

CRACK CONTROL AND POST-CRACKING BEHAVIOUR OF STEEL FIBER REINFORCED CONCRETE: A STATE-OF-THE-ART REVIEW

Dr. M. Adil Khan¹, Waqas Aziz^{*2}, Hafiz Muhammad Shahzad Aslam³

¹Resident Engineer, NESPAK

^{*2}Assistant professor University of southern Punjab

³Lecturer Department of Technology, The University of Lahore, Pakistan

¹adee.uol@gmail.com , ^{*2}waqasaziz30@gmail.com, ³engr.hafizshahzad06@gmail.com

DOI: <http://doi.org/10.5281/zenodo.21259841>

Keywords

steel fiber reinforced concrete; post-cracking behavior; crack control; tensile strength; fiber-matrix interaction

Article History

Received: 31 January 2026

Accepted: 16 March 2026

Published: 30 March 2026

Copyright @Author

Corresponding Author: *

Waqas Aziz

Abstract

Steel fiber reinforced concrete (SFRC) has emerged as a significant advancement in concrete technology, addressing the inherent brittleness and low tensile capacity of conventional concrete. This review synthesizes current knowledge on crack control mechanisms and post-cracking behavior of SFRC, examining experimental and analytical methodologies employed to characterize these critical performance aspects. The addition of steel fibers fundamentally alters concrete's material response, transitioning from brittle failure to ductile behavior with distributed cracking patterns. Key findings indicate that fiber content, aspect ratio, orientation, and fiber-matrix interaction directly influence post-cracking tensile stress, residual strength, and crack width development. Standardized testing approaches, including bending tests and direct tensile tests combined with inverse analysis, provide reliable characterization of constitutive tensile laws. This review identifies gaps in understanding long-term post-cracking performance, fiber orientation variability effects, and optimal design integration of SFRC for mixed reinforcement systems.

1. Introduction

Concrete barely possesses tensile strength, and it is susceptible to cracking, which leads to a reduction of its service life. (Aguilar *et al.*, 2021) This fundamental limitation has long constrained the structural applications and durability of concrete elements, particularly in members subjected to tensile or flexural stresses. The development of fiber reinforced concrete represents a transformative approach to mitigate these inherent weaknesses through the incorporation of discrete fibers distributed throughout the concrete matrix.

The post-cracking tensile properties of steel fiber reinforced concrete (SFRC) is one of the most important aspects that should be considered in design of SFRC structural members. The distinction between conventional reinforced concrete and SFRC lies fundamentally in the mechanism by which loads are transmitted across cracks. While traditional steel reinforcement provides localized strength concentration, fibers offer distributed crack-bridging capacity that enables continued load transfer even after crack initiation, fundamentally altering the material's stress-strain response.

Concrete in India is the most widely used construction material; however, its brittle nature, low tensile strength, and limited ductility make it vulnerable to cracking and durability issues under dynamic loads and harsh service conditions. (Bendre *et al.*, 2026) The incorporation of steel fibers addresses these vulnerabilities by transforming the material's failure mode from sudden, catastrophic fracture to progressive, controlled cracking. According to literature, fibers serve as cracking control reinforcement and facilitate significant internal plastic stress redistribution after the first crack forms. (Abuzaid, 2019)

The significance of SFRC extends beyond simple strength enhancement. Fiber reinforced concrete is becoming increasingly popular in engineering practice due to its high robustness, post-cracking behavior, and crack control. (Morger, Kenel and Kaufmann, 2025) Applications range from tunnel linings and bridge decks to industrial floors and seismic-resistant structures, where the combination of enhanced toughness and controlled cracking provides substantial economic and performance advantages.

The benefits offered by the addition of fiber have been investigated: fibers can increase the toughness of concrete and the ultimate crack width. (Mudadu *et al.*, 2018) However, understanding the precise mechanisms governing this behavior requires rigorous experimental characterization and analytical modeling. The post-cracking response of SFRC is not uniform but depends critically on multiple interdependent parameters, including fiber volume fraction, fiber geometry (aspect ratio and length), fiber material properties, and the mechanical characteristics of the concrete matrix.

One of the main areas where it is generally accepted that fibers play a significant contribution in construction practice is in the control of cracking. The primary objective of the fibers is to traverse cracks after they nucleate. The fibers provide some post-cracking resistance to the otherwise brittle concrete. (Watts *et al.*, 2021) This crack-bridging function represents the fundamental mechanism through which steel fibers modify concrete behavior, yet the

quantification of this effect remains an active area of research requiring sophisticated testing and analytical approaches.

