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Composite Beam–Column Joints under Seismic Loading: A State-of-the-Art Review

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ABSTRACT: Composite beam–column joints represent a key structural component in modern seismic-resistant systems, where strength, stiffness, ductility, and energy dissipation capacity are enhanced through the interaction of concrete and structural steel. Steel-reinforced concrete (SRC) beam–column joints have gained a lot of interest among various composite configurations because they combine the high tensile strength, stiffness, and ductile behavior of embedded steel sections with the confinement effect and compressive resistance of concrete. Despite these benefits, the concentration of shear stresses, cyclic load reversals, cracking, bond deterioration, stiffness degradation, and potential strength loss make the joint region one of the most critical zones under earthquake loading. This paper presents a state-of-the-art review of the seismic behavior and shear-resisting mechanisms of composite beam–column joints, with particular emphasis on SRC joint systems. The review discusses the main parameters influencing joint performance, including concrete compressive strength, yield strength of steel sections and transverse reinforcement, joint geometry, axial load ratio, connection type, and the dimensions of embedded steel sections in both beams and columns, such as web height and web thickness. The effects of column height, beam length, reinforcement detailing, and interior versus exterior joint configuration are also examined in relation to shear capacity and cyclic performance. A clear and critical understanding of the mechanical behavior reported in earlier experimental, analytical, and numerical investigations is the goal of this review, in contrast to studies that concentrate on creating new databases or predictive models. According to the reviewed literature, composite beam-column joints, especially SRC joints, can offer better seismic performance when the joint core is appropriately detailed and the steel-concrete interaction is successfully developed. However, several research gaps remain, including the limited availability of experimental data, insufficient modeling of cyclic stiffness and strength degradation, uncertainty regarding bond-slip behavior between steel and concrete, limited studies on high-strength materials, and the lack of consistent reporting of key experimental parameters. Addressing these challenges is essential for improving future analytical models and supporting the development of reliable seismic design provisions for composite beam–column joint systems.

Keywords: Composite joints; Shear capacity; Beam-Column joints; Seismic Loading; Seismic Loads; Exterior joints; Interior joints;; Steel reinforced concrete (SRC) joints; Embedded steel sections in RC members.

INTRODUCTION

The aftershocks that follow an earthquake can be extremely damaging. Numerous buildings and structures were badly damaged or completely destroyed in nearly every powerful earthquake event, which resulted in a large number of fatalities as well as a significant economic impact. To protect people and their property, infrastructure and buildings should be built to withstand both the main earthquake and its aftershocks. Appropriate design and detailing guidelines are necessary for new construction in order to lessen the effects of the earthquake. The capacity design principle is frequently used in frame structures, and it is widely adopted by various codes of practices. The capacity design concept outlines how members are constructed and meticulously designed to guarantee the ductility of the frame's inelastic response, thereby preventing shear failure and achieving a robust beam that is weak in the column. Of all members of frame structures, the beam-column joint should be given special attention, as it is assumed to be rigid in both analysis and design. The importance of beam-column joints in transferring forces and moments between beams and columns has been widely recognized. In comparison to the connecting members, the lateral earthquake load causes immense shear stresses to develop in the joint when subjected to the moment reversal across the joint. The seismic performance of the beam-column joints has a major impact on the earthquake response of the frame structures. Therefore, the beam-column joints must be properly designed and detailed to ensure the frame is stable and stable. One of the most popular types of joints is reinforced concrete (RC) beam-column joints, which are inexpensive and well-suited to monolithic construction techniques. However, in times of earthquakes, RC joints are frequently regarded as one of the weakest points in frames that resist motion. Brittle shear failure modes can be observed in the core of joints, which are typically subjected to high shear stresses, when not accurately detailed, particularly in older structures or areas with lax seismic codes [1]. In practical structural engineering, steel reinforced concrete (SRC) structures have grown in popularity because of their advantages in both structural performance and ease of construction. By combining the strength and quick construction of structural steel with the rigidity and moldability of reinforced concrete, this system creates an affordable structure. In addition to increasing the structural steel's strength and stiffness, the concrete used to encase it also increases its fire resistance. Numerous researchers have studied the seismic behavior of SRC members and the factors that influence it, both domestically and abroad. [2] point out that inadequate longitudinal bar anchoring, inadequate transverse reinforcement, and inadequate concrete confinement are all contributing factors. These deficiencies can limit the joint's ability to dissipate energy, which can cause early joint degradation or failure [3]. Any framed structural system's beam–column joint is an essential location where moments, shear forces, and axial loads are transferred between horizontal and vertical members. In addition to preserving a structure's geometry and stability, these joints are crucial for their overall energy dissipation and load redistribution mechanisms, especially in dynamic or extreme loading situations like earthquakes. Their efficacy directly affects the overall strength, ductility, and mode of failure of the frame. Because of the complex interaction of multidirectional forces, the joints are particularly vulnerable to seismic excitation. Earthquakes in the past, such as those in Kobe (1995) and Sichuan (2008), have demonstrated that inadequate performance or failure in these areas can lead to progressive collapse or serious damage. Joints need to be carefully planned and detailed for both safety and structural integrity. Considering these constraints, engineers and researchers investigated alternative configurations that led to the development and adoption of steel-reinforced concrete (SRC) joints. By integrating steel profiles into the joint core, as illustrated in Fig. 1, SRC joints capitalize on the complementary relationship between structural steel and concrete. This combination significantly increases the joint's overall seismic resilience, ductility, confinement, and shear resistance.. [4], [5] have demonstrated that SRC joints exhibit superior energy dissipation and a delayed onset of damage when subjected to cyclic loading compared to conventional RC joints.

