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Strengthening Techniques for Deficient Beam-Column Joints Using FRP Composites

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Abstract: Corner beam-column joints are critical and vulnerable elements in reinforced concrete moment-resisting frames due to their complex stress state and lack of confinement. This paper presents a comprehensive state-of-the-art review of strengthening techniques for these joints, with a principal focus on Fiber-Reinforced Polymer (FRP) composites, including externally bonded (EB-CFRP/GFRP) and near-surface mounted (NSM) systems. The analysis is extended to alternative methods such as Fabric-Reinforced Cementitious Matrix (FRCM) and high-performance concrete.

Consolidated findings demonstrate that FRP interventions significantly enhance shear strength, energy dissipation, and ductility. Crucially, effective retrofitting shifts the failure mechanism from brittle joint shear to ductile beam hinging, upholding the "strong-column weak-beam" principle. The review critically identifies key influential factors: FRP configuration, area fraction, anchorage systems preventing debonding, and material type. A comparative analysis reveals that while FRPs offer superior strength-to-weight ratios, emerging materials like FRCM provide advantages in fire resistance and compatibility.

This synthesis establishes that advanced composites are a superior alternative to conventional techniques for seismic upgrading. Finally, the review outlines essential research frontiers, including long-term durability, performance under bidirectional loading, and the development of standardized design codes for hybrid solutions, providing a critical reference for researchers and engineers.

Introduction

Reinforced concrete (RC) structures consist of various structural elements that work together to provide stability and support. Among these elements, beam-column joints are of particular significance as they play a critical role in transferring the forces between the beams, columns, and stories. During an earthquake, beam-column joints are exposed to higher levels of shear forces than the surrounding beam and column members. This makes the design and construction of beam-column joints a crucial consideration in ensuring the structural safety and performance of RC buildings. Figure 1.1 illustrates the shear forces acting on a beam-column joint during an earthquake, highlighting the significance of this element in RC structures. Post-earthquake analyses have indicated that the beam-column joints of many existing RC structures contributed to their partial or complete collapse.

This was attributed to severe damage sustained by the joints, which resultedin a loss of axial load continuity to the lower level [1]–[4]. Several structural deficiencies have been identified as the reason behind the severe damage sustained by the beam-column joints in many RC structures.

These deficiencies include inadequate transverse reinforcement in the joint region, insufficient anchorage of longitudinal bars in the beam, a strong beam-weak column design, and the use of inferior quality materials. As a result of these deficiencies, the beam-column joints were unable to withstand inelastic deformation generated during an earthquake, ultimately leading to their failure and the partial or complete collapse of the RC structures [5]–[6].

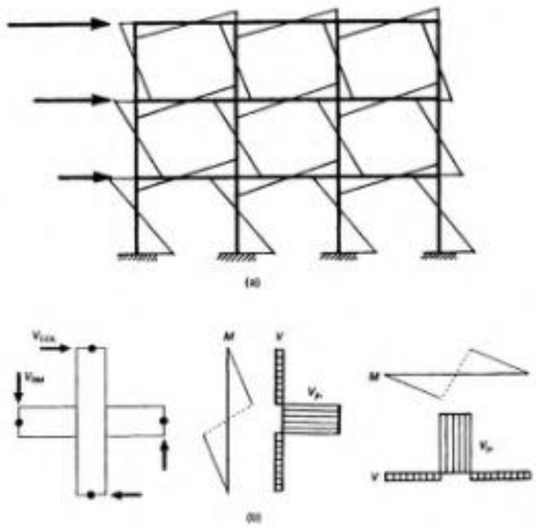


Figure 1.1 Shear force and bending moment diagram for beam-column joins during theearthquake [8].

Figures 1.2 through Figure 1.6, visually demonstrate the severe consequences that can result from the failure of beam-column joints in RC buildings. The examples depicted in the figures showcase the devastating effects of structural deficiencies in beam-column joints, such as inadequate transverse reinforcement, insufficient anchorage of longitudinal bars, strong beam-weak column design, and the use of substandard materials. By studying the visual examples provided, engineers can better understand the significance of beam-column joints in ensuring the safety and stability of RC structures during seismic events.

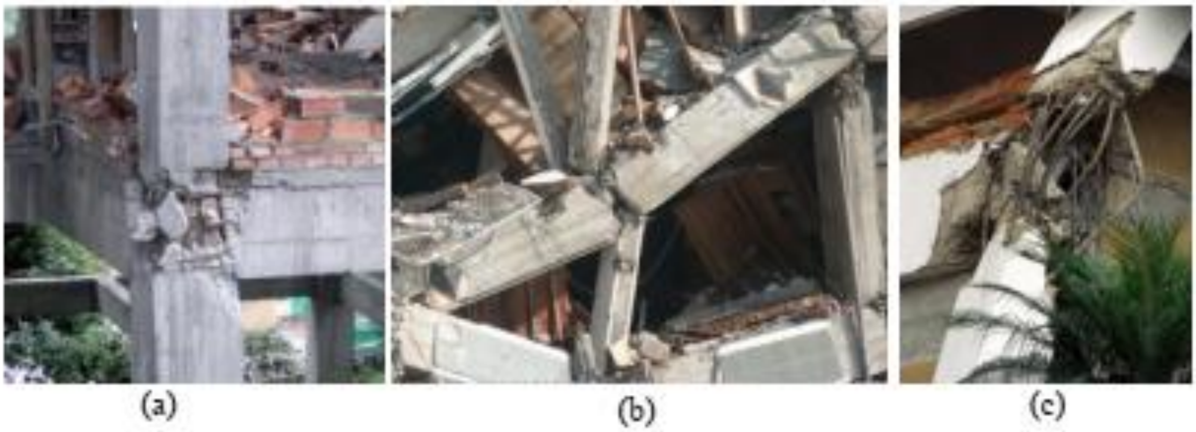


Figure 1.2 Collapsed or partially collapsed buildings due to failure of beam-column joints,(a)beam-column joint failures due to insufficient transverse reinforcement at the joint [2],(b) Strong beam-weak column and failure of beam-column joints [1], and (c) collapsed building due to poor details of joint [4]

Figure 1.3 Buildings collapse due to failure of beam-column joints, Izmit, Turkey, Earthquake in 1999 [9], [9]. (a) (b) (c)

Figure 1.4 Collapse of the reinforced concrete building; a) Turky, Duzce earthquake,1999; b) Sarpole-Zahab earthquake, Iran 2017 [10][11].

Figure 1.5 Damage to partial damage of reinforced concrete building due to beamcolumn failure in Chi-Chi, Taiwan, earthquake, 1999 [12]

Shear strength mechanism of beam-column joints

During an earthquake, beam-column joints sustain shear forces greater than those generated in adjacent framing beams and columns [16]. If the joint is not appropriately designed, collapse or partial collapse might occur due to the shear failure of the beam-column joints. In 1978, Paulay et al. [12] suggested two mechanisms governing joint shear strength: a diagonal compressive strut and a truss mechanism. Figure 2.1 (a) illustrates that internal forces transferred from adjoining framing members to the joint core, causing diagonal tension (ft) and compression (fc) stresses. As a result, the joint is subjected to shear, compressive, tensile, and sometimes torsion forces.

The truss mechanism is mainly composed of the combined effect of beam and column forces transmitted by bond stresses through longitudinal bars to the joint core. Consequently, tensile resisting forces develop within the joint transverse reinforcement, as illustrated in Figure 2.1(b) [13][14]. However, the joint truss mechanism can't be developed without joint transverse reinforcement owing to the limited contribution of the force transmitted by bond stresses along the longitudinal bar of the beam and column. Furthermore, this small contribution of the longitudinal bar rapidly diminishes once bond deterioration initiates within the core [24]. Based on previous research studies, the diagonal concrete compression strut plays an important role in resisting horizontal and vertical shear forces. The diagonal concrete strut transmits a compression force at an angle (βc), as shown in Figure 2.1 (c). The concrete strut mechanism is capable of transmitting a significant amount of both horizontal and vertical shear forces across the joint core [22]. The strut is anchored in a node formed inside of the standard hook of the beam longitudinal reinforcement, which establishes the requirement that hook should be bent into the joint core, as indicated in Figure 2.1 (d).