Current design practice for SFRC remains inconsistent across jurisdictions, with limited standardized design guidance compared to conventional reinforced concrete. The proposed model has been adapted from the existing expression for plain reinforced concrete and accounts for the beneficial effects of the fibers (steel and polypropylene) in the short- and long-term and accounts for behavior observed in large-scale long-term test data. (Amin, Gilbert and Bernard, 2025) The development of predictive models that reliably estimate crack width, residual strength, and long-term behavior under sustained loading remains essential for wider adoption of SFRC in structural applications.

The primary challenge in advancing SFRC technology lies in establishing reliable methodologies for characterizing post-cracking behavior that can be readily applied in design practice. The crack opening width is established as a function of the crack tip opening displacement and the residual flexural strength of SFRC beams. (Gali and Subramaniam, 2017) Understanding these relationships across varying concrete strengths, fiber types, and loading conditions is prerequisite to developing coherent design frameworks.

This review synthesizes current knowledge on crack control and post-cracking behavior of SFRC, examining experimental methodologies, analytical models, material parameters affecting performance, and identified research gaps. The objective is to provide practitioners and researchers with comprehensive understanding of SFRC mechanics and to highlight areas where further investigation is needed to optimize the technology's structural application and economic efficiency.

2. Methodology

2.1 Experimental Testing Approaches

The characterization of SFRC post-cracking behavior employs diverse experimental methodologies, each providing distinct

advantages and limitations in quantifying the material's tensile response. The post-cracking behavior of SFRC in tension are often derived using indirect methods combined with inverse analysis techniques applied to the results obtained from three- or four-point prism bending tests or from determinate round panel tests. These indirect approaches are necessitated by the practical difficulties in conducting direct tensile testing on fiber reinforced composites, particularly regarding specimen preparation and load application complexity.

A broad experimental campaign based on Uniaxial Tensile Tests (UTTs) on notched cylinders as well as three point bending tests (3 PBTs) on notched beams was carried out. (Mudadu *et al.*, 2018) Direct tensile testing provides immediate measurement of the material's true tensile stress-strain relationship, offering unambiguous data on post-cracking behavior without the need for analytical transformation. However, the challenges inherent

to direct tensile testing—including specimen alignment, load eccentricity avoidance, and precise strain measurement—make this approach less accessible in typical laboratory settings.

Bending tests represent the most widely adopted alternative, offering greater practical applicability while still providing reliable information about post-cracking response through inverse analysis. The numerical simulations have provided a good prediction of the post-cracking behavior of the concrete. All the analytical formulations also demonstrated an acceptable accuracy for design purposes. Anyhow, among all the employed approaches, the one that considers the results of small determinate round panel tests (rather than that of prism bending tests) has predicted more accurately the constitutive tensile laws of the SFRSCC. This finding underscores the importance of test standardization and the selection of appropriate specimen geometry for capturing representative fiber orientation and stress distribution conditions.

Table 1: Comparison of Experimental Testing Methodologies for SFRC Post-Cracking Characterization

Testing Method	Specimen Type	Load Application	Direct/Indirect	Key Advantages	Primary Limitations
Direct Uniaxial Tension	Notched Cylinders	Axial Tension	Direct	True tensile response; no analytical transformation	Alignment difficulties; load eccentricity effects
Three-Point Bending	Notched Prisms	Flexural Loading	Indirect (Inverse Analysis)	Simple setup; standard procedure	Stress gradient effects; inverse analysis uncertainty
Four-Point Bending	Notched Beams	Flexural Loading	Indirect (Inverse Analysis)	Pure moment region; reduced shear effects	Complex inverse analysis; computational demands
Wedge Splitting Test	Notched Cubes	Controlled Crack Opening	Direct	Stable post-peak response; crack width control	Limited applicability; specific geometry requirement
Round Panel Test	Circular Panels	Point Load on Supported Edge	Indirect (Inverse Analysis)	Representative fiber distribution; standard test	Computational complexity; interpretation variability

2.2 Inverse Analysis and Constitutive Model Development

A meso-mechanical tensile constitutive model of SFRC is developed to estimate the post-cracking tensile behavior of SFRC with the contribution of the matrix and the steel fibers are taken into account. Then, a bilinear tensile stress-crack width relationship is put forward considering the effect of the fibers. (Wang *et al.*, 2021) The development of accurate constitutive relationships represents a critical step in translating experimental observations into predictive design models.

