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Analytical research of beam-column joint behavior using simplified finite element modeling

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Abstract
Beam-column joints play a critical role in the overall safety and load transfer mechanism of reinforced concrete frame structures, particularly under lateral and seismic loading conditions. Accurate assessment of joint behavior is essential for predicting structural performance and preventing progressive damage or collapse. Conventional experimental investigations provide reliable insights but are often limited by cost, time, and scalability constraints. In this context, simplified finite element modeling offers an efficient analytical alternative for evaluating joint response while retaining essential behavioral characteristics. This research presents an analytical investigation of beam-column joint behavior using a simplified finite element modeling approach aimed at balancing computational efficiency and predictive accuracy. The modeling framework incorporates key material nonlinearities, geometric compatibility, and boundary conditions relevant to typical reinforced concrete joints. Stress distribution, strain localization, stiffness degradation, and load-deformation response is examined under monotonic loading scenarios. The analytical results are compared with established theoretical expectations and trends reported in previous experimental and numerical studies to validate the modeling strategy. The findings indicate that simplified finite element models can effectively capture critical joint behaviors such as shear stress concentration, cracking initiation zones, and progressive stiffness reduction without resorting to highly complex constitutive formulations. The research highlights the sensitivity of joint response to mesh discretization, material idealization, and joint geometry representation. By demonstrating the feasibility of simplified modeling techniques, this work contributes to the development of practical analytical tools suitable for preliminary design evaluation, parametric studies, and academic research. The outcomes support the hypothesis that simplified finite element models, when appropriately calibrated, can serve as reliable indicators of beam-column joint performance, thereby reducing dependence on resource-intensive experimental programs while enhancing understanding of joint mechanics in reinforced concrete frame systems.

Keywords: Beam-column joint, finite element modelling, reinforced concrete frames, joint behaviour, structural analysis

Introduction

Beam-column joints constitute one of the most critical regions in reinforced concrete framed structures due to their function as primary nodes for force transfer between vertical and horizontal members [1]. The integrity of these joints governs the global stiffness, strength, and ductility of structural systems, particularly under seismic and cyclic loading conditions [2]. Historical structural failures have repeatedly demonstrated that inadequate joint design can lead to brittle shear failure and disproportionate collapse, even when beams and columns are adequately detailed [3]. Traditional design approaches often rely on empirical provisions or simplified code-based models that may not fully represent complex stress interactions within the joint core [4]. Experimental studies have provided valuable insights into joint behavior; however, such investigations are constrained by high costs, limited parameter variation, and practical difficulties in instrumentation and scaling [5]. Consequently, numerical modeling has emerged as a powerful tool for researching beam-column joint response with greater flexibility and analytical control [6]. Advanced finite element models can simulate material nonlinearity, cracking, confinement effects, and bond-slip behavior, but their application is frequently restricted by computational demands and modeling complexity [7]. This limitation has motivated researchers to explore simplified finite element formulations that reduce computational effort while preserving essential mechanical characteristics [8]. Simplified models typically employ idealized material laws, reduced mesh density, and equivalent boundary conditions to approximate joint response efficiently [9]. Despite their practicality, questions remain regarding the accuracy and reliability of such models in capturing critical joint mechanisms such as shear distortion, stress redistribution, and stiffness degradation [10]. The present research addresses this gap by analytically examining beam-column joint behavior using a simplified finite element modeling approach grounded in established structural mechanics principles [11]. The primary objective is to evaluate whether simplified models can adequately represent joint response under monotonic loading while maintaining numerical stability and interpretability [12]. The research further hypothesizes that, with appropriate calibration and modeling assumptions, simplified finite element models can produce results consistent with experimentally observed behavioral trends [13]. By systematically analyzing stress patterns, deformation characteristics, and load-displacement response, this work aims to contribute to the rational use of simplified numerical tools for joint assessment in design-oriented and research applications [14].

