1, RSJ2, and RSJ3) were strengthened versions of the deficient control specimens. Experimental results showed that non-seismic control specimens suffered from brittle joint shear failure, rapid stiffness degradation, and poor energy dissipation. In contrast, the retrofitted specimens exhibited increased strength, stiffness, ductility, and energy dissipation. The retrofit strategy effectively redistributed shear forces, mitigated premature joint failure, and promoted flexural yielding in the beam. The study concluded that this retrofitting method was a viable and efficient solution for improving the seismic performance of deficient BCJs while minimizing architectural modifications.

Figure 15. Retrofitted system set up [25], all dimensions in mm.

Zaki et al. [16] investigated a seismic retrofitting technique for deficient RC exterior BCJs using steel plates and angles. The study involved testing six half-scale BCJs under quasi-static cyclic loading, including two control specimens and four retrofitted specimens. One control specimen (SC1) was designed according to modern seismic code provisions, while the other (SC2) represented non-seismically detailed joints with inadequate joint transverse reinforcement and insufficient anchorage length for beam bars. The retrofitting scheme involved strengthening the joints using various steel plate and angle configurations to compensate for the lack of joint transverse reinforcement and enhance anchorage conditions. The retrofit designs included X-shaped diagonal plates, horizontal steel plates, and external or internal anchor rods to provide additional confinement and improve force transfer mechanisms, as shown in Figure 16. One of the retrofitting methods was designed specifically for joints with transverse beams. Test results showed that the deficient control specimen (SC2) suffered from brittle joint shear failure, rapid stiffness degradation, and low energy dissipation. In contrast, the retrofitted specimens demonstrated significant improvements in strength, stiffness, ductility, and energy dissipation. The retrofitting techniques successfully prevented brittle joint failure, redistributed shear forces, and ensured beam flexural yielding instead. The study concluded that the proposed retrofitting methods provided an effective and practical solution for strengthening deficient BCJs, enhancing their seismic performance while maintaining structural integrity.

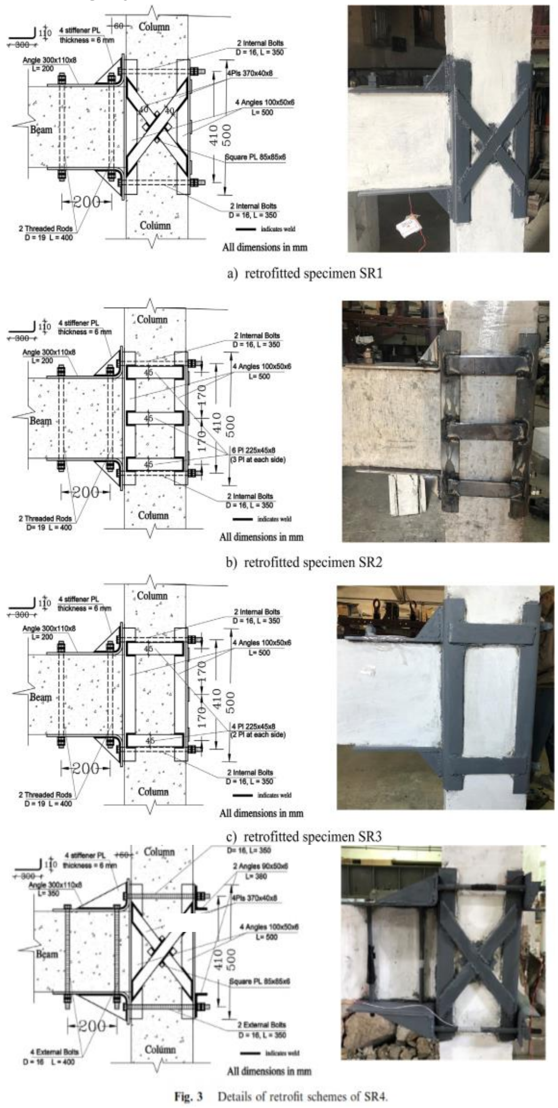

Figure 16. Details of retrofitted joints [16], all dimensions in mm.

