STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 12, Special Issue 2, 2024
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Review JoPC

Investigation on Structural Behavior of RC Beam-Column Joints: State-of-The-Art

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Abstract

Beam-column joints (BCJs) are critical structural elements in buildings, influencing overall structural performance and safety. This review paper presents a comprehensive analysis of findings of research showing concern about various aspects of BCJs, focusing on eccentricity effect, numerical investigation, joint behavior, shear strength, retrofitting strategies, and recent advances. Through experimental studies, numerical simulations, and analytical approaches, various studies have made significant progress in understanding BCJ response to various loading circumstances including cyclic, monotonic, and axial loading. Studies addressing eccentricity effect have elucidated the influence of displacement asymmetry on joint response, offering valuable insights for design and performance evaluation of structures. Numerical simulations have presented detailed understandings of BCJ behavior, aiding in the advancement of accurate modeling techniques and design methodologies. Research on joint behavior has explored the complex interaction mechanisms within BCJs, enhancing comprehension of failure modes and performance under various loading scenarios. Furthermore, investigations into shear strength have contributed to refining design provisions and retrofitting strategies aimed at enhancing BCJ resilience and ductility. Recent advancements have leveraged innovative experimental techniques and computational methods to delve deeper into BCJ mechanics and performance characteristics. This review consolidates existing knowledge and identifies emerging trends, providing a significant resource for engineers, and practitioners engaged in the design, assessment, and retrofitting of reinforced concrete structures, particularly focusing on beam-column joints.

Keywords: Beam-column joints, eccentricity effect, numerical investigation, joint behavior, shear strength, retrofitting strategies

INTRODUCTION

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In this investigation, a joint is described as a constituent ideally integrated with the column. Over the past four decades, multiple experiments have been undertaken worldwide to comprehend the structural response of BCJs during seismic events. Reversal of forces within the joints under cyclic lateral loading, such as from strong winds or earthquakes, can lead to distress and eventual failure in the case of inadequately detailed joints. Often, the proper detailing of joints is neglected. Failures in reinforced concrete (RC) moment resisting frame (MRF) structures typically stem from joint failures, potentially resulting in the collapse of the entire structural system without sufficient warning. Joints are of utmost importance as they ensure the continuity of structural members and facilitate force transfer at their ends. A joint must preserve connected members integrity and designed stronger compared to members framing into it. This present investigation aims to comprehend the behavior of exterior BCJs in an RC moment resisting frame and forecast the shear strength of these joints. The MRF with various kinds of BCJs are shown in Figure 1.

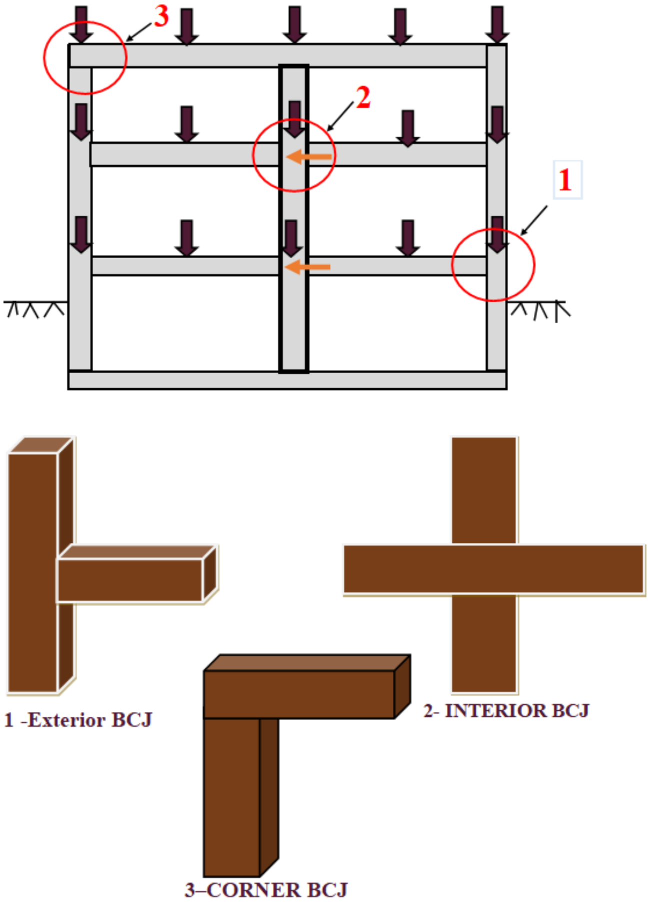


Figure 1. MRF with Various Types of BCJs

In general design of reinforced concrete framed structure, joint capacity is typically not assessed. This study serves the objective to review joint shear strength, enabling the evaluation of beam or column failure before joint failure occurs. The actual understanding of the force-resisting mechanisms and capacity of joints can only be gained through shear failure testing Design requirements outlined in various codes of practice are largely empirical, based on experimental data or equilibrium conditions derived from diagonal truss and strut mechanisms within the joint. However, the efficacy of these mechanisms is significantly influenced by bond stresses in reinforcing bars passing through the joint and the amount of hoop reinforcement present. Insights into the factors influencing joint behavior have been gleaned from a disparate array of experimental studies. Typically, these studies involve a limited number of specimens, each designed to examine specific variables, often revealing disparities in joint behavior. In construction, particularly from an architectural standpoint, it's typical for beams to be flushed with supporting columns in exterior frames, resulting in an eccentric BCJ. This arrangement causes a misalignment between the beam and column axes, inducing secondary torsion within the joint. This torsion introduces additional shear stress, impacting the joint's shear capacity. As a result, adjustments to design recommendations originally intended for concentric joints are necessary.

Various codes of practice address how eccentricity affects joint shear strength by defining an effective joint width, but there's considerable variation in the methods used to calculate it. Although various research has provided insights into eccentric joints and clarified certain aspects, many joint failures are attributed to beam flexural yielding rather than shear failure. Consequently, the applicability of these findings in comparing joint shear strength is limited.

Joint behavior refers to how a beam and a column are connected in a structural system. In the scenario of a BCJ it involves understanding how the joint reacts under several loading scenarios, including tension, compression, and shear. The behavior of a beam-column joint is crucial for ensuring the stability and safety of the overall structural system. A numerical investigation of a beam-column joint involves using computational methods, such as finite element analysis (FEA) or computational fluid dynamics (CFD), to study the behavior and performance of the joint under various conditions. This approach allows researchers to simulate different loading scenarios, analyze stress distribution, predict failure modes, and optimize the design of the joint. Wrapping techniques for a beam-column joint involve applying additional materials, such as fiber-reinforced polymer (FRP) wraps or steel plates, around the joint to enhance its structural performance and increase its load-carrying capacity. These techniques are generally applied to strengthen existing joints or retrofit them to meet updated design requirements or improve resilience against specific loading conditions, such as seismic events or blast loads. The shear strength of a beam-column joint refers to its ability to resist shear forces, which act parallel to the plane of the joint surface. In reinforced concrete structures, shear strength is a critical parameter for ensuring the structural integrity and safety of the joint, as failure in shear can lead to progressive collapse and compromise the stability of the entire structure. Eccentricity in a beam-column joint occurs when the axis of the beam is not aligned with the axis of the supporting column. This misalignment creates additional bending moments and shear forces in the joint, affecting its behavior and structural performance. The eccentricity effect on a beam-column joint refers to how this misalignment influences the joint's load-carrying capacity, stiffness, and overall response to external loads.

The investigation of shear strength in BCJs has been initiated through enormous research methodologies, each contributing unique perspectives into the behavior of these critical structural elements. Experimental research has been the predominant approach, with studies such as those conducted by Hanson and Cannor (1967) [1], Taylor and Clarke (1976) [2, 3], Meinhiet and Jirsa (1983) [4], Durrani and Wight (1985) [5], Ehsani and Wight (1985) [6], Fujii and Morita (1991) [7], Joh et al. (1991) [8, 9], Tsonos et al. (1992) [10], Agbabian et al. (1994) [11], Gombosuren and Maki (2020) [12], and Anuja et al. (2021) [13]. These experiments have utilized various types of specimens, from exterior joints unconfined by spandrel beams to RC interior beam-column joints, and have explored various test variables including column size, axial load, reinforcement types, and geometric configurations. Loading conditions in experimental studies have encompassed reversible elastic and plastic load cycles, monotonic loading, load reversal, cyclic loading, seismic loading, vertical earthquake ground motion, and reversed cyclic loading.

In addition to experimental investigations, alternative research techniques have also been employed. Hakuto et al. (2000) [14] conducted simulation-based research to study reinforced concrete one-way interior and exterior beam-column joints, focusing on shear reinforcement and seismic loading. Numerical investigation by Hegger et al. [15][16] involved the investigation of 200 exterior beam-column joints, examining failure load and modes of failure under the condition of monotonic loading. Furthermore, Hafiz et al. (2023) [17] utilized finite element numerical modeling to investigate RC exterior beam-column joints, specifically focusing on various shear reinforcement configurations under monotonic loading.

Through the utilization of diverse methodologies and precise examination of multiple test variables and loading conditions, these investigations collectively elevate understanding of the shear strength attributes in beam-column joints. This effort provides valuable insights for the design and assessment of reinforced concrete structures across various loading scenarios. The different loading positions on RC BCJ specimens are shown in Figure. 2.

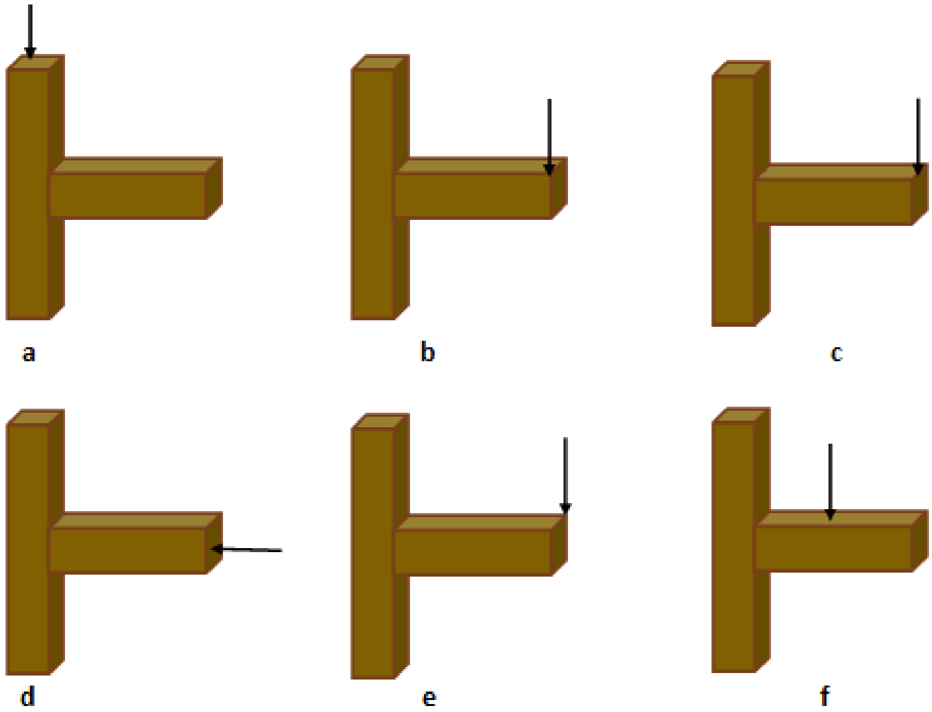


Figure 2. Different positions of load on RC BCJ specimens

The exploration of joint behavior in structural engineering holds paramount importance in guaranteeing the safety and stability of constructed structures, particularly when subjected to diverse loads. Over several decades, a multitude of studies have positively enriched the comprehension of joint behavior, each presenting distinct insights and methodologies. Paulay et al. (1978) [18] conducted a study using analytical models to investigate interior beam-column joints subjected to reversed cyclic loading. They highlighted the significance of yield penetration on the anchorage of longitudinal bars, providing valuable insights into joint behavior under cyclic loading, Pantazopoulou and Bonacci (1992) [19] explored the influences of stirrups and axial load on beam-column joints in laterally loaded frame structures. This investigation has given a significant understanding of joint behavior under lateral loading conditions.

