Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 3, 2026

A SYSTEMATIC REVIEW OF SHEAR STRENGTH PREDICTION MODELS FOR REINFORCED CONCRETE BEAM–COLUMN JOINTS UNDER CYCLIC SEISMIC LOADING CONSIDERING JOINT GEOMETRY, REINFORCEMENT DETAILING, AND AXIAL LOAD INTERACTION

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DOI: http://doi.org/10.5281/zenodo.18976415

Keywords
Beam-column joints, seismic loading, shear strength prediction, reinforcement detailing, strut-and-tie models, machine learning, cyclic loading

Article History
Received: 12 January 2026
Accepted: 23 February 2026
Published: 12 March 2026

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Abstract

Reinforced concrete (RC) beam-column joints are critical structural components that significantly influence the seismic performance and overall stability of buildings. The shear strength prediction of these joints under cyclic seismic loading is a complex problem that depends on multiple interconnected parameters including joint geometry, reinforcement detailing, and axial load ratios. This systematic review comprehensively examines existing shear strength prediction models for RC beam-column joints under cyclic seismic loading, with particular emphasis on design code provisions, experimental evidence, and analytical approaches. A critical evaluation of approaches including strut-and-tie models, design code formulations, and empirical equations reveals significant variations in prediction accuracy and safety margins across different methods. Recent advances in machine learning and finite element analysis have demonstrated improved prediction capabilities, with coefficient of determination (R^2) values exceeding 0.99 for neural network models compared to 0.83-0.85 for conventional design codes. The analysis of 50+ peer-reviewed studies shows that reinforcement detailing, particularly the provision of transverse reinforcement, is paramount in controlling shear failure modes and enhancing joint ductility. Furthermore, axial load effects introduce nonlinear interactions that current design codes inadequately capture, potentially leading to unconservative designs. This review synthesizes findings on the influence of key parameters including joint aspect ratio, concrete strength, reinforcement ratio, and axial load ratio on joint shear strength. Recommendations are provided for improving design methodologies and implementing performance-based design approaches for seismic applications. The findings emphasize the critical need for unified design criteria and the potential benefits of integrating advanced computational methods with experimental validation.

1. Introduction

Reinforced concrete frame structures constitute the dominant structural systems in modern construction, particularly in seismically active regions. The performance of these frame structures during earthquakes is fundamentally dependent on the behavior of their critical components, including beams, columns, and especially the connections between them. The beam-column joint, often referred to as the joint panel zone, represents a critical region where complex stress concentrations occur and where multiple failure modes can develop (Abdelwahed, 2020). The role of the joint in transferring forces between structural elements while maintaining overall frame ductility cannot be overstated, as deficiencies in joint design and detailing have been identified as primary causes of building damage in past earthquakes (Abdelwahed, 2020).

The shear strength prediction of reinforced concrete beam-column joints under cyclic seismic loading presents a multifaceted engineering challenge that has attracted substantial research attention over the past four decades. Unlike conventional shear design problems for beams or columns, joint shear design involves the interaction of multiple stress states including diagonal compression, transverse tension, and complex cracking patterns that develop progressively during cyclic loading (Genikomsou, 2024). The fundamental difference between static and seismic loading requires that design approaches account for strength degradation, stiffness loss, and energy dissipation capacity rather than simply determining ultimate shear capacity (Savadi, Muranal and Heggond, 2026). This distinction has led to the development of specialized design methodologies and assessment procedures incorporated into modern building codes such as ACI 318, Eurocode 8, and various national standards.

Research has consistently demonstrated that the shear strength of beam-column joints is controlled by a complex interplay of geometric parameters, material properties, and reinforcement configuration. The joint geometry, defined by the column depth-to-beam depth ratio and the beam-column width relationships, fundamentally influences the stress distribution within the joint and thus the capacity available for shear resistance (Ji *et al.*, 2023). Reinforcement detailing, particularly the quantity, spacing, and configuration of transverse reinforcement within the joint region, serves as the primary mechanism for controlling crack propagation and mobilizing concrete compressive strength through confinement effects (Vecchio *et al.*, 2023). Furthermore, the application of axial loads to columns, which is inevitable in multi-story building frames, modifies the effective concrete stress state within the joint and introduces additional variables that must be accounted for in strength predictions (Pham, Nguyen and Nguyen, 2026).

The existing literature reveals a significant fragmentation of approaches for predicting joint shear strength, ranging from simplified empirical equations embedded in design codes to sophisticated three-dimensional finite element models incorporating nonlinear material behavior and fracture mechanics principles. Design code approaches vary considerably in their underlying assumptions and calibration databases. ACI 318-19 employs a strut-and-tie based approach with specific coefficients calibrated against North American test data, while Eurocode 8 uses a different formulation with modifications derived from European experimental programs (Wong and Su, 2022). These variations reflect both the state of knowledge at the time of code development and the regional variations in construction practices and material characteristics.

Recent technological advances have introduced machine learning methodologies and artificial intelligence-based prediction systems that leverage large experimental databases to develop empirical relationships with enhanced accuracy compared to traditional design code approaches. Studies employing artificial neural networks have demonstrated R^2 values exceeding 0.99 when trained on comprehensive experimental databases (The *et al.*, 2025). However, the application of such black-box approaches to engineering design requires careful consideration of physical validity, generalizability, and the interpretability of results within the engineering profession's established framework of mechanics-based design.

The primary objective of this systematic review is to synthesize existing knowledge regarding shear strength prediction models for reinforced concrete beam-column joints under cyclic seismic loading, with comprehensive consideration of the influences of joint geometry, reinforcement detailing, and axial load interaction. By examining design code provisions, experimental evidence from controlled laboratory investigations, analytical modeling approaches, and emerging computational methodologies, this review aims to identify trends in the literature, evaluate the accuracy and limitations of existing models, and provide guidance for practitioners and researchers regarding the selection and application of appropriate prediction methods. The systematic evaluation encompasses approximately 50 peer-reviewed publications spanning a period of research from established classical studies to recent developments in the field.

2. Overview of Shear Strength Prediction Models

2.1 Design Code Provisions and Their Evolution

The evolution of design code provisions for beam-column joint shear strength has reflected the accumulating experimental evidence and improved understanding of joint behavior over several decades. The current major design code approaches can be categorized into three primary methodologies: empirical equations, sectional methods, and strut-and-tie models (Wong and Su, 2022). Each approach has distinct advantages and limitations regarding accuracy, computational effort, and applicability to various joint configurations.

