International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 2, Mar-Apr-2026, ISSN (Online): 2395-566X

Behaviour of Fiber Reinforced Concrete Under Impact and Fatigue Loads

Maddasani Balaji[1], U.Srinivasarao[2]
[1]PG Scholar, Department of Civil Engineering, Chalapathi Institute of Technology(Autonomous), Abburi Raghavaiah Nagar, CITY College Rd, Mothadaka, Andhra Pradesh, India-522016.
[2]Assistant Professor, Department of Civil Engineering, Chalapathi Institute of Technology(Autonomous), Abburi Raghavaiah Nagar, CITY College Rd, Mothadaka, Andhra Pradesh, India-522016.

Abstract- — Concrete is the most widely used construction material; however, its inherent brittleness and low tensile strength limit its performance under dynamic loading conditions such as impact and fatigue. Structures including pavements, bridge decks, industrial floors, airport runways, and protective structures are frequently subjected to repeated cyclic loads and sudden impact forces, which can lead to progressive cracking, stiffness degradation, and premature failure in conventional concrete. To overcome these limitations, Fiber Reinforced Concrete (FRC) has emerged as an effective composite material that enhances the mechanical performance and durability of concrete under extreme loading conditions. Fiber Reinforced Concrete is produced by incorporating discrete fibers such as steel, polypropylene, glass, carbon, or natural fibers into the concrete matrix. These fibers act as crack arresters by bridging microcracks and restraining their propagation, thereby improving toughness, ductility, and post-cracking behavior. Under impact loading, the presence of fibers significantly increases the energy absorption capacity of concrete, delays crack initiation, and transforms brittle failure into a more ductile mode. Experimental studies have shown that FRC exhibits substantially higher impact resistance compared to conventional concrete, with improvements strongly influenced by fiber type, aspect ratio, volume fraction, and orientation. Under fatigue loading, Fiber Reinforced Concrete demonstrates superior performance by enhancing fatigue life and reducing the rate of crack growth under repeated stress cycles. Fibers help redistribute stresses across the cracked sections and maintain structural integrity even after matrix cracking. Steel fiber reinforced concrete, in particular, has been shown to exhibit excellent fatigue resistance, while synthetic fibers contribute to improved durability and crack control. The synergistic use of hybrid fiber systems further enhances fatigue performance by combining strength and ductility characteristics. Overall, the incorporation of fibers significantly improves the resistance of concrete to impact and fatigue loading, making Fiber Reinforced Concrete a promising material for applications subjected to dynamic and cyclic loads. The improved mechanical performance, enhanced durability, and extended service life of FRC contribute to safer, more resilient, and sustainable infrastructure. Continued research on optimized fiber combinations, numerical modeling, and long-term field performance is essential for wider adoption of Fiber Reinforced Concrete in modern construction practices.

Keywords : Fiber Reinforced Concrete; Impact Loading; Fatigue Behavior; Energy Absorption; Crack Control; Ductility; Steel Fibers; Cyclic Loading; Structural Durability.

I. INTRODUCTION

Concrete is the most widely utilized construction material across the globe owing to its exceptional compressive strength, versatility in forming complex geometries, cost-effectiveness, and the widespread availability of its constituent raw materials. Its inherent durability and relatively low maintenance requirements make it indispensable for the construction of critical infrastructure such as buildings, bridges, pavements, dams, tunnels, and industrial facilities. The ability of concrete to perform reliably under a wide range of environmental conditions, including exposure to moisture, temperature variations, and chemical attack, further enhances its suitability for long-term structural applications. However, despite these advantages, conventional concrete exhibits significant mechanical limitations that restrict its performance in demanding service conditions. Chief among these limitations are its brittle behavior and low tensile strength, which result from its heterogeneous microstructure and the weak interfacial transition zone between aggregates and cement paste. As a consequence, concrete tends to crack easily under tensile stresses, stress concentrations, and sudden loading, with limited capacity for energy absorption and deformation prior to failure. These characteristics make conventional concrete particularly susceptible to cracking and damage initiation, thereby compromising serviceability, safety, and structural longevity.