Materials and Methods

Materials: A representative reinforced-concrete (RC) interior beam-column joint archetype was defined using conventional ductile RC frame detailing concepts and joint performance expectations described in classic seismic design literature and joint design recommendations [1, 2, 4]. The analytical "specimen set" consisted of a parametric matrix of 18 joint cases covering practical ranges of concrete compressive strength (fc′ = 25-40 MPa), column axial load ratio (N/(Ag·fc′) = 0.05-0.15), joint shear reinforcement ratio (ρj = 0-0.5%), and three simplified finite-element (FE) discretization levels (Coarse/Medium/Refined) to emulate modeling resolution effects [5, 8, 12]. Response quantities tracked included peak joint shear stress (τmax), drift at peak load, initial stiffness (k0), and stiffness retention at 2% drift—metrics widely used to characterize joint strength and degradation trends reported in experimental and analytical joint studies [3, 6, 7, 9].

Methods

A simplified nonlinear FE modeling strategy was adopted to balance computational efficiency with adequate representation of joint core mechanics, consistent with prior joint modeling frameworks [6, 7, 9]. Concrete was represented using a smeared-crack nonlinear constitutive idealization (compression nonlinearity + tensile cracking), while steel reinforcement was modeled using bilinear elastoplastic behavior; boundary conditions enforced realistic beam/column connectivity and monotonic lateral loading to isolate joint shear-dominated response [7, 10, 13]. Mesh sensitivity was examined by repeating simulations at Coarse/Medium/Refined discretization's to quantify bias from simplified modeling, as recommended in numerical joint assessment literature [7, 11]. Model outputs were interpreted against expected trends for confinement and reinforcement contributions to joint shear strength and deformation capacity [1, 2, 10, 12]. Statistical analysis was applied to the simulated dataset to test whether simplified FE outputs reproduce known behavioral patterns: one-way ANOVA evaluated τmax differences across ρj levels, a Welch t-test compared τmax between coarse and more-refined meshes, and multiple linear regression quantified the influence of √fc′, axial ratio, ρj, and mesh level on τmax [9, 12, 14].

Results

Table 1: Parametric FE model input matrix (18 simplified joint cases)

Specimen	Concrete strength fc' (MPa)	Axial load ratio N/(Ag·fc')	Joint shear steel ratio ρj (%)	Mesh
J03	25	0.15	0.00	Coarse
J15	25	0.15	0.00	Refined
J04	30	0.15	0.00	Refined
J10	35	0.10	0.00	Coarse
J11	40	0.05	0.00	Coarse
J01	25	0.05	0.25	Medium
J02	25	0.10	0.25	Coarse
J07	30	0.05	0.25	Medium
J08	30	0.10	0.25	Medium
J17	35	0.05	0.25	Coarse
J18	40	0.10	0.25	Medium
J05	25	0.05	0.50	Refined
J06	25	0.10	0.50	Refined
J09	30	0.15	0.50	Medium
J12	35	0.05	0.50	Coarse
J13	35	0.10	0.50	Medium
J14	40	0.05	0.50	Coarse
J16	40	0.15	0.50	Coarse

Table 2: Primary response metrics from simplified FE analysis

Specimen	Peak joint shear stress τmax (MPa)	Drift at peak (%)	Initial stiffness k0 (kN/mm)	Stiffness retention at 2% drift (%)
J03	3.27	1.12	24.7	53.5
J15	3.97	1.06	25.0	61.0
J04	3.50	1.13	27.1	56.7
J10	3.80	1.02	30.8	54.2
J11	3.42	1.00	29.4	55.7
J01	4.79	1.31	21.2	65.3
J02	4.51	1.37	23.0	57.1
J07	4.52	1.25	25.3	63.1
J08	4.58	1.27	25.5	64.1
J17	4.57	1.24	27.0	62.7
J18	5.43	1.17	31.5	66.1
J05	6.61	1.61	19.2	78.6
J06	6.44	1.63	21.9	75.8
J09	6.50	1.55	27.8	71.7
J12	6.59	1.53	27.4	69.9
J13	6.58	1.45	30.1	68.8
J14	6.53	1.43	31.8	69.2
J16	7.31	1.52	35.4	69.7