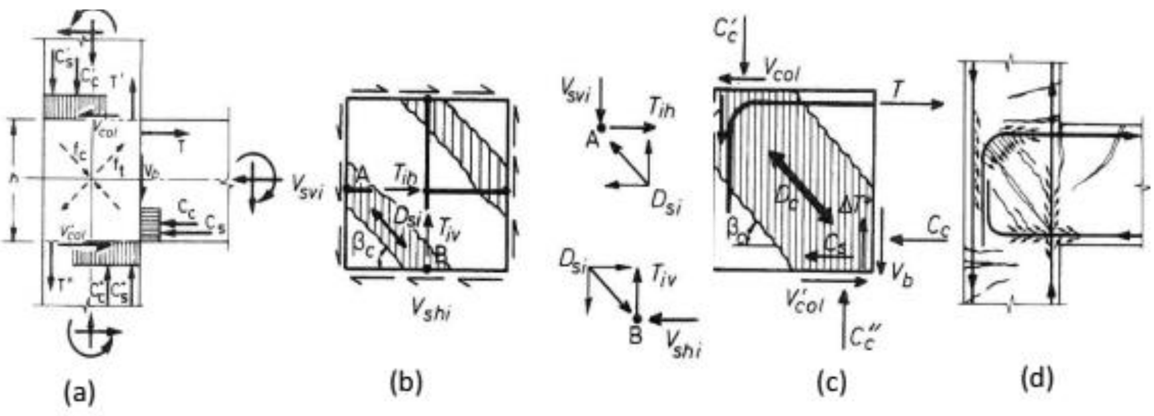


Figure 2.1 Forces transmitted to the joint core (a) forces acting on the joint core, (b), (c) strut mechanism, and (d) truss mechanism [63].(a) (b) (c) (d)

The failure mode of beam-column joint

The beam-column joint is generated from the intersection of the beam and column. As a result, each component (beam, column, and joint) may fail in various ways, including beam flexural/shear failure, column flexural/shear failure, joint shear failure, and so on. It is well known that shear and anchorage failure mechanisms should be avoided if the beam-column joint undergoes large plastic deformations. Due to the limited deformation capacity of such failure mechanisms, they may result in the collapse of the entire frame [55]. Joint shear failure (J-failure) occurs when the maximum shear capacity of the joint is reached without yielding beam and column (i.e. pure shear failure). This indicates that the structure will collapse before the beam and column have reached their maximum flexural capacity [46]. The second type of failure mechanism is called (BJ-failure). In this type of failure, the top or bottom reinforcement of the beam yields at the face of the column shortly before the joint shear failure occurs. This type of failure is considered more ductile than pure joint shear failure [12]. The failure also may occur due to the pullout of beam reinforcement bar from the joint core (P-failure) before reaching its joint shear capacity. This is due to the poor anchorage condition of the longitudinal beam bar. If the joint shear capacity remains greater than the demand to the end. In that case, the maximum strength may be controlled by the beam flexure capacity (B-failure) or column flexural capacity

Effect of concrete compressive strength

The compressive strength of concrete significantly affects the behavior of beam-column joints. The 2019 CSA Standard A23.3.19 [10] restricts the application of the design equations to concrete compressive strengths of up to 80 MPa ($\sqrt{fc`}$ not exceed 8 MPa) for ductile structures. While New Zealand Standard [13] limits the compressive strength to 70 MPa. This cautious limit was selected because of concerns regarding the brittleness of high-strength concrete (HSC) under compression. Ehsani and Alameddine [17] found that using high compressive strength concrete improves joint shear strength but shows low ductility. Furthermore, the bond strength of the HSC specimen was higher than the corresponding to NSC specimen under cyclic load [15]. Despite the fact that HSC improves the ultimate shear capacity of the joint, once failure occurs, the high strength specimens lose their strength more rapidly than their corresponding NSC specimens [24]. Sarsam and Al-Azzawi [14] reported that using HSC in exterior joints without fibers exhibited sudden failure, even with transverse reinforcement in the joint region. Many codes and proposals models assumed that the joint shear strength is a proportion of the square root of concrete compressive strength ($\sqrt{fc`}$) [17], [33], [45], [38]. The same assumption is also adopted in the current study. Figure 2.2 shows the relation between the square root of concrete compressive strength and joint shear strength coefficient for the reinforced joints. The results were agreed well with the previous assumption that the joint shear strength is significantly affected by the concrete compressive strength of joint, but this was only for the interior joints .However, the assumption was not true for the exterior joints. The general trend of results showed that the shear strength of exterior joints was not affected by the concrete compressive strength. This could be attributed to the confinement provided by the transverse beam in the interior joints.

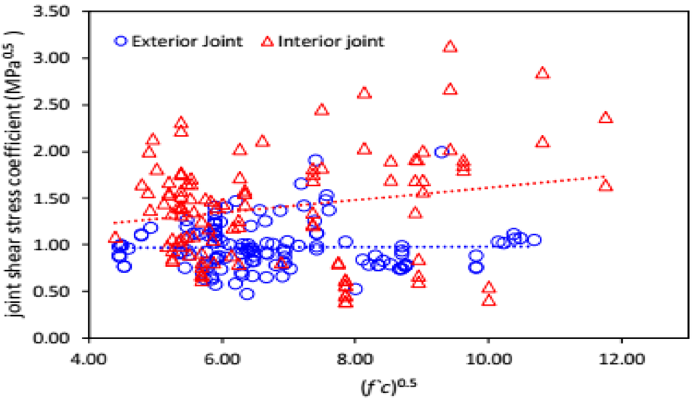


Figure 2.2 Effect of concrete compressive strength on the joint shear strength

Effect of eccentric connection

An eccentric connection occurs when the beam centerline is offset from the column centerline. This is often utilized for architectural consideration within an external frame of a reinforced concrete building. As illustrated in Figure 2.3, tension and compression forces are transferred from the spandrel beam to the joint with an eccentricity that may cause torsion in the joint region. This torsion will generate extra shear stresses, which may affect the joint's inelastic performance.

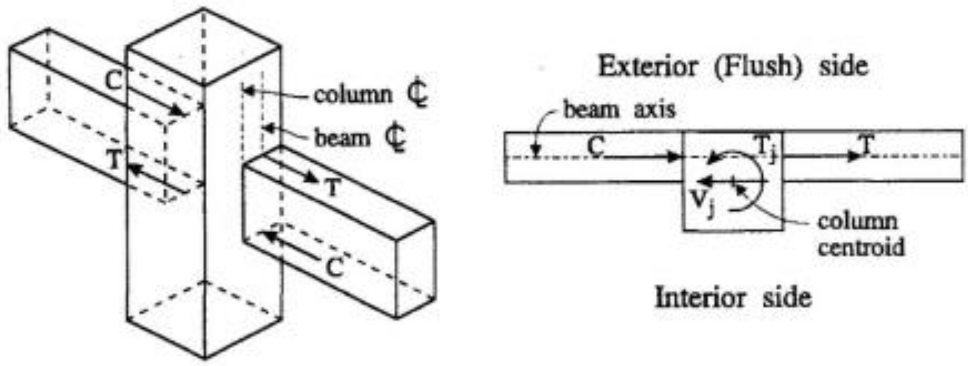


Figure 2.3 Forces acting on the eccentric beam-column connection [29].

In 1973, Ohno and Shibama [54] investigated the reason of the collapse of just one school building at Hakodate College in Japan, which had been severely damaged by the 1968 Tokachiokrk earthquake. However, little or no damage was observed in the other reinforced concrete constructions in the same area. It was found that the structure suffered damage due to a large eccentricity between the columns and spandrel beam.

The eccentric connection resulted in more severe crack damage on the flush side of the joint than interior side, significant bond degradation for the main reinforcement of beams, and a reduction in the joint's shear strength[2][3][49]. Raffaelle and Wight [59] reported that joint shear strength calculated based on ACI-ASCE Committee 352 [19] does not adequately account for the torsion in eccentric connections. However, It was concluded that floor slabs diminished the effect of eccentricity. Moreover, the differences between the seismic performance of these eccentric connections and current ACI building code provision [17] for estimating nominal joint shear strength were quite conservative for the case of the tested eccentric beam-column connections with floor slabs [10][11]. Other than that, ACI code needs much more investigation about this topic since its predictions in many cases were unsafe

Effect of anchorage detail of longitudinal bars in beam that

terminated in the joint core. The forces in beam and column are transmitted across the joint core primarily through a diagonal compression strut. As shown in Figure 2.9 (a), bending the hooks at the ends of the longitudinal beam reinforcement into the joint core, as recommended by all practice codes, allows the diagonal compression strut to transfer bearing stresses effectively with the hooks bending into the joint core, because the bearing stresses at the bend in the bar act in the direction of the strut. Before the 1970s, it was common to anchor the longitudinal beam bars at exterior joints by bending the hooks out of the joint core or in the form of hook bend in 180^o to avoid congestion of steel reinforcement in this region.