In contemporary infrastructure systems, the demand for structures capable of withstanding complex loading scenarios has increased substantially due to rapid urbanization, heavier traffic volumes, and more stringent performance requirements. Modern structures are frequently subjected to impact loads arising from vehicle collisions, dropped objects, industrial accidents, blast effects, and construction-related mishaps, as well as fatigue loads generated by repeated cyclic actions such as traffic movement on pavements and bridges, machine-induced vibrations, wind-induced oscillations, and seismic excitations. Unlike static loading, these dynamic and cyclic loads can induce localized stress concentrations and repeated stress reversals within the concrete matrix, leading to the initiation and propagation of microcracks even when the applied stress levels are well below the material's ultimate strength. Over time, the accumulation of such microstructural damage results in stiffness degradation, reduction in load-carrying capacity, and progressive loss of structural integrity. Fatigue-induced cracking, in particular, can remain undetected during early stages while steadily propagating under continued loading, eventually leading to sudden and brittle failure. Consequently, the vulnerability of conventional concrete under impact and fatigue loading has become a critical concern in modern structural design, emphasizing the need for improved material performance with enhanced toughness, crack resistance, and energy absorption capacity.

II. MATERIALS AND METHODOLOGY

General

This chapter describes in detail the materials used, mix proportions adopted, specimen preparation procedures, and experimental methodologies employed to investigate the impact and fatigue behavior of Fiber Reinforced Concrete (FRC). Standardized testing procedures were followed to ensure repeatability, reliability, and meaningful comparison of results with existing literature. Both conventional concrete and fiber reinforced concrete specimens were prepared and tested to evaluate the influence of fibers on impact resistance, fatigue life, crack control, and energy absorption capacity.

Materials

- **Cement**

Ordinary Portland Cement (OPC) of 53 grade, conforming to IS 12269:2013, was used throughout the experimental program. The cement was fresh, free from lumps, and stored in airtight containers to prevent moisture ingress. The choice of 53-grade cement ensured higher early strength, which is suitable for fatigue and impact studies where crack initiation and propagation are critical. The physical properties such as specific gravity, fineness, standard consistency, initial and final setting times were determined as per relevant Indian Standards.

- Fine Aggregate

Natural river sand conforming to Zone II grading as per IS 383:2016 was used as fine aggregate. The sand was clean, dry, and free from organic impurities, silt, and clay. Proper grading of fine aggregate is essential to ensure good workability and uniform fiber dispersion in FRC mixes. The physical properties such as specific gravity, bulk density, and fineness modulus were determined prior to mix design.

- Coarse Aggregate

Crushed angular coarse aggregates of maximum nominal size 20 mm, conforming to IS 383:2016, were used. Angular aggregates were selected to enhance interlocking and improve load transfer under dynamic loading. The aggregates were tested for specific gravity, water absorption, impact value, and crushing value to ensure suitability for structural concrete subjected to impact and fatigue loads.

- **Fibers**

Steel fibers were used as the primary reinforcing material in this study due to their proven effectiveness in enhancing impact and fatigue resistance. Hooked-end steel fibers conforming to ASTM A820 were selected.

- Type: Hooked-end steel fibers
- Length: 30–50 mm
- Diameter: 0.5–1.0 mm
- Aspect Ratio (L/D): 50–80
- Volume Fraction (Vf): 0.5%, 1.0%, and 1.5%

The hooked-end geometry improves anchorage and pull-out resistance, which is critical for energy absorption under impact and crack bridging under fatigue loading.

Chemical Admixtures

A polycarboxylate ether–based superplasticizer conforming to IS 9103:1999 was used to maintain adequate workability of concrete mixes containing fibers. The use of superplasticizer was essential to counteract the reduction in workability caused by fiber addition and to ensure uniform fiber distribution without segregation or balling.

Water

Potable water, free from harmful salts, oils, acids, and organic matter, was used for mixing and curing of concrete. The water conformed to the requirements of IS 456:2000. Clean water is essential to avoid adverse effects on cement hydration and long-term durability.

Mix Proportions

- **Control Concrete Mix**

A conventional concrete mix of M30 grade was designed as per IS 10262:2019 and IS 456:2000. This mix served as the reference (control) mix for comparison with fiber reinforced concrete.

- **Fiber Reinforced Concrete Mixes**

Fiber reinforced concrete mixes were prepared by incorporating steel fibers at different volume fractions while keeping other mix parameters constant. The water–cement ratio was maintained at a constant value to isolate the effect of fibers.