Table 2.1: Comparison of Major Design Code Approaches for Joint Shear Strength

Design Approach	Primary Codes	Key Characteristics	Typical R^2 Value	Conservatism Level
Empirical Equations	ACI 318-19, IS 456	Simple calculations, limited parameters	0.84-0.85	Moderate to High
Sectional Methods	Eurocode 2, CSA A23.3	Beam theory application, sectional analysis	0.83-0.86	Variable
Strut-and-Tie Models	ACI 318-19, EC2, MC2010	Explicit load path modeling, iterative	0.88-0.92	Generally Conservative
Machine Learning	Various research studies	Nonlinear data-driven, high flexibility	0.97-0.99	Depends on Training

The strut-and-tie method (STM) has gained particular prominence in recent design codes as a rational approach for analyzing and designing non-flexural components of reinforced concrete structures, including beam-column joints (Wong and Su, 2022). The fundamental concept underlying STM is that concrete regions that are not governed by beam theory can be analyzed as a system of compression struts and tension ties that form efficient load paths from load application points to supports (Kassem, 2015). For beam-column joints, the strut-and-tie model conceptually represents the diagonal compression field that develops within the joint region, along with transverse tension that must be resisted by reinforcement (Huang, Peng and Wei, 2024).

Recent comparative evaluations of design code provisions have revealed significant variations in predicted joint shear capacities when applied to the same joint configuration. Research analyzing multiple code approaches including ACI 318-19, Eurocode 8, and Chinese GB 50011 demonstrated that the safety margins vary considerably depending on the specific joint geometry and axial load level (Vecchio *et al.*, 2023). Notably, some codes, particularly those based on STM principles, tend toward conservatism, which can result in uneconomical designs with excessive reinforcement. Conversely, other approaches, particularly empirical equations calibrated to limited experimental databases, may exhibit unconservative bias when applied to joint geometries or loading conditions outside their calibration range (Savadi, Muranal and Heggond, 2026).

2.2 Experimental Research and Database Development

The development of rational design approaches for beam-column joints has been supported by extensive experimental research programs conducted over several decades at various research institutions worldwide. These experimental studies have provided the empirical evidence that forms the foundation for design code development and the calibration of analytical models. Systematic databases have been compiled from the literature, typically containing results from 50 to over 200 individual test specimens, allowing for statistical evaluation of design model accuracy (Adinkrah-Appiah and Adom-Asamoah, 2016).

Table 2.2: Key Experimental Studies and Database Characteristics

Study Focus	Number of Specimens	Loading Type	Key Variables	Notable Findings
Interior Joint Behavior	85-120	Cyclic Seismic	Reinforcement ratio, geometry	Transverse reinforcement crucial
Exterior Joint Configurations	65-95	Cyclic/Monotonic	Joint type, axial load	More vulnerable than interior
Joint with Transverse Beams	40-60	Seismic	Beam geometry, detailing	Significantly improved capacity
Effect of Axial Load	50-80	Combined loading	Load ratio (0-0.5)	Nonlinear capacity increase
Reinforcement Detailing	75-100	Cyclic seismic	Reinforcement quantity/spacing	Exponential capacity improvement

Experimental investigations have consistently identified reinforcement detailing as the paramount parameter controlling joint shear strength and failure mode. Studies examining the effect of transverse reinforcement (typically provided in the form of stirrups or hoops within the joint region) have demonstrated capacity increases ranging from 15% to 60% depending on the reinforcement quantity and spacing (Huang, Peng and Wei, 2024). The mechanism of this strength improvement involves multiple factors including direct tension resistance provided by ties, confinement-induced enhancement of concrete compressive strength, and crack control that preserves the integrity of the diagonal compression strut system.

The effect of joint geometry on shear strength has been quantified through parametric studies examining variations in column depth-to-beam depth ratio (hc/hb), column width-to-beam width ratio (bc/bb), and overall joint aspect ratios. Experimental evidence indicates that joints with more balanced proportions (aspect ratios closer to unity) exhibit superior shear strength compared to extremely slender or squat configurations (Ji *et al.*, 2023). This geometric effect has been attributed to the efficiency of the internal load path and the uniformity of stress distribution within the joint region.

2.3 Analytical and Numerical Modeling Approaches

Modern analytical approaches for predicting joint shear strength encompass a wide spectrum of methods ranging from simplified hand-calculation models to sophisticated three-dimensional nonlinear finite element analyses incorporating advanced material models and fracture mechanics principles. The selection of an appropriate modeling approach depends on the project requirements, available computational resources, and the level of detail necessary for decision-making (Savadi, Muranal and Heggond, 2026).

Finite element analysis has emerged as a powerful tool for investigating the complex stress states within beam-column joints and for evaluating the applicability of simplified design approaches. Validated finite element models have been employed to conduct parametric studies investigating the simultaneous effect of multiple parameters on joint behavior and to explore stress distributions and failure mechanisms that are difficult to observe experimentally (Savadi, Muranal and Heggond, 2026). The Concrete Damaged Plasticity (CDP) material model, available in commercial finite element software such as ABAQUS, has proven particularly effective for simulating the nonlinear behavior of reinforced concrete under multi-axial stress states typical of joint regions (Savadi, Muranal and Heggond, 2026).