Pampanin *et al*. [5] investigated the behavior of external beam-column joints reinforced with a plain bar bent in 180^o at the end. The experimental results revealed a localized concentrated force generated at the compression bar edge after the joint diagonal crack coupled with an ineffective strut mechanism. It results in concrete expulsion in the form of a wedge, as shown in Figure 2.9 (b). Similarly, when the hook bends away from the joint core, the diagonal compression strut does not effectively engage the beam hook. But, rather pushed against the longitudinal column reinforcing bars, resulting in a wide splitting crack along column reinforcement which can then cause a joint failure at early stage, as illustrated in Figure 2.9 (c) [37][38]. This old detail does not provide an effective node point at the top of the diagonal compression strut to equilibrate the horizontal component force of the compression strut[12] [18][5]. When the beam longitudinal bars end in the joint region with a short length, as illustrated in Figure 2.9 (d), the bond mechanism becomes the key factor. The crack begins near the end of the short bar. And thus, it may cause the bond to breakdown before the diagonal compressive strut mechanism was completely developed [29].

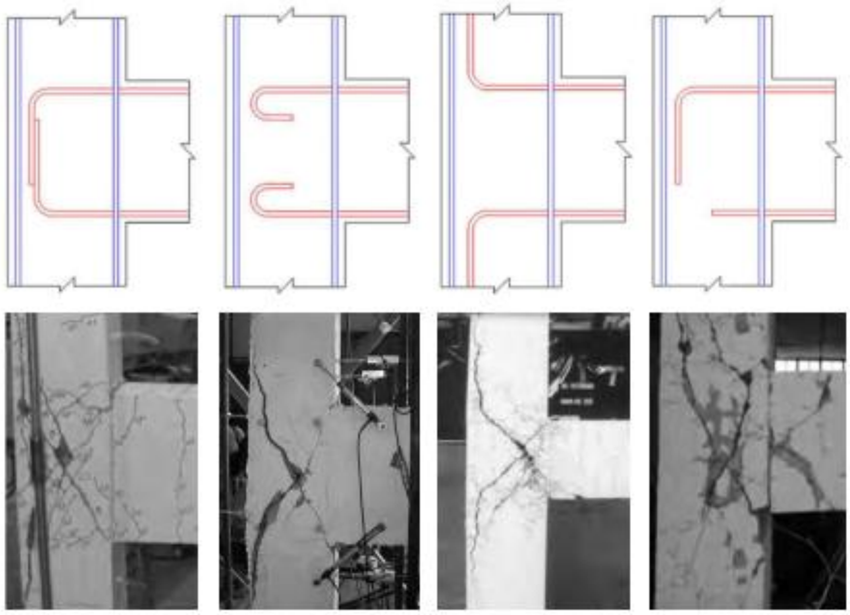


Figure 2.9 Failure mode of common end anchorage of beam longitudinal bars in joint core (a) beam bar bend in the joint core [62],(b) end-hook bend by 180^{o} [5],(c) beam bar bend away from joint core [18] and, (d)short bar terminated in the joint core [29].

Effect of the transverse reinforcement in the joint core

The joint transverse reinforcement can directly contribute to the overall joint behavior. There are two viewpoints on the function of transverse reinforcement.

- **First**, it can provide shear forces resistance with an upper limit equal to the area of the transverse reinforcement times its yield stress (tie action), which is adopted by the New Zealand building code [23].
- **Second**, the transverse reinforcement can provide confinement to the joint, which is proportional to the number of transverse reinforcement placed in the joint. This is adopted by ACI-ASCE, and most building codes [45].

Many studies have shown that diagonal compression struts withstand shear forces in the joint core. In contrast, joint transverse reinforcement confined the joint concrete core, thereby enhancing joint diagonal compressive strength, thus, transverse reinforcement contributes indirectly to the shear resistance of the joint [30][31]. The ACI 318 [17] and ACI-ASCE 352 [32][16] assumed that joint transverse reinforcement provides confinement for the joint core and can not withstand shear force due to severe bond deterioration and the shear forces are resisted by diagonal compression strut only.

On the contrary, the New Zealand standard code [27] assumes that the bond of reinforcement bars in the joint core is sufficient to resist shear forces in transverse reinforcement, and therefore, the internal shear force is resisted by diagonal compression strut and joint transverse reinforcement [33].Hwang et al. [38] investigated the role of joint transverse reinforcement of external beam-column joints under reversed cyclic load through an experimental program consisted of nine specimens. The results indicated that the joint transverse reinforcement plays no role in confining the concrete core. This is because the confinement role by transverse reinforcement can be achieved for the structural elements controlled by Bernoulli's compatibility. Whereas the beam-column joint element is subjected to high shear, thus the joint deformation is governed by Mohr's compatibility. Therefore, joint transverse reinforcement are added to retard the strength deterioration of concrete and not to enhance the strength of concrete. Ehsani and Wight [38] experimentally investigated the effect of transverse reinforcement in the joints core of beam-column joints. The results indicated that specimens with lower flexural strength ratios (the sum of the flexural capacities of the columns to that of the beam) can only slightly improve the shear strength of joints when additional transverse reinforcement. Furthermore, providing a larger number of transverse reinforcement with a lower yield stress is more advantageous than providing fewer transverse reinforcement with a greater yield stress, even though the maximum potential shear capacity for both cases may be the same.

Effect of beam longitudinal reinforcement ratio

The beam reinforcement ratio (ρ_b) plays an important role in controlling the ductility of the beam-column joints. The experimental results conducted on the exterior and interior unconfined beam-column joints indicated the dependency of joint shear strength on the amount of beam reinforcement [26][34]. Based on the database adopted in this study, as the longitudinal reinforcement ratio (ρ_b) increases, the joint shear strength also increases, as illustrated in Figure 2.10. This is because the increasing of the beam longitudinal reinforcement ratio leads to an increase in the horizontal joint shear force without yielding of the beam longitudinal bars and with less deterioration of bond resistance around the bars in the joint region. Consequently, a wider diagonal strut was produced which can carry greater horizontal joint shear forces [35]. However, Dabiri et al. demonstrated that increasing the longitudinal reinforcement ratio of a beam reduces both displacement and curvature ductility. As a result, in a structure with a high need of ductility, the computed reinforcement of beams and columns should be adjusted for the necessary ductility [36].

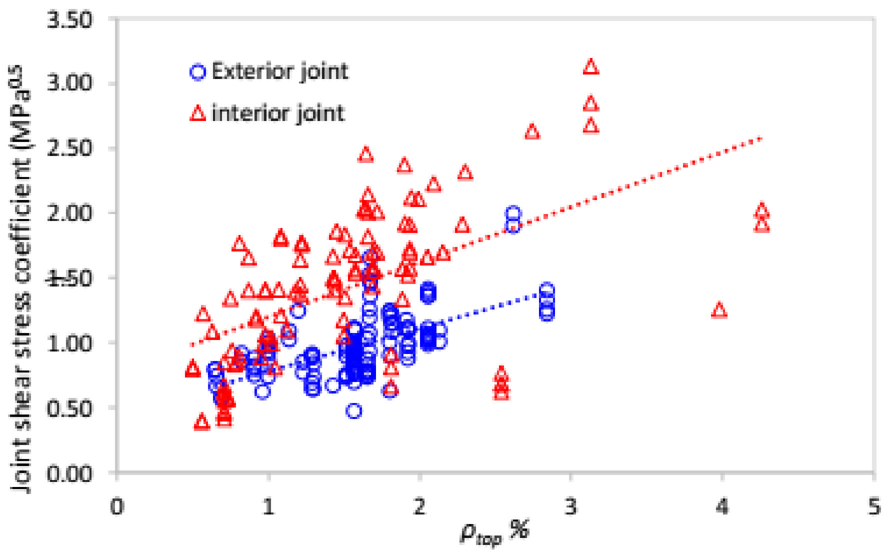


Figure 2.10 Effect of beam longitudinal reinforcement ratio on the joint shear strength.