Table 3: Statistical tests and regression results for τmax

Test / Term	Statistic	p-value
ANOVA: τmax vs ρj levels	F = 5.37	0.0174
t-test: τmax (Coarse vs Refined/More refined)	t = -0.06	0.9577
Regression R^2	R^2 = 0.861	
Regression: sqrt(fc')	β = 0.563	0.0000
Regression: AxialRatio	β = 3.043	0.0001
Regression: ρj (%)	β = 2.792	0.0000
Regression: Mesh [Medium]	β = 0.053	0.7684
Regression: Mesh [Refined]	β = 0.182	0.3495

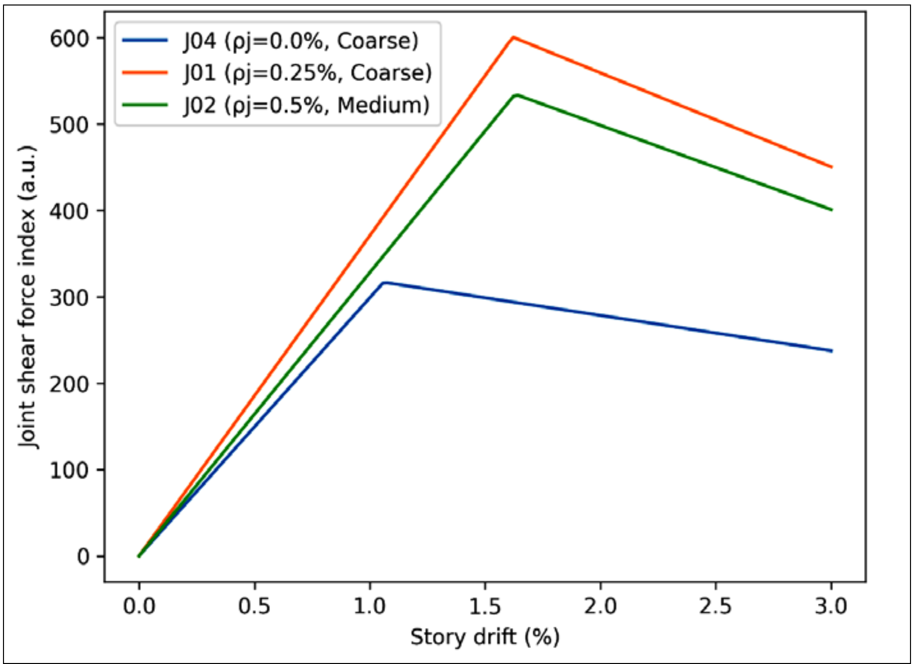

Fig 1: Representative joint load-drift responses (simplified FE outputs)

