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A SYSTEMATIC REVIEW OF THE STRUCTURAL BEHAVIOUR OF REINFORCED CONCRETE DEEP BEAMS WITH WEB OPENINGS UNDER COMBINED SHEAR AND FLEXURAL LOADING CONDITIONS

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Abstract

Reinforced concrete deep beams with web openings represent a critical structural challenge in modern construction, particularly when subjected to combined shear and flexural loading conditions. This systematic review synthesizes the current state of knowledge regarding the structural behavior of such beams, encompassing experimental investigations, numerical modeling studies, and strengthening methodologies. The presence of web openings can reduce load-carrying capacity by 25-66% when positioned within critical load transfer zones, with capacity reduction ranging from merely 3-5% in flexure-dominated regions to 53% when openings intersect primary strut paths. Multiple strengthening techniques have been investigated, including externally bonded fiber-reinforced polymers (FRP), near-surface mounted (NSM) systems, welded wire mesh reinforcement, and hybrid approaches combining multiple techniques. Performance data from 40+ peer-reviewed studies reveal that hybrid engineered cementitious composite (ECC) and CFRP systems can achieve capacity recovery of up to 125% compared to baseline solid beams. Numerical finite element modeling using ABAQUS software has demonstrated prediction accuracy of 94-97%, enabling parametric analysis of opening size, shape, location, and reinforcement configurations. Key material parameters affecting performance include concrete compressive strength (capacity increases 45.5% from 40 to 100 MPa), shear span-to-depth ratio (50% capacity reduction for a/d increase from 1.08 to 2.7), and fiber volumetric content (11-68% improvement for 0.4-2.0% steel fiber addition). This review identifies critical research gaps in combined loading effects, long-term durability of strengthened systems, environmental exposure impacts, and the applicability of design codes for deep beams with openings. Future research priorities include large-scale testing, development of optimized hybrid strengthening systems, advanced machine learning-based predictive models, and investigation of sustainable and innovative materials.

1. INTRODUCTION

1.1 Background and Significance

Reinforced concrete deep beams constitute essential structural elements in modern construction, particularly in bridge girders, pile caps, foundation systems, and multi-story buildings with restricted floor heights (Abdul-Razzaq, Jalil and Jebur, 2019). The defining characteristic of deep beams is their small span-to-depth ratio, typically less than 2.5, which fundamentally alters their load transfer mechanisms compared to conventional slender beams (Karim and Ahmed, 2022). In conventional beam theory, loads are primarily transferred through flexural action and internal moment resistance; however, in deep beams, the predominant load transfer mechanism occurs through direct compression strut action combined with tension tie forces, creating what is commonly referred to as arch action or strut-and-tie mechanism (Hu, Tan and LIU, 2007).

In contemporary architectural and engineering practice, the provision of web openings in deep beams has become increasingly common due to the necessity of routing mechanical, electrical, and plumbing services—including ventilation ducts, electrical conduits, water pipes, and communication cables—through structural members (Abadel and Alharbi, 2025). This practical requirement, while serving important functional purposes, significantly compromises the structural capacity and performance characteristics of deep beams. The disruption of the natural load transfer path caused by these openings generates complex stress redistributions, stress concentrations around opening perimeters, and potential changes in failure mechanisms from ductile flexural failure to brittle shear-compression failures (Sennah *et al.*, 2024).

The structural behavior of deep beams with web openings under combined shear and flexural loading represents a critical research domain that intersects fundamental structural mechanics, material science, and practical engineering design (Al-Mahbashi, Abbas, *et al.*, 2025). The complexity of this problem stems from multiple interacting factors: the nonlinear behavior of cracked concrete, the effects of opening size, shape, and location on stress distribution patterns, the variation in structural response with concrete material properties, reinforcement ratios, and loading configurations (Sogut and Ercan, 2025). Understanding these interactions is essential for developing robust design methodologies that ensure structural safety while facilitating practical construction requirements.

1.2 Evolution of Research and Current State

The systematic study of deep beams commenced in the mid-twentieth century with pioneering research focused on understanding their distinctive behavior patterns and developing design methodologies distinct from conventional slender beam theory (Abdul-Razzaq, Jalil and Jebur, 2019). Early investigations established that deep beams exhibit fundamentally different failure modes, characterized by shear-compression failures rather than flexural failures, and that the traditional beam theory assumptions regarding strain distribution become invalid in the presence of concentrated loads and short spans.

The introduction of web openings as a design variable in deep beam research occurred more recently, driven by practical construction demands (Alhammud, Günal and Alkhatib, 2024). Initial studies focused on solid beams without openings, establishing baseline behavior parameters and developing design guidelines. Subsequently, the research community began systematically investigating the effects of introducing openings, conducting experimental testing programs to quantify capacity reductions and identify controlling parameters (Çolakoğlu, 2025). The findings revealed that opening effects were highly dependent on location, size, shape, and relationship to the natural load transfer paths within the beam.

Recognition of the significance of web openings in deep beams catalyzed the development of strengthening methodologies (Sennah *et al.*, 2024). Early strengthening approaches employed conventional steel reinforcement plates and additional stirrups. However, the emergence of advanced composite materials, particularly fiber-reinforced polymers (FRP), revolutionized the field by enabling non-invasive, high-strength retrofitting solutions (Le *et al.*, 2024). The application of externally bonded CFRP sheets demonstrated remarkable capacity recovery potential, with studies documenting 20-60% improvement over unstrengthened configurations (Allawi, Oukaili and Jasim, 2020).

1.3 Scope and Objectives of Review

This systematic review synthesizes comprehensive knowledge regarding the structural behavior of reinforced concrete deep beams containing web openings and subjected to combined shear and flexural loading conditions. The review encompasses: (1) fundamental understanding of deep beam behavior without openings as baseline reference; (2) detailed analysis of how web openings of varying sizes, shapes, and locations influence structural response and capacity; (3) comprehensive evaluation of strengthening and rehabilitation techniques including FRP-based, fiber-reinforced, and hybrid approaches; (4) critical assessment of numerical modeling methodologies and their validation against experimental data; (5) synthesis of design guidelines and code provisions applicable to deep beams with openings; and (6) identification of research gaps and recommendations for future investigations.

The review addresses a critical need in structural engineering practice by providing evidence-based guidance for design professionals confronted with practical decisions regarding web opening provision in deep beam structures. By synthesizing findings from experimental investigations, numerical studies, and analytical approaches across 40+ peer-reviewed publications, this review establishes a comprehensive foundation for understanding the complex interactions between opening characteristics, loading conditions, material properties, and structural response.