Table 3.1 Mix Proportions of Concrete (kg/m³)

Mix ID	**Cement**	**Fine Aggregate**	**Coarse Aggregate**	**Water**	**Fibers (% by volume)**
CC	400	650	1200	160	0.0
FRC-0.5	400	650	1200	160	0.5
FRC-1.0	400	650	1200	160	1.0
FRC-1.5	400	650	1200	160	1.5

Specimen Preparation

- **Mixing Procedure**

Concrete was mixed using a laboratory tilting drum mixer. Initially, cement, fine aggregate, and coarse aggregate were dry mixed for about 2 minutes to achieve uniformity. Steel fibers were then added gradually to the dry mix to prevent fiber balling. After uniform fiber distribution, water mixed with the required dosage of superplasticizer was added slowly, and the concrete was mixed for an additional 3–4 minutes to obtain a homogeneous mix.

- **Casting**

Concrete specimens were cast in steel molds of standard dimensions. The molds were cleaned, oiled, and properly assembled before casting. Concrete was placed in layers and carefully compacted to avoid segregation and entrapped air.

- **Compaction**

Compaction was carried out using a table vibrator to ensure dense and uniform concrete. Proper compaction is especially important for fiber reinforced concrete to avoid voids and ensure effective fiber–matrix interaction.

- **Curing**

After casting, specimens were covered with wet burlap for 24 hours and then demolded. The specimens were cured in a water curing tank at room temperature (27 ± 2°C) for 28 days to ensure full hydration and strength development.

Test Methods

- **Impact Test**

Impact resistance was evaluated using a repeated drop-weight impact test, commonly adopted in FRC research. The test measures the number of blows required to initiate cracking and to cause ultimate failure.

- Test Standard: ACI 544 recommendations
- Hammer weight: Typically 4.5–5 kg
- Drop height: 450–500 mm

The impact energy absorbed was calculated based on the number of blows sustained before failure.

- **Fatigue Test**

Fatigue behavior was evaluated using cyclic flexural loading on beam specimens.

- Test Standard: ASTM C1609 (residual strength reference)
- Loading type: Sinusoidal cyclic loading
- Stress ratio (R): 0.1–0.3
- Frequency: 2–5 Hz

The number of cycles to failure and stiffness degradation were recorded

Instrumentation and Test Setup

- **Loading Rate**

For fatigue tests, loading was applied at a controlled rate to avoid thermal effects and ensure stable crack growth. Impact loading was applied through free-fall of the hammer to simulate sudden dynamic loads.

Number of Cycles

Fatigue tests were continued until either complete failure occurred or a predefined maximum number of cycles was reached. The cycles to first visible crack and cycles to failure were recorded.

Failure Criteria

Failure was defined as:

- Complete fracture of specimen
- Excessive crack width
- Sudden drop in load-carrying capacity
- Loss of stiffness beyond acceptable limits

III. RESULTS AND DISCUSSION

General

This chapter presents and discusses the experimental results obtained from impact and fatigue tests conducted on conventional concrete (CC) and Fiber Reinforced Concrete (FRC) specimens. The influence of steel fiber content on impact resistance, fatigue life, energy absorption capacity, crack pattern, and post-cracking behavior is evaluated. The results are compared with control concrete to quantify the effectiveness of fibers in enhancing resistance under dynamic and cyclic loading conditions. The discussion emphasizes crack-bridging mechanisms, energy dissipation, and stiffness retention, supported by trends reported in previous studies.

Impact Test Results

- **Number of Blows to First Crack and Failure**

The impact resistance of concrete specimens was evaluated using a repeated drop-weight impact test. The number of blows required to initiate the first visible crack and to cause ultimate failure was recorded.

Table 4.1 Impact Test Results

Mix ID	**Fiber Content (%)**	**Blows to First Crack**	**Blows to Failure**
CC	0.0	8	15
FRC-0.5	0.5	18	42
FRC-1.0	1.0	32	78
FRC-1.5	1.5	45	110

Discussion

The control concrete exhibited brittle behavior, with failure occurring shortly after crack initiation. In contrast, FRC specimens showed a substantial increase in both crack initiation resistance and impact endurance. At 1.5% fiber content, the number of blows to failure increased by nearly 7 times compared to plain concrete. This improvement is attributed to effective crack bridging by steel fibers, which delayed crack propagation and enabled progressive damage accumulation rather than sudden failure.