Zhang et al. [26] proposed a novel seismic retrofitting strategy for prefabricated steel exterior BCJs using unilateral steel knee braces. Three half-scale specimens were tested under cyclic loading: one unbraced (J-N) and two retrofitted with different brace cross-sections, square steel tube (J-T) and angle steel (J-A) (illustrated in Figure 17). The unbraced specimen exhibited typical local flange buckling and asymmetric hysteretic responses, whereas both retrofitted specimens demonstrated enhanced seismic behavior. The knee braces significantly redistributed stress away from the joint core, moving the plastic hinge outward and improving joint integrity. Notably, the J-A specimen (angle steel knee brace) showed superior performance with the highest energy dissipation capacity, improved ductility, and better control of strength degradation. Quantitatively, the peak bearing capacity of the J-A and J-T specimens increased by 1.63 and 1.39 times, respectively, compared to the unbraced J-N specimen. Their initial stiffness improved by 2.18 and 2.37 times, respectively. The J-A specimen exhibited a cumulative energy dissipation increase of 81.9% at 64 mm displacement relative to the control, while the J-T showed a 34.5% improvement. The angle steel brace also better delayed plasticity onset and maintained stable performance under negative loading, despite experiencing some local instability. Overall, the study validated the efficacy of steel knee braces, especially angle-section braces, in enhancing the seismic resilience of semi-rigid steel BCJs.

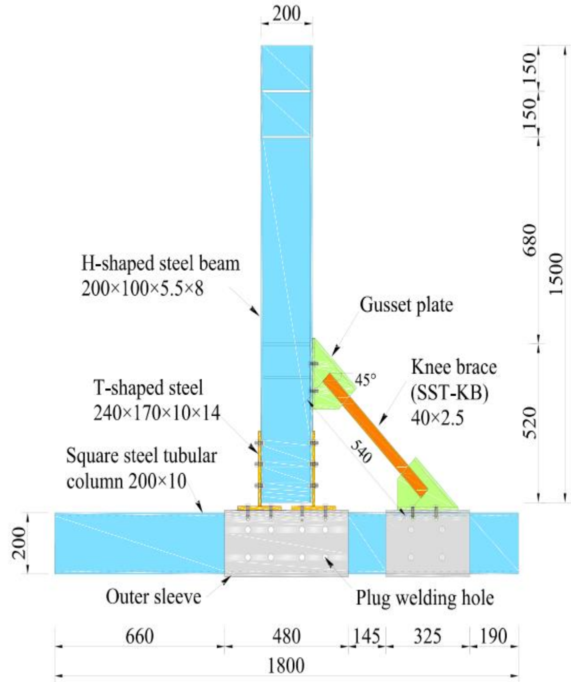

Figure 17. Specifications of strengthened joints [26], all dimensions in mm.

3.3. *Embedded Bars Retrofitting Technique*

A third category of retrofitting involves embedded bar systems, where high-strength steel or CFRP rods are bonded into drilled holes using epoxy resin. This method engages internal strut-and-tie mechanisms and improves confinement, offering enhanced strength, stiffness, and energy dissipation with minimal visual or structural alteration.

Rahman et al. [27] investigated the effectiveness of strengthening shear-deficient RC exterior BCJs using embedded steel and CFRP bars. Six specimens were tested under cyclic lateral loading, including one seismically compliant control specimen and five shear-deficient specimens designed according to pre-1980s building codes. The retrofitting involved embedding additional steel or CFRP bars into epoxy-filled holes drilled within the joint core to enhance shear resistance and improve confinement, as seen in Figure 18. Test results showed that the control specimen experienced brittle joint shear failure with extensive diagonal cracking and rapid stiffness degradation, while the retrofitted specimens exhibited improvements in joint shear strength (6%–21%), ductility (6%–93%), and energy dissipation (10%–54%). Specimens strengthened with embedded steel bars demonstrated better ductility than those with CFRP bars, and increasing the number of embedded bars further enhanced performance by effectively distributing strains. The study concluded that the strengthening technique significantly improved the seismic performance of deficient BCJs while minimizing construction complexities.

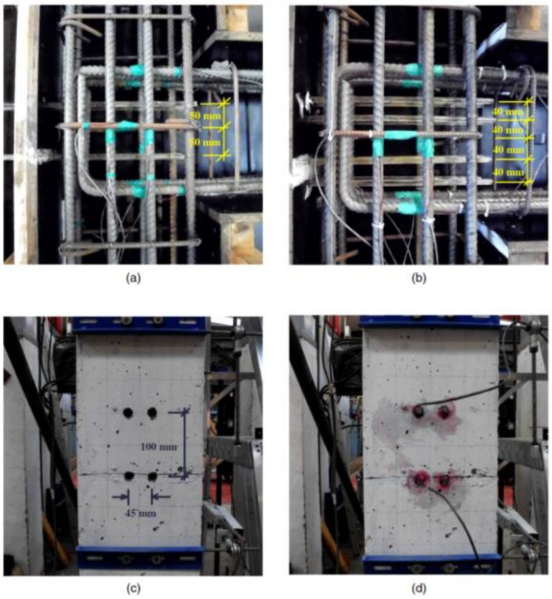

Figure 18. Retrofitting Schemes for Tested Joints [27].