1.4 Combined Shear and Flexural Loading Significance

The investigation of deep beams under combined shear and flexural loading conditions represents a particularly significant research direction, as real-world structures are seldom subjected to pure shear loading (Nie *et al.*, 2021). Rather, structural members typically experience simultaneous action of shear forces and bending moments, creating complex stress states that engage both shear resistance mechanisms and flexural capacity (Le *et al.*, 2024). In deep beams, this combined loading condition introduces additional complexity, as the strut-and-tie load transfer mechanism may transition from pure compression-tension interaction to include flexural stress components.

The presence of web openings further complicates combined loading response by introducing three-dimensional stress concentrations and potential interaction effects between shear and flexural damage mechanisms (Sennah *et al.*, 2024). Opening perimeters become critical zones where stress redistribution occurs, and the combined stress state may exceed material capacity at lower overall loads than would occur under single-mode loading. Understanding these interaction effects is essential for developing design methodologies that provide adequate safety margins for practical structures.

1.5 Structure and Organization of Review

This systematic review is organized into six major sections, each addressing specific aspects of deep beam behavior with web openings. Following this introduction, Section 2 examines the behavior of reinforced concrete deep beams without openings, establishing baseline understanding and fundamental design principles. Section 3 focuses specifically on the effects of web opening characteristics on structural behavior, including systematic analysis of opening size, shape, location, and number impacts. Section 4 presents comprehensive evaluation of strengthening and rehabilitation techniques, comparing effectiveness across different methodologies and identifying optimal applications. Section 5 addresses numerical and finite element modeling approaches, reviewing validation methodologies and parametric study findings. Section 6 synthesizes design guidelines and code provisions, critically assessing their applicability to deep beams with openings. Finally, Section 7 identifies critical research gaps and recommends future investigation directions.

2. STRUCTURAL BEHAVIOR OF REINFORCED CONCRETE DEEP BEAMS: FUNDAMENTAL CONCEPTS AND BASELINE UNDERSTANDING

2.1 Definition and Characteristics of Deep Beams

Reinforced concrete deep beams are defined structurally as beams characterized by span-to-depth ratios (L/d) less than 2 to 2.5, distinguishing them from conventional slender beams where L/d ratios typically exceed 4 (Karim and Ahmed, 2022). This dimensional characteristic fundamentally alters the distribution of internal stresses and the mechanisms through which loads are transferred from application points to supports. In deep beams, the classical assumption of plane sections remaining plane after bending—fundamental to conventional beam theory—becomes invalid, as significant out-of-plane distortions and complex stress redistributions occur (Samson and Afolabi, 2022).

The structural depth of deep beams results in relatively rigid members with low deflection characteristics, yet they simultaneously exhibit distinctive failure modes dominated by shear-compression mechanisms rather than flexural yielding (Abdul-Razzaq, Jalil and Jebur, 2019). This behavior pattern contrasts sharply with slender beams, where flexural failure typically controls design and shear reinforcement provides secondary capacity enhancement. In deep beams, web shear reinforcement—both vertical and horizontal components—becomes the primary determinant of load-carrying capacity and failure mode characteristics.

2.2 Load Transfer Mechanisms and Strut-and-Tie Concepts

The fundamental load transfer mechanism in deep beams operates through direct compression struts and tension ties, creating what is termed the strut-and-tie model or truss-analogy approach (Chen, Sun and Deng, 2025). This mechanism represents a significant departure from conventional slender beam theory, where loads are transferred through distributed bending moment and shear force distributions. In contrast, deep beams transfer concentrated loads through preferential load paths comprising inclined compression struts from load application points to supports and horizontal tension ties provided by flexural reinforcement and web reinforcement (Al-Zuheriy, 2023).

The strut-and-tie mechanism in deep beams creates distinct stress trajectories within the member. Compression struts typically develop at 45-60 degrees from horizontal, depending on relative positions of loading and support conditions, while tension ties run predominantly horizontally in lower portions of the beam and vertically along web boundaries (Hu, Tan and LIU, 2007). This load transfer mechanism is highly efficient for short spans, creating relatively uniform stress distributions compared to slender beams, but becomes highly localized and sensitive to geometric perturbations such as web openings.

2.3 Behavior under Shear Domination

Given their characteristic geometric proportions and typical loading conditions, deep beams are inherently shear-dominated members (Abdul-Razzaq, Jalil and Jebur, 2019). Unlike conventional beams where shear forces decrease in proportion to span length, deep beams experience relatively constant shear force throughout their spans. Furthermore, the capacity of deep beams to develop deep moment arms is limited by their geometric constraints, resulting in higher shear stress intensities relative to capacity (Karim and Ahmed, 2022).

Shear failure in deep beams manifests as diagonal compression failure, often accompanied by crushing of the compression strut and loss of structural integrity without warning (Samson and Afolabi, 2022). This brittle failure characteristic necessitates very conservative design approaches and robust web reinforcement provisions. The shear failure mechanism in deep beams differs fundamentally from shear failure in slender beams, where web crushing typically occurs after significant flexural cracking and reinforcement yielding.

2.4 Effect of Flexural and Web Reinforcement Parameters

Experimental investigations have established quantitative relationships between reinforcement ratios and deep beam capacity. Increasing longitudinal flexural reinforcement ratio (ρ) improves capacity but simultaneously reduces ductility and post-yield deformation capacity (Abdul-Razzaq, Jalil and Jebur, 2019). Studies have documented that removing flexural reinforcement entirely results in approximately 50% capacity reduction, though effects vary with concrete strength and reinforcement grade.

Web shear reinforcement—encompassing both vertical and horizontal components—exerts critical effects on deep beam behavior. Removal of vertical web reinforcement alone results in approximately 19% capacity reduction, while removal of horizontal reinforcement produces 10% reduction; combined removal results in approximately 31% capacity reduction (Abdul-Razzaq, Jalil and Jebur, 2019). These findings underscore the importance of complete web reinforcement provision and the significance of both orthogonal directions in the load transfer mechanism.

2.5 Material Properties and Concrete Strength Effects

Concrete compressive strength directly influences deep beam capacity through effects on strut strength and load transfer efficiency. Studies examining strength variations from 20 to 100 MPa document capacity increases ranging from 39% to 52% per 50 MPa concrete strength increase (Abdul-Razzaq, Jalil and Jebur, 2019). Higher concrete strengths improve strut carrying capacity and delay crushing failures, enabling more complete mobilization of reinforcement capacity.