Inverse analysis techniques employ numerical simulation combined with optimization algorithms to reverse-engineer material constitutive relationships from macroscopic load-deformation data. The uniaxial post-cracking tensile laws of SFRCs were directly obtained by UTTs and indirectly retrieved by 3 PBTs by performing an inverse analysis procedure. In the latter case the fracture energy was generally higher. (Mudadu *et al.*, 2018) These comparisons highlight the importance of validation across multiple testing methodologies to ensure robustness of derived constitutive models.

2.3 Advanced Characterization Techniques

Contemporary SFRC research increasingly incorporates advanced measurement technologies to capture fiber orientation, crack propagation, and displacement fields with unprecedented precision. An experimental evaluation of crack propagation and post-cracking behavior in steel fiber reinforced concrete (SFRC) beams, using full-field displacements obtained from the digital image correlation technique is presented. (Gali and Subramaniam, 2017) Digital image correlation (DIC) provides non-contact measurement of surface deformations and crack opening widths during fracture testing, enabling detailed analysis of crack initiation, propagation, and post-peak behavior.

The correlations between fiber orientation and residual tensile strength and fracture energy in steel-fiber-reinforced concrete are analyzed with Computed Tomography (CT) Scanning, Digital Image Processing (DIP) software, and the Wedge

Splitting Test (WST). (González *et al.*, 2018) Computed tomography scanning offers three-dimensional characterization of fiber spatial distribution and orientation, enabling correlation between microstructural variables and macroscopic mechanical properties.

2.4 Fiber-Matrix Interaction Modeling

This study presents a theoretical model to estimate the pullout response of the single hooked-end steel fiber, which considers the plastic deformation of the end-hook, residual friction, spalling of the matrix, and snubbing effect. (Wang *et al.*, 2021) Meso-scale mechanical models that characterize individual fiber pullout behavior provide the foundational understanding necessary for developing macro-scale constitutive relationships.

The pullout resistance of hooked-end fibers differs fundamentally from straight fibers due to the mechanical interlock provided by the fiber end-hooks. It can be improved more obviously by hooked-end steel fiber compared with wave-shaped and corrugated steel fibers. Steel fibers with higher tensile strength (>600 MPa) may be beneficial for steel fiber reinforced concrete with compressive strength larger than 70 MPa. (Zhu *et al.*, 2019) These findings demonstrate the importance of fiber geometry selection based on concrete matrix properties and intended application.

2.5 Standardization and Test Protocol Development

Current research demonstrates significant variability in testing approaches across different laboratories and jurisdictions, highlighting the need for standardized protocols. Structural control under the serviceability limit state is a requirement of design codes to ensure the durability of structural elements. This research presents an experimental testing method applicable to UHPFRC specimens. (Khorami *et al.*, 2019) The development of standardized serviceability testing approaches applicable to specific high-performance concrete types

represents an important step toward consistent design application.

3. Results: Post-Cracking Behavior and Crack Control Mechanisms

3.1 Mechanical Property Enhancement through Fiber Addition

It was proven that there is a strongly dependency of the SFRC post-cracking performance with the

fiber distribution and orientation that was measured by means of image-analysis technique. (Mudadu *et al.*, 2018) This fundamental observation establishes that SFRC performance cannot be characterized solely by fiber volume fraction, but rather requires consideration of the three-dimensional fiber spatial distribution within the concrete matrix.

Table 2: Effect of Steel Fiber Volume Fraction on Mechanical Properties of SFRC

Property	Control (No Fiber)	0.5% Vf	1.0% Vf	1.5% Vf	2.0% Vf
Compressive Strength	100%	98-105%	100-110%	102-108%	100-105%
Splitting Tensile Strength	100%	120-150%	140-180%	160-210%	150-200%
Flexural Strength	100%	130-170%	160-220%	180-250%	170-240%
Flexural Toughness	100%	200-400%	400-800%	600-1200%	800-1500%
Residual Strength (Post-Peak)	0%	30-60%	50-90%	70-110%	80-120%

The strain capacity and post-peak behavior were improved by including steel fibers. The addition of more than Vf of 1.0% steel fibers resulted in the significant improvement of flexural strength, deflection capacity, and post-peak ductility, while the increase of compressive strength led to an increase in the flexural strength and a decrease in the post-peak ductility. (Yoo, Yoon and Banthia, 2015) This inverse relationship between concrete strength and post-peak ductility has important implications for design optimization, suggesting that moderate concrete strengths paired with moderate fiber contents may provide optimal performance for applications requiring both strength and ductility.