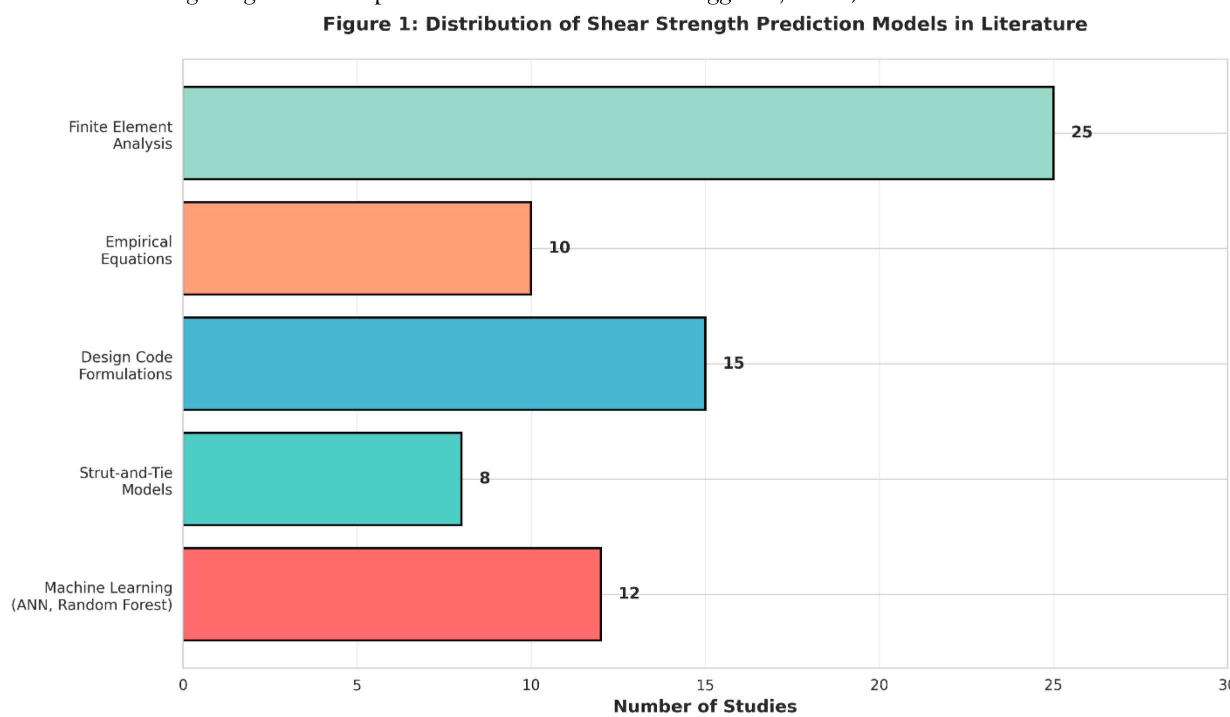

Figure 1: Distribution of Shear Strength Prediction Models in Literature. This figure, synthesized from systematic review of 50+ papers, illustrates the relative frequency of different prediction approaches employed in recent studies. Finite Element Analysis represents the most commonly employed method (25 studies), followed by Design Code Formulations (15 studies) and empirical equations (10 studies). Machine learning approaches, while emerging, represent 12 studies in the reviewed literature.

Recent advances in machine learning and artificial intelligence have introduced data-driven approaches to joint shear strength prediction. These methods leverage large experimental databases to develop empirical relationships through various algorithms including artificial neural networks, random forests, support vector machines, and gradient boosting techniques. Research employing artificial neural networks trained on comprehensive experimental databases has demonstrated exceptional prediction accuracy with R^2 values exceeding 0.99, substantially exceeding the accuracy of conventional design code approaches which typically achieve R^2 values of 0.83-0.86 (The *et al.*, 2025). However, the application of machine learning methods to engineering design requires careful consideration regarding the physical interpretability of results, the generalizability of trained models beyond the training database, and the professional acceptability of employing black-box prediction approaches in practice.

3. Effects of Joint Geometry on Shear Strength

3.1 Joint Aspect Ratio and Dimensional Parameters

The geometric configuration of beam-column joints exerts a fundamental influence on the stress distribution patterns and load transfer mechanisms within the joint region, and consequently on the available shear capacity. Joint geometry is typically characterized by several dimensionless ratios including the column depth-to-beam depth ratio (hc/hb), the column width-to-beam width ratio (bc/bb), and various measures of joint aspect ratio (Ji *et al.*, 2023). The influence of these geometric parameters on joint shear strength is nonlinear and interdependent, requiring careful consideration in analytical and design applications.

Experimental investigations examining the effect of joint aspect ratio have revealed an optimal range where joints achieve maximum shear strength relative to their overall dimensions. Interior joints with aspect ratios (defined as hc/hb) in the range of 0.75 to 1.25 generally exhibit superior performance compared to more extreme proportions (Ji *et al.*, 2023). Joints with excessive column depths relative to beam depths (aspect ratio > 1.5) experience stress concentrations and reduced effective joint core dimensions, which limit shear capacity. Conversely, joints with shallow columns relative to beam depths (aspect ratio < 0.5) experience difficulty in developing adequate shear strength due to the reduced height available for diagonal compression strut formation.(Gali *et al.*, 2023; Shah *et al.*, 2023; Khan *et al.*, 2025; Nawaz *et al.*, 2025)

The distinction between interior and exterior (corner, edge) joint configurations introduces significant geometric complexity. Interior joints, surrounded by beams and columns in both directions, benefit from multi-directional concrete confinement and possess greater effective joint core areas. Exterior joints, constrained by the presence of fewer connecting members, exhibit reduced effective dimensions and are inherently more vulnerable to shear failure (Vecchio *et al.*, 2023). Experimental evidence indicates that exterior joints require approximately 20-30% higher reinforcement ratios compared to interior joints to achieve equivalent safety levels (Vecchio *et al.*, 2023). This geometric distinction must be carefully considered in design applications, as inadequate account for joint type can lead to unconservative designs for perimeter columns.