Bonacci and Pantazopoulou (1993) [20] has provided an empirical study compiled data from 86 beam-column joint tests, presenting a comprehensive overview of factors impacting joint behavior based on experimental data. This study examines the impacts of axial force, lateral reinforcement, concrete durability, the existence of lateral beams, and bond requirements, providing valuable insights for structural design and assessment. Parker and Bullman (1997) [21] introduced a mathematical shear model, offering a theoretical approach to understanding joint shear behavior, although with a restricted dataset. This model, tested against 12 specimens, lays the further exploration foundation into joint behavior under various loading conditions.

Hwang and Lee (1999) [22] focused on seismic loading conditions, utilizing an analytical model to validate experimental shear strength data, crucial for seismic-resistant design. Lowes and Altoontash (2003) [23] study investigated reinforced-concrete beam-column joints under reversed-cyclic loading, analyzing material, geometric, and design parameters to optimize joint behavior in cyclic loading conditions. Patil and Rasal (2015) [24] push-over analysis provided practical implications for designing moment resisting frame structures by investigating the impact of beam-column ratio on cyclic loading performance.

Recent studies, such as Maram and Faidhi (2021) [25] exploration, incorporated theoretical analysis, parametric study, and deep learning techniques to comprehend beam-column connection behavior under

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

cyclic loading. This approach offers potential innovative insights into joint behavior, aligning with advancements in computational methodologies. Lastly, Muhammad et al. (2024) [26] integrated analytical and experimental approaches to study RC beam-column joints with Cementitious Composites which is engineered under the influence of cyclic loads, addressing contemporary material applications.

These collective research endeavors enhance our understanding of joint behavior across various loading conditions, materials, and methodologies. While every study shows its own limitations, the accumulated understanding obtained from these diverse approaches aids in improving structural design, ensuring the safety, resilience, and sustainability of constructed environments.

The research on numerical investigation of beam-column joints spans over the course of several decades and covers a diverse range of methodologies and parameters. Baglin and Scott (2000) [27] employed nonlinear technique for finite element analysis (FEA) using the SBETA software package, focusing on external beam-column connections under monotonic loading. Their study validated results with 19 experimental tests, laying a foundational understanding for subsequent research. Bakir and Boduroglu (2002) [28] introduced an equation validated through experiments for exterior beam-column joints, specifically targeting the beam longitudinal reinforcement ratio under monotonic loading conditions. Hegger et al. (2004) [29] delved into nonlinear FEA alongside shear strength equations, investigating parameters such as joint slenderness and reinforcement ratios in exterior and interior beam-column joints. Eligehausen et al. (2009) [30] introduced a Microplane-based Finite Element approach utilizing the MASA code, focusing on RC BCJ under cyclic loading. Yang et al. (2018) [31] used numerical investigations employing ABAQUS software, exploring rigid steel beam-column joints under impact loads, emphasizing the impact energy and span-depth ratio. Faisal (2023) [32] presented an experimental and numerical study using ABAQUS software on semi-rigid composite cold-formed steel beam-to-column joints, varying parameters like rebar diameters and concrete slab thickness under axial point loads. Jianguo et al. (2023) [33] investigated demountable RCS joints utilizing FE software ABAQUS 2021, focusing on parameters like beam flange thickness and bolt strength under cyclic loading. Higazey et al. (2023) [34] validated a numerical investigation based on accredited experimental data, studying BCJs reinforced utilizing steel rebars and shape memory alloys under axial loads, considering factors like reinforcement ratios and SMA properties. Das and Singh (2024) [35] conducted numerical analysis using ANSYS-v21 on hybrid fiber-reinforced concrete beam-column joints under static and cyclic loading, assessing parameters such as compressive and flexural strengths of the hybrid mix. Overall, these studies contribute significantly to the understanding of beam-column joint behavior under various loading conditions, offering insights into design optimization and structural performance enhancement.

These investigations collectively offer a thorough understanding of the nature of RC BC-connections under eccentric loading conditions. Raffaelle and Wight (1995) [36] initiated the exploration by investigating the influence of beam width, depth, and longitudinal reinforcement on joints for reversed cyclic loading. Chen and Chen (1999) [37] extended this exploration to full-scale eccentric corner beam-column subassemblies, focusing on structural responses under cyclic loading. Vollum (1999) [38] proposed a new design methodology for external beam-column joints, emphasizing factors like concrete strength and joint detailing under monotonic loading.

Subsequent studies by Teng and Zheu (2003) [39], Li et al. (2009) [40], and Srinivas et al. (2019) [41] delved into various aspects such as interior joints, non-seismic detailing, and knee joints, respectively, providing insights into eccentricity effects under different loading conditions. Hwang and Kim (2021) [42] conducted nonlinear analyses for moment frames, considering beam eccentricity under cyclic loading, while Zhihang et al. (2022) [43] performed experimental studies on joint displacements and shear failure, particularly focusing on column eccentricity.

Choi and Lee (2023) [44] further expanded the scope by examining the impact of eccentricity, slabs, and transverse beams on RC joints under lateral loads. Mostafa et al. (2023) [45] contributed nonlinear finite element models to analyze eccentricity effects, adding depth to the understanding of structural behavior. These collective efforts not only enhance design guidelines but also aid in refining methodologies for assessing structural performance, especially in seismic regions. However, further research could aim to unify findings and establish more standardized protocols for evaluating eccentricity effects, ensuring robustness and reliability in structural design and analysis.

Seismic retrofitting has become essential to ensure the structural integrity and safety of older buildings in the face of evolving seismic standards and codes. Over the years, various techniques have been studied, explored, and refined to reinforce critical elements like BCJs, which are particularly vulnerable during seismic events. Concrete jacketing, a widely used method, has been extensively studied. Alcocer and Jirsa (1993) [46] studied interior joint sub-assemblages, while Tsonos (1999) [47] focused on strengthening exterior joints with RC jackets. Beschi et al. (2011) [48] showcased the efficacy of High-Performance Fiber Reinforced Concrete (HPFRC) jacketing. More recent studies by Hugo et al. (2018) [49] and Karim and Karim (2020) [50] studied repairing and upgrading RC elements and strengthening RC columns, respectively. Recently, natural fiber reinforced polymer composites have drawn a lot of interest for a range of uses, including many industrial uses [64]. Alternative methods such as steel plate attachment (Ghobarah et al. 1997a and b) [51, 52] and Glass Fiber Reinforced Polymer (GFRP) sheet wrapping (Ghobarah and Said, 2002; El-Amoury and Ghobarah, 2002) [53, 54] have also been explored. The concept of haunch elements (Pampanin and Christopoulos, 2003) [55] and the use of externally bonded composites (Rajai and Ayah, 2021) [56] further contribute to the arsenal of retrofitting strategies. Pooja et al. (2021) [57] provided a comprehensive review of concrete reinforcement techniques, including various fiber types. These collective efforts underscore the multidisciplinary approach and ongoing advancements in seismic retrofitting to enhance the resilience of structures against seismic hazards. The retrofitting of BCJ specimens is shown in Figure 3.

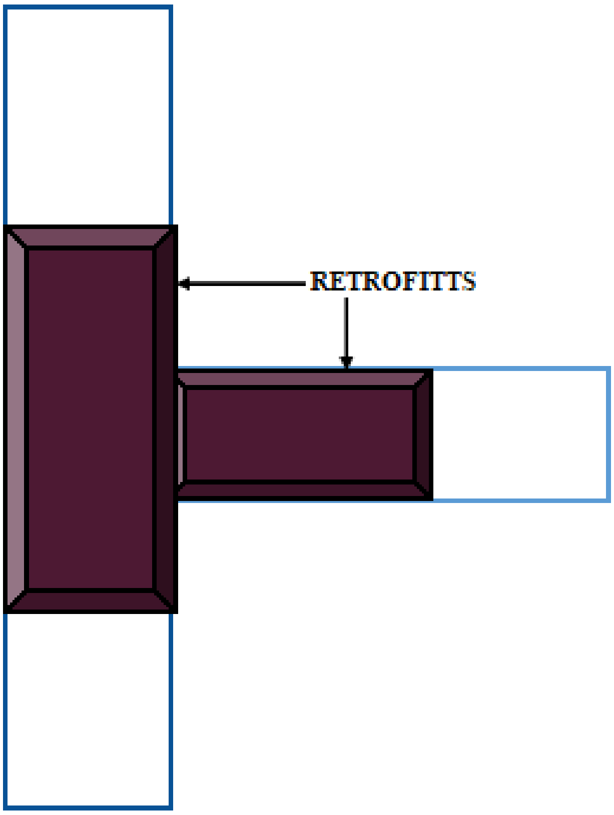


Figure 3. Retrofitting of BCJ

LITERATURE REVIEW

In this section the comprehensive literature review has been discussed elaborately.