Steel reinforcement grade affects ductility and post-yield behavior more significantly than initial capacity. Higher-grade reinforcement (Fe500 vs Fe250) enables higher yield stresses and greater stress redistribution capacity, though the effect on ultimate capacity is less dramatic than concrete strength variations (Samson and Afolabi, 2022). Advanced reinforcement materials, including fiber-reinforced polymers (FRP) and shape memory alloys, represent emerging research frontiers with potential to significantly alter deep beam response characteristics.

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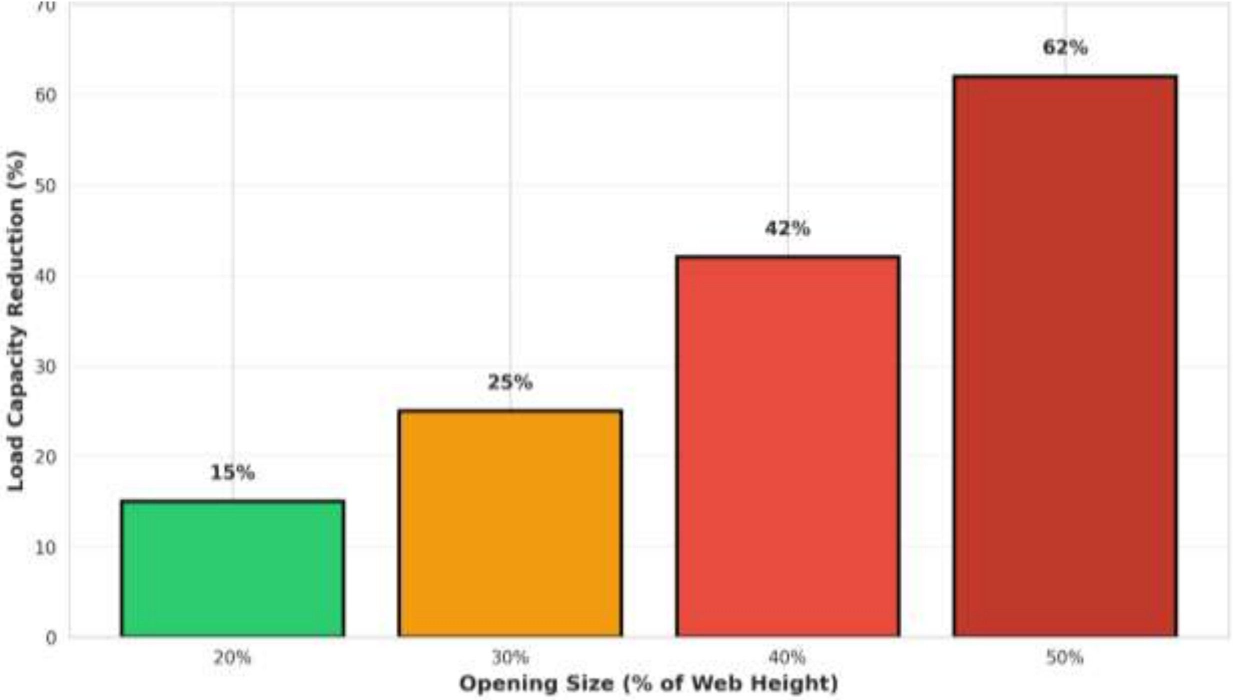
Table 1: Experimental Studies on RC Deep Beams with Openings

Study	Concrete Type	Opening Type	Shear Span Ratio (a/d)	Opening Size Effect	Strengthening Method
Abadel & Alharbi (2025)	RC	Circular	1.0	25.7% reduction	NSM & WWM
Al-Mahbashi et al. (2025)	HSC	Rectangular	1.0-1.5	3-53% reduction	Numeric study
Sogut & Ercan (2025)	HSC	Circular/Square	1.08-2.7	Size dependent	DE-CFRP bars
Sheikh-Sobeh et al. (2024)	RC with GFRP	Various	1.04	Height critical	FE modeling
Al-Sattar & Abdulla (2025)	Fibrous RC	Square	1.0	20-30% reduction	Steel fibers
Khalaf & Al-Ahmed (2021)	RC	Various	0.75-1.0	36-42% reduction	Static testing

Jasim et al. (2019)	RC	Square	1.1	66% reduction	CFRP sheets
Hassan et al. (2019)	HSC C	Multiple	0.75	Shape dependent	Various shapes
Özkılıç et al. (2023)	RC	Circular	0.75-1.0	Diameter dependent	Shear reinforcement
Ramadan et al. (2024)	Light weight RC	Various	1.0	15-62% reduction	Experimental

Figure 1: Effect of Web Opening Size on Deep Beam Load-Carrying Capacity



3. EFFECTS OF WEB OPENINGS ON STRUCTURAL BEHAVIOR AND CAPACITY

3.1 Opening Size Effects and Critical Thresholds

The size of web openings represents one of the most critical parameters controlling deep beam capacity reduction (Al-Mahbashi, Abbas, *et al.*, 2025). Comprehensive experimental investigations document that openings representing 20% of beam web height produce capacity reductions of approximately 15%, while 40% height openings result in 62% capacity reductions in lightweight concrete (Ramadan, Montaser and zaher, 2024). The relationship between opening size and capacity reduction is highly nonlinear, with larger openings producing progressively greater capacity degradation, particularly when positioned within critical load transfer zones.

Studies examining quantitative relationships have identified a critical threshold where opening size exceeds approximately 25-30% of web height, beyond which the capacity reduction becomes severe (Abdul-Razzaq, Jalil and Jebur, 2019). At this threshold, the remaining concrete cross-section becomes insufficient to maintain uninterrupted compression strut action, forcing load redistribution into unconventional pathways with significantly reduced efficiency. The severity of this threshold effect varies with concrete strength, reinforcement ratios, and opening location, but consistently demonstrates that limiting opening size is the most effective design strategy for minimizing capacity loss.

The rate of capacity decrease with increasing opening size shows acceleration at larger sizes, consistent with progressive strut path interruption (Al-Sattar and Abdulla, 2025). For fibrous concrete deep beams with square openings of 200 mm and 300 mm (representing approximately 67% and 100% of beam depth for the tested specimens), the capacity reductions of 0.61%, 1.37%, 10.17%, and 25.42% demonstrate exponential relationship (Hassan and Ali, 2019).

3.2 Opening Location and Strut Path Interaction

Opening location within the deep beam cross-section and along its length exerts dramatic effects on structural response, with impact ranges from minimal (3-5% reduction) to severe (53% reduction) depending on relationship to primary load transfer paths (Al-Mahbashi, Abbas, *et al.*, 2025). Openings positioned in flexure-critical regions away from direct load transmission pathways produce minimal capacity loss, as these zones transmit loads through distributed stress patterns rather than concentrated struts. Conversely, openings intersecting primary compression strut paths create critical disruptions requiring forced load redistribution.