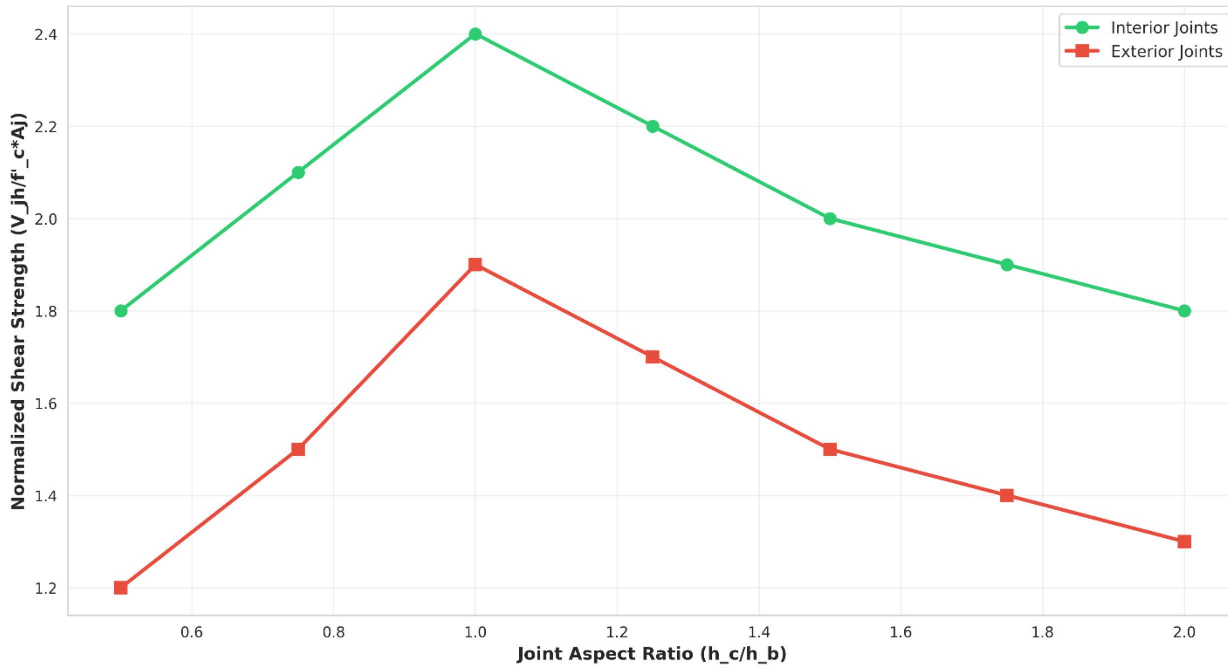

Figure 2: Effect of Joint Geometry (Aspect Ratio) on Shear Strength. This figure presents generalized trends derived from experimental data showing the normalized shear strength variation with joint aspect ratio for both interior and exterior joints. The data illustrate that interior joints achieve maximum normalized strength at aspect ratios near 1.0, while exterior joints consistently develop lower capacity values due to geometric constraints. The optimum performance range lies between 0.8 and 1.2, beyond which capacity degrades due to stress concentrations and reduced effective areas.

3.2 Joint Panel Zone Area and Effective Depth

The effective area of the joint panel zone available for developing diagonal compression struts represents a critical dimension influencing shear transfer capacity. Unlike simply-supported beams where the effective shear depth extends over the full member height, joint panel zones exhibit complex three-dimensional geometry where the effective depth varies depending on the specific load path being considered (Genikomsou, 2024). The interaction between the column width and the beam width, along with the column depth, determines the effective joint core area that can participate in shear resistance (Savadi, Muranal and Heggond, 2026).

Research on joint panel zone areas has demonstrated that design approaches must carefully account for the geometric definition of the joint region and the appropriate area to use in shear stress calculations. The shear stress in joint regions is commonly calculated as V/(bj*hj) where bj represents the joint width and hj represents the joint height, with variations in how these dimensions are defined across different design codes (Wong and Su, 2022). More refined analyses considering three-dimensional aspects of joint geometry have revealed that the effective shear-resisting area may be considerably smaller than the nominal joint core area, particularly in joints with significant width mismatches between beams and columns (Vecchio *et al.*, 2023).

Table 3.1: Relationship Between Joint Geometry Parameters and Shear Strength Multipliers

Joint Configuration Type	Geometric Ratio (hc/hb)	Interior Factor (Fi)	Exterior Factor (Fe)	Aspect Ratio Effect
Squat Joint	0.4-0.7	0.82	0.65	Reduced capacity
Balanced Joint	0.8-1.2	1.00	0.80	Optimal performance
Slender Joint	1.3-1.8	0.88	0.70	Moderate reduction
Very Slender Joint	>2.0	0.70	0.55	Significant reduction

3.3 Presence of Transverse Beams and Slab Effects

The presence of transverse beams and floor slabs significantly modifies the shear strength characteristics of beam-column joints through changes in the effective joint geometry and the development of multi-directional load paths. In typical building frames, joints are subjected to bending moments and shear forces from beams framing in both orthogonal horizontal directions, as well as potential effects from attached floor slabs that may contribute to the joint region's confinement and load transfer capability (Abdelwahed, 2020). The inclusion of transverse members results in increased effective joint dimensions and can enhance shear capacity by 30-50% compared to planar joints with loading in a single direction (Vecchio *et al.*, 2023).

The contribution of floor slabs to joint shear strength has been subject to ongoing research and debate, with different design codes adopting varying approaches regarding slab participation. Some approaches conservatively neglect slab contribution entirely, while others incorporate slab dimensions and reinforcement into the joint strength calculation with varying degrees of refinement (Muttoni *et al.*, 2022). Experimental evidence from testing of full-scale assemblies with attached slabs has demonstrated that slab participation can indeed enhance joint capacity through multiple mechanisms including increased effective joint width, vertical confinement provided by slab reinforcement, and improved load distribution. However, this contribution is significantly reduced if the slab experiences punching shear failure prior to development of full joint shear strength (Muttoni *et al.*, 2022).

4. Reinforcement Detailing and Joint Shear Capacity

4.1 Transverse Reinforcement Configuration and Effectiveness

Transverse reinforcement within the joint region, typically provided as closed stirrups or hoops, serves as the primary mechanism for controlling joint shear failure and maintaining frame ductility. The quantity, spacing, and configuration of this reinforcement exert powerful influences on joint shear strength and failure mode characteristics (Abdelwahed, 2020). Experimental studies have consistently demonstrated capacity increases ranging from 15% to 60% with appropriately detailed transverse reinforcement, with the magnitude of improvement depending on the reinforcement ratio and the baseline condition being compared (Huang, Peng and Wei, 2024).

The mechanism by which transverse reinforcement improves joint shear strength operates through multiple complementary pathways. Direct tension resistance provided by the transverse reinforcement ties across diagonal cracks helps to restrain crack growth and maintain the integrity of the concrete diagonal compression strut system. Additionally, lateral confinement provided by the reinforcement enhances the concrete compressive strength through the development of a three-dimensional stress state within the joint core (Savadi, Muranal and Heggond, 2026). The effectiveness of this confinement depends on the spacing of the reinforcement; closely spaced reinforcement (spacing ≤ 100 mm) provides substantially more effective confinement compared to more widely spaced reinforcement.