Shear Strength

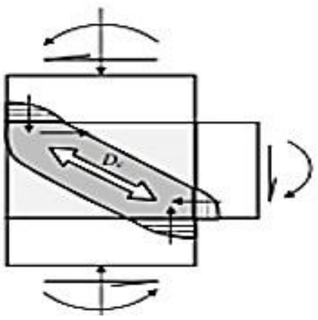
The initial experimentation on beam-column-joint sub-assemblages was conducted by Hanson and Connor in 1967. Their work emphasized the critical need for incorporating limits on joint shear stress to prevent joint shear failure. Subsequently, in 1976, recommendations for designing BCJs in monolithic RC structures were proposed, which included guidelines for limiting joint shear stress. The historical progression of joint shear theories is outlined in the ACI-ASCE Committee 352 report from 2004. Hanson and Connor's study focused on testing six exterior joints unconfined by spandrel beams, each with short, loaded spandrels on both sides of the joints. The experimental parameters included column size, column axial force, and the quantity of joint lateral reinforcement. The study subjected the joints to reversible elastic and plastic load cycles to assess their behavior comprehensively [1]. Taylor and Clarke conducted experimental tests in 1976 on twenty-six exterior joint sub-assemblages to investigate various factors influencing their behavior. Specifically, they examined the effects of beam steel percentage, joint geometry, column load, provision of additional column ties, and beam thrust (axial stress in beam). The study resulted in the development of empirical design equations, specifically twelve equations categorized into SERIES 1, 2, and 3, tailored for experimental external beam-column joints. Parameters such as beam reinforcement anchorage type and bend radius, column axial load, intermediate column bars, and connection transverse reinforcement were examined in the experimental setup. The joints were subjected to monotonically loaded conditions to evaluate their response comprehensively [3]. Meinheit and Jirsa undertook experimental testing in 1981 on fourteen full-scale interior joint sub-assemblages with the objective of assessing the factors affecting the shear capacity of interior beam-column joints. Their investigation yielded significant findings. Firstly, they determined that the shear strength of the joint does not exhibit a linear relationship with the amount of joint transverse reinforcement. Moreover, they observed that the inclusion of column bars offers nominal lateral confinement to the joint, thereby enhancing its shear strength [4]. In 1985, Durrani and Wight investigated the behavior of three interior joint sub-assemblages under earthquake-type loading conditions. The primary aim of their research was to assess the impact of joint ties (hoop reinforcement) and the demand for joint shear stress on various aspects such as strength degradation, stiffness loss, energy dissipation, shear deformation, and the slippage of column and beam bars within the joint. Their findings showed that a lower demand for joint shear stress and an increased presence of hoop reinforcement were effective measures in preventing joint failure. Specifically, they recommended a minimum amount of 0.75 percent transverse reinforcement with at least three layers of ties to enhance joint performance and resilience. Through cyclic loading experiments on internal beam-to-column connections, Durrani and Wight gave significant understanding into the aspects influencing joint behavior under seismic conditions. Their recommendations offer practical guidance for optimizing joint design and reinforcing strategies to enhance the seismic resistance of reinforced concrete structures [5]. In 1985, Ehsani and Wight conducted reversed cyclic loading tests on six exterior joint sub-assemblages, yielding notable observations. They found that maintaining a minimum column-to-beam flexural strength ratio of 1.4 was crucial for avoiding high shear stress demand within the joints. Additionally, they noted that specimens exhibiting minor slippage of column bars and pullout of beam longitudinal bars in later loading cycles demonstrated overall good behavior. Their experimental setup involved testing exterior reinforced concrete beam-column subassemblies, with a focus on parameters such as the ratio of column-to-beam flexural capacity, joint shear stress, and the level of transverse reinforcement in the joint. Through cyclic loading tests, Ehsani and Wight delved into the characteristics of these connections under realistic loading conditions, emphasizing the importance of proper design considerations for enhancing their performance and resilience against cyclic loading [6]. In 1991, Fujii and Morita investigated the structural behavior of interior and exterior joints, culminating in several key conclusions. Their observation showed that the column axial load ratio had no significant impact on interior joints shear strength, whereas for exterior joints, there was an approximate 10 percent improvement in shear strength with increased column axial load ratio. Additionally, they observed that an addition in the ratio of joint transverse reinforcement led to an enhancement in shear capacity of the connections. Moreover, they noted that once the shear strain of the connection reached 0.5%, there was an acceleration in the degradation of joint stiffness under subsequent load reversals. Their experimental setup involved testing 8-1/3 scale specimens comprising interior and exterior beam-column subassemblages within one-way frames. Parameters such as beam bar strength, column axial load, and the quantity of joint hoop reinforcement were considered. Monotonic loading scenarios were applied to comprehensively assess the structural behavior of the joints. Fujii and Morita's observations give significant understanding into the factors influencing the performance of interior and exterior joints, aiding in the advancement of more effective design and retrofitting techniques for RC structures [7]. Joh et al. conducted experimental tests in 1991 on ten interior joint sub-assemblages to investigate their behavior. Their study led to several conclusions. Firstly, they found that a substantial volume of transverse joint reinforcement has the potential to decrease the slip of beam bars within the joint, thereby improving joint stiffness after cracking occurs. However, they noted that an equivalent volume of stirrup reinforcement at the beam end did not significantly mitigate the stiffness degradation resulting from bond deterioration of the beam bars within the joint. They suggested that relocating the beam plastic hinge might prevent such bond deterioration. In their experimental setup, Joh et al. utilized two series, Series I and Series II, focusing on beam-column joints in RC frames. They examined parameters such as lateral reinforcement and the plastic hinge location in the beam, specifically away from the face of the column. The joints were subjected to monotonic loading to analyze their response under these conditions [8, 9]. Tsonos et al. conducted an experimental study in 1992 focusing on exterior joint sub-assemblages featuring diagonal reinforcing bars within the joints. Their investigation, which involved testing twenty full-scale specimens, revealed the effectiveness of incorporating diagonal bars in improving seismic resistance. They introduced a novel shear transfer mechanism to account for the influence of these diagonal bars. In their experimental setup, Tsonos et al. utilized full-scale specimens of external beam-column joints with inclined reinforcing bars. The parameters studied included the quantity of inclined bars, ratio of the column-to-beam flexural capacity, and shear stress of the connection. The samples were subjected to seismic (cyclic) loading to simulate real-world seismic conditions and analyze performance of the joints under such loading scenarios [10]. Agbabian et al. conducted an experimental study in 1994 aimed at quantifying the impact of column axial load on the shear capacity of joints. Their research focused on reinforced concrete RC beam-to-column connections. The study found that decreasing the column axial force from 10 to 0 percent resulted in a 19 percent decrease in overall capacity. This conclusion underscores the significant influence of column axial load on joint’s shear capacity. Their experimental setup involved assessing the RC beam-to-column connections response under vertical earthquake ground motion. Through this study, the relationship between column axial load and joint shear capacity, which is crucial for understanding and designing structures to withstand seismic events is understood significantly [11]. In 2000, Hakuto et al. presented a study on the cyclic performance of six interior and two exterior joint sub-assemblages. These joints were tested with reinforcement detailing typical designs predating the mid-1970s, which often exhibited poor reinforcement characteristics. The study specifically focused on reinforced concrete one-way interior and exterior beam-column joints. Horizontal shear stress was characterized by the concrete’s compressive strength and the imposed curvature ductility factor in the plastic hinges of the beam at the column face. The research also proposed a method of retrofitting aimed at enhancing the seismic performance of these joints. This retrofitting approach involved increasing the column size to limit the shear stress of the joint [14]. In 2003, Hegger et al. investigated the behavior of both exterior and interior joints experimentally under monotonic loading conditions, drawing several significant conclusions. They noted distinct behaviors between exterior and interior joints, with varying parameters affecting their shear capacities. For exterior joints, key factors influencing shear capacity included concrete compressive strength, column reinforcement, joint aspect ratio, and the quantity of ties in the joint. In contrast, the shear capacity of interior joints was primarily influenced by concrete compressive strength. They observed that column axial force affected the magnitude and inclination of cracks in the connection but did not impact directly the joint's shear strength. Additionally, they observed that unloaded transverse beams could enhance shear strength, with the most significant increase being around 20%. Furthermore, the study suggested structural shear strength for interior joints under reversed cyclic loading could be reasonably estimated by reducing joint shear capacity by 40% from its value under monotonic loading conditions. The behavior of both exterior and interior joints under various loading conditions, aiding in the development of more effective design and retrofitting techniques for RC structures observed [15]. In 2004, Shiohara introduced the novel concept of quadruple flexural resistance to estimate the shear strength and also failure of interior, exterior, and knee type joints. This concept considers the resistance offered by four pairs of diagonal members within the joint configuration. Several key observations were made for the behavior of these joints:

1. Joint ties were observed to have a significant effect on the shear strength of exterior joints but did not influence the shear strength of interior joints.
2. Joints with larger aspect ratios were observed to have lower shear strength.

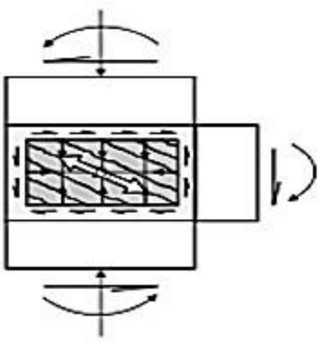
These findings show the significance of considering joint ties and aspect ratios in shear strength prediction and failure of RC joints. Shiohara recommended further investigations to better comprehend the impact of aspect ratios on joint behavior, indicating avenues for further research implications and development in this area [62]. In 2020, Gombosuren and Maki proposed a technique for forecasting the influence of joint deformation on the overall deformation of interior BCJs in RC during pivotal structural distortions. The evolution of this approach involved a combination of analytical and experimental investigations conducted on RC interior RC beam-column joints. The study involved testing eight half-scale BC connection specimens under the influence of reversed cyclic loading scenarios. Additionally, 39 full-scale finite FE models were built, with variations in chosen essential factors. The analytical and experimental observations showed the understanding of "joint shear" serves as a valuable indicator for beam-column joints experiencing high shear stress levels, but it is inadequate for defining failure in connections with moderate or Minimal shear stress levels. Drawing from these outcomes, the researchers developed three equations to forecast the shear deformation index (SDI) of RC interior beam-column connections, associated with three distinct failure modes: joint failure preceding beam yielding, joint failure subsequent to beam yielding, and beam flexural failure. The SDI results obtained from these equations were observed to be in good agreement with 50 experimental outcomes of beam-column joints reported in the literature. This study contributes to enhancing our comprehension of the behavior of RC interior beam-column joints under critical loading conditions and provides a useful instrument for forecasting joint deformation, aiding in the design and assessment of RC structures [12]. The study by Anuja et al. in 2021 focused on experimental investigation of four exterior beam-column joint specimens, each featuring different reinforcement arrangements according to IS 13920:1993 standards. These specimens were subjected to reversed cyclic loading until failure. The testing method employed force-controlled loading, progressively increasing the load levels during each cycle. Both forward and reverse cyclic loading were applied, with deflection measurements recorded at 5kN intervals using linear variable digital transducers (LVDTs) situated at the loading point and the beam center. After sustaining damage, the specimens underwent repair and retrofitting using carbon fiber reinforced polymer (CFRP) to enhance shear resistance and mitigate strength degradation, resulting in a more ductile response. Subsequently, the retrofitted specimens were subjected to similar cyclic loading conditions. Data analysis included displacement measurements to assess hysteresis behavior in both non-retrofitted and retrofitted specimens. Key parameters investigated encompassed ultimate load, maximum displacement, energy dissipation capacity, stiffness degradation, and overall failure pattern. Comparative examination of the results indicated a notable enhancement in shear resistance and energy dissipation capacity with the application of CFRP sheets. Retrofitting effectively reinforced the joints, redirecting failure towards the beams. This redirection facilitated energy dissipation through the formation of plastic hinges in the beams, thereby augmenting the overall structural performance [13]. In 2023, Hafiz et al. conducted a study focusing on finite element modeling (FEM) to analyze RC exterior beam-column joints. The study included the evolution of FE models: one without additional reinforcement and nine with various reinforcement configurations. These models aimed to examine the behavior of RC exterior beam-column joints under monotonic loading conditions, with particular emphasis on different shear reinforcement configurations. The importance of BCJs in RC structures, especially under seismic forces, was highlighted in this study. The challenge of accurately predicting the load-carrying capacity of exterior BCJs under seismic loading conditions prompted the requirement for dependable predictive models to facilitate safe and cost-effective design practices. While the proposed AI-based model utilizing gene expression programming (GEP) addresses this need for load-carrying capacity prediction under monotonic loading, Hafiz et al.'s study took a different approach by employing finite element modeling. The FE models considered various reinforcement configurations to comprehensively analyze the behavior of RC exterior beam-column joints. Comparing the results of the FE models with the proposed GEP model could offer valuable perspectives into the accuracy and reliability of both approaches for predicting joint load-carrying capacity. Ultimately, the findings from Hafiz et al.'s study contribute to enhancing the understanding of RC exterior beam-column joint behavior and may inform more effective design practices for safer and more cost-effective RC structures [17].