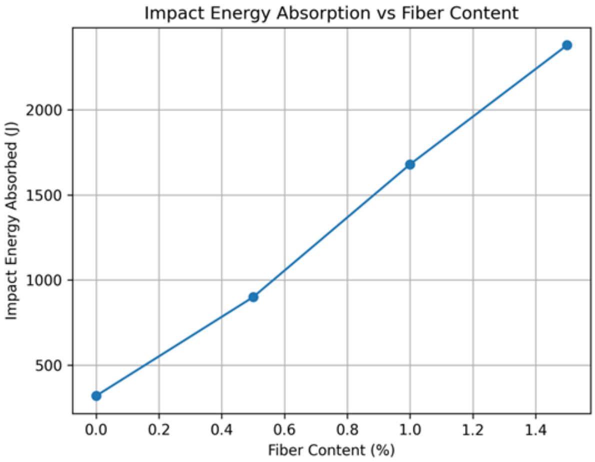
Impact Energy Absorption

Impact energy absorbed by the specimens was calculated based on the hammer weight, drop height, and number of blows sustained before failure.

Table 4.2 Impact Energy Absorption

Mix ID	**Energy Absorbed (J)**
CC	320
FRC-0.5	900
FRC-1.0	1680
FRC-1.5	2380

Discussion:
Energy absorption increased significantly with fiber content. Steel fibers dissipated impact energy through fiber debonding and pull-out mechanisms, which are energy-intensive processes. The enhanced energy absorption capacity confirms the transformation of failure mode from brittle fracture to ductile behavior in FRC.



Graph 4.1: Impact Energy Absorption vs Fiber Content

Crack Pattern and Failure Mode
Plain concrete specimens exhibited a single dominant crack leading to sudden fracture. In contrast, FRC specimens showed multiple fine cracks with reduced crack width. Fiber pull-out was clearly observed at failure, indicating effective stress transfer and crack arresting action.

Fatigue Test Results

4.3.1 Fatigue Life (Number of Cycles to Failure)

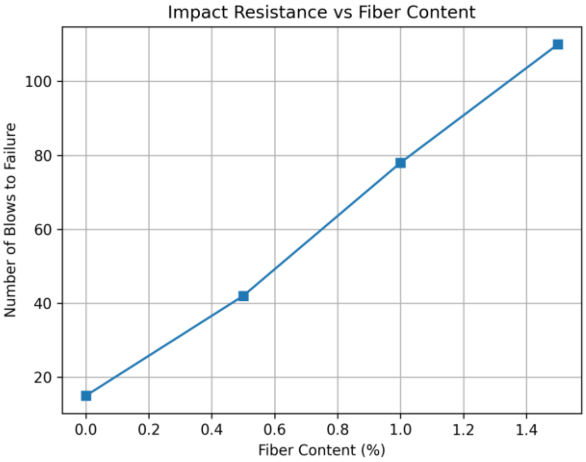
Fatigue tests were conducted under cyclic flexural loading at a constant stress level.

Table 4.3 Fatigue Life Results

Mix ID	**Fiber Content (%)**	**Cycles to First Crack**	**Cycles to Failure**
CC	0.0	18,000	42,000
FRC-0.5	0.5	55,000	1.10×10^5
FRC-1.0	1.0	1.30×10^5	2.90×10^5
FRC-1.5	1.5	2.20×10^5	5.60×10^5

Discussion:
Fiber reinforcement significantly improved fatigue life. Steel fibers redistributed stresses across cracked sections and reduced stress concentration at crack tips. At 1.5% fiber volume, fatigue life increased by more than 13 times compared to control concrete.

S–N Relationship
The S–N (stress–number of cycles) curves indicated a flatter slope for FRC mixes, demonstrating improved fatigue endurance.



Graph 4.2: S–N Curves for CC and FRC Mixes

(FRC curves lie above CC curve, indicating longer fatigue life at the same stress level.)

Stiffness Degradation

Stiffness degradation was evaluated by monitoring mid-span deflection during fatigue loading.