SFRC/NSC hybrid beam-column joints

Adding fibers to concrete is the conventional technique for improving its mechanical performance since concrete is a quasi-brittle material with a limited strain capacity, especially when subjected to tensile stress. The steel fiber may be attributed primarily to their localized reinforcing ability. Their presence in the mortar matrix surrounding coarse aggregates prevents the opening, widening, and later extension of microcracks already present in the concrete [38]. In addition, steel fibers can also serve as bridging mechanisms during cracking and have an ability to change the brittle failure of concrete to more ductile failure [39]. The following section provides an overview of most studies using steel fibers to enhance the behavior of beam column joints with/without reducing transverse reinforcement.

One of the first attempts to use steel fibers reinforced concrete in joints was by Henager in 1977 [26], who examined the use of steel fibers in beam column joints region instead of transverse reinforcement to reduce steel congestion in this region. Two full-scale exterior beam-column joints were tested under cyclic load. The first one was ductile specimen designed based on the seismic requirement of ACI 318 [22], while the second specimen was constructed using steel fibers reinforced concrete (SFRC) in the joint zone (modified joint) without the use of transverse reinforcement, as shown in Figure 2.11. The result indicated that both specimens were very effective in the confinement of the joint zone. Furthermore, no cracks were observed in the SFRC/NSC hybrid beam-column joint, while some hairline cracks and one major crack appeared in the intersection of the beam and column of the conventional specimen. Finally, the SFRC/NSC hybrid joint showed better performance in terms of damage tolerance, ductility, and shear capacity than the conventional specimen.

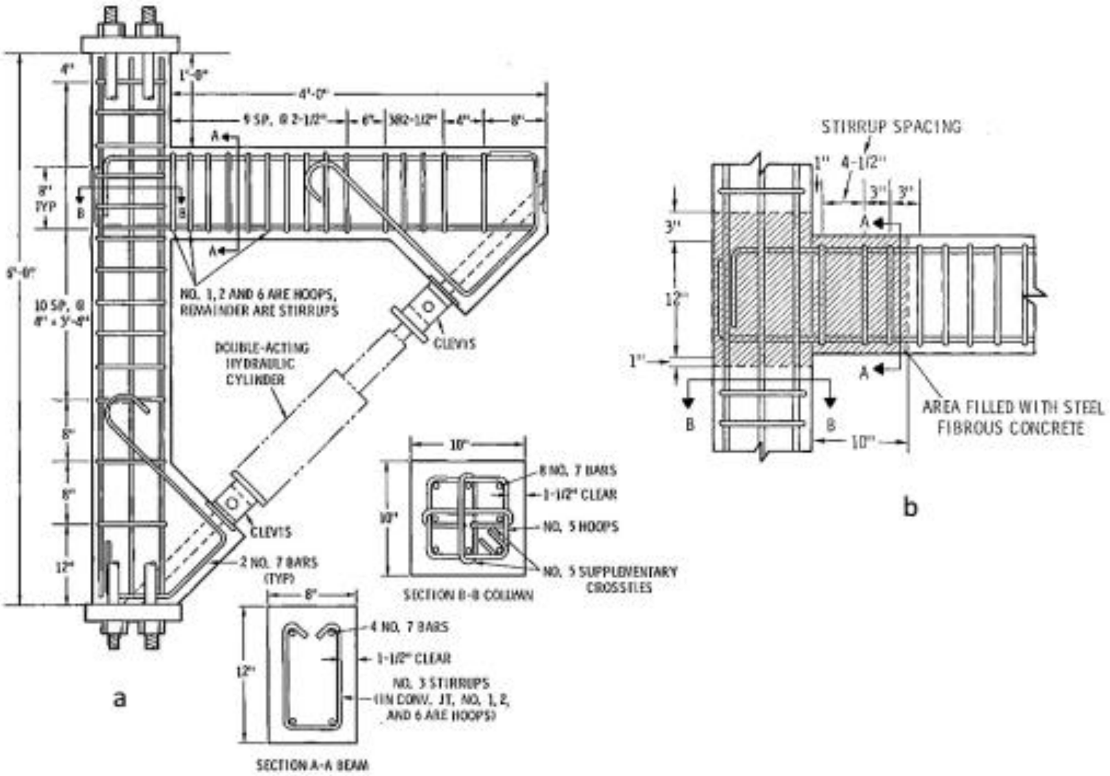
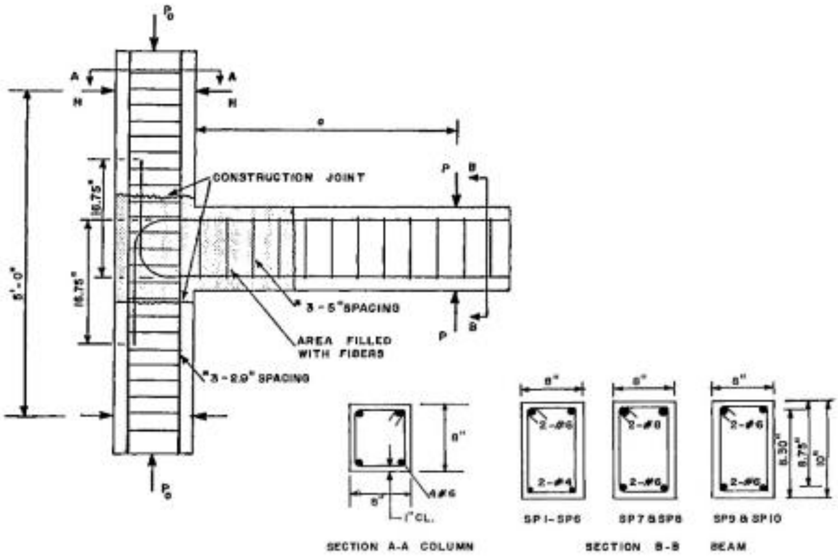


Figure 2.11 Details of the tested specimens, a) ductile specimen, b) modified specimen [26]

Jindal and Hassan [140] also investigated the use of SFRC to reduce reinforcement congestion. Three groups were used in the experiment, including A, B, and C. Group A represents a conventional specimen, whereas in group B and group C, SFRC was used through the specimen length and in the joint region only, respectively. In comparison to the conventional specimen, the result indicated that utilizing SFRC instead of shear reinforcement increased shear capacity by 29% and 19% for groups B and C, respectively. Despite specimens with SFRC (group B and C) failed with shear cracks, more ductile response was observed compared to conventional specimens (group A). John Craig et al. [41] studied the performance of SFRC to improve the seismic behavior of beam-column joints and reduce steel congestion in joints zone. Two specimens were examined; the first one was constructed with reducing transverse reinforcement in the joint region and used SFRC instead of conventional concrete, while in the other one was NSC joint, as shown in Figure 2.12. The results showed that the inclusion of SFRC in the joint region is significantly increased the shear and moment capacities of the joint. Furthermore, SFRC specimens exhibited better concrete confinement, maintained greater structural integrity, and showed less structural damage than the NSC joint. Even though the presence of SFRC in the joint region improved the seismic performance of the beam-column joint, the mechanism of failure was almost identical to that of the conventional specimens .