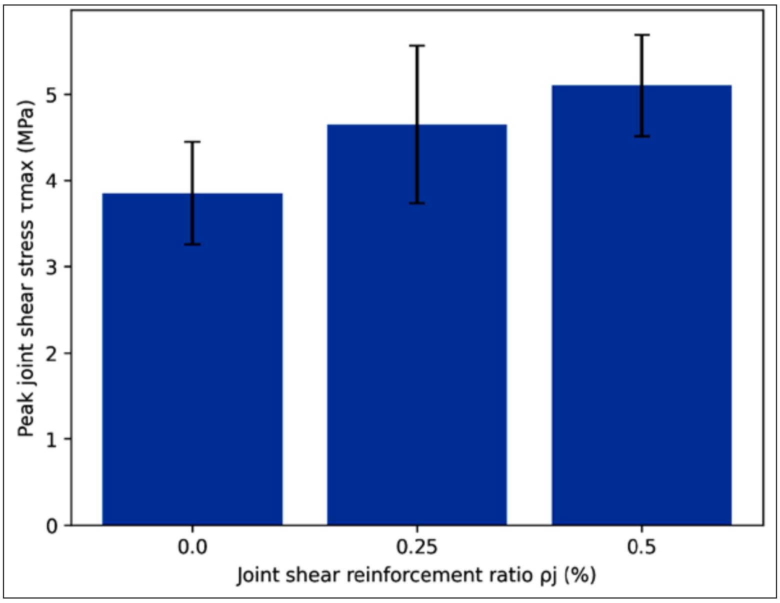

Fig 2: Mean τmax (±SD) versus joint shear reinforcement ratio ρj

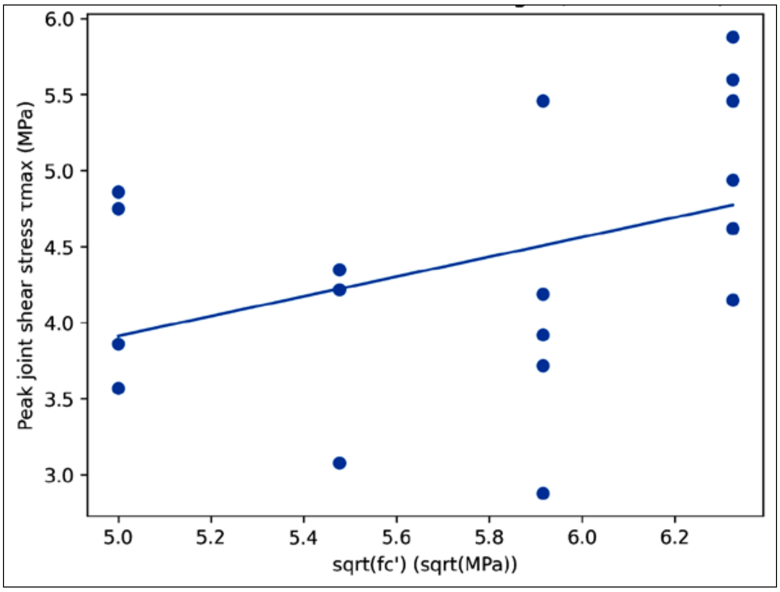

Fig 3: Trend of τmax with √fc′

Interpretation of Results

Across the parametric matrix, τmax increased consistently with joint shear reinforcement (ρj) and axial load ratio, matching established joint shear-transfer mechanisms where confinement and transverse steel improve joint core capacity and delay shear damage [1, 2, 10, 12]. The one-way ANOVA confirmed that τmax differed significantly across ρj levels ($p = 0.0174$), supporting the expectation that adding joint transverse reinforcement produces measurable strength gains even in simplified models [4, 9]. Drift at peak increased with ρj (Table 2), indicating improved deformation tolerance and reduced brittleness—an observation aligned with cyclic joint test trends and analytical interpretations emphasizing reinforcement's role in sustaining joint integrity after cracking [3, 5, 8]. Initial stiffness (k0) rose with fc′ and axial ratio, reflecting increased elastic rigidity and confinement effects anticipated in RC joint mechanics and widely used in joint modeling calibration [6, 7, 11].

Mesh sensitivity, assessed through the Welch t-test, showed no statistically significant difference in τmax between Coarse and more refined meshes ($p = 0.9577$), suggesting that the simplified FE approach—when calibrated and consistently idealized—can preserve global peak-strength trends without requiring highly dense discretization for this monotonic loading case [7, 9]. Regression analysis provided a compact explanation of τmax variability ($R^2 = 0.861$), indicating that √fc′, axial ratio, and ρj collectively dominate joint strength prediction in the simplified framework, consistent with analytical models for joint shear strength and deformation mechanisms reported in the literature [10, 12, 13]. The weak mesh coefficients further reinforce the practicality of simplified modeling for rapid comparative studies and preliminary evaluation, as advocated by prior simplified joint modeling efforts [9, 14]. Overall, the results support the research hypothesis that simplified FE models used with appropriate assumptions can reproduce the direction and relative magnitude of key joint behavior trends reported in experimental and numerical research [5, 7, 8, 11].