Behavior of Joints

The research conducted by Paulay et al. in 1978 introduces analytical models aimed at comprehending the intricate behavior of interior beam-column joints when subjected to reversed cyclic loading. This study focuses on key aspects including the horizontal component of joint shear force and the impact of yield penetration into a joint on longitudinal bar anchorage. By elucidating the interaction between the concrete strut mechanism and the truss mechanism, Paulay et al. establish a robust foundation for comprehension dynamic behavior of beam-column joints. Their analytical models offer valuable perspectives on predicting the response of these connections under different loading circumstances Furthermore, the study investigates the implications of yield penetration for the resilience and ductility of beam-column joints, particularly in seismic regions where structures are susceptible to lateral forces. The findings of this benchmark paper hold substantial significance for the design of earthquake-resistant structures. Their work constitutes a contribution to structural engineering, paving the way for future research directed towards advancing our understanding of structural response to dynamic loading conditions and fortifying the seismic resilience of built environments. The determination of the horizontal component of joint shear force in relation to internal forces was accomplished through a combination of the strut mechanism and the truss mechanism, as illustrated in Figure. 4.



A. Concrete diagonal Strut A Structural Component in Concrete design Characterized by diagonal reinforcement



B. Joint Core truss mechanism

Figure 4. Shear transfer mechanism within the joint (Paulay et al. in 1978)

Truss Mechanism Limitations:

- The efficacy of the truss mechanism relies on the bond resistance of beam bars within the joint, imposing stringent restrictions on bar size and joint dimensions.
- This mechanism results in a consistent shear stress zone within the joint core, necessitating significant horizontal and vertical transverse reinforcement to handle these stresses.

Strut Mechanism Limitations:

- Relying solely on the diagonal strut mechanism for joint modeling might disregard potential bond degradation of beam bars within the joint.

Stability of Strut Mechanism:

- The stability of the strut mechanism is only assured when experiments are carried out with minimal transverse reinforcement in the joint [18].

Pantazopoulou and Bonacci (1992) investigates the mechanics of beam-column joints in laterally loaded frame structures. The analysis presented focuses on ensuring compatibility of strains and stress equilibrium within these joints. Various factors influencing joint behavior, such as the impact of lateral restraint and the decrease in concrete strength due to diagonal tensile strains, are taken into account. The study particularly emphasizes the influence of stirrups and axial load on joint behavior. This investigation explores comprehension of joint mechanics, offering insights into the correlation among design limit state, deformations, and the overall lateral displacement of the structure. Pantazopoulou and Bonacci elucidated the fundamental mechanics of joint behavior, incorporating experimental evidence and taking into account strain compatibility within the concrete and reinforcement [19]. Additionally, Bonacci and Pantazopoulou (1993) drew several conclusions:

- The shear resistance of connections increases with concrete's compressive strength, leading to earlier yielding of hoops as concrete strength increases.
- The presence of lateral reinforcement and beams significantly enhances joint shearing capacity.
- Column axial load primarily affects joint deformability rather than strength.
- Increasing the yield stress and quantity of joint ties contributes to overall response.
- Augmenting column longitudinal reinforcement and axial stresses effectively boost joint shear capacity until hoop yielding occurs [20].

Parker and Bullman (1997) conducted 12 experiments on exterior joint sub-assemblages, introducing a novel approach for forecasting the shear strength of reinforced concrete beam-column joints. Their mathematical shear model relies on the concept of an inclined compression field within the concrete to resist shear forces, a common assumption in shear models. The model predicts the shear strength of the joint by considering the inclination of the compression strut, which offers resistance to shear deformation. This model is expanded to encompass beam-column joints, with or without links. The experiments consistently indicated shear failure within the joint whenever the theoretical flexural strength of the beam or column was not met. They provided charts comparing experimental failure loads with theoretical strengths of specimens, assuming adequate joint details. Statistical analyses of the tests demonstrate that their model predicts beam-column joint strength more reliably than the standards outlined in BS 8110 and EC2. The research highlights several crucial factors that have a notable influence on the shear resistance of beam-column joints, including concrete's compressive strength, column longitudinal reinforcement, the axial force exerted on the column, the quantity of ties in the connection, and the yield capacity of those ties [21]. Hwang and Lee (1999) introduced the softened strut-and-tie model for predicting the shear strength of exterior joints. This model adheres to force equilibrium principles and considers the constitutive relationships of both concrete and steel. It encompasses five scenarios of tie yielding when the concrete strut reaches its capacity:

- Both horizontal and vertical ties remain within the elastic range.

- Horizontal ties yield while vertical ties remain elastic.
- Vertical ties yield while horizontal ties remain elastic.
- Horizontal ties yield before vertical ties.
- Vertical ties yield before horizontal ties.

Their analytical model calculates shear strengths based on experimental data from previous literature, particularly focusing on seismic load conditions [22]. Lowes and Altoontash (2003) introduced an analytical model to analyze the response of reinforced-concrete beam-column joints subjected to reversed-cyclic loading. This model serves to encapsulate the primary inelastic mechanisms dictating joint behavior, focusing on the failure of the joint core under shear loading and the anchorage failure of longitudinal reinforcement within the beam and column. To facilitate its application in the nonlinear analysis of two-dimensional reinforced concrete frames, the model is devised as a four-node 12-degree-of-freedom element (Figure 5), effectively integrating with typical hysteretic beam-column line elements. Central to its efficacy is the establishment of constitutive relationships, intricately defining the load-deformation response of the joint model. These relationships encompass a spectrum of factors, including material properties, geometric configurations, and design parameters. Through a combined consideration of shear panel action, bar-slip behavior, and interface-shear components, the model offers comprehensive insights into the intricate mechanics at play within the joint. By encompassing these elements, it enables a more accurate prediction of the joint's response under reversed-cyclic loading, crucial for seismic design and analysis. A pivotal element of the model's utility lies in its capacity to capture the dynamic interplay between material properties, joint geometry, and reinforcement distribution. This thorough strategy ensures that the model's predictions closely match observed behavior, thereby enhancing its reliability in practical applications. The model's effectiveness is further validated through a rigorous comparison of simulated responses with experimental observations from a series of joint subassemblages featuring diverse design details. This comparative analysis underscores the model's aptitude for accurately simulating joint behavior under earthquake loading scenarios, a critical aspect of structural design and assessment [23]. Building upon the foundational work of Lowes and Altoontash, Mitra and Lowes (2004) introduced refinements to the model formulation, aiming to enhance its predictive capabilities and address potential limitations. These modifications include adjustments to the height of tension-compression couples formed by bond-slip springs at the perimeter of the joint, as well as revisions to the damage rules governing bar-slip material response. Additionally, a unique definition of the bar anchorage length was proposed, further refining the model's representation of reinforcement behavior within the joint [63]. In summary, the analytical model developed by Lowes and Altoontash (2003) represents a significant advancement in the analysis of reinforced-concrete beam-column joints subjected to reversed-cyclic loading.

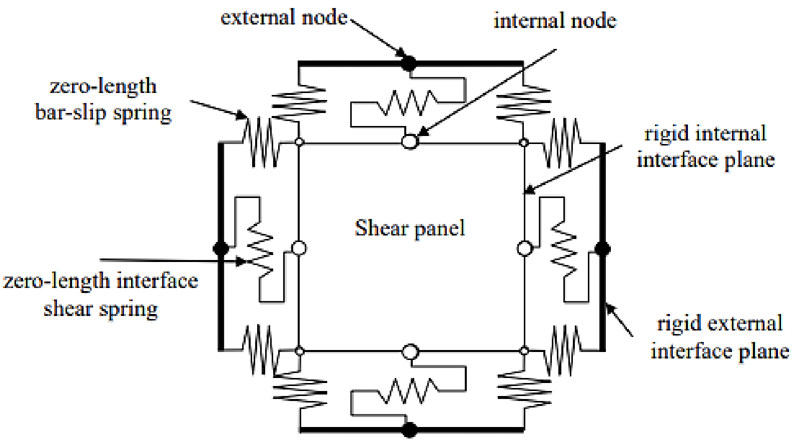


Figure 5. Model of Beam Column Joint (Lowes and Altoontash, 2003)

Patil and Rasal (2015) conducted pushover analysis on RC MRF structures, particularly focusing on buildings with irregular plans. Using SAP2000 software, they modeled RC framed buildings with various plan irregularities. The primary objective was to explore the influence of increasing the beam-column ratio on the ductility and lateral structural strength. Additionally, they examined the consequences of augmenting the moment capacity of columns through additional reinforcement, analyzing the reinforcement ratio in relation to the beam-column connection. Their study is based on a 12-story building characterized by three different types of plan irregularities [24]. Maram and Faidhi (2021) conducted an investigation into the behavior of beam-column connections under cyclic loading. The research amalgamated insights from previous experimental studies, which explored various strengthening techniques for beam-column joints, including ferrocement, Carbon Fiber Reinforced Polymer (CFRP), and various kinds of stirrups like rectangle confining or spiral confining concrete. Theoretical analysis was performed utilizing finite element software, incorporating considerations for cyclic loading effects. Several structural behaviors under cyclic loading were evaluated, encompassing stiffness degradation scalar, energy dissipation capacity, stress distribution, self-centering capability, ductility, and damage in both compressive and tensile regions. Theoretical analyses were confirmed through experimental findings to ensure accuracy. In the subsequent parametric study, various parameters were evaluated, and their behaviors were predicted employing sophisticated deep learning methodologies, leveraging neural networks. The goal aimed to establish connections between these parameters and develop prediction equations, ultimately identifying the most effective reinforcing details with minimal errors. Notably, unconventional strengthening methods, such as DCM-DOUBLE and DCM-SINGLE, demonstrated superior performance in terms of damage dissipation energy density, magnitude of plastic strain, and plastic dissipation energy density, while samples ND-T1 and ND-T2 exhibited low scalar stiffness degradation values. The research involved a total of 15 specimens categorized into three main groups: a) The first category comprised six specimens (Non-Ductile ND-1, Ductile DD-1, Non-Ductile ND-T1, Non-Ductile-T2, Ductile-T1, Ductile-T2), differing primarily in the spacing between strips in the beam-column connection and the number of layers of Ferrocement laminates. b) The second category included six specimens (Target, Control, Sample 1, Sample 2, Sample 3, Sample 4), with changes in the presence of CFRP on joints or members, or the inclusion of diagonal bars on beam-column joints. c) The third category consisted of three specimens differing in stirrup configurations (common closed stirrups DCM-CONVEN, rectangular spiral reinforcement DCM-SINGLE, twisted opposing rectangular spiral DCM-DOUBLE).These categorizations enabled a systematic exploration of the effects of different parameters on the behavior of beam-column connections under cyclic loading conditions, facilitating a deeper understanding of their performance and contributing to the advancement of structural engineering practices[25]. Muhammad et al. (2024) conducted a study focusing on the response of RC beam-column joints subjected to cyclic loads, employing FEA using the Abaqus. The research aimed to examine the impact of different grades of Engineered Cementitious Composite (ECC) in the joint zone on the joint's behavior. A plasticity model of concrete damage was proposed for both concrete and ECC materials under cyclic loading conditions. Subsequently, an FEA model was developed, considering various integral material models for both concrete and ECC. The precision of the FEA model was confirmed by comparing it with experimental outcomes.The research explored various joint behavior aspects under cyclic loading, including failure mechanisms, crack propagation, moment-rotation relationships, and energy absorption. Controlled deformations were applied to the samples at the beam's end until failure occurred. The findings provide clarity that utilizing different grades of ECC in the joint zone effectively enhanced the ultimate moment capacity by up to 38.50%, ductility by up to 13.72%, and stiffness degradation by up to 28.57% compared to conventional concrete joints. Moreover, a significant reduction in crack propagation was observed, highlighting the effectiveness of ECC in improving the overall performance and durability of RC beam-column joints under cyclic loading conditions [26].