.Figure 2.12 Details of the tested specimens [41]

The experimental program performed by Gefken and Ramey [17] included testing of a series of Type-2 exterior beam-column joints comprising of two control specimens (made from NSC only) and eight hybrid specimens. the variable was the spacing of transverse reinforcement. It was found that when SFRC was used in the joint region, the spacing of transverse reinforcement in the joint can be increased to 1.7 times the recommended value in ACI-ASCE 352 [19]. The authors recommended using Type-1 beam-column joints with SFRC in the joint region rather than Type-2 beam-column joints. Bond failure caused by the longitudinal bar of the cantilever beam were the most apparent mechanism of concrete failure in all specimens. This may be due to bending the hook of the longitudinal beam bar away from the joint core. Even though specimens with SFRC exhibited little or no spalling compared with the NSC specimen, using of SFRC did not change the failure mode compared to NSC specimen. SFRC was also used by Filiatrault et al. [42] to eliminate transverse reinforcement in the joint region. Four full-scale exterior beam-column joints were examined under reversed cyclic load. Two types of SFRC were used to enhance the non-seismic specimens and compare the result with the full seismic detailed specimens constructed based on the National Building Code of Canada [43]. The experimental results demonstrated that specimen with steel fiber of 1.6% and fiber aspect ratio (lf/df) equal to 100, had greater shear strength allowing to develop a plastic hinge in the beam rather than joints. Furthermore, these specimens have a higher level of energy dissipation, with around 95% of the total energy dissipated in the complete seismic detailed specimen. Finally, the results showed that the efficiency of SFRC/NSC hybrid joints was influenced by the volume fraction and aspect ratio of the steel fiber. Despite the use of SFRC in the joint region, shear cracks in the joint region cannot be avoided. Filiatrault et al. [44] studied the use of SFRC to improve the seismic performance of internal beam-column joints and reduce transverse reinforcement. Three full-scale specimens were examined, including a specimen without seismic details, one meeting seismic requirements, and one without seismic details but with SFRC in the joint region (hybrid joint), as illustrated in Figure 2.13a. The SFRC/NSC hybrid specimen, according to the results, represented a transition between the first and second specimens. Finally, the hybrid specimen was able to dissipate about 85% of the energy dissipated via the full seismic detailed specimen. Again, the diagonal shear crack at the joint cannot be prevented even with using SFRC in the joints region, as shown in Figure 2.13b. Similarly, Mustafa and Ilhan in 2002 [45] investigated the response of SFRC/NSC joints but for exterior joints only by testing four full-scale specimens. The variables were the spacing between transverse reinforcement in the joints region and the material used in the joints zone. The result reported that SFRC could not avoid the development of a shear crack in the joint zone. It is worth noting that using a single transverse reinforcement in addition to SFRC in the joint region was insufficient to avoid shear cracking.

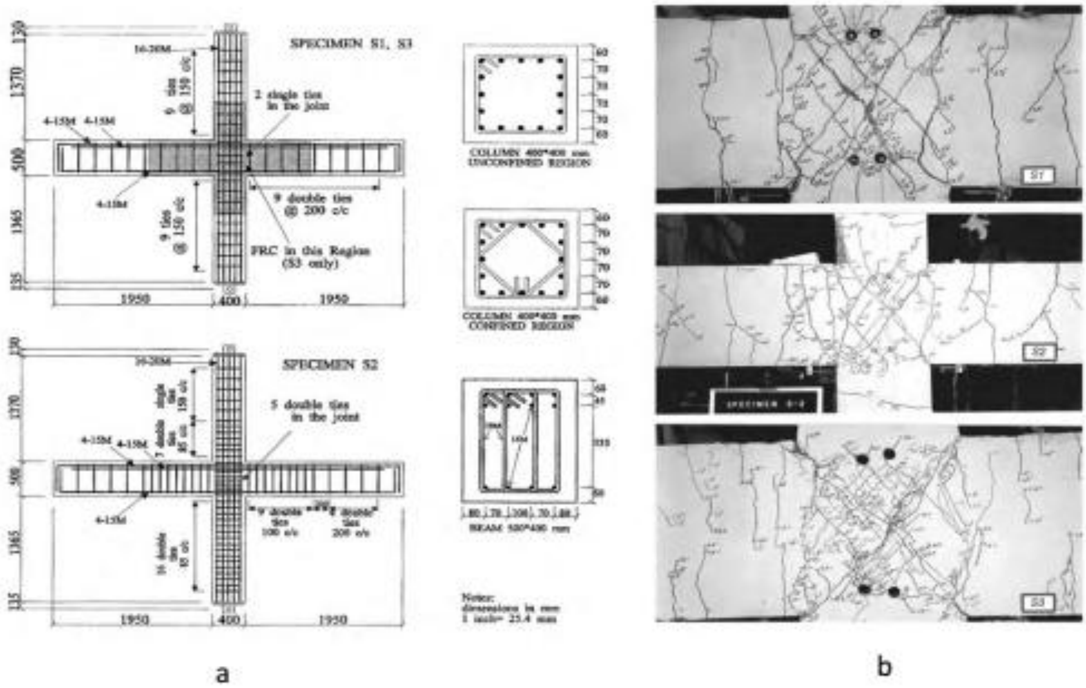


Figure 2.13 a) Details of the tested specimens, b) crack pattern of examined specimens [44].

In tests conducted by Liu [12] on three groups of exterior beam-column joints under lateral cyclic load in order to determine the contribution of SFRC on the shear capacity of joints. The first group represents the specimens designed without seismic detail similar to joints prior the 1970s but by replacing the conventional concrete by SFRC in the joint region. The second group was designed according to NZS 3101 [43] and minimized shear reinforcement in the joint and the plastic hinge region, then the conventional concrete was replaced by SFRC in these regions. Simultaneously, the third group was constructed as a reference specimen according to NZS (full seismic details), as shown in Figure 2.14. This study revealed that the use of SFRC in beam-column joints can improve shear resistance, ductility, energy absorption, and confining stress. Additionally, the necessity for closely spaced joint transverse reinforcement was reduced. It was also observed that using SFRC in joints region has the ability to change the failure mode from the joint shear failure to beam or column flexural failure. Finally, the presence of SFRC in the joint region alone could not prevent the longitudinal bars in columns from buckling. As a result, a minimum amount of transverse reinforcement should be placed in joints to provide sufficient confinement which can prevent the longitudinal bars in columns from buckling. Using of high-strength concrete (HSC) in exterior beam-column joints was found to be causing a sudden failure [54]. However, adding steel fibers to HSC in the joints region can only help maintain better specimens’ integrity at failure.

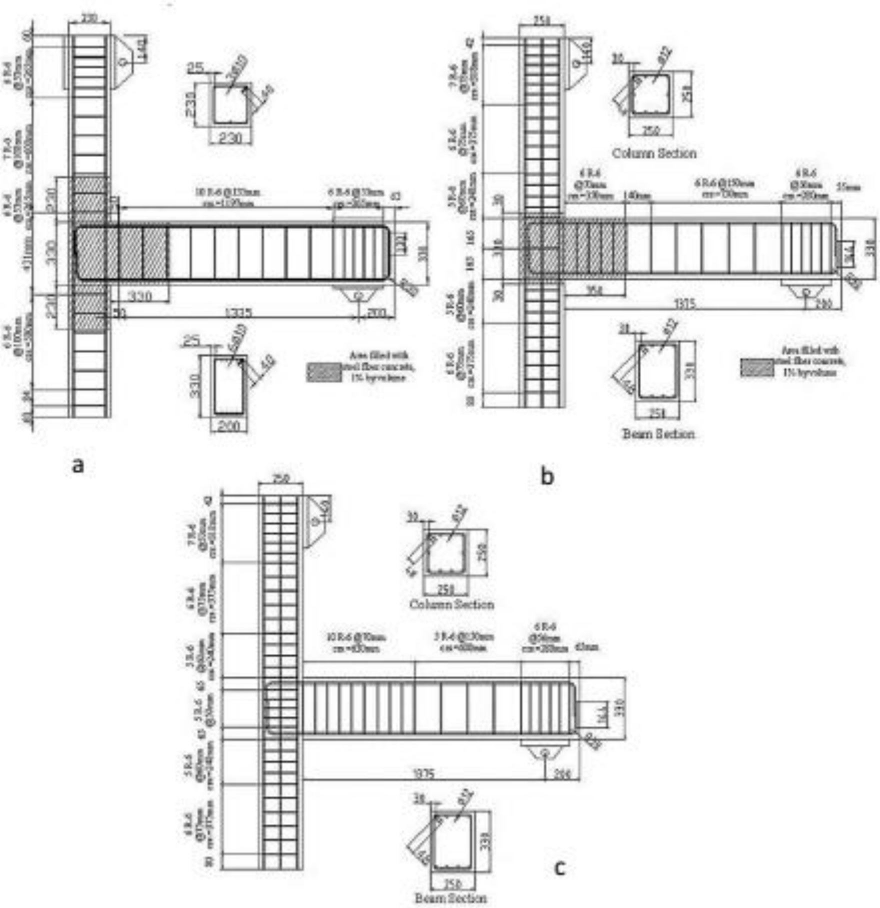


Figure 2.14 Details of the tested specimens, a) first group, b) second group and c) tired group [52].