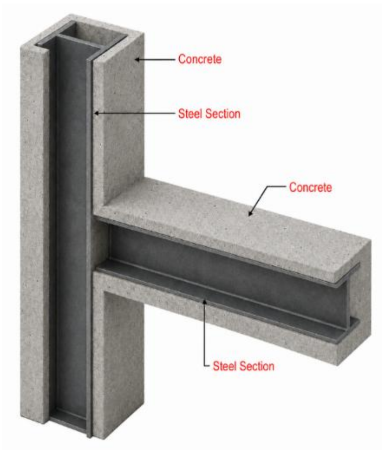

Fig. 1. Graphical sketch of Steel-reinforced concrete (SRC).

Key Parameters Influencing the Shear Strength of Beam–Column Joints

Effect of Compressive concrete strength (f_{cu})

[6], The strength of the joints is directly related to the strength of the compressive concrete. In order to assess how different concrete strengths affect beam-column joint behavior, researchers have carried out a number of studies using laboratory tests on beam-column specimens. It is known that using stronger concrete in the column will enhance the structural response of the joint. An increase in the concrete's compressive strength increases the joint's shear resistance through two mechanisms: a stronger compressive strut inside the joint and a stronger bond between the reinforcement and the surrounding concrete.

Effect of Axial load ratio

For many years, there has been discussion about how axial load affects the behavior of the beam-column joint. Some experts disagree, while others think it has a positive impact. Axial load, according to proponents, confines the joint core and increases the shear resistance of beam-column joints. However, the results of the research on this subject are conflicting and inconclusive. The confinement of the joint core is somewhat improved by the axial compression load on the column, which improves the bond condition within the joint core [7],[8]. As some experimental reports, e.g. [9], [10] claim that a high axial load on columns strengthens joints. when designing a weak column-strong beam system, it is obvious that increasing the column axial load up to the balanced point improves the joint shear strength because the column moment capacity is positively affected by the axial load. On the other hand, in the case of strong column–weak beam design, which is the case of most tests, there have been reports that column axial load gives joint shear strength both beneficial and detrimental effects. In summary, for column axial load less than 0.20 A_g f_c ', little and unclear influence on the joint shear strength is observed.

Note that $A_g = h_c b_c$ is the gross area of the column cross section.

Effect of yield strength of steel (f_y)

The yield strength of the steel used in a steel-reinforced concrete (SRC) beam-column joint has a significant impact on the joint's structural behavior and performance under seismic loads. Higher yield strength steel usually results in a stronger joint that can bear greater seismic forces before giving way. This enhances the structure's overall robustness and durability. The joint's capacity to dissipate energy is influenced by the yield strength of the steel. Reducing damage during seismic events depends on a structure's ability to absorb and release energy. Higher yield strength steel may enhance the joint's capacity to dissipate energy, potentially improving seismic performance. This is particularly crucial for preventing brittle failure and ensuring that a structure can sustain repeated seismic loads. Seismic loading often causes plastic hinges in structural components. The yield strength of the steel affects the position and size of these plastic hinges. Plastic hinges with larger rotations could be made from steel with a higher yield strength, which would improve ductility and reduce the stress on other joint components [11].