Numerical Investigation

The study conducted by Baglin and Scott in 2000 focused on the behavior of exterior BCJs under monotonic load using nonlinear FEA with the SBETA software package. They compared the findings of their FE model with those obtained from 19 experimental tests. The primary objective was to validate the suitability of both the software package and the applied modeling technique in accurately representing the behavior of these beam-column connections. They investigated various factors, such as column load, joint capacity, and behavior of beam column connections. The notable discovery from their investigation was the impact of column load on the structural behavior of the connection details in beam column joints. They observed that increasing the column load resulted in stiffening of the joint and improved the transfer of stress from the beam reinforcement. This suggests that higher column loads contribute to enhanced structural performance and potentially increased joint capacity. The parametric study conducted involved systematically varying different parameters, such as column load, beam size, reinforcement detailing, etc., to assess their individual and combined effects on joint capacity and behavior. Their study demonstrated the effectiveness of nonlinear FEA in modeling external beam-column connections and provided valuable insights into the behavior of these structural components under varying loading conditions [27].

In a study conducted in 2002, Bakir and Boduroglu proposed an equation for exterior beam-column joints, focusing on the beam longitudinal reinforcement ratio under monotonic loading conditions. They conducted a numerical investigation using three-dimensional numerical models of RC BCJs in the ABAQUS finite element package. The analysis incorporated nonlinearities in concrete and reinforcement bars materials, as well as the bonding properties among the reinforcing bars and the adjacent concrete. They conducted a parametric investigation comprising 30 joint models to explore the impacts of various factors on the load and displacement capacities at the beam tip. These factors included concrete strength, column axial load, joint stirrups, and the configuration of the beam's top reinforcement. The dimensions as well as the reinforcement of the models were selected to ensure joint failure occurred during the study. Their findings indicated that increasing column axial load, concrete strength, and joint stirrups led to a notable rise in thebeam tip ultimate load. Additionally, connections featuring L-shaped reinforcement bars at the beam top demonstrated comparable performance to those employing U-shaped bars. However, utilizing straight bars for reinforcement at the beam top was found to significantly reduce the beam tip ultimate load. Their research yielded notable insights on the behavior of exterior RC BCJs under monotonic loading scenarios, offering practical implications for the design and structural reinforcements of elements [28]. In 2004 Hegger et al. conducted a nonlinear FEA to explore the behavior of exterior and interior BCJs under monotonic loading conditions. Their focus was on investigating parameters influencing shear strength, including joint slenderness, column reinforcement ratio, compressive concrete strength, efficiency of beam reinforcement anchorage, and the amount and efficiency of shear reinforcement. The study utilized calibrated models based on tests conducted by the third author. The observations show that the behavior of exterior beam-column joints differed from that of interior connections. Furthermore, the parameters influencing shear strength varied between the two types of connections. This may result in optimal values for hardness, impact strength, flexural strength, tensile strength, and various other properties [66]. For exterior beam-column joints, the study identified concrete compressive strength, joint slenderness, reinforcement ratio of column, efficiency of beam reinforcement anchorage, and the amount and efficiency of shear reinforcement as the major factors impacting shear resistance. Conversely, for interior beam-column joints, compressive strength of concrete was found to be the primary factor influencing shear resistance. The study also involved a comparison with proposed shear strength equations, likely to assess the accuracy and applicability of these equations in predicting the behavior of beam-column connections [29]. Eligehausen et al. (2009) introduced a Microplane-based FE approach utilizing the FE Code MASA to facilitate three-dimensional (3D) modeling of RC BCJs. Their study centered on exploring the impact of various parameters on the behavior of these joints under both monotonic and cyclic loading conditions. Specifically, the researchers investigated the reinforcement ratio impact within the joint, emphasizing its significance in determining structural response. They conducted a comparison between experimental findings obtained from exterior joint sub-assemblages and numerical simulations executed using the non-linear finite element code MASA (Macroscopic Space Analysis). Among the parameters scrutinized, the study investigated the influence of different bend angles (90° and 180°) of the beam bars, the constitutive relationship governing bond-slip characteristics of the beam reinforcement, and the local bending rigidity of the beam bars on joint response. Through meticulous analysis and rigorous experimentation, Eligehausen et al. discerned the substantial impact of these factors on the behavior of

RC BCJs, particularly under cyclic loading conditions. The findings of their research highlighted the importance of considering these parameters in the design and analysis of such structural elements. Moreover, the utilization of advanced numerical techniques like the Microplane-based FE approach with the MASA code represents a remarkable advancement in computational modeling. By identifying and analyzing the influential parameters affecting joint response, the study provides a foundation for further advancements in design methodologies and computational modeling techniques, ultimately contributing to the development of safer and more resilient structures [30]. Yang et al. (2018) conducted numerical investigation using ABAQUS to analyze rigid steel beam-column joints under impact loading. Key points of their study include:

- Development of numerical fracture models for both ductile and shear failure.
- Recognition that steel joints with horizontal restraints can generate horizontal tension forces in the beam during impact loading.
- Noting that horizontal tension can decrease joint deformation, particularly when the span-depth ratio is high.

Their numerical model incorporated solid elements to represent beams, columns, and bolts, with surface-to-surface contact pairs defining interactions between these components. A simplified fracture model in ABAQUS linked fracture strain to stress triaxiality. They employed a dynamic solver to address convergence challenges stemming from contact and fracture. Comparison between numerical and experimental results indicated the model's capability to predict dynamic responses, including impact load and vertical displacement, with reasonable accuracy. Furthermore, the model enabled the determination of horizontal tension forces within joints, shedding light on their role in resisting impact loads. Furthermore, parametric studies explored the impacts of variables such as impact energy and span-depth ratio (SDR) on joint response. Practical design guidelines for steel connections exposed to impact loading were derived from these analyses. Yang et al.'s numerical investigations offers valuable understanding into the behavior of rigid steel beam-column joints under impact loading, offering practical guidance for their design and performance evaluation [31]. The study conducted by Faisal in 2023 focused on examining the structural behavior of semi-rigid composite cold-formed steel beam-to-column joints. Their study employed both experimental testing and numerical simulations using ABAQUS software. Here are the key aspects of their investigation: Their objective was to assess the strength and stiffness of composite joints under axial point loads.5 different composite joints were tested, varying in parameters such as the diameter of rebar (8 mm and 10 mm), types of reinforcing bars (high-strength rebar, mild-strength rebar, and high-strength steel wire mesh), and thicknesses of the concrete slab (100 mm and 125 mm).The joints were subjected to axial point loads using a 100 kN capacity hydraulic jack. Non-linear FE models were created using ABAQUS software for simulating the joint configurations. A 3-D stress option with an eight-node linear brick element (C3D8) was used to represent all steel and concrete components accurately. They compared their experimental results with numerical investigations. The strength ratios ranged from 0.92 to 0.98, indicating a good correlation between experimental and numerical findings. Their research discovered that augmenting the diameter of steel reinforcement, thickness of the concrete slab, and using high-strength steel reinforcing bars improved the joints ultimate strength. This research enhanced understanding into the behavior of semi-rigid composite cold-formed steel beam-to-column connections under axial loading scenarios, contributing to the understanding of structural performance and potential optimization strategies for such joints [32]. In 2023, Jianguo et al. introduced three novel types of demountable connections, specially crafted for RC columns and steel beams. The earthquake resilience of these connections was evaluated through cyclic loading tests. Their study employed FE software ABAQUS 2021 to analyze various parameters such as beam flange thickness, bolt strength, and connecting steel strength, and their impact on the seismic behavior of the connections. The demountable RCS joints demonstrated good seismic performance. Notably, the ductility coefficients of specimens RCS-1 and RCS-2 showed significant improvements of 69% and 109%, respectively, compared to the reference group (RCS-0) specimens. The numerical analysis conducted using ABAQUS 2021 revealed insights into the influence of different parameters on the earthquake performance of the beam-column connections. Beam flange thickness was identified as a critical parameter affecting joint behavior, with variations significantly impacting performance. However, the study found that connector steel strength and bolt type had minimal effects on the load-carrying capacity of the joints. The study highlighted the sensitivity of the demountable RCS joints to changes in beam flange steel thickness. This suggests that careful consideration and optimization of this parameter are crucial for ensuring desired seismic performance. This study also discussed various theoretical approaches for calculating the shear bearing capacity in the panel zone of joints, providing insights into different methodologies utilized in the field. This study contributes to the advancement of demountable connections for RC column and steel beam structures. Their findings highlight the importance of optimizing parameters such as beam flange thickness while highlighting the relatively minor influence of connector steel strength and bolt type on joint performance under cyclic loading conditions [33]. The study conducted by Higazey et al. in 2023 presents a comprehensive numerical investigation into the performance of reinforced concrete beam–column joints (RC-BCJ) utilizing shape memory alloys (SMA) in conjunction with steel rebars. The purpose was to enhance seismic resistance in RC-BCJ through the integration of SMA and steel rebars. A non-linear finite element model in ABAQUS was proposed and validated using accredited experimental data. Parametric study was conducted to optimize the use of SMA bars while preserving the joint's energy dissipation capacity. The validated model proved effective in predicting RC-BCJ performance under monotonic lateral loading. It accurately determined the optimal length of SMA bars to relocate the plastic hinge away from the column face, thus preventing permanent deformations. The hybrid SMA–steel reinforcement system indicated significant improvements in joint performance, utilizing the stiffness of steel and the self-centering capability of SMA. Results suggest that elastic modulus increment of SMA bars and using high-strength concrete in the joint region enhance joint efficiency. Increasing the elastic modulus of SMA bars led to a notable increase in joint stiffness. Higher concrete strength resulted in increased load capacity, stiffness, and energy dissipation. Application of column axial load on the end of the column significantly improved lateral load capacity, stiffness, and energy dissipation. The study suggests extending the investigation to analyze other structural members like column-footing connections, bridge piers, and beams. Further research on the bond performance of SMA bars embedded in concrete and the coupler connecting steel reinforcement with SMA bars is recommended for safe design practices. Overall, the study provides valuable insights into optimizing the seismic performance of RC joints with SMA reinforcement, contributing to the advancement of smart materials in construction and potentially reducing post-maintenance requirements in seismic zones [34]. The Experimental and Numerical simulations conducted by Das and Singh in 2024 focus on the behavior of BCJs in RC structures, particularly under static and cyclic loading conditions. The joint region of such structure experiences significant shear stress, both vertically and horizontally, due to the transfer of shear forces from adjoining beams and columns. The strength of the joint core is influenced by factors like shear capacity and bond stress capacity. Key observations from the study include: Their study demonstrates the ductile behavior of the entire structure under repeated loading as an important discovery. Concrete behavior beyond the elastic limit, particularly in the concrete hardening zone, significantly influences ductility. High-strength fibers with ductile behavior enhance material ductility. Hybridization of different fibers can incorporate various characteristics, potentially improving overall performance. Their study employs ordinary M25 grade concrete and fiber mixed M25 grade concrete under both static and cyclic loading conditions. Hooked-end steel fiber with basalt fiber and crimpled steel fiber with polypropylene fiber are used in the hybrid mix, with volume fractions ranging from 1% to 1.4% of the concrete. Tests are conducted to evaluate compressive strength, split-tensile strength, and flexural strength of the hybrid fiber-reinforced concrete at 28 days of age.5 full-scale models of BCJs are designed according to Bureau of Indian Standards specifications. Numerical models of concrete and steel reinforcement are developed, and finite element software ANSYS-v21 is used for numerical analysis. Under static loading, crack patterns, first crack load, initial displacement, ultimate load, and ultimate displacement are observed. Under cyclic loading, hysteresis load vs. displacement, energy dissipation, and stiffness degradation are examined. The hybridization of hooked steel with basalt fiber and crimpled steel with polypropylene fiber depicts improvements in mechanical strengths and energy dissipation capacity. The study provides insights into the behavior of BCJs in RC structures under different loading circumstances and highlights the potential benefits of hybrid fiber reinforcement for enhancing structural performance [35].