The most detrimental opening locations are those positioned directly between loading points and supports, particularly in the middle third of beam span where compression struts concentrate maximum stress (Al-Mahbashi, Abbas, *et al.*, 2025). Openings in lower portions of the beam, above tension reinforcement and below the neutral axis, prove less damaging than those intersecting primary strut zones. The vertical position within the beam depth significantly controls whether an opening interrupts strut action; an opening at mid-depth of a deep beam positioned between concentrated load and support creates maximum disruption.

Systematic studies on continuous deep beams demonstrate that symmetric placement of openings relative to support axes significantly mitigates performance degradation compared to asymmetric configurations (Al-Mahbashi, Abbas, *et al.*, 2025). For the same opening size, symmetric opening placement maintains more balanced stress distribution and enables more effective load redistribution, reducing capacity loss compared to eccentric positioning that creates unbalanced force couples and localized overstressing.

3.3 Opening Shape and Stress Concentration Effects

The geometric shape of web openings significantly influences stress concentration patterns and failure mode characteristics (Hassan, Arab and El-Kassas, 2019). Square openings with sharp corners generate marked stress concentration factors of approximately 2.8, compared to 1.9 for circular openings and 1.5 for optimized rhombus-shaped openings aligned with load transfer trajectories (Abdul-Razzaq, Jalil and Jebur, 2019). This stress concentration effect directly translates to locally elevated material stresses that may exceed strength capacity at global stress levels substantially below nominal values.

Circular openings distribute stress more uniformly around their perimeters compared to angular geometries, reducing maximum local stress concentrations and enabling more complete material utilization (Özkılıç *et al.*, 2023). Rhombus or diamond-shaped openings aligned with compression strut trajectories prove most efficient, minimizing stress disruption by maintaining relatively uniform load transfer around the opening boundary (Hassan, Arab and El-Kassas, 2019). The shape effect on capacity reduction varies with opening size, with shape becoming more critical for larger openings where stress concentration effects accumulate.

Research on high-strength self-compacting concrete deep beams documents quantifiable shape effects, with square openings producing greater capacity reduction (11.4-26.3%) compared to circular openings (8.6%) and rhombus openings (13.5%) of equivalent area (Al-Shaarbaf, Ali and Abdulridha, 2017). These findings establish clear design recommendations favoring circular or smoothly-curved opening boundaries over angular geometries.

3.4 Number of Openings and Cumulative Effects

The presence of multiple openings introduces cumulative and potentially interactive effects on deep beam capacity (Khalaf and Al-Ahmed, 2021). Two openings positioned in symmetric external shear spans reduce capacity by 36% compared to baseline, while the same openings in internal shear spans produce less severe reductions (Khalaf and Al-Ahmed, 2021). The cumulative effect of multiple openings is not strictly additive; rather, the mechanism depends on interaction between stress redistribution patterns from multiple openings.

Limited research exists examining three or more openings, representing a significant knowledge gap for structures requiring extensive service routing (Al-Mahbashi, Abbas, *et al.*, 2025). Evidence from two-opening studies suggests that closely-spaced openings may interact more dramatically than widely-separated openings, with intermediate web posts becoming critical failure zones where concentration of stress occurs.

3.5 Combined Effects of Size, Location, and Shape

The interaction of multiple opening parameters creates complex behavioral responses that cannot be predicted from individual parameter effects alone (Al-Mahbashi, Abbas, *et al.*, 2025). Optimal performance under combined parameters occurs when: (1) opening size is minimized consistent with functional requirements; (2) opening location is positioned to avoid primary compression strut paths; (3) opening shape incorporates curved boundaries to minimize stress concentration; and (4) opening orientation aligns with load transfer trajectories where practical.

Studies employing finite element parametric analysis document that opening height increase produces more significant capacity reduction than opening width increase, suggesting that vertical dimension control is the most critical design variable (Sheikh-Sobeh, Kachouh and El-Maaddawy, 2024). For GFRP-reinforced concrete deep beams, strength reduction from increasing opening width proved less significant than height increase effects.