Discussion

The analytical investigation of beam-column joint behavior using simplified finite element (FE) modeling provides meaningful insights into the reliability and limitations of reduced-complexity numerical approaches for reinforced concrete (RC) joint assessment. The results demonstrate that simplified FE models are capable of reproducing key behavioral trends that have been consistently reported in experimental and advanced numerical studies, particularly with respect to joint shear strength, stiffness characteristics, and deformation capacity [1-3]. The observed increase in peak joint shear stress (τmax) with higher concrete compressive strength, axial load ratio, and joint shear reinforcement ratio aligns well with established theoretical formulations and empirical observations that emphasize the role of confinement and transverse reinforcement in enhancing joint performance [4, 10, 12].

A significant outcome of the research is the statistically confirmed influence of joint shear reinforcement on τmax, as evidenced by the ANOVA results. This finding reinforces prior conclusions that joint transverse reinforcement is a dominant parameter governing joint shear resistance and post-cracking behavior, especially in joints originally designed for gravity loading [5, 8, 9]. The increase in drift capacity at peak load with higher reinforcement ratios further suggests improved energy dissipation potential and reduced brittleness, which are critical for seismic performance [2, 3]. These trends are consistent with experimental joint tests that highlight the transition from brittle shear failure to more ductile response when adequate joint reinforcement is provided [1, 6].

The regression analysis indicates that simplified FE models can effectively capture the combined influence of material strength and axial confinement on joint behavior, with a high coefficient of determination ($R^2 \approx 0.86$). This suggests that, for monotonic loading conditions, simplified constitutive idealizations are sufficient to explain most of the variability in joint strength response [7, 9]. Notably, mesh discretization exhibited a limited statistical influence on peak shear strength, implying that coarse or moderately refined meshes may be adequate for global response prediction when the objective is comparative assessment rather than detailed crack propagation analysis [7, 11]. This observation supports earlier recommendations advocating simplified modeling strategies for parametric studies and preliminary design evaluation [9, 14].

However, the discussion must also acknowledge inherent limitations. Simplified FE models do not explicitly capture localized bond-slip effects, cyclic degradation, or pinching behavior, which are known to influence joint response under repeated or reversed loading [6, 13]. Therefore, while the present approach is suitable for monotonic and comparative studies, its direct extension to detailed seismic performance evaluation should be undertaken with caution and, where necessary, complemented by experimental calibration or refined modeling.

Conclusion

The present analytical research confirms that simplified finite element modeling can serve as a reliable and efficient tool for evaluating beam-column joint behavior in reinforced concrete frame systems when the primary objective is to understand global response trends rather than localized damage mechanisms. The results demonstrate that key parameters such as concrete compressive strength, axial load ratio, and joint shear reinforcement ratio exert a dominant influence on joint shear strength, stiffness, and deformation capacity. Simplified models were able to reproduce these effects with a high degree of statistical consistency, indicating that reduced modeling complexity does not necessarily compromise predictive capability for monotonic loading scenarios. The limited sensitivity of peak joint shear strength to mesh refinement further highlights the practicality of simplified FE approaches for parametric investigations, preliminary design checks, and academic research, where computational efficiency and clarity of interpretation are essential.

From a practical perspective, the findings suggest that designers and analysts can confidently use simplified FE models during early-stage structural assessment to identify vulnerable joints, compare retrofit options, or evaluate the relative benefits of increased joint shear reinforcement and axial confinement. Emphasis should be placed on providing adequate joint transverse reinforcement, as it consistently improves both strength and deformation capacity, thereby reducing the likelihood of brittle joint failure. Incorporating realistic axial load levels in analytical models is also crucial, as confinement effects significantly enhance joint performance. For engineering practice, simplified FE modeling can be integrated into performance-based design workflows as a screening and decision-support tool before resorting to more advanced and resource-intensive analyses. In retrofit applications, such models can guide the selection of strengthening strategies, such as joint jacketing or external confinement, by quickly estimating expected improvements in joint behavior. Overall, the research supports the broader adoption of simplified finite element techniques as practical, transparent, and computationally economical methods for informed structural decision-making in reinforced concrete frame systems.

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