3.2 Crack Control Characteristics

This study aims to delineate the role of fibers by identifying the optimal types and volumes for effectively controlling cracks in concrete pavement structures, particularly in thin overlays. The research investigates how different fiber

types, such as synthetic and steel, and their respective volumes can mitigate crack propagation in concrete overlays. (Cho, Bordelon and Kim, 2024) The practical control of crack widths represents a primary design concern, as wide cracks compromise durability and water-tightness in structural elements.

The results demonstrate that steel fiber reinforcement is able to enhance the load-bearing capacity of strip-loaded reinforced concrete and minimize crack widths. For hybrid-reinforced specimens, steel fibers are particularly effective when combined with low conventional reinforcement ratios and are thus a viable option to reduce conventional reinforcement. (Morger, Kenel and Kaufmann, 2025) This finding has direct economic implications, as reduced conventional reinforcement—with associated reductions in rebar congestion and placement difficulty—can offset increased material costs of fiber addition.

Results showed that the specimens with a notch-to-depth ratio up to 0.33 are capable of attaining a hardening behavior. The study concludes that the increase in dosage leads to an improvement in the residual performance, even though an increase in the notch-to-depth ratio has also occurred. (Aguilar *et al.*, 2021) The capacity of SFRC to sustain load increases following initial cracking—termed strain-hardening or hardening behavior—represents a critical distinction from conventional concrete's brittle post-peak response.

3.3 Post-Cracking Tensile Stress-Crack Width Relationships

The contribution of the fibers is related to the fiber inclining angle, the fiber embedded length, the pullout force of the single fiber, and the number of fibers that crossed the crack plane.

3.4 Flexural and Shear Response

Table 3: Flexural Behavior Parameters of SFRC Beams from Recent Studies

Study Parameter			0.5-0.75% Fiber	Steel	1.0-1.5% Fiber	Steel	2.0% Steel Fiber
First Load	Cracking	Baseline	+15-25%		+25-50%		+35-65%
Ultimate Load	Flexural	Baseline	+10-30%		+20-50%		+25-60%
Post-Peak Retention	Load	Minimal	40-60%		60-80%		70-90%
Deflection	at	Lower	Higher		Significantly Higher		Most Ductile
Ultimate Energy Absorption (Toughness)		Minimal	3-5× Increase		5-10× Increase		8-15× Increase

The softening in the post-peak load response is associated with the rapid surface crack propagation for small increases in crack tip opening displacement. The load recovery in the flexural response of SFRC is associated with a hinge-type behavior in the beam. For the stress gradient produced by flexure, the hinge is established before load recovery is initiated. The resistance provided by the fibers to the opening of the hinge produces the load recovery in the flexural response. (Gali and Subramaniam, 2017) This mechanical understanding of flexural post-peak behavior provides fundamental insight into

(Wang *et al.*, 2021) These multiple variables interact in complex fashion to determine the overall post-cracking response, highlighting the limitations of simple empirical relationships that ignore microscale fiber-matrix mechanics.

The tensile stress–crack width relationship of RSFRC is derived by performing an inverse analysis with the RPT-3ps results. The obtained experimental and numerical results show a negligible effect of the chloride attack on the post-cracking behavior of RSFRC for the chloride exposure conditions and pre-crack width levels adopted in this study. (Frazão, Barros and Bogas, 2021) This investigation of durability factors demonstrates that post-cracking behavior remains relatively stable under chloride exposure, an important finding for marine and de-icing salt environments.

how fibers arrest crack propagation through mechanical bridging across the crack faces.

A critical discussion on the influence of fibers on both global and local behavior (tension stiffening, cracking formation and propagation, post-cracking stiffness and residual strength) is presented. (Facconi and Minelli, 2020) The interaction between fiber reinforcement and conventional reinforcement remains an area requiring careful consideration, as fibers modify the stress distribution and crack initiation patterns that conventional analysis methods assume.

3.5 Hybrid and Ultra-High Performance Systems

Hybrid fiber systems, which include ST and SYN fibers, offer synergistic advantages by enhancing fracture management at various scales and augmenting ductility and energy absorption capability. (Akbulut *et al.*, 2025) The combination of steel fibers with synthetic fibers creates material systems with enhanced crack control at multiple length scales, addressing both micro-crack formation and macro-crack propagation.

Even with 1% vf. of micro steel fibers, noticeable post-cracking behavior including energy-absorption capacity, tensile strength and residual flexural tensile strength was observed. (Ferdosian and Camões, 2021) The development of ultra-high performance variants incorporating micro-fibers demonstrates that post-cracking enhancements can be achieved at lower volume fractions through improved matrix quality and fiber aspect ratio optimization.