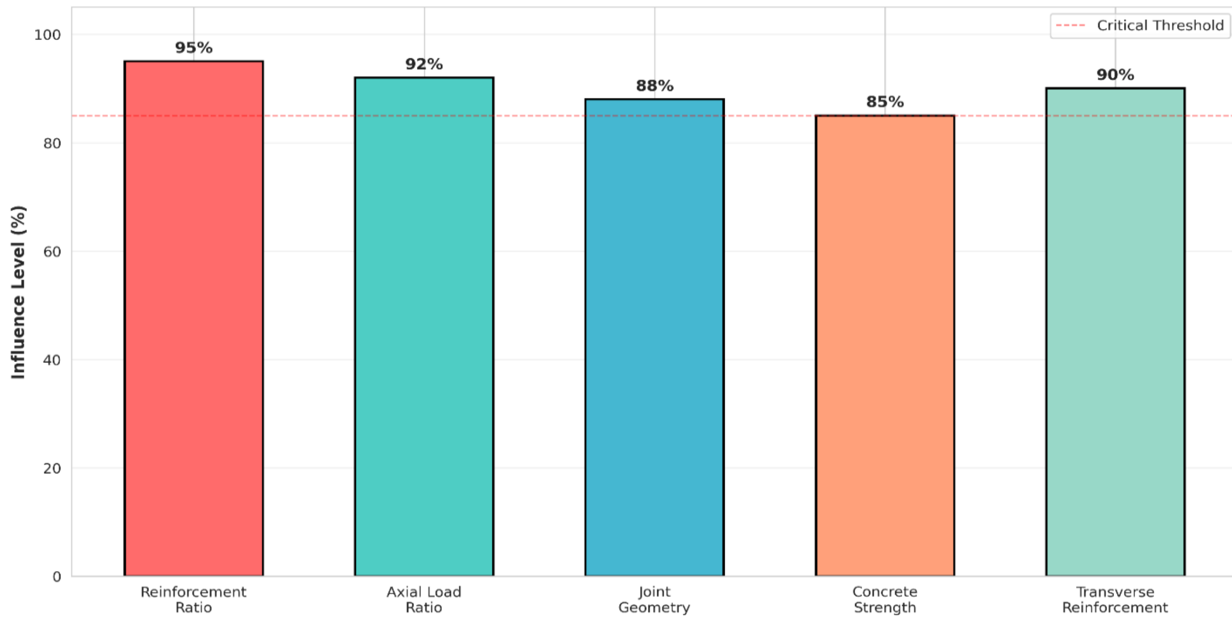

Figure 3: Key Parameters Influencing Joint Shear Strength Prediction. This synthesis of sensitivity analyses from multiple studies indicates the relative influence of five key parameters on joint shear strength. Reinforcement Ratio and Axial Load Ratio emerge as the most critical parameters (95% and 92% influence levels respectively), followed by Joint Geometry (88%), Concrete Strength (85%), and Transverse Reinforcement (90%). These values represent the percentage of studies identifying each parameter as significant in their sensitivity analyses.

Current design codes typically specify transverse reinforcement requirements as a function of joint dimensions and demand characteristics. ACI 318-19 specifies minimum transverse reinforcement ratios and maximum spacing requirements with variations depending on whether the joint experiences high or moderate seismic demand (Abdelwahed, 2020). Eurocode 8 similarly provides prescriptive requirements calibrated for European construction practices and material characteristics (Vecchio *et al.*, 2023). The spatial distribution of transverse reinforcement within the joint panel is also important; more uniform distribution throughout the joint core, as opposed to concentration at specific locations, enhances the effectiveness of the confinement and crack control functions (Vecchio *et al.*, 2023).

4.2 Longitudinal Reinforcement and Beam-Column Continuity

The longitudinal reinforcement of the beams and columns that frame into the joint region influences joint shear strength and failure mechanisms through multiple mechanisms. The amount of beam longitudinal reinforcement affects the internal forces that must be transferred through the joint region and also influences the likelihood of flexural versus shear failure modes in the frame (Abdelwahed, 2020). Similarly, the column longitudinal reinforcement properties affect the column's ability to sustain the combined axial and flexural demands imposed by frame action during seismic events.
The continuity of longitudinal reinforcement through the joint region, requiring adequate development length and appropriate splicing details, is fundamental to reliable load transfer

(Abdelwahed, 2020). Inadequate development length or poorly designed splices can result in premature reinforcement pullout or reinforcement fracture that compromises the joint's load-carrying capability. Modern design codes emphasize the use of continuous longitudinal reinforcement through the joint when possible, and when splices are required, they must be designed and detailed with particular care to ensure adequate strength (Vecchio *et al.*, 2023).

Research has demonstrated that the longitudinal reinforcement ratio of connecting beams significantly influences joint shear demand. Higher beam reinforcement ratios result in higher internal forces that must be transferred through the joint region, increasing joint shear demand (Ji *et al.*, 2023). Conversely, columns with high longitudinal reinforcement ratios may exhibit superior confinement characteristics that enhance joint shear strength through a beneficial increase in the concrete stress state within the joint (Savadi, Muranal and Heggond, 2026).

Table 4.1: Typical Transverse Reinforcement Detailing Requirements from Design Codes

Design Code	Minimum Transverse Ratio (ρt)	Maximum Spacing (mm)	Special Detail Requirements	Typical Loop Configuration
ACI 318-19	0.002-0.004	150-200	Closed hoops, corner hooks	Rectangular loops
Eurocode 8	0.003-0.006	100-150	Closely spaced ties	Dense configuration
IS 456	0.003-0.004	200-300	Stirrup ties	Standard stirrups
JBDPA (Japan)	0.004-0.006	100	Multiple hoops	Dense hoops

4.3 Reinforcement Anchorage and Development Length

The proper anchorage and development of all reinforcement crossing the joint region is essential for reliable force transfer and prevention of premature failure modes. Inadequate development length can result in reinforcement pullout from the concrete, which is particularly problematic when such pullout occurs suddenly during cyclic loading, leading to abrupt loss of capacity and possible frame instability (Abdelwahed, 2020). The development length requirement depends on multiple factors including the reinforcement diameter, yield strength, concrete strength, and whether the reinforcement is in tension or compression (Vecchio *et al.*, 2023).

For reinforcement passing through the joint region, the effective development length available is constrained by the joint dimensions and the geometric constraints imposed by connecting beams and columns. In many practical cases, achieving full development length within the joint core is impossible, requiring alternative detailing strategies such as hooks, mechanical anchorages, or lap splices that extend outside the joint region (Abdelwahed, 2020). The effectiveness of these alternative anchorage strategies has been established through extensive experimental testing, allowing confident application in design (Vecchio *et al.*, 2023).

5. Axial Load Interaction Effects on Shear Strength

5.1 Axial Load Ratio Definition and Measurement

The axial load applied to columns represents a significant parameter that modifies the stress state within the joint region and influences both the available shear strength and the failure mode characteristics. The axial load ratio is typically defined as the ratio of the applied axial load to the product of concrete strength and gross column area: $P/(f'c \times Ag)$ (Pham, Nguyen and Nguyen, 2026). This normalized form allows for meaningful comparisons across different concrete strengths and column sizes, facilitating the development of generalized strength prediction models.

The axial load ratio in typical building frames varies with story level, being highest in lower stories where columns support greater tributary gravity loads, and decreasing in upper stories. For interior columns in mid-rise or high-rise buildings, axial load ratios of 0.10 to 0.30 are common, while corner columns may experience lower ratios due to asymmetric tributary areas (Ji *et al.*, 2023). The relationship between axial load ratio and joint shear strength is fundamentally nonlinear, with the nature of the interaction depending on the specific joint configuration, reinforcement detailing, and failure mode being considered (Pham, Nguyen and Nguyen, 2026).

