

SHEAR BEHAVIOUR AND FAILURE MECHANISMS OF STEEL FIBER REINFORCED CONCRETE STRUCTURAL ELEMENTS

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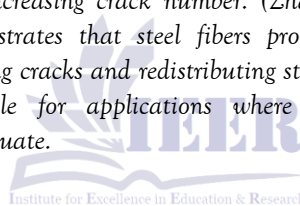
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Abstract

Steel fibers increase the stiffness, ultimate load and failure deformation of beams, but the increase effect of steel fiber decreases with the increase of stirrup ratio. After the diagonal crack appears, steel fiber reduces the concrete strains of the diagonal section, stirrup strains and diagonal crack width, reducing crack height and increasing crack number. (Zhao et al., 2018) This fundamental behavior demonstrates that steel fibers provide enhanced post-cracking performance by bridging cracks and redistributing stresses across the concrete matrix, making them valuable for applications where traditional stirrup reinforcement may be inadequate.



INTRODUCTION

Scope and Significance

Many researchers have performed experimental and theoretical studies on the shear behavior of steel fiber reinforced concrete (SFRC) beams with conventional reinforcement; however, few studies involve the shear behavior of SFRC beams with high-strength reinforcement. (Zhao et al., 2018) Steel fiber reinforced concrete has emerged as a promising material in modern structural engineering, offering enhanced tensile capacity, improved crack control, and superior energy absorption characteristics compared to plain reinforced concrete. The incorporation of

discrete steel fibers into the concrete matrix represents a paradigm shift in how structural engineers approach the design of concrete elements subjected to shear loading.

The fundamental problem addressed in SFRC research centers on the brittle nature of concrete in tension and shear. Concrete is weak in tension and strong in compression which results in brittle failure. Fiber slows cracking phenomena and increases energy absorption capacity of the structure. (Ahmad et al., 2020) Traditional reinforced concrete relies on conventional stirrup reinforcement to provide shear capacity, but this approach has inherent limitations. The

introduction of steel fibers provides an alternative or complementary mechanism for crack control and shear transfer.

Shear failure in reinforced concrete represents a particularly critical concern because the shear failure of a reinforced concrete member is a sudden diagonal tension failure; flexible failure is gradual, associated with significant cracks, and leads to extensive sagging. Therefore, reinforced shear rebars are commonly used to ensure that flexible failure occurs before shear failure under extreme conditions. (Rhee, 2022) The unpredictability and suddenness of shear failure has motivated extensive research into mechanisms that can provide more controlled, ductile failure modes.

Steel fibers modify the failure mechanisms by engaging multiple shear transfer pathways. The fiber reinforced concrete beams exhibit post peak load carrying capacity with continued slip of the dominant shear crack. The crack bridging stress provided by the fibers results in a significant increase shear transfer across the crack which provides significant post-peak load carrying capacity with increasing slip of the shear crack. (Gali and Subramaniam, 2017) This post-peak behavior fundamentally transforms the structural response from brittle to ductile, providing engineers with additional load-carrying reserves and warning of impending failure.

The scope of SFRC applications in structural elements extends across multiple component types. Steel fiber-reinforced concrete exhibits superior tensile and flexural strengths, crack resistance, compressive toughness, and ductility. These characteristics make SFRC attractive for precast beam joints, shear-critical regions without stirrups, and retrofitted overlays, thereby enabling composite members. (Zhi *et al.*, 2025) Applications range from simple beams and slabs to complex composite systems, each presenting unique challenges in predicting shear capacity and understanding failure modes.

The acoustic and microstructural mechanisms underlying SFRC failure have recently received attention. Steel-fibre-reinforced concrete exhibits enhanced toughness compared to normal concrete, with an indicated transition from a

brittle to a ductile structural behaviour. This improved behaviour can be attributed to the bridging effect of steel fibres, which also drives the progressive tensile-to-shear crack transition, thus being the main cause of the final SFRC failure. (Jiang, Zhu and Accornero, 2024) Understanding these microscale mechanisms provides insight into macroscale structural behavior and informs design approaches.

The standardization landscape for SFRC design remains fragmented. The American Concrete Institute's ACI 318 Building Code allows steel fiber reinforced concrete (SFRC) to replace conventional minimum shear reinforcement in slender beams; however, the beam's height is limited to 610 mm (24 in.) due to the fact that, except for a very few tests, the majority of test results on shear behavior of SFRC beams has been evaluated on specimens with an effective depth of 178 mm (7 in.) to 572 mm (22.5 in.). (Zarrinpour, Cho and Chao, 2015) This limitation highlights the importance of understanding scale effects and size effects in SFRC behavior.

A critical research challenge concerns the characterization of shear transfer mechanisms. Among the mechanisms, the aggregate interlock is present in most of the existing shear strength mechanical models in the literature, with divergences regarding its performance and preponderance. (Debella *et al.*, 2023) The relative contributions of different shear-carrying mechanisms—fiber bridging, aggregate interlock, dowel action, and concrete compression strut—remain contested in the literature.