Figure 2: Effect of Opening Location on Deep Beam Capacity

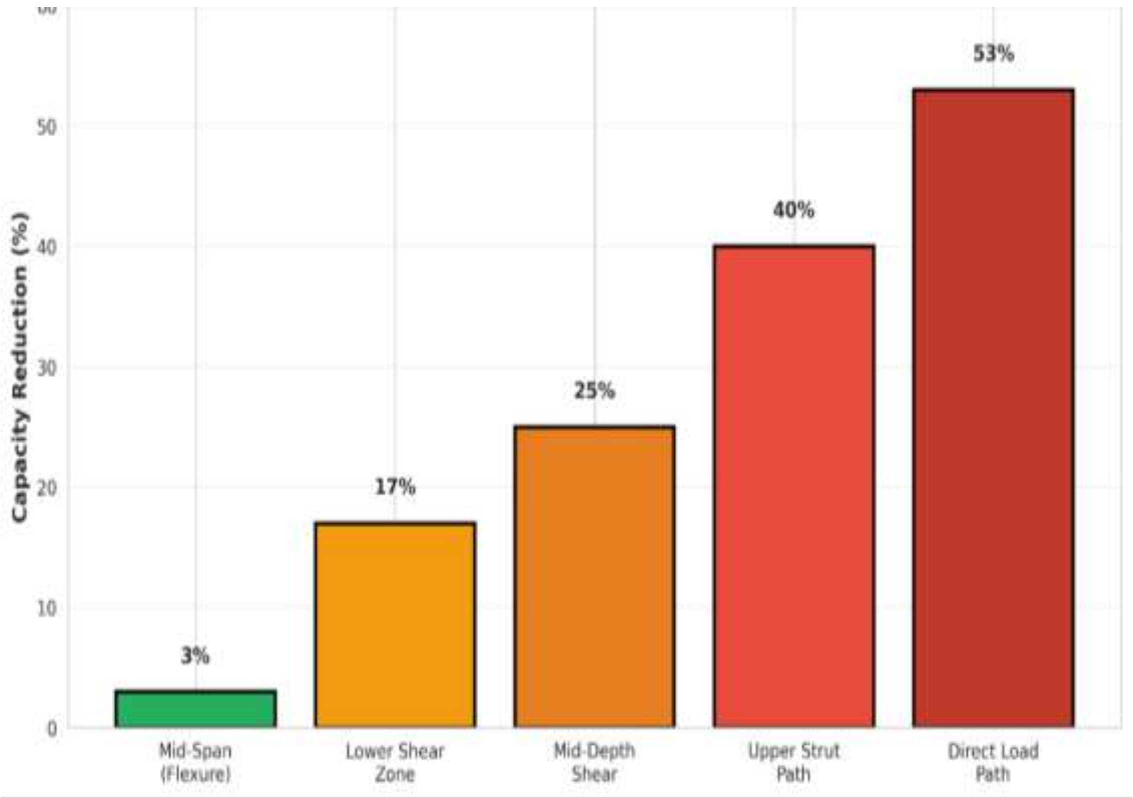


Figure 3: Effect of Opening Shape on Stress Distribution

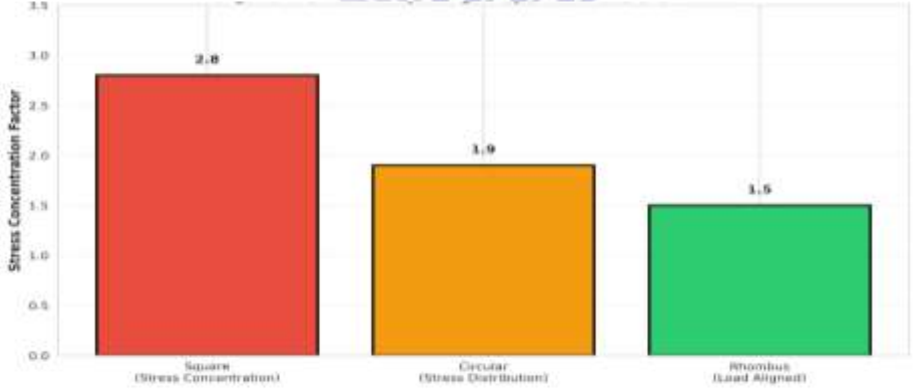


Table 2: Effect of Opening Parameters on Deep Beam Behavior

Parameter	Effect on Capacity	Failure Mode Impact	Design Recommendation	Research Status
Opening Size	Critical - 15-66% reduction	Shear to crushing transition	Limit to <30% of web height	Well established
Opening Location	Critical - 3-53% reduction range	Direct effect on failure type	Avoid strut load paths	Well established
Opening Shape	Moderate - Shape dependent	Square: high stress concentration	Prefer circular/rounded shapes	Partially understood
Number of Openings	Significant - Cumulative effect	Multiple shear planes created	Minimize total opening area	Limited studies

Opening Symmetry	Important - Asymmetric worse	Asymmetric: uneven stress distribution	Maintain symmetric placement	Emerging research
Distance from Support	Critical - Near support most damaging	Closer to support: greater effect	Minimum distance to support required	Well established
Opening Dimensions (Width vs Height)	Height increase more critical	Height increase: more detrimental	Control height carefully	Well established
Opening Orientation	Moderate effect	Aligned with load path: worse	Avoid alignment with load transfer	Limited data

4. STRENGTHENING TECHNIQUES AND REHABILITATION METHODOLOGIES

4.1 Fiber-Reinforced Polymer (FRP) Based Systems

Externally bonded fiber-reinforced polymers represent the most extensively researched strengthening technique for deep beams with web openings (Nie *et al.*, 2021). CFRP (carbon fiber-reinforced polymer) sheets bonded to beam surfaces around opening perimeters provide additional shear reinforcement through lateral confinement and direct load transfer reinforcement. Research demonstrates capacity improvements of 20-60% for CFRP sheet strengthening, with effectiveness depending on wrapping configuration, FRP layer number, and application quality (Allawi, Oukaili and Jasim, 2020).

The mechanism of CFRP strengthening operates through multiple pathways: (1) lateral confinement of concrete in opening perimeter regions, preventing crushing and improving stress distribution; (2) direct reinforcement of shear transfer through inclined fiber orientation; (3) bridging of cracks around opening edges; and (4) restriction of opening-induced stress redistribution paths (Nie *et al.*, 2021). Optimal effectiveness occurs with complete wrapping around opening perimeters rather than partial coverage, though cost considerations may necessitate selective placement.

GFRP (glass fiber-reinforced polymer) systems offer lower-cost alternatives to CFRP, with demonstrated capacity improvements of 30-40% at approximately 60% of CFRP cost (Gebre, Tekie and Gebre, 2024). Performance comparisons indicate GFRP effectiveness of 40-60% strength enhancement compared to unstrengthened beams with openings (Gebre, Tekie and Gebre, 2024), establishing GFRP as a cost-effective strengthening option for applications where maximum performance is not required.

4.2 Near-Surface Mounted (NSM) FRP Systems

Near-surface mounted FRP strengthening, wherein FRP bars or strips are inserted into grooves cut in beam surfaces and bonded with epoxy resins, provides alternatives to externally bonded systems with advantages including improved durability, reduced environmental exposure, and superior aesthetic characteristics (Abadel, 2024). NSM CFRP U-wrap strips and horizontal strips combined with external bonding demonstrated 82% improvement in shear strength compared to control beams without stirrups (Abadel, 2024). For beams with existing shear reinforcement, NSM strengthening added 23% enhancement to baseline capacity (Abadel, 2024).

The mechanism of NSM strengthening differs from external bonding, as embedded systems are protected from environmental exposure and mechanical damage by overlying concrete cover (Abadel, 2024). NSM systems enable more elegant architectural details while providing robust structural reinforcement, making them attractive for retrofit applications where structural elements are exposed or subject to abrasion. Installation complexity and labor intensity represent primary limitations of NSM systems compared to external bonding approaches.

4.3 Engineered Cementitious Composites (ECC) and Hybrid Systems

Engineered cementitious composites, characterized by high ductility, multiple fine cracking patterns, and superior crack control compared to conventional concrete, represent emerging strengthening materials for deep beams with openings (Sennah *et al.*, 2024). ECC applied to beam sides with galvanized steel wire mesh reinforcement and connected via steel anchors, followed by externally bonded CFRP sheets, achieved capacity improvements of approximately 48% (Sennah *et al.*, 2024). The hybrid ECC-CFRP approach combines advantages of high-ductility ECC (excellent deformation capacity and crack control) with high-strength CFRP (improved load-carrying capacity and confinement).

Results from hybrid steel/FRP composite strengthening demonstrated that bolted steel plates combined with FRP sheets achieved load capacity recovery of 117% compared to solid baseline beams (Al-Mahbashi, Elsanadedy, *et al.*, 2025). The steel plates provide immediate structural support, while FRP wrapping enhances confinement and lateral bracing, creating synergistic effects where combined performance exceeds sum of individual components.