Eccentricity Effect

The experimental study conducted by Raffaelle and Wight in 1995 focused on testing four interior eccentric BCJs exposed to reversed cyclic loading. The primary design parameters under examination included the width and depth of the beam, as well as the quantity of longitudinal reinforcement at both the top and bottom of the beam. The existence of eccentricity in the connection resulted in a reduction in its strength. Because of this reduction, the investigated specimens were not able to reach the estimated shear strength of the story. The eccentricity introduced additional stresses on the joint, particularly on the near face. These stresses were attributed to both horizontal shear and torsion. As a result, the strain in the joint links was higher on the near face compared to other areas of the joint. To adequately account for the effect of torsion on joint shear strength, they proposed a new equation for the effective joint width. Their equation aimed to provide a more accurate estimation of the nominal joint shear strength, considering the influence of torsional effects induced by earthquake motions. The investigation demonstrates the importance of considering eccentricity in the design of beam-column connections, especially in case of seismic loading. The proposed equation for estimating joint shear strength with torsional effects offers significant understanding for enhancing thedesign and performance of such connections in seismic regions [36]. Chen and Chen (1999) conducted experimental investigation focusing on evaluating the earthquake resilience of eccentric corner beam-column subassemblies, particularly investigating the influence of beam configuration and reinforcement details on joint behavior. The study investigated six full-scale BCJs subjected to cyclic loading, comparing joints connecting spread-ended beams with those connecting ordinary beams. The term "spread-ended beams" refers to beams with enlarged width and modified reinforcement near the joint, designed to enhance seismic resistance. The results of the experiments show significant differences in the seismic behavior between joints with spread-ended beams and conventional joints. The joints with spread-ended beams exhibited superior performance in terms of resisting seismic forces. This superiority is attributed to the enhanced stiffness and strength provided by the spread-ended configuration, which effectively redistributed loads and mitigated the detrimental effects of eccentricity. Traditional design approaches often overlook the influence of beam configuration on joint behavior, leading to underestimation of joint capacity. The guidelines proposed by Chen and Chen offer practical insights into optimizing joint width to ensure adequate strength and ductility under seismic loading conditions. Furthermore, the study addressed the importance of shape and reinforcement specifics in the conception of spread-ended beams. Their guidelines provide important recommendations for optimizing beam geometry and reinforcement detailing to maximize seismic resilience while maintaining structural integrity. By incorporating their proposed guidelines into design practices, engineers can effectively improve the seismic performance of reinforced concrete structures, ensuring greater safety and reliability in earthquake-prone regions [37]. Vollum in 1999 addresses the complexities of designing RC beam-column connections subjected to monotonic loading. The study highlights the lack of consensus on the variables affecting joint behavior and analyzes existing test data to understand the influence of various factors such as concrete strength, column loading, joint aspect ratio, reinforcement detailing, and joint stirrups on joint shear strength.

Key findings from the study include.

- Joint shear strength decreases as the joint aspect ratio increases.
- The presence of joint stirrups increases connection shear strength.
- The joint shear strength is influenced by joint aspect ratio contradicts several design codes such as EC 8 and ACI/ASCE Committee 352.

In response to these findings, the paper proposes a new design method for external BCJs based on a comprehensive analysis of existing test data. The proposed design method is subsequently contrasted with other existing methods to validate its efficacy. The study contributes to the advancement of RC design by offering a more accurate understanding of the factors affecting joint behavior and presenting a refined design approach supported by empirical evidence. Vollum and Newman (1999) focuses on the analysis and design of external beam-column joints, specifically those with eccentricity and subjected to monotonic loading. They extend previous work on simplified design methods for external BCJs to accommodate cases where one of the beams is eccentric to the column. Such configurations are encountered due to architectural and geometrical constraints in practical applications. They investigated 10 specimens to explore the behavior of joints where one of the beams is eccentric to the column. These tests aimed to comprehend the impacts of eccentricity and reinforcement detailing connection strength, cracking, and deformation. The investigations demonstrate that these joints can be viable in practice as long as the torsional capacity of the joint is not exceeded. Different modes of failure were identified, including column flexure, uniaxial joint shear, torsion in the concentric beam, biaxial joint shear, and yielding of reinforcement. Failure modes involving column failure were deemed undesirable. Recommendations were made to prevent such failures by ensuring that applied loads and design actions are within defined strength envelopes. They developed an analytical model to predict the strength of eccentric BCJs. Their model helps in making preliminary design recommendations. In Analytical modelling, cracking was observed to be more severe in these eccentric joints compared to conventional joints. However, crack widths remained small until the reinforcement yielded. Reducing eccentricity led to improved performance of the BCJ in terms of crack control and strength. Their study contributes to the understanding and design of eccentric beam-column joints, offering insights into their performance under different loading scenarios and offering practical recommendations for design [38]. The study conducted in 2009 by Li et al. investigated the response of RC structures to seismic forces interior beam-wide column joints, particularly those with nonseismic detailing and design. 6 full-scale interior beam-wide columns made of RC lacking seismic-specific detailing. Connections were subjected to axial compression forces ranging from 0 to high magnitude, and also earthquake actions simulated by quasi-static cyclic loading. The overall response of each investigation’s assembly was evaluated in terms of stiffness, drift, joint shear strength, lateral load capacity, and energy dissipation capability. Axial compressive column load at three different levels was examined to understand how they affect the joint's functionality. It was noted that minimal amounts of axial compression loading could enhance capacity for dissipating energy and stiffness, but detrimental effects were noted as the bond resistance degraded. Eccentric loading resulted in higher capacity of energy dissipation and stiffness is lower compared to concentric loading at lower compressive axial loading levels. However, at higher compressive axial loading levels, similar stiffness degradation and capacity of energy dissipation were observed regardless of eccentricity. Anchorage failure in eccentric specimens was noted to override the effect of eccentricity. The low attainment of stiffness and strength in the joints was attributed to bond weakening of the longitudinal bars through the joint core. The joints energy dissipation first occurred in the beams, with the failure of beams in strong column-weak beam connections potentially overriding the effects of column axial loading in terms of global behaviors [40]. Srinivas et al. conducted a study in 2019 to examine the seismic behavior of RC beam-column knee joints, which are comparatively complex to conventional interior and exterior joints due to the differing closing and opening force actions they experience. The significant finding was that the strong-column weak-beam design principle, commonly applied in conventional joints, may not be directly applicable to knee joints due to their location at the roof level, resulting in comparatively weaker columns in terms of flexural capacity. To address the lack of experimental data on knee joints, they tested four full-scale knee BCJs under reversed cyclic loading, focusing on investigating the effects of the eccentricity of the beam axis concerning the column center line and the ratio of beam-column flexural capacity. The study provided insights into the cyclic performance of knee joints, particularly in terms of shear strength, hysteretic behavior, joint cracking, and reinforcement strain during both closing and opening actions. Additionally, the study found that stronger columns had a positive impact on improving the opening capacity of knee joints [41]. In 2021, Hwang and Kim focused on nonlinear analysis for performance-based design of RC moment frames, particularly investigating the behavior of beam-column joints under cyclic loading conditions. They observed that while current design codes offer various models

Journal of Polymer & Composites
Volume 12, Special Issue 2
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

for BCJs, these predominantly focus on concentric joints. However, in practice, eccentric beam-column joints are also common and require more thorough investigation. To study this gap, a simplified plastic hinge model was proposed to address the effect of beam eccentricity on joint behavior. They utilized the effective joint width specified in current design codes to develop their model. Subsequently, they compared the response of this proposed model with respect to experimental findings obtained from cyclic loading investigations conducted on BCJs, both without and with beam eccentricity. The comparison revealed that the simplified plastic hinge model, incorporating the effective joint width specified in standards such as NZS 3101-2006 or Eurocode 8, demonstrated satisfactory agreement with experimental data. The suggested model is considered satisfactory for design intents, providing a simplified yet accurate means to describe the inelastic behavior of BCJs subjected to cyclic loading, particularly in cases involving beam eccentricity [42]. Zhihang and Eddie conducted a study in 2022 to examine the robustness of strengthening strategies for BCJs with upper and lower columns of different sizes, a configuration not uncommon in gravity-load designed structures. They focused on the installation of unsymmetrical chamfers on the soffits of beams as a method to enhance the performance of non-seismically designed BCJs. The experimental setup involved six 2/3 scale specimens, including 3 interior and 3 exterior specimens, subjected to joint shear failure testing under consistent axial load and cyclic displacements until failure. Their primary objective was to compare the performance of BCJ specimens with different detailing approaches, including non- seismic detailing, joint shear reinforcements, and strengthening with chamfers. They found in their study that column eccentricity, common in gravity-load designed structures, had both positive and negative effects on BCJs when subjected to cyclic displacements. Chamfers were observed to contribute to joint shear capacity, particularly when experiencing compression, leading to the formation of an additional strut within the chamfer. The positive effects of chamfers were more evident for exterior joints, especially under push direction loading. Additionally, the width of the additional strut formed within the chamfer was found to be associated with the size of the chamfer. Their study demonstrated the effectiveness of unsymmetrical chamfers in enhancing the performance of BCJs with upper and lower columns of different sizes, particularly in cases involving cyclic displacements. These findings contribute to the understanding of strengthening strategies for non-seismically designed BCJs, potentially improving the resilience of gravity-load designed structures. Choi and Lee conducted a study in 2023 to evaluate the behavior of RC BCJs under cyclic lateral loading. They focused on 3 key experimental variables: eccentricity, presence of slabs, and number of transverse beams. Eight full-scale joint specimens were prepared for the experiment. These specimens varied in terms of eccentricity, presence of slabs, and number of lateral beams. Most of the specimens exhibited joint shear failure after beam yielding. This shows that the shear strength of connection was a critical factor in the behavior of these joints under cyclic lateral loading. The study found that eccentricity reduced the joint shear strength. This suggests that variations from concentric loading can significantly affect the performance of RC beam-column joints. Despite the joints having non-seismic detailing, the presence of slabs and an increased number of transverse beams enhanced the confinement within the joints. This resulted in an improvement in the shear strength of the connection. Their study showed a notable difference between the shear strength mathematically calculated for the joint using the ASCE 41-17 equation and the actual measurements. This disparity was mainly due to overlooking the influence of slabs and the number of transverse beams in the calculation. To improve performance prediction, the study suggests taking into account the true three-dimensional shape of the joints, showcasing the importance of considering all relevant geometric and structural factors. Additionally, the study underscores the significance of updating engineering standards to include additional factors affecting joint behavior, reflecting ongoing advancements in structural understanding. Their study gives important understanding into the response of RC BCJs during cyclic lateral loading, stressing the need to accurately consider various factors like eccentricity, slab presence, and transverse beam count for precise performance prediction [43]. Mostafa et al. in 2023 conducted a study that presents 3D nonlinear FE models for RC beams that are strengthened externally with mechanically fastened (MF) and externally bonded (EB) aluminum alloy (AA) plates. These models were expected to accurately represent the structural response observed during testing, incorporating parameters such as diameter, embedment depth, arrangement of expansion anchor bolts