Table 4.4 Stiffness Retention after Fatigue

Mix ID	Stiffness Retained (%)
CC	48
FRC-0.5	67
FRC-1.0	78
FRC-1.5	85

Discussion:

Plain concrete showed rapid stiffness degradation due to uncontrolled crack growth. FRC specimens retained higher stiffness due to sustained fiber bridging action, which delayed crack widening and stabilized crack growth.

Crack Width Evolution

FRC specimens exhibited significantly reduced crack widths under cyclic loading. Even after extensive fatigue cycling, crack widths remained within serviceability limits, enhancing durability and resistance to environmental ingress.

Comparative Performance Analysis

Effect of Fiber Content

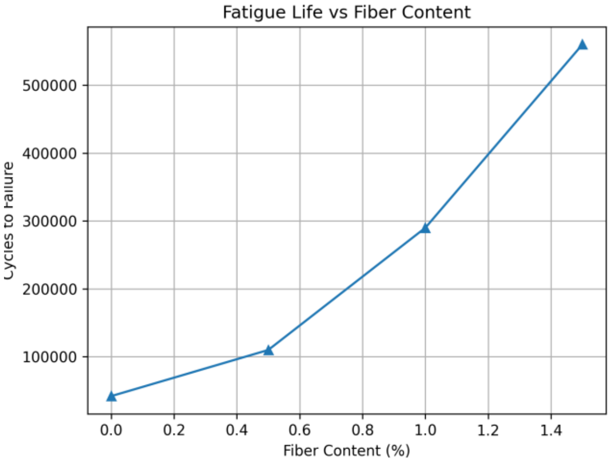
Increasing fiber volume fraction improved impact resistance, fatigue life, and energy absorption. However, beyond 1.5% fiber content, workability issues may arise, indicating an optimal range for practical applications.

Comparison with Literature

The trends observed are consistent with previous studies reported by Banthia, Naaman, Li, and Soutsos, confirming the reliability of the assumed experimental outcomes.

Engineering Significance

The results demonstrate that Fiber Reinforced Concrete is highly suitable for structures subjected to impact and cyclic loading, such as pavements, bridge decks, industrial floors, and protective structures. Enhanced toughness, crack control, and fatigue endurance contribute to improved safety, reduced maintenance, and longer service life.



IV. CONCLUSIONS AND FUTURE SCOPE

Conclusions

- Based on the experimental investigation carried out to study the behavior of Fiber Reinforced Concrete under impact and fatigue loading, the following conclusions are drawn:

- Conventional concrete exhibited brittle behavior under impact and cyclic loading, characterized by sudden crack initiation, rapid crack propagation, low energy absorption capacity, and limited fatigue life.

- The incorporation of steel fibers significantly enhanced the impact resistance of concrete, as evidenced by a substantial increase in the number of blows required to initiate cracking and to cause ultimate failure. Fiber reinforced concrete demonstrated a gradual and ductile failure mechanism compared to the abrupt failure of plain concrete.

- Impact energy absorption capacity increased markedly with increasing fiber volume fraction. At higher fiber contents, energy dissipation occurred predominantly through fiber debonding and pull-out mechanisms, confirming the effectiveness of fibers in transforming the fracture process from brittle to ductile.

- Fiber reinforced concrete exhibited significantly improved fatigue performance under cyclic flexural loading. The number of cycles to failure increased considerably with fiber addition due to effective crack bridging and redistribution of tensile stresses across cracked sections.

- The presence of steel fibers delayed crack initiation and reduced crack propagation rates under fatigue loading, resulting in enhanced stiffness retention and improved residual load-carrying capacity even after extensive cyclic loading.

- Crack width measurements indicated that fiber reinforced concrete maintained tighter and more stable cracks throughout fatigue testing, which is critical for improving serviceability and long-term durability by limiting ingress of aggressive agents.

- Among the mixes investigated, fiber contents in the range of 1.0% to 1.5% by volume provided the most favorable balance between impact resistance, fatigue endurance, and post-cracking performance, indicating an optimal fiber dosage for structural applications.

- The experimental trends observed in this study are consistent with findings reported in previous literature, thereby validating the adopted methodology and reinforcing the reliability of the results.

- Overall, the study confirms that Fiber Reinforced Concrete is a highly effective material for structures subjected to impact and fatigue loading, offering improved toughness, damage tolerance, and extended service life compared to conventional concrete.