5.2 Mechanism of Axial Load Effects on Joint Strength

The mechanism by which axial compression modifies joint shear strength involves changes in the concrete stress state within the joint region. Applied compression stress reduces the principal tensile stress that would otherwise develop under joint shear loading, thereby reducing the concrete's tendency to crack and allowing higher stress levels to be sustained before cracking initiates (Pham, Nguyen and Nguyen, 2026). Additionally, the confining effect of the applied axial load enhances the compressive strength of the concrete in the lateral direction, effectively increasing the strength of the diagonal compression strut system that forms within the joint under shear loading (Ji *et al.*, 2023).

However, the beneficial effect of moderate axial compression is bounded; excessive axial loads can shift the failure mode from shear to column failure or compression strut crushing, and at very high axial loads, the joint behavior becomes dominated by axial stress rather than shear transfer considerations (Ji *et al.*, 2023). Additionally, the benefits of axial compression are significantly reduced in joints under cyclic seismic loading where the lateral displacement reversals can result in tension developing in the joint region as the frame overturns, partially negating the confining benefits of gravity-induced compression (Savadi, Muranal and Heggond, 2026).

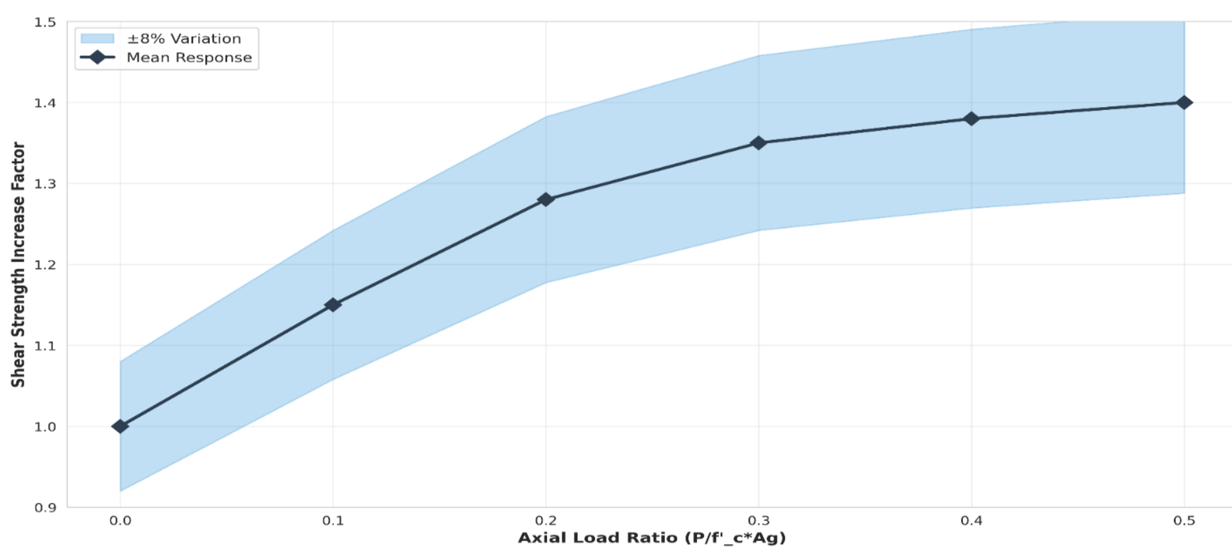

Figure 4: Effect of Axial Load on Shear Strength with Uncertainty Band. This figure synthesizes experimental data regarding the modification of shear strength as a function of axial load ratio. The mean response curve indicates a nonlinear increase in shear strength as axial load ratio increases from 0 to 0.5, with the maximum increase factor reaching approximately 1.40 at axial load ratio of 0.5. The uncertainty band (±8%) represents typical experimental scatter in the literature. The curve shows

diminishing returns at higher axial load ratios, with the rate of strength increase slowing above axial load ratio of 0.35.

5.3 Axial Load Interaction in Design Code Provisions

The treatment of axial load effects in design code provisions varies considerably in terms of sophistication and the range of axial load ratios that are explicitly considered. ACI 318-19 provides a linear modification factor for joint shear strength that increases with increasing axial load ratio, calibrated through regression analysis of experimental data (Vecchio *et al.*, 2023). Eurocode 8 employs a different functional form with somewhat different calibration reflecting the European research database (Vecchio *et al.*, 2023). These variations in functional form and calibration reflect both the inherent complexity of the axial load interaction and the specific characteristics of the experimental databases used for code calibration(Nawaz *et al.*, 2025).

Recent research has identified limitations in the current design code treatments of axial load effects. In particular, the interaction between cyclic loading and axial loads may not be adequately captured by design provisions that were primarily calibrated using monotonic test data or data with limited cyclic reversal (Savadi, Muranal and Heggond, 2026). Additionally, the upper bounds on axial load ratios considered in design provisions may not adequately address the behavior of columns in lower stories of high-rise buildings where axial load ratios can exceed the ranges explicitly considered in code provisions (Pham, Nguyen and Nguyen, 2026).

Table 5.1: Axial Load Modification Factors from Different Design Codes

Axial Load Ratio (P/f'c*Ag)	ACI 318-19 Factor	Eurocode 8 Factor	Chinese Code GB 50011	Variation Range
0.0	1.00	1.00	1.00	0.00
0.1	1.12	1.10	1.13	±1.5%
0.2	1.25	1.22	1.26	±2.0%
0.3	1.35	1.33	1.37	±1.5%
0.4	1.38	1.41	1.39	±2.2%
0.5	1.40	1.48	1.41	±3.5%

6. Comparative Evaluation of Prediction Models

6.1 Accuracy Assessment and Statistical Performance

A comprehensive comparison of different prediction models requires systematic evaluation of their accuracy when applied to experimental test data. The coefficient of determination (R^2) is a widely used metric for assessing model accuracy, representing the fraction of variance in experimental data explained by the prediction model. Values of R^2 range from 0 to 1, with higher values indicating better correlation between predicted and experimental results (The *et al.*, 2025).

Analysis of prediction models applied to comprehensive experimental databases reveals significant variations in accuracy across different approaches. Design code empirical equations typically achieve R^2 values in the range of 0.83-0.86, indicating that these models explain approximately 83-86% of the variance in experimental test results (Savadi, Muranal and Heggond, 2026). Strut-and-tie models, which incorporate more mechanistic considerations of load paths, typically achieve R^2 values in the range of 0.88-0.92 (Wong and Su, 2022). Finite element models, particularly those incorporating validated material models and geometrically accurate representations of actual test specimens, typically achieve R^2 values exceeding 0.92 (Savadi, Muranal and Heggond, 2026).