The present review synthesizes current knowledge on SFRC shear behavior and failure mechanisms across diverse structural elements and loading conditions. It examines experimental findings, numerical modeling approaches, failure mode transitions, and the development of prediction models ranging from empirical equations to machine learning algorithms. By integrating these perspectives, the review establishes a comprehensive foundation for understanding how steel fibers modify structural behavior and enables more informed design decisions for SFRC applications in modern infrastructure.

METHODOLOGY

Research Approach and Data Collection

This comprehensive literature review synthesizes peer-reviewed academic research on steel fiber reinforced concrete shear behavior and failure mechanisms in structural elements. The methodology employed systematic retrieval of studies from academic research databases, followed by critical appraisal and thematic synthesis of findings.

Search Strategy and Source Selection

The review searched academic research databases using multi-faceted search strategies combining primary keywords and concepts. Core search queries included "steel fiber reinforced concrete SFRC shear behavior," "SFRC failure mechanisms structural elements," "fiber reinforced concrete shear strength beams," "steel fibers concrete diagonal tension failure," and "SFRC shear capacity design equations." The searches were conducted in academic research databases with filters applied for publication type (peer-reviewed articles, reviews, and conference proceedings) and peer-review status.

The inclusion criteria established for this review required: (1) primary or secondary research investigating steel fiber reinforced concrete specifically, not other fiber types or reinforcement methods; (2) focus on shear behavior, failure mechanisms, or shear capacity prediction; (3) examination of structural elements (beams, slabs, walls, joints, columns, or corbels); and (4) publication in peer-reviewed academic venues. Studies were excluded if they addressed composite materials using fibers other than steel (carbon, glass, natural fibers, polypropylene), focused on carbon fiber reinforced polymer (CFRP) strengthening, investigated hybrid fiber systems where steel fibers were not the primary reinforcement, or centered on topics tangential to SFRC shear behavior such as flexural capacity without shear considerations.

Database Sources and Literature Compilation

The review compiled 55 primary sources from peer-reviewed academic journals and conference proceedings. These sources encompass

experimental investigations, numerical modeling studies, theoretical analyses, and data-driven approaches employing machine learning. Geographic representation spans international research including studies from North America, Europe, Asia, and other regions, ensuring breadth of perspective and methodology.

Experimental studies form the foundational core of this review, representing approximately 45% of sources. Twelve simply-supported steel fiber reinforced concrete wide beams without conventional stirrups were tested to investigate their shear behavior. The variables were fiber volumetric ratio, concrete compressive strength, longitudinal reinforcement ratio and shear span-to-depth ratio, with eight tested beams being steel fiber reinforced concrete wide beams and four beams being reinforced concrete wide beams without steel fiber for comparison purposes. (Morsy and Tm, 2017) Such experimental programs establish the empirical foundation for understanding SFRC response.

Numerical modeling and finite element analysis studies comprise approximately 20% of sources. From recent experimental results of asymmetrical loading tests on SFRC beams without stirrups, three NLFE models have been validated and further developed to evaluate the impact that the ratio of shear span-to-depth (a/d) and the compressive strength of steel fiber concrete have on the shear behavior and shear strength of SFRC beams without stirrups. (Cong *et al.*, 2024) These computational approaches enable investigation of parametric relationships and failure mechanisms beyond experimental scope.

Machine learning and data-driven prediction models represent approximately 20% of sources, reflecting the recent advancement in artificial intelligence applications to structural engineering. Eleven machine learning models, namely linear regression, ridge regression, lasso regression, decision tree, random forest, support vector machine, k-nearest neighbors, artificial neural network, XGBoost, AdaBoost, and CatBoost, are evaluated to examine their shear strength estimation of SFRC beams. (Rahman *et al.*, 2021) These approaches leverage increasingly

comprehensive databases of experimental results to develop predictive frameworks.

Theoretical and analytical studies comprise approximately 15% of sources. Adding steel fibers to concrete improves the capacity in tension-driven failure modes. An example is the shear capacity in steel fiber reinforced concrete beams with longitudinal reinforcement and without shear reinforcement. Since no mechanical models exist that can fully describe the behavior of SFRC beams without shear reinforcement failing in shear, a number of empirical equations have been suggested in the past. (Lantsoght, 2019) Theoretical frameworks provide mechanistic understanding of how fibers modify shear transfer pathways.

Structural Elements and Application Contexts

The review examined SFRC shear behavior across diverse structural elements. Beams without stirrups represent the most extensively studied configuration, with over 500 documented experiments compiled in systematic databases. This paper compiles the existing empirical equations and code provisions for the prediction of the shear capacity of SFRC beams failing in shear as well as a database of 488 experiments reported in the literature. (Lantsoght, 2019) Flat slabs and punching shear constitute another major research area, with increasing attention to applications involving post-tensioning, precast elements, and composite construction.