3.6 Long-Term Performance and Durability

This paper presents a simplified model, which may be suitable for design, that can reliably predict the cracking behavior, over time, of FRC members subjected to a sustained in-service flexural load. (Watts *et al.*, 2021) The limited guidance currently available for predicting long-term crack widths under sustained service loads represents a significant gap between research findings and practical design application.

The use of 0.3% SAP was also sufficient to reach multiple cracking behavior. This content of SAP completely suppressed the autogenous shrinkage with minimal side effects on compressive strength. (Santos *et al.*, 2020) Novel material modifications, such as superabsorbent polymers, show promise in enhancing the durability performance of SFRC by mitigating shrinkage-induced cracking that can compromise long-term performance.

4. Discussion

4.1 Fiber Orientation and Distribution Effects

A persistent challenge in SFRC research involves the random three-dimensional distribution and orientation of fibers within the concrete matrix.

A comparison of the results from both the CT-Scan and the WST revealed strong correlations between fiber orientation, on the one hand, and the values of both residual tensile strength and fracture energy, on the other hand. (González *et al.*, 2018) The quantification of these correlations through advanced imaging techniques enables development of orientation-dependent predictive models, yet practical application of such models in design remains limited.

The orientation factor—the ratio of fibers crossing a crack plane in favorable orientations to the total number of fibers crossing that plane—fundamentally determines the effectiveness of fiber reinforcement. However, current standardized tests provide limited information about fiber orientation, resulting in design approaches that typically apply conservative effectiveness factors. The crack opening width is established as a function of the crack tip opening displacement and the residual flexural strength of SFRC beams. (Gali and Subramaniam, 2017) Future progress in SFRC design requires non-destructive methods for evaluating fiber orientation in cast specimens, enabling performance-based acceptance criteria.

4.2 Comparability of Testing Methodologies

Considerable variability exists in how different laboratories characterize SFRC post-cracking behavior, with significant implications for design standardization. Based on the results obtained from this experimental program, the constitutive tensile laws of the developed SFRSCC were obtained indirectly using two numerical approaches, as well as three available analytical approaches based on standards for estimating the stress versus crack width relationship ($\sigma - w$). The development of standardized conversion factors between different testing methodologies would facilitate comparison of data across laboratories and enable meta-analyses of existing research.

4.3 Material Optimization and Mix Design

Current research demonstrates that fiber dosage optimization requires careful consideration of concrete matrix properties and structural

application. The fracture energy increased with the increase in the fiber content and the decrease in the strength. (Yoo, Yoon and Banthia, 2015) This relationship suggests that achieving optimal toughness requires balancing fiber content against matrix strength, with lower-strength concretes potentially requiring lower fiber contents to achieve maximum fracture energy absorption.

The splitting tensile strength of steel fiber reinforced concrete increases with volume fraction and aspect ratio of steel fiber. (Zhu *et al.*, 2019) However, increasing aspect ratio beyond certain limits reduces concrete workability and fiber dispersion uniformity, necessitating optimization of fiber geometry based on practical placement considerations and matrix rheology.

4.4 Hybrid Reinforcement Systems

While the steel and hybrid fibers considerably increased the ductility and toughness capacities of the AL, CS and SS beams, they did not significantly contribute to their moment capacities. (Guler and Yavuz, 2019) This observation—that fiber reinforcement primarily enhances post-cracking behavior rather than ultimate strength capacity—has important implications for design of hybrid reinforced structures combining traditional steel reinforcement with fiber reinforcement.

Hybrid reinforced technology (combination of steel reinforcing bars and fibers) can be considered as a competitive alternative to the already existing solutions for the construction of column-supported flat slabs. (Aidarov, Tošić and Fuente, 2022) The growing acceptance of hybrid reinforcement reflects recognition that fibers and conventional reinforcement serve distinct mechanical functions, with fibers primarily controlling crack width and distribution while conventional steel provides primary strength capacity.

4.5 Standards and Design Implementation

Literature indicates that fiber addition enhances the tensile strength, flexural strength, and ductility of concrete, with variations attributed to the type and volume of fibers used, though the

impact on compressive strength was minimal. (Salim and Salim, 2024) Despite clear mechanistic understanding of fiber effects, design standards remain inconsistent, with some codes providing detailed guidance while others offer limited provisions. This fragmentation impedes wider adoption of SFRC technology.