As shown in Figure 2.15a, the piers of railway bridges are braced by intermediate beams to provide a rigid frame. This will produce a large number of joints. In 1995, the Hyogo-ken Nambu earthquake occurred near the city of Kobe, Japan, railway structures suffered severe damage (Figure 2.15b) [37]–[40]. According to the new railway design standards (Design standards for railway structures and commentary,2004) [33], huge steel reinforcement with special seismic details was mandatory in rigid-framed railways. Practically, closely spaced joint transverse reinforcement and large number of rebars often make it impossible to install beam longitudinal rebars at the beam-column joints. Niwa et al. in 2012 [26] tested eight one-sixth scale specimens, four of which were external joints, and the others were knee joints. The reference specimens were designed based on Japan's rigidframed railway bridge [33]. The transverse reinforcement in the T-joints and Knee-joints were reduced by roughly 29.2 % in the other specimens. Steel fibers (0, 1%, and 1.5 %) were utilized to compensate the loss of strength due to the reduction in the steel reinforcement. The results indicated that adding steel fiber by 1.5% of volume improved the specimens' performance in terms of load capacity, ductility, stiffness, and energy dissipated compared to the reference specimens. The test also revealed that, except the reference T-joint, all others showed longitudinal rebar debonding and anchoring failure in varying degrees depending on the volume fraction of fiber, as shown in Figure 2.16. As a result, even with the above-mentioned enhancement, 1.5 % steel fiber was insufficient to prevent anchoring failure.

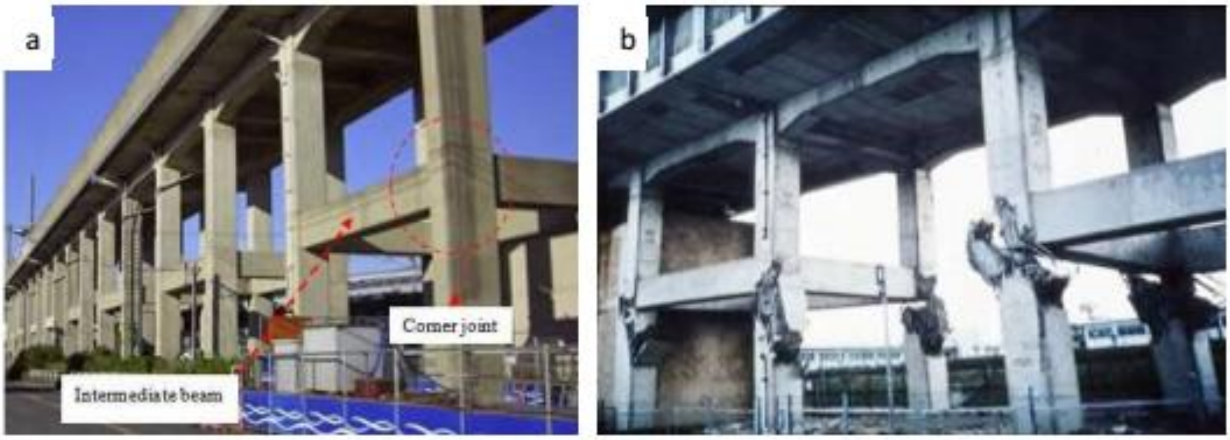


Figure 2.15 a) Rigid-framed railway bridges [15],b) collapse the railway bridge due to the Kobe earthquake/Japan.

Figure 2.16 Damage at the column external face of exterior joints specimens, a) reference specimen, b) modified specimen 0% steel fibers, C) modified specimen 1% steel fibers and d) modified specimen 1.5 % steel fibers [52]

Six exterior beam-column specimens were tested under reversed cyclic load by Röhm et al. [13]. The investigated parameters were the longitudinal reinforcement ratio, number of transverse reinforcement in the joint region, length of the SFRC portion, and steel fibers volume fraction. It was found that, as compared to the reference specimen, the damage in the joint zone was not severe. It has been demonstrated that the steel bar was yielding in the joint region, meaning that the addition of steel fibers did not enhance the large bar diameter anchorage state.

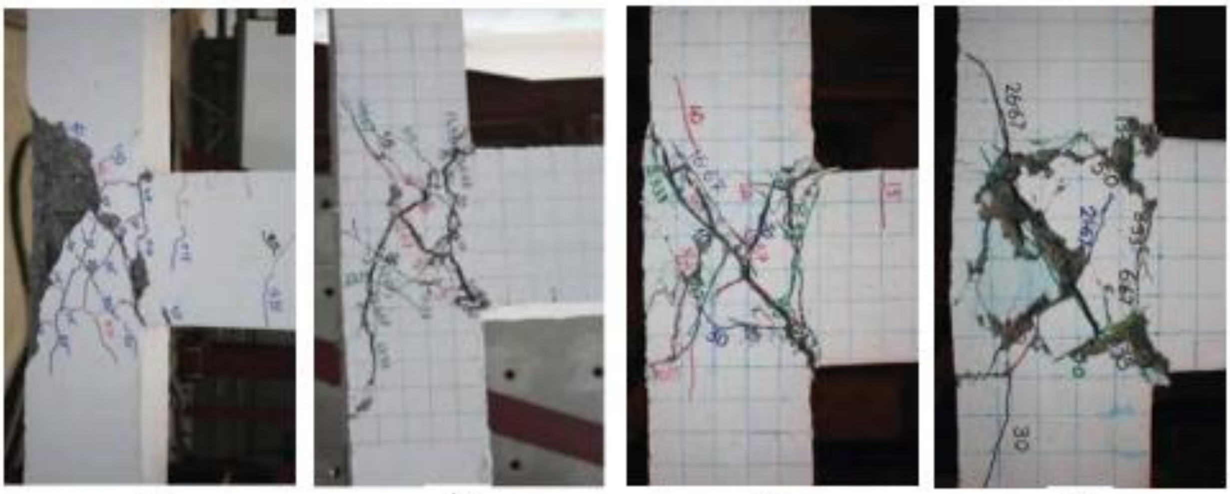
A numerical study conducted by Abbas [14] assesses the effect of introducing steel fibers into the concrete mix to compensate for a reduced amount of transverse steel reinforcement in the joint core for both interior joint and exterior joint. It was found that the spacing of transverse reinforcement in the joint core can be duplicated, compared to those having full seismic detail by adding 1% and 1.5% steel fiber for interior and exterior joints, respectively. Nevertheless, the transverse reinforcement in the joint core can’t be omitted even with 2.5% steel fiber.

Shi et al. [29] in 2021 used high-strength steel fiber reinforced concrete in the joint area to improve the performance of interior beam-column joints.This study considers the effect of concrete strength, stirrups ratio in the joint core, the volume ratio of steel fiber, and column axial load were considered in this study. Seven ½ scale interior RC beam-column joints were tested under cyclic load. It was found that utilizing high-strength concrete with 1% steel fiber improves the ductility and energy consumption by 45.2% and 120%, respectively, compared with the control specimen. Moreover, the failure mode was changed to a plastic hinge at the face of the column rather than joint shear failure in control specimens. On the other hand, it was found that specimens with smaller stirrup ratios or volume ratios of steel fiber in the joint core were subjected to joint shear failure. As mentioned previously, steel fiber reinforced concrete alone without transverse reinforcement in the joint core can’t prevent joint shear failure. Furthermore, a small amount of steel fiber shows no significant enhancement in the behavior of tested specimens with respect to NSC specimens

Utilize hybrid fibers in SFRC/NSC beam-column joints

It is well-known that the presence of fibers in concrete can improve the resistance of concrete to develop cracks, and when the cracks exist in concrete, even before loading in the form of microcracks. Then these microcracks develop and connect to produce macrocracks when the concrete member is subjected to load. These kinds of cracks (macrocracks) can propagate further to cause fractures and since the fibers can only offer reinforcement for one level of cracking (micro or macro-cracks) with a limited field of strains. Therefore, a hybrid form of several kinds of fibers can be provided a better performance[45]–[28]. One form of fiber is stronger, resulting in sufficient initial crack strength and ultimate strength, while another type of fiber is more flexible, resulting in greater post-crack toughness. Another combination uses a smaller fibre to restrict microcracks growth and a larger fiber to stop macrocracks propagation and hence improves the ductility of concrete [159]. Based on that, Kheni et al. [16] investigated the use of hybrid fibers RC (HyFRC) to enhance the ductility of beam-column joints rather than seek increases in strength. Four 2/3 scale exterior beam-column joints were designed based on IS 13920 [36] to satisfy ductile performance. The first specimen was used as a reference specimen, whereas the second and third specimens utilized HyFRC in the joint region containing (1% steel fiber+0.15% polypropylene) and (1% steel fiber + 0.15% polyester), respectively. The last specimen utilized 1% steel fiber only in the joint region.