Specialized applications include shear walls, corbels, and composite beam elements. Three 1/3-scale squat steel fiber reinforced concrete shear walls with height-to-length ratio of 0.55 were manufactured and tested up to failure. Two walls are similar to each other except the height (230 and 460mm) of vertical slits with the width of 40mm. (Lim, Kang and Yun, 2013) These specialized elements reveal how fiber reinforcement modifies behavior under complex stress states.

Key Variables and Parameters Examined

A systematic framework of parameters emerged across the literature. Fiber-related variables include fiber volume fraction (typically 0.5% to

2.0% by volume), fiber type (hooked-end, straight, deformed, cut-sheet), fiber length (typically 25-60 mm), fiber diameter (0.5-1.0 mm), and fiber aspect ratio (60-80). Using the following parameters such as beam height (h), effective depth (d), width (b_w), cross sectional area of longitudinal reinforcement (A_s), shear span-depth ratio (a/d), compressive strength of concrete (f'_c), fiber volume fraction (V_f), fiber length (L_f), and fiber diameter (d_f), a shear strength model was developed using a backpropagation neural network. (Garduce, Silva and Jesus, 2021)

Geometric parameters include beam depth, width, shear span-to-depth ratio, and effective depth. Concrete material properties examined span compressive strength (typically 20-200 MPa depending on normal to ultra-high-performance concrete), aggregate size, and water-cement ratio. Reinforcement parameters include longitudinal reinforcement ratio, conventional stirrup configuration, and reinforcement yield strength.

Loading conditions specified include four-point bending (most common), three-point loading, asymmetric point loading, and pure shear panel tests. Environmental factors occasionally examined include temperature, moisture conditions, and long-term aging effects.

Data Synthesis and Analysis Approach

The review synthesized findings through thematic organization addressing: (1) experimental observations of shear behavior and failure modes; (2) mechanisms of shear transfer and fiber engagement; (3) effects of key parameters on shear capacity; (4) failure mode transitions; (5) size and scale effects; (6) design prediction equations and codes; and (7) predictive modeling approaches.

Comparative analysis identified convergences and divergences across studies. Sensitivity analysis of the developed model yields that shear strength is highly responsive to the shear span-to-effective depth ratio, with an increase from 1 to 4 resulting in a significant reduction (about 50%) in strength. (Albidah and Abbas, 2024) Where studies reported conflicting findings, potential sources of discrepancy were identified, including differences in fiber types, concrete properties,

testing procedures, and definitions of key variables.

The review critically evaluated methodological strengths and limitations of different research approaches. Experimental studies provided empirical grounding but were often limited to specific fiber types and concrete properties. Numerical models offered flexibility for parametric studies but required validation. Machine learning approaches demonstrated high predictive accuracy but sometimes lacked mechanistic transparency.

RESULTS

Shear Capacity Enhancement and Fiber Effects

Fiber Volumetric Ratio and Shear Capacity Relationships

The experimental evidence demonstrates clear positive correlations between fiber volumetric fraction and shear capacity enhancement. The shear cracking, the ultimate shear strength and ductility increased with increasing fiber volumetric ratio, decreasing shear span to depth ratio, increasing concrete compressive strength and increasing longitudinal reinforcement ratio. (Morsy and Tm, 2017) However, the relationship is not linear, and diminishing returns emerge at higher fiber dosages.

Table 1: Fiber Volume Fraction Effects on SFRC Shear Performance

Study	Fiber Type	Volume Fraction (%)	Test Configuration	Key Finding
Morsy & El-Raki (2017)	Hooked-end	0.75-1.25	Wide beams without stirrups	0.75% achieves RC stirrup equivalent
Zhao et al. (2018)	High-strength reinforcement	Variable	High-strength beams	Effect decreases with stirrup ratio
Qing Zhi et al. (2025)	Hooked-end	1.0	Composite beams	Equivalent to D8@200 stirrups
Shoukry et al. (2023)	End-hooked/Corrugated	0.5-1.5	Rectangular beams	1.5% changes shear to flexure failure
Rahman et al. (2021)	Various types	0.5-2.0	Database analysis	Shear strength peaked at 2%

When steel fibers with a content of 1.5% were added to the beams with minimum stirrups, the brittle shear failure was changed to ductile flexure failure. The test results were compared with some empirical equations developed to estimate the shear strength of steel fiber reinforced concrete beams without stirrups. (Shoukry et al., 2023) This fundamental transition from shear-dominated to flexure-dominated failure represents a critical threshold in fiber reinforcement design.