(EAB), and the presence of epoxy. They developed 3D nonlinear FE models to simulate the behavior of RC beams strengthened with AA plates. These models aimed to accurately capture various aspects of behavior, including parameters such as endplate debonding (ED), local plate debonding (LD), and plate rupture (PR). The FE The models underwent validation against experimental outcomes. and it was observed that they nearly matched the measured parameters like load-carrying capacity and failure modes. This suggests that their FE models effectively captured the mechanical behavior observed during testing. Their FE models were able to capture failure modes such as endplate and local plate debonding, which are critical aspects of the behavior of strengthened RC beams. This indicates that the models were comprehensive in their representation of structural response. A parametric investigation was conducted to investigate the response of various parameters on the structural behavior of the models. Parameters like flexural steel reinforcement ratio and AA plate grades were varied to analyze their influence on the response of the strengthened beams. Their paper concludes that the developed FE models offer a reasonable predictive platform for simulating the flexural performance of RC beams enhanced with MF and EB AA plates. This suggests that the models have utility in predicting the response of such strengthened beams under various loading circumstances and configurations. Their study contributes to the comprehension of the structural behavior of RC beams strengthened with AA plates and provides a valuable tool for engineers and researchers in designing and assessing such strengthening techniques [45]. To investigate how beam eccentricity affects beam–column joint behavior, a more basic plastic hinge model was proposed in Hwang and Kim work [61], utilizing the effective joint width of the present design codes. We compared the proposed model with the outcomes of the cyclic loading tests of beam-column junctions with and without beam eccentricity.

Retrofitting Strategies

Retrofitting generally involves making improvements or modifications to an existing structure to improve its performance, durability, or safety. When it comes to seismic retrofitting, the primary goal is to strengthen a building's structure to withstand seismic forces, such as those from earthquakes. This typically entails reinforcing key structural elements to enhance their strength, stiffness, and ductility, thereby reducing the risk of structural damage or collapse during an earthquake. Seismic retrofitting aims to bring older buildings in accordance with current seismic safety standards and codes, which have developed gradually over the years as our understanding of seismic hazards and building design has advanced. "Refitting in a single line with martensitic stainless steel AISI 440C provides remarkable strength, resistance to corrosion, and durability, assuring extended service life and improved performance [65]. Retrofitting a BCJs aims to increase shear and flexural capacity of beam and provide effective confinement. However, retrofitting joints can be challenging because of the existence of other framing members adjacent to the joint faces. This necessitates strengthening the entire BCJs. Different retrofitting procedures have been documented in the literature, including:

Concrete jacketing is a familiar technique used in retrofitting BCJs. Alcocer and Jirsa conducted a study in 1993 in which four interior joint sub-assemblages were tested, focusing on various variables:

1. Repairing damaged BCJ specimens by jacketing the column with bundled bars.
2. Retrofitting the sub-assemblage by jacketing the column with bundled bars and distributed bars.
3. Retrofitting the sub-assemblage by jacketing the beams and column with distributed bars.

The confinement cage effectively prevented spalling of the concrete core. The retrofitted reinforcement cage provided confinement comparable to the recommendations in the ACI-ASCE Committee 352 report. Using distributed reinforcement in jacketing showed more effective results compared to bundled reinforcements. Jacketing of beams led to a widening of the beam, which in turn increased confinement in the joint. The study conducted by Tsonos in 1999 investigated the effectiveness of adding RC jackets to strengthen exterior joint sub-assemblages. Two types of joints were investigated:

1. Joints with sufficient reinforcement and proper detailing.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

2. Joints with beam reinforcement featuring deficient anchorage.

Reinforcement details for the jacketing process included:

- Welding additional reinforcement to the existing column reinforcement.
- Using diagonal ties made of steel flat bar for the joint.
- Extending and anchoring additional beam reinforcement to enhance anchorage.
- Providing adequate anchorage to the beam reinforcing bars by constructing new stubs, where longitudinal beam bars were extended and anchored.

Their study found that this retrofitting technique significantly increased the strength, stiffness, and energy dissipation capacities of the sub-assemblages compared to the original specimens [46]. Beschi et al. in 2011 further emphasizes the efficiency of High-Performance Fiber Reinforced Concrete (HPFRC) jacketing technique for retrofitting existing RC structures particularly BCJs. The application of HPFRC jackets significantly increased the bearing capacity of both columns and BCJs. This enhancement suggests that HPFRC effectively reinforced the structural elements, enabling them to withstand higher loads. The retrofitting with HPFRC resulted in achieving an adequate level of ductility in the beam-column joints. This is crucial for seismic retrofitting as it allows structures to deform plastically under severe loading conditions without catastrophic failure. This study suggests that the HPFRC jacketing technique is feasible for strengthening existing RC structures characterized by low concrete strength and low reinforcement ratios. This indicates its suitability for a broad spectrum of structures in need of retrofitting. Applying a thin HPFRC jacket did not substantially alter the stiffness of the structure. This is advantageous, particularly when the stiffness distribution of the original building should not be significantly modified. It ensures that the structural integrity and behavior remain consistent. The use of Self-Compacting HPFRC jackets resulted in very smooth cast surfaces. This eliminates the need for a finishing plaster layer, reducing geometry variations in the structure and simplifying construction processes. Their study Presents the practicality and effectiveness of HPFRC jacketing as a retrofitting technique for improving the seismic performance of existing RC structures. Its ability to increase bearing capacity, enhance ductility, and maintain structural stiffness while providing a smooth surface finish makes it an effective solution for strengthening vulnerable structures in seismic regions [48]. Hugo et al. in 2018 investigated the crucial domain of repairing and upgrading RC elements. They acknowledge the extensive exploration in recent years aimed at rectifying design flaws, addressing issues in concrete production, and fulfilling repair requirements following earthquakes or accidents. Their study emphasizes the importance of RC jacketing as a widely utilized method for enhancing structural integrity, capable of rectifying design flaws, overcoming concrete production challenges, and mitigating damage from seismic events or accidents. Through an extensive review of literature encompassing both numerical and experimental studies, the research offers significant understanding into the effectiveness and advancements in reinforced concrete jacketing. Additionally, Hugo et al. discuss recommendations for detailing, general criteria, and procedural guidelines pertinent to this technique, essential for its effective utilization and achieving desired outcomes. Their inclusion of practical case studies, such as the correction of a soft-story mechanism in an existing RC building and the implementation of reinforced concrete jacketing at Kathmandu University following the 2015 Gorkha Earthquake, showcases its practical significance in real-world contexts, particularly in seismic retrofitting endeavors [49]. Karim and Karim in 2020 presented a review on strengthening RC columns through reinforced concrete jacketing. Despite numerous experimental studies, there's a need for innovative approaches to enhance classical RC jacketing. Due to continuous loading, columns are prone to damage, necessitating immediate attention and repair through jacketing. The paper explores the impact of dowel rebars and different concrete types, showing increased bond strength and load capacity. Key considerations include reinforcement limits, concrete properties, surface preparation, and high-temperature recommendations to prevent failures. This review offers understanding for improving the response of RC structures [50].

Steel Jacketing

Different methods were applied to reinforce BCJs, such as attaching steel plates with bolts and applying corrugated steel sheets as jackets (Ghobarah et al., 1997a and b). These methods were observed to significantly enhance both the shear strength and ductility of the joints [51][52].

Haunch Element

The concept of a haunch element, as proposed by Pampanin and Christopoulos in 2003, is an engineering solution aimed at reducing demand in a structural joint by redistributing forces to surrounding beams and columns. The two primary design strategies for haunch elements are:

- *Stiffening elements*: These haunch elements are designed with sufficient strength to ensure an elastic response during applied loads. They essentially reinforce the joint and adjacent structural members, thereby reducing demand and potential damage.
- *Energy dissipating devices:* In this design approach, haunch elements are engineered to exhibit suitable hysteretic behaviour, meaning they can absorb and dissipate energy during seismic or dynamic loading events. This helps in reducing the overall demand on the joint and enhances the structure's resilience to seismic forces [55].

FRP Wrapping

Ghobarah and Said in 2002 employed Glass Fiber Reinforced Polymer (GFRP) sheet wrapping to reinforce joints, particularly those with non-ductile detailing. The application of GFRP jacketing was found to significantly enhance both the shear strength and ductility of the joints. El-Amoury and Ghobarah in 2002 conducted tests on joints constructed according to pre-1970s' codes, where GFRP sheets were encased around the joint and affixed to the beam's soffit to strengthen inadequately anchored bottom bars. Retrofitting with GFRP sheets resulted in improved ductility of the joints. Mukherjee and Joshi in 2005 utilized both GFRP and CFRP sheets and strips for joint strengthening. Their observations included:

- Enhanced joint strength regardless of the reinforcement detailing.
- The strength and stiffness were influenced by the number of sheet overlays around the joint.
- Joints strengthened with CFRP exhibited greater stiffness compared to those with GFRP [53].

Pooja et al. in 2021 provided a comprehensive review of concrete reinforcement by incorporating various types of fibers such as steel fiber, glass fiber, and recron fiber. To analyze and compare the test results after incorporating these fibers into concrete, the study focuses on enhancing the structural behavior of BCJs, particularly under the sudden application of lateral loads which demand flexible structures capable of undergoing large inelastic deformation. Their experimental investigation examines the behavior of internal BCJs under seismic conditions according to IS: 13920–1993 standards. The experimental program includes four types of specimens: RC (Reinforced Concrete), SFRC (Steel Fiber Reinforced Concrete), HFRC-1 (Hybrid Fiber Reinforced Concrete type 1), and HFRC-2 (Hybrid Fiber Reinforced Concrete type 2). Various parameters such as load-bearing capacity, load–deflection behavior, stiffness degradation factor, energy dissipation capacity, ductility factor, and cracking properties of internal beam-column joints are thoroughly investigated. Their study showcased significant insights into the benefits of employing fibers in the beam-column joint region [57]. Rajai and Ayah in 2021 investigated the efficacy of utilizing FRP composite with externally bonded material to enhance the response of affected BCJs, employing the Non-Linear Finite Element Analysis (NLFEA) approach. The study validated the model against experimental data, then expanded it to explore the effects of axial column load and concrete compressive strength on reinforced and unreinforced FRP models. They assessed structural performance, including failure modes, stress distribution, ultimate capacities, and hysteretic behavior. Their results showcased that FRP reinforcement improved cyclic performance by increasing load capacity, displacement ductility, and energy dissipation while mitigating stiffness degradation. Notably, the mode of failure shifted from brittle to ductile with FRP reinforcement, forming a plastic hinge on the beam side when the axial column load exceeded 25%. Additionally, they noticed increased stiffness degradation with higher axial loading and damage levels, though absorbed energy decreased with damage [56].