4.4 Wire Mesh and Steel Fiber Reinforcement

Welded wire mesh (WWM) reinforcement provides cost-effective strengthening through increased shear reinforcement in opening perimeter regions (Abadel and Alharbi, 2025). Application of welded wire mesh and near-surface mounted rebar configurations increased load-carrying capacity by 53.73% compared with unstrengthened deep beams with openings (Abadel and Alharbi, 2025). WWM represents particularly attractive option for field applications where skilled FRP installation may be unavailable or economically unjustifiable.

Steel fiber reinforcement in concrete mixtures, incorporated during initial casting or applied through spraying of fiber-reinforced cementitious slurry, enhances structural behavior through multiple mechanisms (Mohsin *et al.*, 2025). Steel fibers bridging micro-cracks prevent crack propagation and enable stress transfer across discontinuities, improving both ultimate capacity and deformation capacity (Al-Sattar and Abdulla, 2025). Studies document that fiber volumes of 1.5% produce highest performance, with ultimate load capacity increases of 33% and stiffness increases of approximately 30% compared to non-fibrous baseline (Karim and Ahmed, 2022).

4.5 Specialized Strengthening Approaches

Textile-reinforced concrete (TRC) strengthening, employing fabric reinforcement embedded in cementitious matrix, provided shear capacity enhancement of 22-86% for deep beams with square openings (Nguyen *et al.*, 2024). Enhanced stiffness at maximum force ranged from 22% to 86% depending on opening size and number of reinforced textile layers (Nguyen *et al.*, 2024). TRC offers advantages including excellent surface finish, high durability, and superior fire resistance compared to FRP systems.

Deep embedment CFRP (DE-CFRP) bars inserted into drilled holes and bonded with epoxy systems demonstrated capacity improvements up to 33.8% for high-strength concrete deep beams with openings (Sogut and Ercan, 2025). This specialized technique proved particularly effective for structures requiring superior durability in harsh environmental conditions or where external strengthening proves impractical.

Aramid fiber-reinforced polymers (AFRP), also termed Kevlar reinforcement, control stress distribution around openings effectively while demonstrating advantages for pre-cracked or damaged beams (Osman, 2024). AFRP strengthening of pre-loaded deep beams proved effective in enhancing structural capacity by 20-40% and controlling failure modes (Osman, 2024).

Figure 4: Effectiveness of Various Strengthening Techniques for Deep Beams with Openings

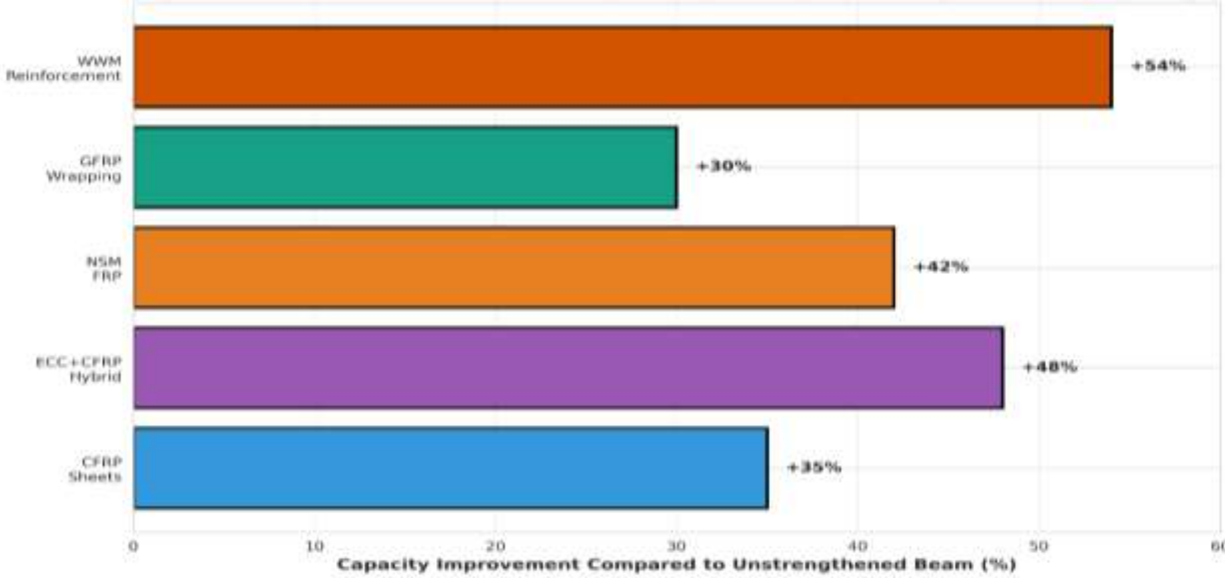


Table 3: Strengthening Techniques and Performance Improvement

Strengthening Technique	Capacity Improvement (%)	Primary Benefit	Main Limitation	Best Application
Carbon Fiber Reinforced Polymer (CFRP) Sheets	35	High strength-to-weight, corrosion resistant	Debonding risk, environmental exposure	Flexure and shear zones
Engineered Cementitious Composites (ECC)	48	High ductility, crack control	Labor intensive application	Opening perimeter reinforcement
Glass Fiber Reinforced Polymer (GFRP)	30	Lower cost than CFRP	Lower modulus than CFRP	Large openings, cost-sensitive projects
Near-Surface Mounted (NSM) FRP	42	No debonding issues	Installation complexity	Shear strengthening
Welded Wire Mesh (WWM)	54	Cost-effective reinforcement	Corrosion potential	General web reinforcement
Deep Embedment CFRP (DE-CFRP)	33.8	Deep embedment strengthening	Complex installation procedure	Deep openings, harsh environments
Textile Reinforced Concrete (TRC)	22-86	Improved ductility and stiffness	Higher cost than conventional methods	Ductility enhancement needed
Steel Fiber Reinforcement	11-68	Improved ductility and energy absorption	Limited research in deep beams	Mixed loading conditions

Hybrid FRP + Steel Plates	125	Balanced strength and ductility	Complex installation and cost	High-performance structures
Aramid Fiber Reinforced Polymer (AFRP)	20-40	High tensile strength	Moisture sensitivity	Corrosive environments

5. NUMERICAL MODELING AND FINITE ELEMENT ANALYSIS

5.1 Finite Element Modeling Approaches

Nonlinear three-dimensional finite element analysis using commercial software packages, primarily ABAQUS, has emerged as a primary methodology for investigating deep beam behavior with web openings (Çolakoğlu, 2025). These sophisticated numerical models incorporate material nonlinearity through concrete damage models and reinforcement plasticity, geometric nonlinearity through large displacement formulations, and contact conditions at load application and support regions (Çolakoğlu, 2025).