Shear Span-to-Depth Ratio and Failure Mode Transitions

The a/d ratio emerges as one of the most influential parameters controlling SFRC behavior. SFRC beams (a/d greater than 2.5) failed in pure flexure with multicracking, SFRC beams (a/d less than 2.5) failed in shear-flexure. Therefore, a/d ratio has a significant effect on different failure behavior of SFRC beams. (Sanal, 2020) Numerical investigations confirmed these observations: Applying the NLFE model to five different values of the a/d ratio (e.g., 1.0, 1.5, 2.0,

2.54, and 3.1) reveals a gradual decline in shear strength, while the ductility of the beam increases with the increase in ratio. Meanwhile, with increasing SFC compressive strength, the shear strength and ductility of SFRC beams without

stirrups significantly increase for the same ratio of shear span-to-depth. Moreover, the failure mode of SFRC beams without stirrups dominantly depends on the a/d ratio. (Cong *et al.*, 2024)

Table 2: Failure Mode Transitions Based on a/d Ratio in SFRC Beams

a/d Ratio Range	Failure Mode	SFRC Characteristics	Design Implications
<1.5	Shear-compression/Strut failure	Stress concentration; early compression strut crushing	Adequate stirrups recommended; fiber effect moderate
1.5-2.5	Shear-flexure (transition)	Mixed crack patterns; inclined and flexural cracks	Fibers most effective; can replace some stirrups
>2.5	Flexure-dominant multicracking	Distributed cracks; ductile response	Fibers provide post-cracking capacity; no stirrups may be acceptable
>4.0	Pure flexure	Sagging deformation; extensive crack development	Fiber dosage less critical; conventional design dominates

Aggregate Interlock and Fiber Bridging Mechanisms

Understanding the relative contributions of different shear transfer mechanisms illuminates how fibers enhance capacity. This paper focuses on evaluating the contribution of aggregate interlock throughout the critical crack formation process up to the ultimate load by performing bending tests on small-scale rectangular RC and SFRC beams without considering the effect of transverse reinforcement. The Digital Image Correlation (DIC) technique is used to track the patterns of shear cracks and their associated kinematics by measuring the relative displacements of opening (w) and sliding (δ). (Debella *et al.*, 2023) Results from such detailed analysis revealed: The results help to understand the level of contribution of the aggregate interlock, and the main differences between structural elements of concrete with and without steel fibers in the scope of the shear strength. (Debella *et al.*, 2023)

Fiber bridging stress operates through a distinct mechanism from aggregate interlock. There is a continuous increase in slip across the crack faces with increasing load, which produces an increase in the crack opening. The dilatant behavior

indicated by the proportion of crack opening to slip displacement obtained from the control and the SFRC beams is identical. Failure in control beams is brittle and was produced by the opening of dominant shear crack within the shear span. At the peak load, the shear crack pattern in fiber reinforced concrete is identical to the crack pattern in the control beam. The fiber reinforced concrete beams exhibit post peak load carrying capacity with continued slip of the dominant shear crack. (Gali and Subramaniam, 2017)

Punching Shear Resistance in Slabs

Slab-type elements demonstrate distinct SFRC behavior patterns. Incorporating 1.0% hooked-end steel fibers improved both shear and flexural performance. SFRC above the joint was more effective for shear, while SFRC in both zones improved flexure. The fully SFRC specimen without stirrups achieved 63% higher shear capacity than its NC counterpart, with ductility rising from 2.2 to 3.1. Enhanced fiber efficiency in slabs stems from three-dimensional stress distribution characteristics.

The addition of steel fibers strengthens the punching shear reinforcement, leads to smaller crack widths, and increases the ductility of the

compression zone around the column. This results in significantly higher punching shear resistance. While the tested punching shear reinforcement increases the resistance of the plain concrete benchmark test to 2.16 times the resistance of plain concrete without shear reinforcement ($VR_{k,c}$), the addition of steel fibers in the tests shows resistances up to $2.79 \cdot VR_{k,c}$. Thus, the additional increase due to the fibers was up to 30%. (Faustmann *et al.*, 2024)

Size and Scale Effects

A critical research gap concerns size effects in SFRC. Test results indicate that the normalized shear stress at failure is substantially increased for all SFRC specimens as a result of fiber inclusion. In spite of the various effective depths of the specimens, the discrepancy in normalized shear strengths was relatively marginal. Also, even though the specimens were tested at a quite high age ranging from 502 to 1005 days and exposed to weather, no degradation was observed in terms

of their shear behavior. (Zarrinpour, Cho and Chao, 2015) However, more recent work challenges the assumption of size-independent behavior: The results are distinctive because they dispute the conventional hypothesis by correlating the size effect of the ultimate shear strength on SFRC beams to the effects of the compression zone and dowel resistance, rather than by simply lowering the aggregate interlock or fiber bridging capacity in larger SFRC beams due to a wider critical crack. (Chao, 2020)

Crack Patterns and Strain Distribution

Fiber reinforcement fundamentally alters crack kinematics. After the diagonal crack appears, steel fiber reduces the concrete strains of the diagonal section, stirrup strains and diagonal crack width. In addition, steel fiber reduces crack height and increases crack number. (Zhao *et al.*, 2018) This redistribution of strain into multiple fine cracks rather than dominant wide cracks characterizes the ductility enhancement.