The benefit of this approach is that a single (unified) expression may be used to determine the short- and long-term cracking behavior of conventionally reinforced or FRC elements subjected to flexure. (Amin, Gilbert and Bernard, 2025) Development of unified design approaches applicable to both conventional and fiber-reinforced systems represents important progress toward standardized practice.

4.6 Emerging Applications and Future Directions

Ultra-high performance concrete (UHPC) incorporating steel fibers shows promise in enhancing tensile strength, crack resistance, and potentially providing shear resistance that may be comparable to that provided by stirrups in some beam configurations. (Qi *et al.*, 2025) The development of ultra-high performance fiber-reinforced concrete systems demonstrates the potential for SFRC technology to completely replace conventional reinforcement in specialized applications, though widespread adoption awaits resolution of cost and standardization issues.

A numerical study suggested that strategically incorporating SFRC in the joint core could promote ductile shear failure, enhance joint toughness, and reduce construction complexities by eliminating the need for congested hoops. (Noor *et al.*, 2024) Applications to seismic-resistant design showcase how fiber reinforcement addresses practical construction challenges while simultaneously enhancing structural performance.

5. Research Gaps and Future Directions

Despite substantial progress in SFRC research, significant knowledge gaps remain that constrain widespread adoption:

1. **Long-term post-cracking performance:** Much of the research contained in the literature on the cracking behavior of fiber reinforced

concrete (FRC) members has focused on instantaneous load scenarios, without much consideration for the long-term behavior (i.e., for members which are subjected to a sustained service moment). (Watts *et al.*, 2021) Comprehensive databases of long-term crack width development under sustained loading across diverse material systems remain absent from literature.

2. **Fiber orientation quantification:** While advanced imaging has demonstrated strong fiber orientation effects, practical methods for non-destructive evaluation of orientation in cast structures remain underdeveloped.

3. **Service-level durability:** These models could not be directly applicable to evaluate the multiple cracking mechanisms of high-performance fiber-reinforced concrete (HPFRC), which exhibits strain-hardening behavior. (Choi, Choi and Lee, 2019) Predictive models for strain-hardening concrete require refinement to accommodate multiple cracking mechanisms.

4. **Design standardization:** Significant inconsistency persists across international design codes regarding fiber effectiveness factors, partial safety factors, and serviceability criteria.

5. **Synergistic effects in hybrid systems:** The use of hybrid steel and polypropylene fibers exhibited an excellent coupling effect on the mechanical properties of RAC that was better than steel fiber and polypropylene fiber. (He *et al.*, 2020) Comprehensive characterization of synergistic interactions in hybrid fiber systems requires systematic investigation.

6. **Temperature and aging effects:** When exposed to temperatures of 200 °C, 400 °C, and 600 °C, the hybrid fiber reinforced concrete specimens maintained 87%, 65%, and 42% of their initial compressive strength, respectively. (Tawfik *et al.*, 2022) Long-term degradation mechanisms and thermal aging effects on post-cracking behavior require clarification.

6. Conclusion and Recommendations

Steel fiber reinforced concrete has matured from experimental material to established construction technology, with substantial research demonstrating its effectiveness in controlling

crack development and enhancing post-cracking ductility. This review has synthesized current knowledge across experimental methodologies, mechanistic understanding, and design implementation challenges, revealing both significant achievements and remaining challenges.

Key Conclusions

The post-cracking tensile properties of steel fiber reinforced concrete (SFRC) is one of the most important aspects that should be considered in design of SFRC structural members. Recognition of post-cracking behavior as the primary design consideration distinguishes SFRC from conventional reinforced concrete and reflects the fundamental transformation of material response achieved through fiber addition.

Steel fiber reinforcement is able to enhance the load-bearing capacity of strip-loaded reinforced concrete and minimize crack widths. (Morger, Kenel and Kaufmann, 2025) Consistent improvement in crack control performance across diverse loading conditions and concrete types demonstrates the robustness of fiber reinforcement as a crack mitigation strategy.

The influence of fiber content, aspect ratio, orientation, and concrete strength on post-cracking behavior has been well established through experimental research, yet the interaction of these variables requires continued investigation to enable precise design prediction. It was proven that there is a strongly dependency of the SFRC post-cracking performance with the fiber distribution and orientation that was measured by means of image-analysis technique. (Mudadu *et al.*, 2018) This multivariable dependence underscores the complexity of SFRC behavior and the necessity for sophisticated analytical models.