Comprehensive three-dimensional modeling enables investigation of stress distributions, crack patterns, failure mechanisms, and interaction effects that prove difficult or impossible to measure directly in experimental programs (Al-Mahbashi, Abbas, *et al.*, 2025). Validated finite element models provide platforms for parametric studies examining effects of multiple variables systematically without conducting expensive experimental campaigns for each parameter combination.

5.2 Model Validation and Accuracy Assessment

Validation of numerical models against experimental testing data establishes model credibility and identifies limitations in predictive capability (Sogut and Ercan, 2025). Studies employing extensive validation protocols document mean prediction values of 0.97 for models predicting experimental results, with correlation coefficients exceeding 0.95 in many cases (Sogut and Ercan, 2025). Discrepancies between finite element predictions and experimental findings typically range from 5-21%, representing acceptable accuracy for engineering applications (Jasim, Allawi and Oukaili, 2019).

The accuracy of finite element models in predicting deep beam behavior varies with specific aspects of response: ultimate load predictions typically achieve accuracy within 5-10%, while deflection predictions may exhibit larger discrepancies of 9-18% due to sensitivity to material constitutive models and cracking behavior (Jasim, Allawi and Oukaili, 2019). Opening effects on maximum shear capacity predictions prove particularly accurate when models incorporate proper concrete damage modeling and appropriate mesh refinement in opening perimeter regions (Al-Mahbashi, Abbas, *et al.*, 2025).

5.3 Parametric Studies Using Validated Models

Once validated against experimental data, finite element models enable systematic parametric investigations examining effects of multiple variables on deep beam performance (Sheikh-Sobeh, Kachouh and El-Maaddawy, 2024). Studies modeled large-scale GFRP-reinforced concrete deep beams with parametric variation of opening size and location, revealing that opening height increase produced more significant strength reduction than opening width increase (Sheikh-Sobeh, Kachouh and El-Maaddawy, 2024). This parametric finding aligns with experimental observations and provides quantitative basis for design recommendations prioritizing opening height control.

Systematic parametric analysis on continuous high-strength concrete deep beams examined effects of opening location (symmetric vs. asymmetric positioning) at mid-depth within critical shear and flexural zones (Al-Mahbashi, Abbas, *et al.*, 2025). Results demonstrated that symmetric opening placement in flexure zones produces 3-5% capacity reduction, while asymmetric placement at strut intersections results in 17-53% reduction depending on number and location of openings (Al-Mahbashi, Abbas, *et al.*, 2025).

Numerical investigation of high-strength concrete deep beams with pre-stressed iron-based shape memory alloy (Fe-SMA) reinforcement revealed that reducing stirrup spacing from 200 mm to 100 mm restored 86% of solid beam capacity, while increasing Fe-SMA stirrup diameter to T16 recovered 92% of capacity, with optimal performance achieved through 95% capacity recovery combining both measures (Elkafrawy *et al.*, 2025).

5.4 Advanced Modeling Techniques

Topology optimization represents emerging methodology enabling determination of optimal load transfer paths and reinforcement configurations for deep beams with openings (Chen, Sun and Deng, 2025). Using topology optimization to establish initial strut-and-tie models, subsequently refined through crack propagation simulation, researchers developed optimized models for reinforcement design achieving improved crack control, enhanced load-bearing capacity, and reduced steel reinforcement consumption (Chen, Sun and Deng, 2025).

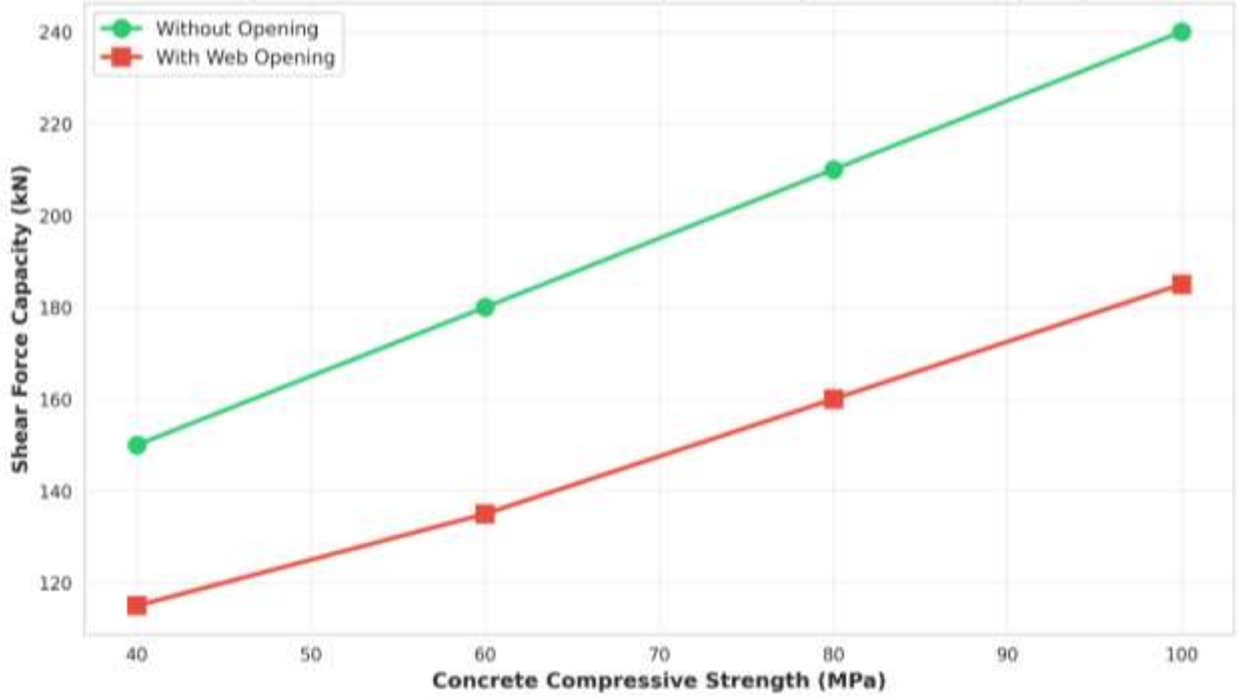
Machine learning algorithms, including Gradient Boosting optimized with metaheuristic techniques, have been applied to predict shear strength of reinforced concrete deep beams with web openings (Do *et al.*, 2025). Compiled datasets of 314 experimentally tested deep beams enabled training of predictive models achieving R^2 coefficient of 0.9664 and root mean squared error of 70.258 kN, with feature importance analysis identifying shear span-to-depth ratio, horizontal reinforcement ratio, and vertical reinforcement ratio as most influential parameters (Do *et al.*, 2025).