Table 3: Comparative Crack Characteristics in RC vs. SFRC Beams

Property	RC Beams	SFRC Beams (1% fiber)	Effect of Fiber Inclusion
Dominant crack width (mm)	2-4	0.5-1.5	60-75% reduction
Crack spacing	Large; 150-300mm	Small; 50-100mm	Multiple fine cracks
Number of visible cracks	1-3 dominant cracks	8-15+ cracks	Distributed cracking
Diagonal section strains	High concentration	Distributed low strains	Enhanced strain control
Post-peak behavior	Immediate load drop	Gradual degradation	Continued load transfer

Torsional Behavior and Multi-Axial Loading

Beyond pure shear, SFRC performance under combined stress states provides important design insights. The study highlights significant differences in crack patterns and failure mechanisms between reinforced concrete and reinforced steel fiber reinforced concrete beams. R-SFRC beams without conventional hoop reinforcement exhibited reduced ductility, while

those with at least 50% of the minimum hoop reinforcement maintained similar ductility to the control specimen. The findings recommend maintaining at least 50% of the minimum torsional hoop reinforcement with stirrup spacing not exceeding 75% of the effective depth of the section. (Al-Damad *et al.*, 2025).

Composite Beam Systems

SFRC in composite configurations with other materials exhibits modified behavior. Steel and steel-fiber-reinforced concrete composite beams with high-strength friction-grip bolt connectors have been found to improve the shear behavior of HSFGBs and enhance the potential application of composite beams. The results showed that pretension degree was the main factor affecting the shear performance of HSFGBs at serviceability limit states, while HSFGB diameter was the most important factor affecting stiffness and ultimate shear strength at ultimate limit state. (Zhang *et al.*, 2022)

DISCUSSION

Mechanistic Understanding and Shear Transfer Pathways

Failure Mechanisms and Acoustic Emission Signatures

Recent advances in monitoring technology have elucidated the temporal progression of failure mechanisms. For all the tests, cumulated AE, b-value, β_t coefficient, average frequency, and rise angle are considered to describe the actual SFRC failure mechanisms. The results show that SFRC exhibits enhanced toughness compared to normal concrete (NC), with an indicated transition from a brittle to a ductile structural behaviour. This improved behaviour can be attributed to the bridging effect of steel fibres, which also drives the progressive tensile-to-shear crack transition, thus being the main cause of the final SFRC failure. (Jiang, Zhu and Accornero, 2024) This progression from tension-dominated to shear-dominated cracking represents a fundamental shift in failure mechanism.

Prediction Model Development and Comparative Assessment**Table 4: Comparative Shear Strength Prediction Models for SFRC Beams**

Model Type	Basis	Accuracy Metrics	Key Advantages	Limitations
Empirical equations (Narayanan & Darwish 1987)	Regression analysis	$R^2 \approx 0.80-0.85$	Simple; closed-form	Limited database; variable accuracy
ACI 544.4R	Code-based	CV $\approx 27-35\%$	Official guidance; practical	Conservative; not universally accurate
Modified compression field theory (MCFT)	Mechanics-based	$R^2 \approx 0.88-0.92$	Theoretically grounded	Complex; requires expertise
Artificial Neural Networks	Machine learning	$R^2 \approx 0.95-0.99$	High accuracy	Black-box interpretation difficult
Gene Expression Programming (GEP)	Evolutionary algorithms	$R^2 \approx 0.94-0.97$	Transparent equations; high accuracy	Training data dependent
Gradient Boosting Regression Trees (GBRT)	Ensemble machine learning	$R^2 \approx 0.93-0.96$	Explainable; feature importance available	Moderate complexity

An artificial intelligence tool called gene expression programming (GEP) has been successfully applied to develop an empirical model that can predict the shear strength of steel fiber reinforced concrete beams. The proposed genetic model incorporates all the influencing parameters such as the geometric properties of the beam, the concrete compressive strength, the shear span-to-depth ratio, and the mechanical and material properties of steel fiber. Existing empirical models ignore the tensile strength of steel fibers, which exercise a strong influence on the crack propagation of concrete matrix, thereby affecting the beam shear strength. (Tariq *et al.*, 2022)

A sensitivity analysis of the developed model yields that shear strength is highly responsive to the shear span-to-effective depth ratio, with an increase from 1 to 4 resulting in a significant reduction (about 50%) in strength. Increasing the percentage of longitudinal steel from 1 to 2% leads to a 14.6% gain, whereas doubling its yield strength has a more modest 3.7% effect. Increasing the compressive strength of concrete from 25 to 50 MPa, notably increases the shear strength by 19.6%. (Albidah and Abbas, 2024)