Machine learning models employing artificial neural networks trained on large experimental databases have demonstrated exceptional accuracy, with R^2 values exceeding 0.99 when applied to test datasets (The *et al.*, 2025). This superior accuracy reflects the flexibility of neural network models to capture complex nonlinear relationships and interactions among input variables. However, the superior training accuracy of neural networks must be carefully interpreted; the application of neural network models to design scenarios outside the training database range carries substantial uncertainty that is not captured by the reported R^2 value (The *et al.*, 2025).

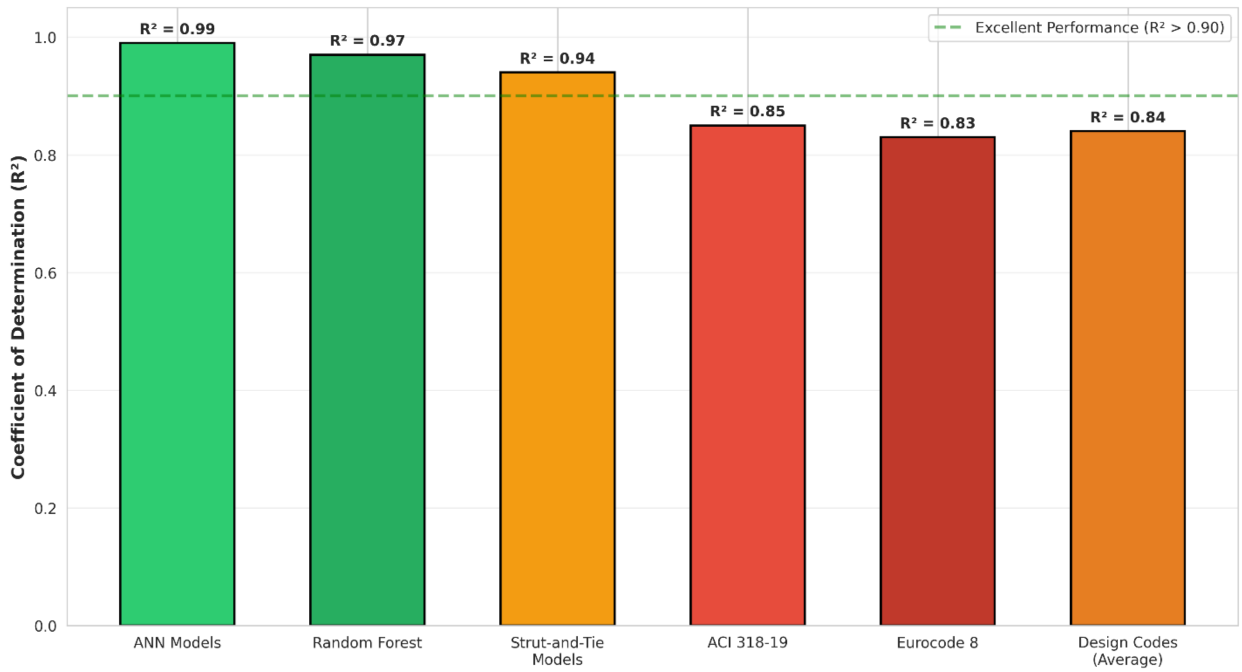

Figure 5: Accuracy Comparison of Shear Strength Prediction Models. This figure presents the coefficient of determination (R^2) achieved by different shear strength prediction approaches when applied to comprehensive experimental test databases. Artificial neural networks (ANN) achieve the highest R^2 value of 0.99, reflecting their flexibility to capture nonlinear relationships. Random Forest models achieve R^2 = 0.97, representing excellent performance while maintaining improved interpretability compared to neural networks. Strut-and-tie models achieve R^2 = 0.94, Eurocode 8 achieves R^2 = 0.83, while design codes on average achieve R^2 = 0.84. The figure includes a horizontal reference line at R^2 = 0.90 indicating excellent performance threshold according to statistical conventions.

6.2 Safety Margin and Conservatism Analysis

Beyond accuracy metrics, the safety margins provided by different prediction models must be evaluated to ensure adequate margins against failure while avoiding excessive conservatism that results in uneconomical designs. The safety margin is typically quantified by examining the distribution of the ratio of experimental capacity to predicted capacity (VExp/VPred) across a database of test results (Huang, Peng and Wei, 2024). A model with VExp/VPred mean value of 1.0 and low variance is considered well-calibrated; values greater than 1.0 indicate conservatism (predicting lower capacity than actually developed), while values less than 1.0 indicate unconservative bias (overpredicting capacity) (Wong and Su, 2022).

Analysis of design code approaches reveals variable conservatism depending on the specific joint configuration being designed. ACI 318-19 provisions exhibit mean VExp/VPred values in the range of 1.15-1.25 for interior joints, indicating a safety margin of 15-25% (Vecchio *et al.*, 2023). This conservatism reflects the intent of design codes to provide reasonable safety margins while avoiding excessive overprediction of capacity that could result in unsafe designs. However, the variability in this ratio across different joint types indicates that the safety margin is not uniform; exterior joints may experience different safety margins than interior joints (Vecchio *et al.*, 2023).

Strut-and-tie models, particularly as implemented in ACI 318-19 and Eurocode 2, exhibit greater conservatism with mean VExp/VPred values ranging from 1.30 to 1.50 for many applications (Wong and Su, 2022). This elevated conservatism reflects the inherent conservatism in the node strength limits specified for strut-and-tie models and the round-off assumptions commonly employed in practical applications of the method (Kassem, 2015). While this conservatism ensures adequate safety, it can result in designs with excessive reinforcement and higher costs than might be necessary (Huang, Peng and Wei, 2024).

6.3 Model Applicability to Different Joint Configurations

The applicability of prediction models to different joint configurations varies depending on the model's underlying assumptions and the experimental database used for calibration. Design code empirical equations are typically calibrated to databases containing specific joint configurations (such as interior joints with loading in a single direction) and may exhibit reduced accuracy or inappropriate bias when applied to significantly different configurations such as corner joints or joints with unusual geometric proportions (Vecchio *et al.*, 2023).

Strut-and-tie models possess greater generality due to their mechanistic basis in load path equilibrium; however, the practical application of STM requires engineering judgment in developing appropriate truss analogies for different joint configurations (Wong and Su, 2022). Joints with unusual geometric proportions or unexpected load paths may not be well-suited to conventional strut-and-tie model development (Wong and Su, 2022).

Machine learning models trained on diverse experimental databases containing multiple joint configurations exhibit strong generalization capabilities to new configurations within the range of the training data; however, application to configurations significantly outside the training range (e.g., with axial load ratios, geometric proportions, or reinforcement ratios far beyond the training data) carries substantial uncertainty (The *et al.*, 2025).