Effect of beam Reinforcement

The ACI Code for beam-column joints (ACI-ASCE 352R-02, 2002) states that if joint details satisfy the minimal requirements of confinement, joint shear capacity can be calculated based on joint types, dimensions, and concrete strength. However, tests on interior beam-column joints without joint transverse reinforcement [12], [13] showed that joints failed in shear at different levels of shear stress demand: from 10.9 to 15.7 $\sqrt{f_c^`}$ $b_j$ $h_c$ (Ib) by [12] and from 8.5 to 25.0 $\sqrt{f_c^`}$ b_j h_c (Ib) [13], although all specimens had the same geometrical dimensions and column axial load. From these observations,[14] pointed out that rather than joint shear capacity, joint strength and failure mode are dependent on joint shear stress demand or the amount of beam reinforcement. A similar observation was made in exterior beam-column joint tests by [15]. Two different reinforcement ratios were considered in the beam cross section. According to the test results, specimens with low reinforcement ratios showed ductile behavior followed by joint shear failure, whereas specimens with high reinforcement ratios experienced joint shear failure without beam reinforcement yielding.

Effect of Joint Aspect Ratio

The dimensions of the joint, which in turn impact the degree of joint shear stress and the shear strength of the beam-column joint, are the primary determinant of the joint's strength. Furthermore, there are particular requirements for anchorage, specifically the ratios of column depth to beam bar diameter (hb / dc) and the ratio of column depth-to-beam bar diameter (hc / db), [16,17] [18] It is clear that increasing the column axial load to the equilibrium point improves the joint shear strength in weak column–strong beam designs because of the beneficial effect on the column moment capacity. However, reports show that column axial load has both positive and negative effects on joint shear strength in strong column–weak beam designs, which are common in most tests. In conclusion, there is minimal and unclear impact on joint shear strength for column axial loads less than 0.2 fc` Ag. If there is no transverse reinforcement in a joint region, the SAT approach develops a steeper diagonal strut because there is no truss mechanism. As a result, there is less effective shear resistance to balance the horizontal joint shear force due to the steeper diagonal strut. As a result, the aspect ratio of unreinforced exterior joints has an inverse relationship with their shear strength.

Effect of Joint stirrups

Vertically distributed bars within the column can enhance the shear strength of beam-column joints by withstanding vertical shear forces. While the ACI 318-14 code [19] does not include provisions for vertical shear reinforcement, it does require the positioning of intermediate column bars with prescribed spacing on each face of the column. In contrast, the New Zealand Standard [20] and European [21] offer specific guidelines for vertical reinforcement in relation to horizontal shear reinforcement.

Effect of beam sectional steel height h_b

It is clear that the sectional height has a direct and significant relationship with the increase in both the ultimate bearing capacity and the initial stiffness. Consequently, the bearing capacity and initial stiffness of SRC variable-column exterior joints are significantly influenced by the sectional height of the steel beam web. Additionally, the joints' performance continuously improves as the sectional height rises [4].

Effect of Steel shape

The way a building behaves structurally, especially when exposed to seismic forces, is greatly influenced by the relationship between the steel shapes in a column and the beam-column joint. To ensure the structural stability and earthquake resistance, it is essential to take these components' performance and design into account. The effect of steel shapes in a column on the beam-column joint under seismic loads: How seismic forces are transferred from the beams to the columns is greatly influenced by the choice of steel shapes in the column or the beam. The mechanism of load transfer within the structure can be affected by different column shapes, such as pipe sections and hollow sections, which are superior to standard IPE sections. Furthermore, the distribution of forces within the joint, which influences the effectiveness of load transfer and reduces stress concentrations, is greatly influenced by the size and geometry of steel shapes. The capacity of a structure to undergo deformation without losing strength is known as ductility, and it is essential for withstanding seismic demands. The ductility of the column and joint is directly impacted by the steel shape selection. In order to lessen the strain on the joint and avoid brittle failure, well-designed shapes can aid in controlled and dissipative deformations.[22].

Effect of steel web

In order to improve the structural behavior of steel-reinforced concrete (SRC) column-beam joints, especially under seismic or lateral loading conditions, the steel web must be incorporated into the beam element [11]. According to[23]. the steel web facilitates a more even distribution of stresses within the joint core by acting as an efficient medium for shear force transmission. According to [24], this increases the joint's overall stiffness and shear capacity, Additionally, the steel web delays the start and spread of cracking in the surrounding concrete and helps to lessen localized joint deformations [25].

Effect of Bond-slip

Since bond-slip regulates the transfer of internal forces between the steel reinforcement and the surrounding concrete, it is regarded as one of the key mechanisms controlling the seismic response of beam–column joints.