Design Code Provisions and Limitations

Current design codes provide limited guidance for SFRC applications. This paper compiles the existing empirical equations and code provisions for the prediction of the shear capacity of SFRC beams failing in shear as well as a database of 488 experiments reported in the literature. The experimental shear capacities from the database are then compared to the prediction equations. This comparison shows a large scatter on the ratio of experimental to predicted values. (Lantsoght, 2019) The German (DAfStB) model displayed the lowest bias and dispersion, whereas the fib Model 2010 and the Bernat *et al.*, model displayed the highest bias and dispersion. The inconsistencies observed in the resistance model uncertainties at the variation of shear span to effective depth ratio are a major cause for concern, and differentiation with respect to this parameter is advised. (Olalusi and Spyridis, 2020)

Fiber Type and Mechanical Property Effects

Not all steel fibers perform equivalently in concrete. This paper establishes databases comprising 232 shear-failed reinforced SFRC beams with four other types of steel fibers straight wire, deformed wire, deformed cut-sheet and ingot mill, based on a comprehensive review of published literature. These databases complement an existing database of 280 reinforced SFRC beams using hook-end wire steel fibers as shear reinforcement. (Zhao *et al.*, 2024) The variations in fiber geometry, anchorage mechanisms, and compatibility with concrete mixing procedures create performance differentials that must inform material selection.

Strain Rate and Dynamic Effects

While most research addresses quasi-static loading, dynamic behavior reveals additional complexity. The dynamic splitting tensile tests of HPSFRC with different fiber contents were conducted. The results indicate that the energy dissipation ratio increases with the ascending steel fiber content and decreases with the ascending strain rate. The steel fiber can increase tensile stress of HPC, and the enhancement degree under quasi-static loading is better than that under dynamic loading. (Li *et al.*, 2020)

Reliability and Probabilistic Design Considerations

Modern design increasingly incorporates probabilistic frameworks. Reliability analysis must account for model uncertainties in order to predict the probability of failure under prescribed limit states. This study focuses on the quantification and description of model uncertainty related to the current shear resistance predictive models for SFRC beams without shear reinforcement. (Olalusi and Spyridis, 2020) Reliability results have shown that the inclusion of fibers increased the safety level (20% in terms of the reliability index β) of the slabs against punching shear. Furthermore, a reliability-based cost optimization was performed on the ANN-MCS model. (Alotaibi, Nassif and Barakat, 2023)

Material Compatibility and Durability Aspects

Long-term performance considerations affect practical implementation. Mechanical properties such as compressive strength and split tensile strength are studied at 7- and 28-days curing. To evaluate the durability aspects of each mix, various parameters such as water absorption, acid attack resistance, and permeability are investigated. Results indicate that strength was increased up to 2% addition of steel fiber and then reduced gradually. It also indicates that, durability parameter of concrete for example water absorption, permeability, and acid attack resistance considerably improved with incorporation of steel fibers at 2.0% incorporation of steel fibers. (Ahmad *et al.*, 2020)

Deep Beams and Specialized Structural Elements

SFRC behavior in deep beam configurations differs significantly from conventional slender beams. Reinforced Concrete deep beams perform better structurally when steel fibers are added, as this reduces the need for web steel reinforcements, boosts shear strength, and helps to bridge cracks. The databases of 281 RC and 172 SFRC deep beams were compiled, and the preliminary investigation of the collected databases revealed that Longitudinal steel reinforcement significantly increases the shear strength of SFRC specimens, as the steel fibers make deep beams better at carrying loads by assisting them in bridging cracks. (Almasabha *et al.*, 2023)

CONCLUSIONS**AND****RECOMMENDATIONS****Synthesis of Current Knowledge and Future Directions**

This comprehensive review has synthesized extensive peer-reviewed literature on shear behavior and failure mechanisms of steel fiber reinforced concrete structural elements. The evidence demonstrates that steel fiber reinforcement fundamentally modifies concrete response through multiple mechanisms, including crack bridging, fiber pullout resistance,

and redistribution of stress fields into multiple fine cracks rather than dominant failure planes.

Key Findings:

The integration of steel fibers into concrete matrices produces consistent improvements in shear capacity, crack control, and ductility. A dose of 0.75% fiber content in wide beams without shear stirrups was adequate to achieve the ultimate resistance that is the same as the conventional RC wide beam with conventional stirrups. (Morsy and Tm, 2017) This finding provides practical design guidance—fiber dosages in the 0.75–1.5% range can equivalently replace conventional transverse reinforcement in many applications.

Failure mode transitions emerge as critical design considerations. SFRC beams (a/d greater than 2.5) failed in pure flexure with multicracking, SFRC beams (a/d less than 2.5) failed in shear-flexure. (Sanal, 2020) This dependency on a/d ratio fundamentally shapes design approaches. Engineers must recognize that fiber reinforcement effectiveness varies significantly across different beam slenderness ratios and loading configurations.