Sayed Ahmed et al. [28] numerically investigated the effectiveness of strengthening shear-deficient RC exterior BCJs using embedded U-shaped steel bars. Four retrofitted specimens were modeled with variations in bar diameter and length to evaluate their influence under monotonic loading. The retrofitting involved embedding U-shaped bars around the joint region, extending into the beam as stirrups, with epoxy used to secure the bars in place, as illustrated in Figure 19. Test results showed that the control specimen exhibited brittle joint shear failure, while the retrofitted specimens demonstrated significant enhancements in joint shear strength (31.6%–47.48%), ductility (2.25–3.13), and improved stress distribution. The study noted limitations related to joint accessibility and bar anchorage, particularly in interior joints. Nevertheless, the embedded U-shaped bar technique was concluded to be effective in improving the seismic performance of deficient BCJs.

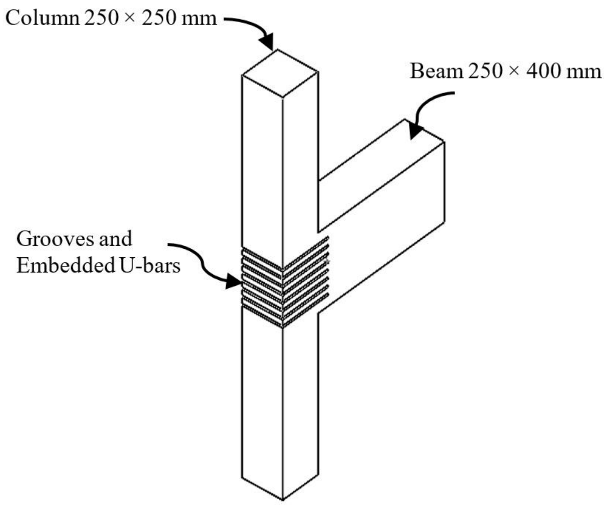

Figure 19. Schematic view of the retrofitted specimen [28].

4. Conclusion and Future Recommendations

Based on the literature review regarding the retrofitting of substandard RC beam-column joints the following insights were:

1- Key non-seismic detailing issues in existing RC structures have been clearly identified, as illustrated in Figure 1. However, the assessment of their impact on seismic performance has largely been limited to tests on isolated one-way joints, without floor slabs, transverse beams, or bidirectional loading, and on small-scale building models, which may not fully capture the real structural behavior of these details.

2- Externally bonded fiber-reinforced polymer systems are effective for retrofitting seismically deficient RC beam–column joints due to their high tensile strength, lightweight, and ease of installation. They offer improved shear strength, ductility, stiffness, and energy dissipation, especially with U-wrap or X-pattern applications. However, issues like premature debonding and weak anchorage limit their full potential. Hybrid techniques and mechanical anchorage have shown promise, but further research is needed to enhance durability and ensure performance in real three-dimensional joints.

3- Steel-based retrofitting methods, such as angle jacketing, post-tensioned bars, and haunch retrofitting, are highly effective for upgrading substandard joints. These methods improve load-carrying capacity, deformation tolerance, rigidity, and seismic energy absorption. Innovations like prestressed steel angles and joint enlargement improve performance with minimal architectural impact. Challenges include corrosion risk, installation in tight spaces, and aesthetic concerns, but with proper detailing and protection, steel retrofits remain a robust and adaptable solution.

4- Embedded bar retrofitting is a practical and effective solution for enhancing the seismic resilience of deficient RC beam–column joints. Both straight and U-shaped embedded steel bars have been shown to improve shear resistance, deformation capacity, and energy dissipation. Increasing the number of embedded bars further boosts performance, with steel bars outperforming CFRP in ductility. Although issues such as anchorage reliability and accessibility in interior joints persist, this minimally invasive method remains a promising and efficient strategy for structural strengthening.

5- Most of the retrofitting techniques proposed to date have shown limited practical use, primarily because they either overlook structural floor components such as transverse beams and slabs or are constrained by architectural limitations. As a result, this field of research remains incomplete, and considerable effort is still needed to establish effective, economical, and widely applicable strengthening solutions. To achieve this, future testing should incorporate key joint configurations (e.g., corner joints) subjected to bidirectional cyclic loading.

6- Promising future research directions include the integration of hybrid retrofitting techniques, smart materials, and AI-based optimization methods. Combining different materials, such as FRP with steel or embedded bars, could offer enhanced performance. Smart materials, such as self-healing concretes and shape-memory alloys, could introduce adaptive and self-monitoring capabilities, while AI and machine learning could optimize retrofit designs for cost-effectiveness and performance. These emerging technologies offer significant potential for improving seismic resilience and should be prioritized in future studies.

Statements and Declarations

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Authors Contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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The author reported no potential conflict of interest.

Data availability statement

Data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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