Repeated stress reversals under cyclic earthquake loading may cause the steel–concrete interface to gradually deteriorate, causing pinching of hysteresis loops, loss of anchorage efficiency, stiffness degradation, slippage of the reinforcement, and a decrease in energy dissipation capacity. [26] highlighted that, in existing seismically deficient structures where reinforcement anchorage, transverse confinement, and seismic detailing are inadequate, bond-slip can be a significant contributing factor to brittle failure in beam–column joints. As a result, assuming a flawless bond between steel and concrete could result in a misrepresentation of the real cyclic behavior of joints. In composite and SRC beam–column joints, the overall performance depends on the interaction between concrete, reinforcement, and embedded steel sections. The composite action may be diminished, resulting in early cracking, decreased shear transfer, and decreased ductility if the bond and interface mechanisms are not adequately developed. Bond-slip research is therefore crucial to comprehending the actual mechanical behavior of composite joints under seismic loading and to enhancing the accuracy of analytical and numerical models used to forecast their cyclic performance and shear capacity.

Conclusions

1- Earlier research has shed important light on the seismic behavior of composite and SRC beam–column joints, there are still a number of issues with the literature that need to be carefully taken into account.

2- The majority of research indicates that joint shear resistance, stiffness, ductility, and energy dissipation capacity are all enhanced by the addition of embedded steel sections. However, the effectiveness of the composite action between concrete, reinforcing bars, transverse reinforcement, and the embedded steel profile determines the extent of improvement rather than the presence of steel alone. Therefore, rather than the independent effect of a single variable, the seismic behavior of SRC joints should be understood as the outcome of parameter interaction.

3- One important limitation in the existing literature is the limited and scattered nature of the experimental database. A limited number of specimens with various geometries, material characteristics, loading procedures, boundary conditions, and reinforcement details were used in numerous investigations. This lowers the reliability of broad conclusions about the contribution of individual parameters and makes direct comparison between studies challenging. For instance, even though these factors interact significantly within the joint core under cyclic loading, the effects of concrete compressive strength, axial load ratio, joint aspect ratio, and embedded steel section dimensions are frequently reported separately.

4- Axial load's impact is still one of the most contentious factors. According to some research, column axial compression can increase joint shear strength by improving confinement and compression strut action. However, other studies show that when high axial load levels reduce deformation capacity and accelerate damage concentration, its effect may be limited or even harmful. This discrepancy suggests that axial load should be assessed in relation to joint geometry, confinement level, material strength, and failure mode rather than on its own.

5- The lack of knowledge about bond-slip and interface behavior is another serious problem. Effective force transfer between concrete, reinforcing bars, and embedded steel sections determines the seismic performance of SRC and composite beam-column joints. Nonetheless, a lot of analytical and numerical models continue to make the assumption of idealized interaction or perfect bond, which could lead to an overestimation of joint stiffness and shear capacity. Bond deterioration, reinforcement slippage, cracking, and stiffness degradation can all have a substantial impact on energy dissipation and hysteretic behavior under cyclic loading. Consequently, more sophisticated models are needed to account for damage accumulation under repeated load reversals, bond-slip effects, and degradation of the steel–concrete interface.

6- Additionally, only a small number of studies have examined exterior joints, special-shaped steel sections, high-strength materials, bidirectional cyclic loading, and realistic seismic loading histories; the majority of studies that are currently available concentrate on particular joint configurations. These factors are especially crucial because real earthquake demands can result in complex stress states in the joint region and are multidirectional. The development of trustworthy design-oriented equations is further hampered by the inconsistent reporting of important experimental parameters, such as reinforcement anchorage, transverse reinforcement details, embedded steel dimensions, axial load level, loading protocol, and failure mode.

Overall, the reviewed literature supports the superior potential of SRC beam-column joints for seismic-resistant structures, but it also emphasizes the need for more sophisticated numerical models and systematic experimental programs. Establishing thorough databases, measuring parameter interaction, enhancing bond-slip and cyclic degradation modeling, and creating useful design equations for both interior and exterior SRC joints should be the main goals of future research. Such initiatives are necessary to convert the demonstrated experimental benefits of SRC joints into trustworthy seismic design specifications.

Future research should therefore focus on developing larger and more consistent experimental databases, improving numerical models that account for bond-slip and cyclic degradation, investigating the influence of different steel section configurations, and proposing design-oriented equations suitable for both interior and exterior SRC beam–column joints. To improve the safety and performance of composite frame structures under earthquake loading and to develop trustworthy seismic design provisions, a deeper understanding of the relationship between concrete, reinforcing steel, embedded steel sections, and joint detailing is crucial.

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