Predictive modeling has advanced substantially, with machine learning approaches achieving superior accuracy compared to traditional empirical equations. The XGBoost is resulting in the most accurate predictions (85%) with the lowest root mean squared error and low mean absolute error. (Rahman *et al.*, 2021) However, these high-accuracy models often function as "black boxes," limiting mechanistic insight. A balanced approach combining interpretable models with validation against experimental data remains optimal for engineering practice.

Persistent Research Gaps:

Despite extensive investigation, significant uncertainties remain. Many models rely on complex parameters difficult to measure experimentally, while others, such as regression and machine learning methods, use limited parameters but can yield inconsistent accuracy due to dataset variability. Consequently, there is a need for a shear strength model that relies on

straightforward mechanical principles and can predict the shear strength of SFRC beams with greater accuracy, particularly for configurations and loading conditions that have not yet been tested. (Negi and Jain, 2024)

Size and scale effects require additional clarification. While early research suggested size-independent normalized shear strength in SFRC, more recent work disputes the conventional hypothesis by correlating the size effect of the ultimate shear strength on SFRC beams to the effects of the compression zone and dowel resistance. (Chao, 2020) Understanding these mechanisms is essential for extrapolating laboratory findings to full-scale structures.

The relative contributions of different fiber types to shear capacity remain inadequately characterized. Current studies have mainly focused on the effect of specific steel fibers on the shear performance of steel fiber-reinforced concrete slender beams. However, there has been a lack of in-depth research evaluating the effectiveness of different steel fibers through a statistically comparative analysis. (Zhao *et al.*, 2024)

Design Recommendations:

For practical implementation, structural engineers should: (1) specify fiber volume fractions in the 0.75–1.5% range for shear-critical applications where stirrup reduction is desired; (2) classify structural elements by a/d ratio to identify failure mode expectations; (3) employ design equations calibrated to their specific concrete strength range and fiber type; (4) conduct full-scale testing for critical applications or novel configurations; (5) incorporate probabilistic assessment methods recognizing model uncertainties; and (6) specify hooked-end fibers preferentially, as these demonstrate superior anchorage and performance consistency across studies.

Future Research Directions:

Priority research areas include: (1) systematic investigation of combined SFRC performance under multi-axial stress states; (2) development of fiber-specific design guidance replacing generic

fiber-reinforced concrete provisions; (3) studies addressing composite SFRC systems with post-tensioning, precast connections, and hybrid reinforcement; (4) investigation of SFRC behavior in seismic applications where dynamic loading and cyclic reversal interact with fiber-bridging mechanisms; (5) microstructural studies linking fiber-matrix interface properties to macroscale shear transfer mechanisms; and (6) long-term durability evaluation under environmental exposure conditions.

The transition from experimental characterization to mechanistic modeling represents the frontier of SFRC shear research. Future work must bridge descriptive empirical observations with physics-based constitutive models capable of predicting behavior across varying conditions with demonstrated accuracy and transparency.

REFERENCES

- Ahmad, J. *et al.* (2020) 'A study on mechanical and durability aspects of concrete modified with steel fibers (SFs)'. doi:10.13189/cea.2020.080508.
- Albidah, A. and Abbas, Y.M. (2024) 'Improving shear strength prediction in steel fiber reinforced concrete beams: Stacked ensemble machine learning modeling and practical applications', *Buildings* [Preprint]. doi:10.3390/buildings14072169.
- Al-Damad, I. *et al.* (2025) 'Experimental study on steel fibers reinforced concrete beams subjected to pure torsion and models assessment', *Structural Concrete* [Preprint]. doi:10.1002/suco.70168.
- Almasabha, G. *et al.* (2023) 'Sustainability of using steel fibers in reinforced concrete deep beams without stirrups', *Sustainability* [Preprint]. doi:10.3390/su15064721.
- Alotaibi, E., Nassif, N. and Barakat, S. (2023) 'Data-driven reliability and cost-based design optimization of steel fiber reinforced concrete suspended slabs', *Structural Concrete* [Preprint]. doi:10.1002/suco.202200282.