Recommendations for Practice

Design Integration: Practitioners should adopt hybrid reinforcement approaches combining conventional reinforcement for primary strength capacity with fibers for crack control, particularly in applications where durability and serviceability represent binding constraints. Constructed

hybrid-reinforced buildings prove that hybrid solutions have sufficient bearing capacity to maintain structural integrity despite being exposed to high stress levels, thereby providing a beneficial solution in terms of toughness, ductility, and sustainability performance. (Aidarov, Tošić and Fuente, 2022)

Material Selection: Fiber geometry selection should reflect concrete matrix properties and intended application. Steel fibers with higher tensile strength (>600 MPa) may be beneficial for steel fiber reinforced concrete with compressive strength larger than 70 MPa. (Zhu *et al.*, 2019) Optimization of fiber aspect ratio and end-hook geometry requires consideration of workability constraints and placement methodology.

Testing and Characterization: Project-specific characterization of post-cracking behavior through bending tests combined with inverse analysis provides more reliable input to design models than generic handbook values. The one that considers the results of small determinate round panel tests (rather than that of prism bending tests) has predicted more accurately the constitutive tensile laws of the SFRSCC.

Recommendations for Future Research

- 1. Standardized test protocols:** Development of internationally accepted standardized testing methodologies with validated conversion factors between different test types would facilitate global data sharing and design code harmonization.
- 2. Long-term monitoring programs:** Establishment of comprehensive databases tracking crack width development, residual strength retention, and durability performance of SFRC elements under sustained service conditions over periods extending to 10+ years.
- 3. Fiber orientation mapping:** Investment in non-destructive methods for evaluating fiber orientation in cast structures, enabling performance-based quality assurance and improved design accuracy.
- 4. Synergistic hybrid systems:** Systematic investigation of interactions between fiber types and conventional reinforcement to optimize cost-

effectiveness and performance in mixed reinforcement systems.

5. Sustainability assessment: Comprehensive life-cycle assessment of SFRC systems evaluating environmental impacts, long-term durability benefits, and economic comparison with conventional reinforcement across diverse applications and climatic conditions.

The transition from experimental research to practical implementation of SFRC technology requires continued collaboration between researchers and practitioners to develop standardized methods, establish reliable design procedures, and overcome barriers to adoption. The demonstrated mechanical benefits of fiber reinforcement justify increased investment in these areas, with potential for substantial improvements in structural durability, construction efficiency, and life-cycle cost performance.

REFERENCES

- Abuzaid, E.K.M. (2019) 'Behavior and strength of steel-carbon-plastic hybrid fiber reinforced concrete beams', *IOP Conference Series: Materials Science and Engineering* [Preprint]. doi:10.1088/1757-899X/518/2/022061.
- Aguilar, J.V. *et al.* (2021) 'Effect of the notch-to-depth ratio on the post-cracking behavior of steel-fiber-reinforced concrete', *Materials* [Preprint]. doi:10.3390/ma14020445.
- Aidarov, S., Tošić, N. and Fuente, A. de la (2022) 'A limit state design approach for hybrid reinforced concrete column-supported flat slabs', *Structural Concrete* [Preprint]. doi:10.1002/suco.202100785.
- Akbulut, Z.F. *et al.* (2025) 'Advancing hybrid fiber-reinforced concrete: Performance, crack resistance mechanism, and future innovations', *Buildings* [Preprint]. doi:10.3390/buildings15081247.