Recent Advances in Study of BCJ

Kim et al. in 2024 studied the seismic performance evaluation of exterior precast concrete (PC) BCJs using ultra-high-performance fiber-reinforced concrete (UHPFRC) as a grouting agent. The study aimed to investigate the seismic performance of exterior PC beam-column joints with UHPFRC compared to conventional 45 MPa non-shrinkage mortar. PC joint specimens were designed using both 45 MPa non-shrinkage mortar and 120 MPa UHPFRC as grouting agents. The effects of shear reinforcement using UHPFRC were investigated.

Several key points from the study are:

1. Shear reinforcement using UHPFRC significantly reduces shear cracks in the joint core, even with reduced shear reinforcement bars.
2. The addition of a corbel did not significantly affect the maximum moment of the test specimen, suggesting that it may not be necessary for enhancing seismic performance.
3. However, the application of a U-shaped beam led to a reduction in strength and separation between UHPFRC and normal concrete, indicating potential drawbacks to this approach.
4. However, the study suggests that UHPFRC is a viable option for PC joint grouting due to its beneficial properties, such as excellent fluidity and potential for reducing congestion of reinforcement bars [58].

Zhang and Li in 2024 address the pressing need for research on novel materials to strengthen structures against seismic loading, focusing on Engineered Cementitious Composite (ECC). ECC, known for its ductility, holds significance for enhancing structural resilience. The study shows the seismic behavior of BCJs fortified with ECC through both numerical simulations and experimental investigations. A thorough analysis of a compiled database of relevant literature examines the relationship between ECC coverage area and failure characteristics. Experimental testing of interior and exterior BCJs, reinforced with ECC in the joint region, is conducted. Using a validated finite element model, their paper scrutinizes the impact of ECC coverage area on joint seismic response. Additionally, a novel modified strength hierarchy analysis is proposed to account for ECC application within the joint. This analysis identifies the weakest structural element in the joint region, shedding light on ECC joint failure mechanisms under seismic loading. Notably, the strength hierarchy analysis results exhibit a strong correlation with experimental failure patterns, suggesting their potential as a preliminary tool for assessing ECC joint performance [59]. Tong et al. conducted a study in 2024 that focuses on enhancing the seismic performance of BCJs using a novel approach involving steel-polypropylene hybrid fiber reinforced concrete (HFRC). The key findings and methodologies outlined in the study are:

- Twenty-eight HFRC BCJs were subjected to cyclic loading to assess their seismic performance.
- Factors such as types of fibers, axial compression ratio, concrete strength, and characteristic parameters of hybrid fiber were varied to understand their effects on seismic behavior.
- Incorporating steel-polypropylene hybrid fiber led to significant improvements in various aspects of seismic response.
- Concrete damage within the core region was significantly reduced.
- Initial cracking load, displacement ductility coefficient, and energy dissipation coefficient of the joints were increased by an average of 40.5%, 31.4%, and 37.3%, respectively.
- To understand the seismic responses of HFRC-BCJs accurately, a modified super degree-of-freedom (DOF) element was utilized.
- A user-defined UMAT subroutine was developed to capture the effects of fiber inclusion more precisely on tensile and compressive stress-strain behaviors of HFRC, as well as the associated damage evolution.
- The study shows the potential of steel-polypropylene hybrid fiber in improving the seismic performance of beam-column joints.
- The findings contribute to advancing understanding and design practices for seismic-resistant structures.

Their research shows the effectiveness of steel-polypropylene hybrid fiber in enhancing the seismic resilience of beam-column joints, offering insights for improved design and construction practices in earthquake-prone regions [60].

COMPARITIVE ANALYSIS

The literature survey figures, Figure 6 and Figure 7, show a comprehensive analysis of studies on BCJs from 1950 to 2023 and from 1950 to the present, respectively for this review paper. These figures were specifically generated for the current review, serving as visual representations of the research landscape surrounding BCJs. Figure. 6 delves into the scholarly contributions up to 2023, depicting the distribution of analytical research, experimental investigations, and numerical simulations over the years. On the other hand, Figure 7 extends the analysis to the present, offering insights into the evolving trends and ongoing research endeavors in the field of BCJs.

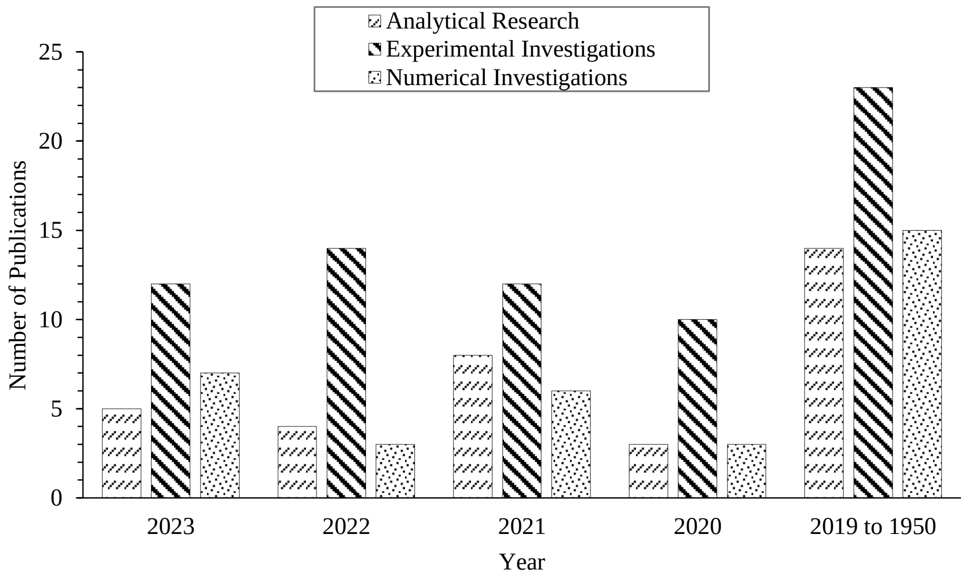


Figure 6. Literature Survey of Studies on BCJs from 1950 to 2023 for this review

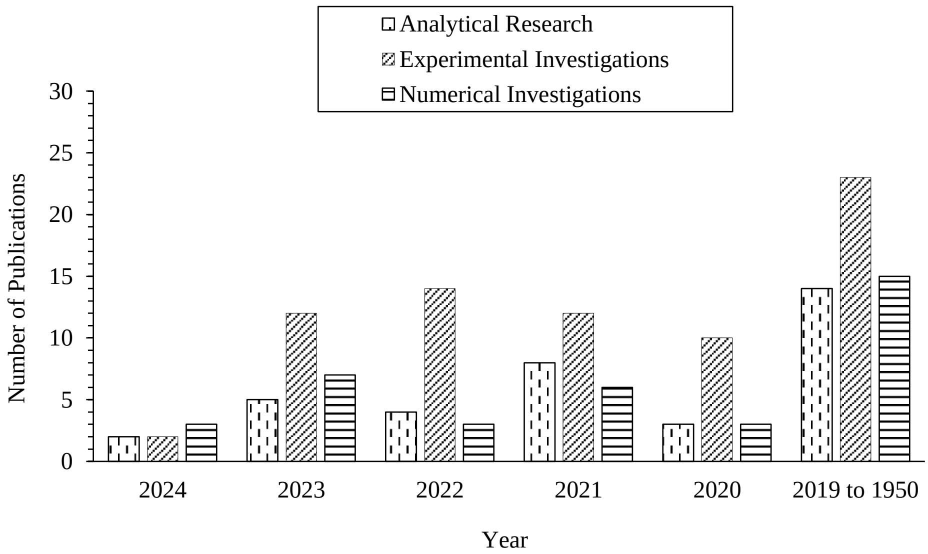


Figure 7. Literature Survey of Studies on BCJs from 1950 to Present for this review

The significant study of RC BCJs encompasses a multifaceted exploration of their structural response under various loading scenarios. Researchers investigate parameters such as joint eccentricity, concrete strength, and reinforcement detailing to discern the intricate mechanics governing these crucial structural elements. While experimental studies offer direct insights into joint behavior, numerical simulations complement these findings by delving deeper into failure mechanisms and exploring a wider range of variables. However, both approaches face challenges, including limited focus on certain aspects such as environmental conditions and long-term behavior. Analytical and theoretical perspectives further enrich the understanding of joint performance, often leading to the proposal of new design methods or models. Despite these advancements, research gaps persist, particularly concerning the effect of innovative reinforcement techniques and the full spectrum of joint behaviors, highlighting the ongoing need for comprehensive investigations to ensure structural safety and resilience, especially under extreme conditions like seismic events.

Research Gaps and Recommendations

From on the observations of the study, it is clear that there are numerous gaps and areas for further research in comprehension of RC beam-column joints and their structural behavior under several circumstances:

i. *Comprehensive Investigation of Combined Effects*: There is a requirement for investigations that give understandings into the combined effects of multiple factors on joint shear capacity under different loading conditions. This encompasses taking into account factors like reinforcement detailing, loading conditions, joint geometry, and material properties simultaneously.
ii. *Understanding Interaction between Variables*: The interaction between reinforcement detailing, loading conditions, joint geometry, and material properties on joint behaviour requires further exploration. Understanding the interaction of these variables can lead to more accurate predictions of joint performance.
iii. *Validation and Refinement of Theoretical Models:* Theoretical models and concepts proposed in literature need rigorous validation and refinement. This involves testing these models with experimental data to ensure their accuracy and reliability.
iv. *Comparative Analyses and Holistic Investigations*: There's a lack of attention given to comparative analyses or holistic investigations considering both interior and exterior joints. Comparative analysis and studies can offer significant insights into the differences in behaviour between different types of joints and loading conditions.
v. *Validation of Innovative Approaches:* There's a gap in research validating innovative approaches for predicting joint shear strength or enhancing seismic resistance against experimental data or real-world applications. It's crucial to validate new methods and techniques to ensure their effectiveness and applicability.
vi. *Long-Term Performance and Durability*: Investigating the long-term performance and durability of RC beam-column joints, particularly under cyclic loading and environmental factors, is essential. Understanding how joints perform over time and in various environmental conditions can inform design practices and maintenance strategies.
vii. Addressing these gaps through further research can contribute to improving the understanding and design of RC beam-column joints, leading to safer and more resilient structures.

CONCLUSIONS

In conclusion, the study of RC BCJs is vital for ensuring the safety and resilience of structures, particularly under diverse loading scenarios like seismic events.

- Through exploration encompassing experimental studies, numerical simulations, and analytical studies, researchers have acquired substantial understanding of thebehaviour of these crucial structural elements. However, several research gaps persist, highlighting the need for further investigations to advance our understanding and design methodologies.

- Comprehensive investigations are required to understand the combined effects of multiple factors on joint shear capacity. This involves taking into account factors such asreinforcement detailing, loading conditions, joint geometry, and material properties simultaneously. Additionally, understanding the interaction between these variables is crucial for accurate predictions of joint performance.
- The validation and refinement of theoretical models proposed in literature are essential to ensure their accuracy and reliability. Comparative analyses and significant investigations considering both interior and exterior joints can offer insights into discrepancies in behaviour under various conditions. Furthermore, validation is a necessary approach for predicting joint shear capacity and enhancing seismic resistance against experimental data or real-world applications. Investigating the long-term performance and durability of RC beam-column joints, particularly under cyclic loading and environmental factors, is also essential for informing design practices and maintenance strategies.
- Tackling these areas of research deficiency through further studies will contribute to improving the understanding and design of RC BCJs, ultimately leading to safer and more resilient structures capable of withstanding extreme conditions. It is imperative that researchers, practitioners, and industry stakeholders collaborate to advance knowledge in this critical area of structural engineering.

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