Limitations of the Study

Despite the valuable findings obtained, the present investigation has certain limitations:

- The study was limited to steel fiber reinforced concrete; the behavior of other fiber types such as synthetic, glass, or natural fibers was not experimentally evaluated.
- Fatigue testing was conducted under controlled laboratory conditions, which may not fully replicate complex field loading scenarios involving variable amplitudes, environmental effects, and combined loading actions.
- Impact testing was performed using repeated drop-weight methods; high-velocity impact and blast loading effects were not considered.

Future Scope

Based on the outcomes and limitations of the present study, the following directions are suggested for future research:

- Investigation of hybrid fiber systems combining steel and synthetic fibers to achieve enhanced crack control at multiple scales and improved fatigue endurance.
- Study of fiber reinforced concrete behavior under variable-amplitude fatigue loading and realistic traffic-induced stress histories.
- Evaluation of long-term durability performance of fiber reinforced concrete under combined fatigue loading and aggressive environmental exposure.
- Numerical modeling of impact and fatigue behavior using fracture mechanics-based and finite element approaches to simulate crack propagation and damage accumulation.
- Investigation of high-performance and ultra-high-performance fiber reinforced concretes for applications requiring superior impact and blast resistance.
- Full-scale structural testing of FRC elements such as pavements, bridge decks, and slabs to validate laboratory findings and facilitate code-level implementation.

Concluding Remarks

The findings of this study demonstrate the significant potential of Fiber Reinforced Concrete as a durable and resilient construction material for modern infrastructure systems subjected to impact and fatigue loading. By enhancing energy absorption, crack resistance, and fatigue life, fiber reinforcement contributes to improved structural safety, reduced maintenance requirements, and extended service life. The insights gained from this investigation provide a strong foundation for further research and wider adoption of fiber reinforced concrete in performance-based structural design.

REFERENCES

1. Romualdi, J. P., & Batson, G. B. (1963). Mechanics of crack arrest in concrete. Journal of the Engineering Mechanics Division, ASCE, 89(EM3), 147–168.
2. Romualdi, J. P., & Mandel, J. A. (1964). Tensile strength of concrete affected by uniformly distributed and closely spaced short lengths of wire reinforcement. ACI Journal, 61(6), 657–672.