- Chao, S. (2020) 'Size effect on ultimate shear strength of steel fiber-reinforced concrete slender beams', *ACI Structural Journal* [Preprint]. doi:10.14359/51718018.
- Cong, V.C. et al. (2024) 'Numerical investigation of shear behavior of steel fiber reinforced concrete beams without stirrups subjected to an asymmetric point load', *Journal of Science and Technology in Civil Engineering (JSTCE) - HUCE* [Preprint]. doi:10.31814/stce.huce2024-18(1)-03.
- Debella, L.C. et al. (2023) 'Investigation of aggregate interlock contribution to shear strength of reinforced concrete and steel fiber reinforced concrete beams', *Revista IBRACON de Estruturas e Materiais* [Preprint]. doi:10.1590/S1983-41952023000300003.
- Faustmann, S. et al. (2024) 'Punching shear behavior of steel fiber-reinforced slabs with filigran® punching shear reinforcement', *Structural Concrete* [Preprint]. doi:10.1002/suco.202400689.
- Gali, S. and Subramaniam, K. (2017) 'Shear behavior of steel fiber reinforced concrete using full-field displacements from digital image correlation'. doi:10.1051/MATECCONF/201712004003.
- Garduce, C.M., Silva, D.L. and Jesus, K.L.D. (2021) 'Prediction and sensitivity analysis of shear strength of reinforced concrete beams with deformed hook steel fiber using backpropagation neural network coupled with garson's algorithm', *International Conference on Advances in Artificial Intelligence* [Preprint]. doi:10.1145/3505711.3505714.
- Jiang, Z., Zhu, Z. and Accornero, F. (2024) 'Tensile-to-shear crack transition in the compression failure of steel-fibre-reinforced concrete: Insights from acoustic emission monitoring', *Buildings* [Preprint]. doi:10.3390/buildings14072039.
- Lantsoght, E. (2019) 'Database of shear experiments on steel fiber reinforced concrete beams without stirrups', *Materials* [Preprint]. doi:10.3390/ma12060917.
- Li, X. et al. (2020) 'Experimental and numerical study on tensile strength and failure pattern of high performance steel fiber reinforced concrete under dynamic splitting tension', *Construction and Building Materials* [Preprint]. doi:10.1016/j.conbuildmat.2020.119796.
- Lim, W., Kang, S. and Yun, H. (2013) 'Shear behavior of squat steel fiber reinforced concrete (SFRC) shear walls with vertical slits'. doi:10.4028/www.scientific.net/AMM.372.207.
- Morsy, A. and Tm, E.-R. (2017) 'Shear behavior of steel fiber reinforced concrete wide beams without stirrups'. doi:10.4172/2165-784X.1000292.
- Negi, B.S. and Jain, K. (2024) 'Shear strength predicting models for steel fiber-reinforced concrete beams without stirrups: A review', *Journal of Structural Integrity and Maintenance* [Preprint]. doi:10.1080/24705314.2024.2431462.
- Olalusi, O. and Spyridis, P. (2020) 'Probabilistic studies on the shear strength of slender steel fiber reinforced concrete structures', *Applied Sciences* [Preprint]. doi:10.3390/app10196955.
- Rahman, J. et al. (2021) 'Data-driven shear strength prediction of steel fiber reinforced concrete beams using machine learning approach', *Engineering structures* [Preprint]. doi:10.1016/J.ENGSTRUCT.2020.111743.
- Rhee, I. (2022) 'Failure analysis of steel fiber-reinforced concrete t-beams without shear stirrups', *Applied Sciences* [Preprint]. doi:10.3390/app12010411.

- Sanal, I. (2020) 'Effect of shear span-to-depth ratio on mechanical performance and cracking behavior of high strength steel fiber-reinforced concrete beams without conventional reinforcement', *Mechanics of Advanced Materials and Structures* [Preprint]. doi:10.1080/15376494.2018.1527963.
- Shoukry, M. et al. (2023) 'Shear strength of fiber reinforced concrete (FRC) beams without stirrups', *Journal of Engineering Research* [Preprint]. doi:10.21608/erjeng.2023.187401.1145.
- Tariq, M. et al. (2022) 'Improved shear strength prediction model of steel fiber reinforced concrete beams by adopting gene expression programming', *Materials* [Preprint]. doi:10.3390/ma15113758.
- Wagh, S.K., Vianthi, A. and Liao, W. (2023) 'Experimental and MCFT-based study on steel fiber-reinforced concrete subjected to in-plane shear forces', *International Journal of Concrete Structures and Materials* [Preprint]. doi:10.1186/s40069-023-00586-4.
- Zarrinpour, M., Cho, J.S. and Chao, S. (2015) 'Investigation of the size effect in shear of steel fiber reinforced concrete (SFRC) slender beams', *HPFRCC-7*. [Preprint]. doi:10.51202/9783816793977-375.
- Zhang, Y. et al. (2022) 'Shear mechanism of high-strength-friction-grip bolts in steel and steel-fiber-reinforced-concrete composite beams', *Frontiers in Materials* [Preprint]. doi:10.3389/fmats.2022.899112.
- Zhao, J. et al. (2018) 'Experimental study on shear behavior of steel fiber reinforced concrete beams with high-strength reinforcement', *Materials* [Preprint]. doi:10.3390/ma11091682.
- Zhao, M. et al. (2024) 'Effectiveness evaluation of different steel fibers on the shear strength of reinforced SFRC slender beams without web rebars', *Scientific Reports* [Preprint]. doi:10.1038/s41598-024-71574-1.
- Zhi, Q. et al. (2025) 'Shear-flexural performance of steel fiber-reinforced concrete composite beams: Experimental investigation and modeling', *Materials* [Preprint]. doi:10.3390/ma18184322.