The test demonstrated the superior performance of HyFRC joints compared to the SFRC specimen. The ductility for the second and third specimen increased by about 140 % and 90%, respectively, compared to the reference specimen, whereas the ductility of SFRC specimen increased by only 44%. The degree of damage in all the HyFRC specimens was significantly less than in the reference specimen, as shown in Figure 3.8. Furthermore, maximum ductility and dissipated energy was observed for the joint with a combination of 1% steel fibers plus 0.15% polypropylene fibers. However, despite the presence of HyFRC in the joint region improved the ductility and dissipated energy, the mode of failure was still joint shear failure, as shown in Figure 2.17.



a b c d

Figure 2.17 Failure modes of the tested specimens a) no fibers, b) 1% steel fibers +0.15% polypropylene fibers, c) steel fibers + polyester and d) steel fibers only [16].

Annadurai and Ravichandran [13] also investigated the employment of HyFRC in the exterior joints. Fourteen specimens were examined under forward cyclic load, one of which was constructed using seismic code IS 13920 [161] and the other specimens were designed without seismic details following ACI 318 [32] and replacing the NSC in the joints region by HyFRC. The results showed that high-strength concrete containing 80 % steel and 20%

polyolefin has increased ductility, energy absorption, and overall strength for all volume fractions. However, as compared to the seismic detail specimen, the hybrid fibers specimen of volume fraction 2% (80% steel+20% polyolefin) exceeded the seismic details specimen in terms of energy absorption capacity and ductility.

Keywords

Concrete Corner Beam-Column Joints; Seismic Strengthening; FRP Composites; CFRP; GFRP; Retrofitting; Externally Bonded Reinforcement (EBR); Near-Surface Mounted (NSM); Structural Performance; Ductility; Energy Dissipation; Debonding; Confinement; Hybrid Strengthening .

Methodology of Review

This comprehensive review was conducted following a systematic approach to ensure a thorough and unbiased synthesis of the existing literature on the strengthening of reinforced concrete corner beam-column joints. The methodology was structured into several key phases:

1. Scope Definition and Research Question Formulation: The primary objective was defined as critically assessing the experimental and analytical findings on the structural behavior of corner beam-column joints strengthened with different treatment methods, with a focus on Fiber-Reinforced Polymer (FRP) composites. Key research questions were established concerning strengthening mechanisms, performance enhancements, influential parameters, and comparative effectiveness.

2. Systematic Literature Search and Selection: A systematic search was performed using academic databases (e.g., Scopus, Web of Science) and keywords including "corner beam-column joint," "FRP," "CFRP," "GFRP," "seismic strengthening," "shear strength," "ductility," and related terms. The search focused on peer-reviewed journal articles, conference proceedings, and dissertations from the last two decades. The provided document served as a core dataset for this analysis.

3. Screening and Data Extraction: The collected literature was screened for relevance based on titles and abstracts. Selected full-text publications were analyzed to extract key data, including:

Strengthening Techniques: Types of FRP (CFRP, GFRP) and other materials (FRCM) used.

Configuration Details: Wrapping schemes (U-jacket, full wrap, diagonal strips, NSM), anchorage methods, and number of layers.

Experimental Parameters: Specimen scale, loading protocol (cyclic, monotonic), level of pre-damage, and axial load ratio.

Performance Metrics: Quantitative data on strength increase, stiffness, energy dissipation, ductility, and failure modes.

Analytical Methods: Details of finite element models, constitutive laws, and design approaches.

4. Categorization and Synthesis: The extracted information was categorized into thematic sections to structure the review logically. These themes included:

Historical development of FRP strengthening for joints.

Fundamental strengthening mechanisms and configurations.

Detailed analysis of experimental and analytical findings.

Comparative assessment of different FRP systems.

Identification of research gaps and future directions.

5. Critical Analysis and Discussion: The synthesized data was critically evaluated to identify trends, consensus points, and contradictions within the research. The discussion focused on

interpreting the collective findings to draw overarching conclusions about the effectiveness of various techniques, the critical role of parameters like anchorage, and the transition from component strengthening to system-level performance-based design.

6. Formulation of Conclusions and Future Needs: Based on the critical analysis, definitive conclusions were drawn regarding the state-of-the-art. Finally, gaps in current knowledge and methodologies were identified, leading to a structured set of recommendations for future research, ensuring the review contributes to guiding subsequent investigations in the field. This methodology ensured a comprehensive, evidence-based, and structured review of the subject matter.

Results and Discussion

1. Experimental Results The comprehensive analysis of experimental studies reveals consistent and significant improvements in the structural performance of corner beam-column joints following FRP strengthening. Key quantitative findings include:

2. Strength and Stiffness: Specimens strengthened with externally bonded CFRP and GFRP sheets demonstrated a remarkable recovery and enhancement of lateral load capacity. Studies reported strength increases ranging from 17% to over 80% compared to control specimens, contingent on the FRP configuration and area fraction. The initial stiffness of the retrofitted joints was also substantially restored, with increases often observed on the order of 50% to 100%, leading to reduced deformations under service loads.

3. Ductility and Energy Dissipation: A paramount result was the transformation of failure mode from brittle joint shear failure to a ductile beam flexural mechanism. This shift was quantified through significant enhancements in displacement ductility factors, with reported increases of up to 60-70%. Consequently, the cumulative energy dissipation capacity—a critical metric for seismic performance—was amplified dramatically, with some studies documenting improvements exceeding 200%. The hysteresis loops of retrofitted joints exhibited reduced pinching and greater fatness, indicating stable energy dissipation through repeated loading cycles.

4. Failure Modes: The effectiveness of the retrofitting scheme was directly reflected in the observed failure modes. Unanchored FRP systems predominantly failed due to premature debonding, limiting the material's utilization. In contrast, specimens with robust mechanical anchorage (e.g., FRP anchors, U-wraps) successfully achieved FRP rupture or developed the intended plastic hinges in the beam, validating the design objective of a strong-column-weak-beam hierarchy.

5. Discussion The synthesis of these results allows for a critical discussion of the underlying mechanisms and influencing factors that govern the performance of retrofitted corner joints.

1) Synergy of Strengthening Mechanisms The performance enhancement is not attributable to a single mechanism but to their synergistic interaction. The joint shear strengthening mechanism, provided by diagonally or orthogonally oriented FRP, directly resists the principal tensile stresses, thereby suppressing diagonal cracking. Simultaneously, the confinement mechanism from wrapping the joint panel enhances the compressive strength and ductility of the concrete core, allowing it to sustain larger shear deformations. Furthermore, anchorage enhancement via L-shaped or U-jackets ensures efficient force transfer from the beam longitudinal bars into the joint, preventing bond-slip failures. The most successful retrofits are those that integrate all these mechanisms to comprehensively address the joint's deficiencies.

2) The Critical Role of Anchorage The experimental evidence unequivocally identifies debonding as the most significant limitation of EB-FRP systems. The discussion, therefore, must emphasize that the design of the anchorage system is as crucial as the design of the FRP reinforcement itself. The results demonstrate that even a high-strength CFRP system with a

sufficient theoretical area fraction will underperform if not properly anchored. The use of transverse wraps, FRP spikes, or through-bolting transforms a brittle debonding failure into a ductile and predictable one, ensuring the FRP contributes effectively up to the joint's ultimate capacity.

3) Comparative Efficacy and Practical Trade-offs The results invite a discussion on the selection of materials and configurations. While CFRP generally provides higher strength and stiffness gains, GFRP often demonstrates superior performance in enhancing deformation capacity due to its higher ultimate strain. This presents a practical trade-off: CFRP is optimal for strength-critical applications, while GFRP may be more suitable for enhancing global ductility in a cost-effective manner. Similarly, while full wrapping offers the most comprehensive confinement, its practical application is often infeasible. Therefore, configurations like U-jacketing combined with mechanical anchors present a more viable and highly effective solution for real-world structures with geometric constraints.