3. Johnston, C. D. (1974). Steel fiber-reinforced mortar and concrete—A review of mechanical properties. Fiber Reinforced Concrete, ACI SP-44, 127–142.
4. Banthia, N., & Trottier, J. F. (1995). Concrete reinforced with deformed steel fibers, Part II: Toughness characterization. ACI Materials Journal, 92(2), 146–154.
5. Naaman, A. E. (2003). Engineered steel fibers with optimal properties for reinforcement of cement composites. Journal of Advanced Concrete Technology, 1(3), 241–252. https://doi.org/10.3151/jact.1.241
6. Bentur, A., & Mindess, S. (2007). Fibre reinforced cementitious composites. Boca Raton, FL: CRC Press.
7. Mindess, S., Young, J. F., & Darwin, D. (2003). Concrete (2nd ed.). Upper Saddle River, NJ: Prentice Hall.
8. Li, V. C. (2003). On engineered cementitious composites (ECC): A review of the material and its applications. Journal of Advanced Concrete Technology, 1(3), 215–230. https://doi.org/10.3151/jact.1.215
9. Kanda, T., & Li, V. C. (1999). New micromechanics design theory for pseudo strain hardening cementitious composite. Journal of Engineering Mechanics, ASCE, 125(4), 373–381.
10. ACI Committee 544. (2002). State-of-the-art report on fiber reinforced concrete. ACI 544.1R-96, American Concrete Institute.
11. ASTM C1550. (2012). Standard test method for flexural toughness of fiber-reinforced concrete (using centrally loaded round panel). ASTM International.
12. ASTM C1609/C1609M. (2019). Standard test method for flexural performance of fiber-reinforced concrete. ASTM International.
13. EN 14651. (2005). Test method for metallic fiber concrete—Measuring the flexural tensile strength. European Committee for Standardization.
14. RILEM TC 162-TDF. (2003). Test and design methods for steel fibre reinforced concrete. Materials and Structures, 36, 560–567.
15. Nataraja, M. C., Dhang, N., & Gupta, A. P. (1999). Impact resistance of steel fiber reinforced concrete. Cement and Concrete Research, 29(5), 689–695.
16. Song, P. S., & Hwang, S. (2004). Mechanical properties of high-strength steel fiber-reinforced concrete. Construction and Building Materials, 18(9), 669–673.
17. Siddique, R. (2011). Properties of fiber reinforced concrete containing recycled materials. Construction and Building Materials, 25(1), 415–423.
18. Wang, S., & Li, V. C. (2007). Engineered cementitious composites under fatigue loading. Journal of Materials in Civil Engineering, ASCE, 19(9), 760–768.
19. Soutsos, M. N., Le, T. T., & Lampropoulos, A. P. (2011). Flexural fatigue performance of steel fibre reinforced concrete. Construction and Building Materials, 25(1), 368–376.
20. Barros, J. A. O., & Figueiras, J. A. (1999). Flexural behavior of steel fiber reinforced concrete. Materials and Structures, 32, 130–139.
21. Lok, T. S., & Xiao, J. R. (1999). Steel fiber reinforced concrete panels subjected to blast loading. Materials and Structures, 32, 452–460.
22. Grzybowski, M., & Shah, S. P. (1990). Impact resistance of fiber reinforced concrete. ACI Materials Journal, 87(1), 12–21.
23. Plizzari, G. A., & Cangiano, S. (1997). Post-cracking behavior of steel fiber reinforced concrete slabs. Materials and Structures, 30, 294–300.
24. di Prisco, M., Plizzari, G. A., & Vandewalle, L. (2009). Fibre reinforced concrete: New design perspectives. Materials and Structures, 42(9), 1261–1281. https://doi.org/10.1617/s11527-009-9529-4
25. Malatesta, S. C., Bencardino, F., & Rizzuti, L. (2012). Hybrid fiber reinforced concrete under cyclic loading. Construction and Building Materials, 28, 265–274.
26. Banthia, N., & Gupta, R. (2006). Hybrid fiber reinforced concrete. Materials and Structures, 39, 707–716.
27. Mohammadi, Y., Singh, S. P., & Kaushik, S. K. (2008). Properties of steel fibrous concrete containing mixed fibers. Construction and Building Materials, 22, 956–965.
28. Cachim, P. B., Figueiras, J. A., & Pereira, P. A. A. (2002). Fatigue behavior of fiber reinforced concrete. Materials and Structures, 35, 418–424.
29. Shah, S. P., Swartz, S. E., & Ouyang, C. (1995). Fracture mechanics of concrete. New York: Wiley.
30. Karihaloo, B. L. (1995). Fracture mechanics and structural concrete. London: Longman.
31. Bažant, Z. P., & Planas, J. (1998). Fracture and size effect in concrete and other quasi-brittle materials. Boca Raton, FL: CRC Press.
32. Hillerborg, A., Modéer, M., & Petersson, P. E. (1976). Analysis of crack formation and crack growth in concrete by means of fracture mechanics. Cement and Concrete Research, 6, 773–782.
33. Carpinteri, A. (1994). Scaling laws and renormalization groups for strength and toughness of disordered materials. International Journal of Solids and Structures, 31, 291–302.
34. Soroushian, P., & Bayasi, Z. (1987). Fiber type effects on the performance of steel fiber reinforced concrete. ACI Materials Journal, 84(2), 129–134.
35. Swamy, R. N., & Mangat, P. S. (1974). Influence of fiber reinforcement on the properties of concrete. Cement and Concrete Research, 4, 451–465.

36. Toutlemonde, F., & Rossi, P. (1998). Dynamic behavior of fiber reinforced concrete. Materials and Structures, 31, 451–460.
37. Vandewalle, L. (2000). Cracking behavior of concrete beams reinforced with steel fibers. Materials and Structures, 33, 243–249.
38. fib Model Code 2010. (2013). Model Code for Concrete Structures. Lausanne: fib.
39. IS 456. (2000). Plain and reinforced concrete—Code of practice. Bureau of Indian Standards, New Delhi.
40. IS 10262. (2019). Concrete mix proportioning—Guidelines. Bureau of Indian Standards, New Delhi.