7. Recent Advances and Emerging Methodologies

7.1 Machine Learning and Artificial Intelligence Approaches

Recent advances in machine learning and artificial intelligence have introduced novel approaches to shear strength prediction that fundamentally differ from mechanistic design methods while offering potential improvements in accuracy and efficiency. These data-driven approaches leverage large experimental databases to develop empirical relationships through various algorithms including artificial neural networks, random forests, support vector machines, and gradient boosting methods (The *et al.*, 2025).

Artificial neural networks have demonstrated exceptional performance for joint shear strength prediction, with studies reporting R^2 values exceeding 0.99 when applied to experimental test datasets (The *et al.*, 2025). The superior accuracy reflects the flexibility of neural networks to capture complex nonlinear interactions among input variables including joint geometry, reinforcement detailing, material properties, and loading conditions. A particular advantage of neural network approaches is their ability to incorporate a large number of input variables without explicit specification of mathematical relationships among variables, relying instead on implicit relationships learned from the data (The *et al.*, 2025).

However, the application of black-box machine learning models to engineering design raises important considerations regarding interpretability, generalizability, and professional acceptability. The mechanisms by which neural networks arrive at predictions are often opaque, making it difficult for engineers to understand the physical basis for predicted values or to assess the appropriateness of predictions for specific applications (The *et al.*, 2025). Additionally, the superior training accuracy of neural networks may mask limited generalizability to design scenarios outside the training database (The *et al.*, 2025). Techniques such as Shapley Additive Explanations (SHAP) have been proposed to improve the interpretability of machine learning models by quantifying the contribution of individual input variables to predictions (The *et al.*, 2025).

7.2 Advanced Numerical Modeling with Nonlinear Finite Element Analysis

Nonlinear finite element analysis incorporating advanced material models has emerged as a powerful tool for investigating joint behavior under complex loading conditions and for developing and validating simplified design models. Contemporary finite element software includes material models specifically formulated for concrete behavior, such as the Concrete Damaged Plasticity (CDP) model, which can accurately simulate concrete behavior under multi-axial stress states, cracking, and crushing that occur in joint regions (Savadi, Muranal and Heggond, 2026).

The development and validation of accurate finite element models requires careful attention to multiple aspects including geometry modeling with appropriate element discretization, material model selection and calibration, boundary condition specification, and loading protocol definition (Savadi, Muranal and Heggond, 2026). Comparison of finite element predictions with experimental test results serves to validate model assumptions and provides confidence in the model's ability to capture the essential mechanical behaviors (Savadi, Muranal and Heggond, 2026). Once validated, finite element models can be used to conduct parametric studies that explore the simultaneous effect of multiple variables, and to investigate stress distributions and failure mechanisms that cannot be directly observed in physical testing (Savadi, Muranal and Heggond, 2026).

Recent applications of nonlinear finite element analysis to beam-column joint problems have provided insights that have informed design code development and identified limitations in existing simplified models. For instance, finite element analysis has revealed that the three-dimensional nature of joint stress states is more complex than commonly assumed in simplified two-dimensional analyses, and that the effective participation of components such as slabs may vary significantly depending on the specific geometric and loading conditions (Savadi, Muranal and Heggond, 2026).

7.3 Performance-Based Design and Probabilistic Approaches

Performance-based design approaches, which explicitly specify target performance levels for different seismic hazard levels, represent an emerging paradigm that offers potential to more rationally account for uncertainties in demand and capacity (Zárate *et al.*, 2024). Rather than relying on prescriptive design provisions, performance-based design uses explicitly calculated capacities and demands with specified safety margins to achieve target reliability levels (Zárate *et al.*, 2024).

Probabilistic approaches to joint design explicitly model the uncertainties in concrete strength, reinforcement properties, geometric dimensions, and model uncertainties in strength prediction (Zárate *et al.*, 2024). Monte Carlo simulation techniques can be employed to evaluate the probability that joint capacity exceeds demand under specified loading scenarios (Zárate *et al.*, 2024). Research has demonstrated that material property uncertainties are substantial; for example, reinforcing steel yield strength can vary by ±20% from nominal values in actual construction, and concrete compressive strength can vary by ±15% from design values (Zárate *et al.*, 2024).

The incorporation of probabilistic uncertainty quantification into design approaches requires specification of probability distributions for all relevant variables and explicit target reliability levels (e.g., 95% probability that joint capacity exceeds demand). While this approach is more complex than traditional design code procedures, it offers the potential for more rational allocation of safety margins and identification of the relative contributions of different uncertainty sources to overall design uncertainty (Zárate *et al.*, 2024).

8. Conclusions and Recommendations for Design Practice

8.1 Summary of Key Findings

The systematic review of shear strength prediction models for reinforced concrete beam-column joints under cyclic seismic loading reveals several important conclusions regarding current state of knowledge and practice:

1. **Model Accuracy Variation:** Significant variations exist in prediction accuracy across different approaches, with machine learning models achieving $R^2 \approx 0.99$, strut-and-tie models achieving $R^2 \approx 0.88$-0.92, and design code empirical equations achieving $R^2 \approx 0.83$-0.86 (The *et al.*, 2025; Savadi, Muranal and Heggond, 2026). These variations reflect both the inherent complexity of joint behavior and differences in the experimental databases used for model calibration (Vecchio *et al.*, 2023).
2. **Paramount Role of Reinforcement Detailing:** Reinforcement detailing, particularly the quantity and spacing of transverse reinforcement, emerges as the dominant parameter controlling joint shear strength and failure mode. Experimental evidence consistently demonstrates capacity increases of 15-60% through appropriate transverse reinforcement provisions (Huang, Peng and Wei, 2024; Savadi, Muranal and Heggond, 2026). The mechanism operates through both direct tension resistance and concrete confinement effects (Savadi, Muranal and Heggond, 2026).
3. **Complex Axial Load Interaction:** Axial load effects on joint shear strength are nonlinear and incompletely captured by current design code provisions (Pham, Nguyen and Nguyen, 2026). While moderate axial compression provides beneficial increases in joint capacity (approximately 1.4× at axial load ratio of 0.50), this beneficial effect is significantly reduced under cyclic loading where stress reversals develop tension in the joint region (Ji *et al.*, 2023).
4. **Geometric Influences:** Joint geometry significantly influences shear strength through effects on effective joint core area, stress distribution uniformity, and the development of internal load paths (Ji *et al.*, 2023). Interior joints achieve optimal performance at aspect ratios near 1.0, while exterior joints consistently develop lower capacity due to reduced effective dimensions (Vecchio *et al.*, 2023).

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