4) Bridging the Gap Between Ideal and Real Conditions A critical point of discussion is the translation of these laboratory results to practice. Many tests are conducted on idealized planar joints, whereas real corner joints are constrained by slabs and transverse beams. The results strongly suggest that future research and application must develop and validate detailing techniques that are effective under these real-world constraints. The exceptional performance demonstrated in controlled experiments is only achievable in practice through designs that thoughtfully address constructability and the specific boundary conditions of the existing structure.

Research Gaps

1. Lack of Studies on Hybrid Corner Joints: The vast majority of experimental and numerical research has focused on exterior and interior joints. The seismic performance of hybrid corner beam-column joints (e.g., using SFRC or HPFRCC) remains significantly under-investigated, despite their vulnerability and complex stress state.
2. Inadequate Investigation under Multi-Axial Loading: Most experimental programs subject specimens to unidirectional cyclic loading. The behavior of hybrid joints under biaxial or triaxial seismic loading, which more accurately represents real earthquake demands, is not well understood.
3. Absence of Unified Predictive Models: While numerous experimental studies exist, there is a scarcity of robust analytical and numerical models capable of accurately predicting the shear strength, ductility, and failure modes of hybrid SFRC/NSC and HPFRCC/NSC joints, considering the interaction between different concrete materials.
4. Limited Understanding of Bond-Slip Performance with Hybrid Fibers: The effectiveness of hybrid fibers (e.g., steel + polypropylene) in mitigating bond degradation and reinforcing bar slip within the joint core, especially for high-strength bars (>420 MPa), requires further in-depth investigation.
5. Uncertain Minimum Transverse Reinforcement Requirements: The literature indicates that transverse reinforcement cannot be fully eliminated in exterior joints, even with HPFRCC. However, the minimum required amount of transverse reinforcement in hybrid joints to prevent bar buckling and ensure a ductile beam-hinging failure mode has not been systematically established.
6. Performance under Real Seismic Records: The behavior of hybrid joints has primarily been evaluated using standard cyclic loading protocols. Their performance under real, variable-amplitude earthquake ground motion records is an area that needs exploration to validate their effectiveness under more realistic conditions.

Future Research Directions

1. **Comprehensive Experimental Program for Corner Joints:** Future work should include a systematic experimental and numerical study on **hybrid corner beam-column joints**, incorporating different material configurations (SFRC, HPFRCC) and reinforcement details under reversible cyclic loading.
2. **Development of Advanced Numerical and Analytical Models:** There is a strong need to develop **high-fidelity finite element models** and mechanics-based analytical formulations. Furthermore, exploring the application of **machine learning techniques** to predict the shear capacity and hysteretic response of hybrid joints could provide powerful new design tools.
3. **Investigating Hybrid Fibers for Enhanced Bond and Confinement:** Research should focus on optimizing **hybrid fiber combinations** (e.g., micro-synthetic + macro-steel fibers) to specifically enhance bond performance, control crack width, and improve confinement, thereby potentially further reducing the reliance on transverse steel.
4. **Systematic Parametric Studies for Design Guidelines:** A large-scale parametric study, combining experimental data and advanced simulations, is essential to:

- Quantify the **minimum transverse reinforcement ratio** for different joint typologies (exterior, interior, corner) and material strengths.
- Establish the **optimal fiber type, aspect ratio, and volume fraction** for both SFRC and HPFRCC in joint applications.

5. **Validation under Real Seismic Excitations:** Testing hybrid beam-column sub-assemblages or frames on a shake table using **real earthquake records** would provide invaluable data on their dynamic response, energy dissipation, and damage tolerance under realistic conditions.
6. **Life-Cycle and Sustainability Assessment:** Beyond structural performance, future research should evaluate the **economic feasibility, constructability, and environmental impact** (Life-Cycle Assessment) of using hybrid concrete solutions in new constructions and for retrofitting existing vulnerable structures.
7. **Integration with Structural Health Monitoring (SHM):** Investigating the integration of **SHM systems** with hybrid joints to monitor damage progression and bond-slip behavior in real-time could pave the way for more resilient and smart structural systems.

Conclusion

1. This comprehensive literature review has critically examined the key factors influencing the behavior of reinforced concrete (RC) beam-column joints, with a particular focus on the efficacy of hybrid concrete techniques in enhancing joint performance under cyclic loading. The following conclusions are drawn:
2. Shear Strength Mechanisms: The shear resistance of beam-column joints is primarily governed by two mechanisms: the diagonal concrete strut and the truss mechanism. The effectiveness of these mechanisms is highly dependent on joint detailing, including anchorage of longitudinal bars and transverse reinforcement.
3. Influential Parameters:
4. Concrete Compressive Strength: While it significantly enhances the shear strength of interior joints due to improved strut action, its effect on exterior joints is marginal, attributed to differences in confinement.
5. Eccentricity: Eccentric beam-column connections introduce torsion, reducing joint shear strength. The presence of a floor slab can mitigate this effect.
6. Aspect Ratio: Unlike unreinforced joints, the aspect ratio has minimal influence on the shear strength of reinforced joints.

7. Axial Load: Column axial load enhances joint shear strength by increasing the depth of the compression strut, particularly in confined joints.
8. Anchorage Details: Proper anchorage of beam longitudinal bars bent into the joint core is crucial for forming an effective diagonal strut.
9. Transverse Reinforcement: There is no consensus on its direct role in shear resistance. However, it significantly improves confinement, ductility, and overall seismic performance, and cannot be entirely omitted in exterior joints.
10. Hybrid Concrete Techniques:
11. SFRC/NSC Joints: The use of steel fiber-reinforced concrete (SFRC) in the joint region enhances ductility, energy dissipation, and damage tolerance. However, it does not prevent diagonal cracking or change the failure mode to flexural in most cases. Transverse reinforcement remains necessary to prevent bar buckling and control shear cracks.
12. HPFRCC/NSC Joints: High-performance fiber-reinforced cementitious composites (HPFRCC) show superior strain-hardening behavior and crack control. In interior joints, HPFRCC can fully replace transverse reinforcement, while in exterior joints, minimal transverse reinforcement is still required to avoid shear failure.
13. Hybrid Fibers: Combinations of different fiber types (e.g., steel + polypropylene) yield better performance than single-fiber composites, offering improved ductility and energy absorption.
14. Research Gaps: Most studies focus on interior and exterior joints, with limited research on corner beam-column joints. Further experimental and numerical investigations are needed to explore the behavior of hybrid corner joints under multidirectional loading.
15. In summary, while hybrid concrete materials significantly improve the seismic performance of beam-column joints, they cannot entirely replace transverse reinforcement in exterior joints. Future work should focus on optimizing fiber types, volume fractions, and hybrid configurations to achieve balanced strength, ductility, and constructability.

List of Abbreviations

Abbreviation	Definition	Abbreviation	Definition
3D	Three Dimension	SD	Standard Deviation
ACI	American Concrete Institute	SEAOC	Structural Engineers Association of California
ACI–ASCE	Joint of American Concrete Institute with American Society of Civil Engineers	SF	Silica Fume
ASTM	American Society for Testing and Materials	SFRC	Steel Fiber Reinforced Concrete
BS EN	British Standard	SP	Super plasticizer
COV	Coefficient of Variation	UHPC	Ultra-High Performance Concrete
CSA	Canadian Standard Code	A str	Cross-sectional area of the concrete strut
DIC	Digital Image Correlation	Ac	Cross-sectional area of column
ECC	Engineering Cementitious Composite	Ds	Depth of concrete strut
FRC	Fiber-Reinforced Concrete	Bc	Total width of the column
GFRP	Glass Fiber Reinforced Polymer	Bs	Width of concrete strut
HPFRCC	High-Performance Fiber Reinforced Cementitious Composite	Bj	Joint width
HSC	High-Strength Concrete	Bc	Angle of strut inclination
IQS	Iraqi Specifications	Fc	Maximum force generated by

			concrete struts
IS	Indian Standard	Db	Bar diameter
LVDT	Linear Variable Differential Transducer	NSM	Near-Surface Mounted
MAE	Mean Absolute Errors	NZS	Standards of New Zealand
NSC	Normal Strength Concrete	RC	Reinforced Concrete

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