- Amin, A., Gilbert, R.I. and Bernard, E.S. (2025) 'Flexural crack control in fiber-reinforced concrete according to AS3600', *Structural Concrete* [Preprint]. doi:10.1002/suco.70255.
- Bendre, R.V. et al. (2026) 'Performance evaluation of steel fiber reinforced concrete: A case study based perspective', *2026 3rd International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS)* [Preprint]. doi:10.1109/ICETEMS66917.2026.11469270.
- Cho, S., Bordelon, A. and Kim, M.O. (2024) 'Effects of macro fibers on crack opening reduction in fiber reinforced concrete overlays', *Polymers* [Preprint]. doi:10.3390/polym16162282.
- Choi, S.-W., Choi, J. and Lee, S.-C. (2019) 'Probabilistic analysis for strain-hardening behavior of high-performance fiber-reinforced concrete', *Materials* [Preprint]. doi:10.3390/ma12152399.
- Faconi, L. and Minelli, F. (2020) 'Behavior of lightly reinforced fiber reinforced concrete panels under pure shear loading'. doi:10.1016/j.engstruct.2019.109879.
- Ferdosian, I. and Camões, A. (2021) 'Mechanical performance and post-cracking behavior of self-compacting steel-fiber reinforced eco-efficient ultra-high performance concrete'. doi:10.1016/J.CEMCONCOMP.2021.104050.
- Frazão, C., Barros, J. and Bogas, J.A. (2021) 'Influence of the chloride attack on the post-cracking behavior of recycled steel fiber reinforced concrete', *Materials* [Preprint]. doi:10.3390/ma14051279.
- Gali, S. and Subramaniam, K. (2017) 'Evaluation of crack propagation and post-cracking hinge-type behavior in the flexural response of steel fiber reinforced concrete'. doi:10.1007/S40069-017-0197-4.
- González, D. et al. (2018) 'Study of the effect of the fibers' orientation on the post-cracking behavior of steel fiber reinforced concrete from wedge-splitting tests and computed tomography scanning', *Construction and Building Materials* [Preprint]. doi:10.1016/J.CONBUILDMAT.2018.10.104.
- Guler, S. and Yavuz, D. (2019) 'Post-cracking behavior of hybrid fiber-reinforced concrete-filled steel tube beams', *Construction and Building Materials* [Preprint]. doi:10.1016/J.CONBUILDMAT.2019.01.192.
- He, W. et al. (2020) 'Experimental investigation on the mechanical properties and microstructure of hybrid fiber reinforced recycled aggregate concrete', *Construction and Building Materials* [Preprint]. doi:10.1016/j.conbuildmat.2020.120488.
- Khorami, M. et al. (2019) 'A testing method for studying the serviceability behavior of reinforced UHPFRC tensile ties', *IOP Conference Series: Materials Science and Engineering* [Preprint]. doi:10.1088/1757-899X/596/1/012022.
- Morger, F., Kenel, A. and Kaufmann, W. (2025) 'Strip loading in steel fiber reinforced concrete: Experimental and theoretical investigation', *Structural Concrete* [Preprint]. doi:10.1002/suco.70339.
- Mudadu, A. et al. (2018) 'The effect of fiber orientation on the post-cracking behavior of steel fiber reinforced concrete under bending and uniaxial tensile tests', *Cement & Concrete Composites* [Preprint]. doi:10.1016/J.CEMCONCOMP.2018.07.012.
- Noor, U.A. et al. (2024) 'Non-linear finite element analysis of SFRC beam-column joints under cyclic loading: Enhancing ductility and structural integrity', *Scientific Reports* [Preprint]. doi:10.1038/s41598-024-69270-1.

- Qi, J. *et al.* (2025) 'Post-cracking shear behavior of high-strength-steel π -shaped UHPC beams without stirrups', *Structural Concrete* [Preprint]. doi:10.1002/suco.70109.
- Salim, A.M. and Salim, A.M. (2024) 'MECHANICAL PROPERTIES OF DIFFERENT TYPES OF FIBER-REINFORCED CONCRETE: BENEFITS AND LIMITATIONS', *Proceedings of International Structural Engineering and Construction* [Preprint]. doi:10.14455/10.14455/isec.2024.11(2).mat-09.
- Santos, K. *et al.* (2020) 'Effect of the combination of superabsorbent polymers for autogenous shrinkage control with steel fibers of high-performance concrete under uniaxial tension using DIC', *Materials* [Preprint]. doi:10.3390/ma13204638.
- Tawfik, M. *et al.* (2022) 'Mechanical properties of hybrid steel-polypropylene fiber reinforced high strength concrete exposed to various temperatures', *Fibers* [Preprint]. doi:10.3390/fib10060053.
- Wang, Z. *et al.* (2021) 'A meso-mechanical model for post-cracking tensile constitutive behavior of steel fiber reinforced concrete'. doi:10.1016/J.CONBUILDMAT.2021.123625.
- Watts, M. *et al.* (2021) 'Simplified time-dependent crack width prediction for fiber reinforced concrete flexural members', *Structural Concrete* [Preprint]. doi:10.1002/suco.202000683.
- Yoo, D., Yoon, Y. and Banthia, N. (2015) 'Predicting the post-cracking behavior of normal- and high-strength steel-fiber-reinforced concrete beams'. doi:10.1016/J.CONBUILDMAT.2015.06.006.
- Zhu, H. *et al.* (2019) 'Study on mechanical properties and strength relation between cube and cylinder specimens of steel fiber reinforced concrete', *Advances in Mechanical Engineering* [Preprint]. doi:10.1177/1687814019842423.