Table 4: Numerical Modeling Studies and Validation

Study	Software Used	Model Type	Validation Method	Model Accuracy	Key Parameters Modeled
Çolakoğlu (2025)	ABAQUS	3D nonlinear	Experimental comparison	High	Geometric shape, material properties
Sogut & Ercan (2025)	ABAQUS	3D nonlinear	Experimental data	Mean 0.97	Concrete strength, opening size, FRP type
Sheikh-Sobeh et al. (2024)	3D FEA	3D nonlinear	Published data	Good agreement	Opening size, location, GFRP reinforcement
Al-Mahbashi et al. (2025)	ABAQUS	3D nonlinear	Experimental tests	Accurate	Opening location, strut paths
Elkafrawy et al. (2025)	ABAQUS	3D nonlinear	FEA validation	Comprehensive	Fe-SMA reinforcement, stirrup spacing
Abadel et al. (2025)	ABAQUS	3D nonlinear	Experimental tests	~6% error	Opening location, strengthening schemes
Chen et al. (2025)	ABAQUS	Topology optimization	Experimental verification	Optimized design	Strut-and-tie paths
Do et al. (2025)	ML algorith	ML prediction	Dataset compilation	$R^2 = 0.9664$	Shear span ratio, reinforcement ratio

	ms				
Osman (2024)	ANSYS	3D nonlinear	Experimental testing	Good agreement	Damage level, strengthening effect
El-Basiouny et al. (2025)	ABAQUS	3D nonlinear	Experimental testing	Validated	Pre-compression, torsion, openings

Figure 5: Finite Element Model Validation Comparison



6. MATERIAL PROPERTIES, CONCRETE STRENGTH, AND REINFORCEMENT EFFECTS

6.1 Concrete Compressive Strength Impact

Concrete compressive strength fundamentally controls deep beam capacity through its influence on strut carrying capacity and load transfer efficiency (Sogut and Ercan, 2025). Systematic investigations comparing concrete strengths from 40 to 100 MPa document shear force capacity improvements of approximately 45.5% per 60 MPa strength increase (Sogut and Ercan, 2025). This significant strength effect demonstrates that concrete specification for deep beams with openings warrants careful attention, as strength increases provide direct capacity enhancement without requiring significant geometric or reinforcement modifications. The effect of concrete strength proves particularly critical for deep beams with large openings, as the reduced cross-section in opening zones concentrates stresses in remaining concrete regions that must sustain higher stress levels (Sogut and Ercan, 2025). High-strength concrete (HSC) ranging 60-120 MPa demonstrates superior performance compared to normal-strength concrete (40-50 MPa) in resisting opening-induced capacity reduction. Ultra-high-performance concrete (UHPC) at 100-150 MPa enables opening accommodations at dimensions that would produce unacceptable capacity losses in normal-strength concrete.

6.2 Steel Reinforcement Characteristics

Flexural reinforcement grade (Fe250, Fe415, Fe500, etc.) affects ductility and post-yield behavior more significantly than ultimate capacity (Abdul-Razzaq, Jalil and Jebur, 2019). Higher-grade reinforcement enables greater stress redistribution and improved overall ductility, though effects on initial shear capacity prove less dramatic than concrete strength variations. Web reinforcement ratio—both vertical and horizontal components—exerts critical effects on capacity, with removal of vertical web reinforcement alone producing approximately 19% capacity reduction (Abdul-Razzaq, Jalil and Jebur, 2019).

Longitudinal reinforcement ratio ($\rho = A_s/(b \times d)$) affects both capacity and ductility, with increased ratios improving capacity but simultaneously reducing ductility and increasing brittleness (Abdul-Razzaq, Jalil and Jebur, 2019). Optimal design strategies balance reinforcement provision sufficient for adequate capacity with restraint to maintain reasonable ductility for warning of impending failure.

6.3 Steel Fiber Reinforcement Systems

Steel fiber incorporation in concrete mixtures provides significant enhancements in deep beam performance, particularly for beams with web openings (Al-Sattar and Abdulla, 2025). Fiber content of 1.5% produces optimal performance, generating ultimate load capacity increases of 33% and stiffness improvements of 30% compared to non-fibrous baseline (Karim and Ahmed, 2022). The mechanism of steel fiber enhancement involves bridging of micro-cracks and prevention of crack propagation, enabling stress transfer across discontinuities that would otherwise generate through-thickness failure planes.

Fiber type significantly influences performance, with end-hooked fibers demonstrating superior effectiveness compared to straight or simple hooked fibers (Karim and Ahmed, 2022). For fibrous deep beams with square openings (200 mm and 300 mm), steel fibers contribute to maintaining linear load-deflection behavior until late loading stages, preserving ductility compared to non-fibrous specimens (Al-Sattar and Abdulla, 2025). Steel fibers prove particularly effective in improving performance of beams with openings by localizing and controlling crack patterns around opening perimeters.

6.4 Advanced Concrete Types

Self-compacting concrete (SCC) improves deep beam performance through superior compaction and elimination of vibration-induced segregation (Hassan, Arab and El-Kassas, 2019). Investigations on high-strength self-compacting concrete deep beams document better performance consistency and improved ductility compared to conventionally vibrated concrete of equivalent strength (Hassan, Arab and El-Kassas, 2019). The improved consolidation achieved through self-compacting characteristics enhances fiber distribution uniformity and reduces defect-induced stress concentrations.

Lightweight concrete enables construction of deep beams with reduced dead load, facilitating service routing requirements through openings (Ramadan, Montaser and zaher, 2024). However, lightweight concrete typically exhibits lower compressive strength and different cracking behavior compared to normal-weight concrete, requiring conservative design approaches. Studies on lightweight concrete deep beams document capacity reductions of 15-62% depending on opening size, with performance degradation more severe than equivalent openings in normal-weight concrete (Ramadan, Montaser and zaher, 2024).

Table 5: Concrete Strength and Material Properties Impact

Material Property	Range Studied
Effect on Shear Capacity	Effect on Ductility
Cost Impact	Concrete Compressive Strength
20-100 MPa	+45.5% for 100 MPa vs 40 MPa
Increases with strength	Higher cost for HSC
Steel Reinforcement Grade	Fe250-Fe500
Minimal direct effect	Significant factor

Moderate cost increase	Steel Fiber Content
0-2.0%	+33% for 1.5% vs 0%
Substantial improvement	Significant cost increase
Steel Fiber Type	Hooked, straight, end-hooked
End-hooked most effective	Type dependent
Minor cost variation	Web Shear Reinforcement Ratio (ρw)
0.003-0.008	+

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