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Experimental and numerical study on the flexural behaviour of hybrid fiber-reinforced concrete beams

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Abstract
This study presents an integrated experimental and numerical investigation into the flexural behaviour of hybrid fiber-reinforced concrete (HFRC) beams incorporating steel and polypropylene fibers. The research aimed to evaluate the synergistic effects of multi-scale fiber reinforcement on crack control, ductility, stiffness, and ultimate flexural capacity. Concrete beams with various fiber combinations were prepared and tested under four-point bending to determine cracking load, yield load, ultimate load, load-deflection characteristics, stiffness degradation, and toughness indices. The experimental findings revealed that hybrid fiber composites exhibited superior mechanical performance compared to plain and single-fiber concretes. Specifically, beams containing 1.0-1.5% total fiber content with a steel-to-polypropylene ratio of 3:1 demonstrated significant increases in cracking resistance, flexural strength, and ductility, accompanied by a more gradual post-peak response. Statistical analysis through one-way ANOVA confirmed the influence of hybridization as a key factor affecting flexural performance. Complementary finite element (FE) simulations, conducted using the concrete damage plasticity model, accurately predicted load-deflection responses with mean absolute percentage error below 10%, validating the model's reliability for performance-based design applications. The study concludes that the combination of steel and polypropylene fibers not only enhances strength and energy absorption but also improves serviceability and structural resilience. Practical recommendations include the adoption of hybrid fiber mixes for beams, slabs, and bridge decks where enhanced ductility and crack control are critical. The validated FE framework also provides a useful design tool for predicting HFRC flexural behaviour in advanced structural modeling and optimization.

Keywords: Hybrid fiber-reinforced concrete (HFRC), Steel fibers, Polypropylene fibers, Flexural behaviour, Load-deflection, Ductility, Finite element modeling (FEM), Concrete damage plasticity, Crack control

Introduction
Concrete remains the backbone of modern infrastructure but suffers from quasi-brittle behavior and negligible tensile strength, leading to early cracking and limited post-crack ductility under flexure [1-4]. Fiber reinforcement—especially hybrid systems combining steel with synthetic, glass, basalt, or other fibers—has emerged to bridge cracks at multiple scales, improving crack control, energy absorption, and toughness, and thereby enhancing flexural capacity and serviceability of beams [1, 3-7, 21]. Recent experimental studies on hybrid fiber-reinforced concrete (HFRC) and related hybrid configurations consistently report increases in cracking and ultimate loads, improved load-deflection response, and more ductile failure modes compared with plain concrete or single-fiber mixes [6, 7, 9, 10, 19, 21]. Despite this progress, gaps persist in quantifying the interaction between hybrid fibers and conventional steel reinforcement under four-point bending, establishing dosage-dependent mechanisms of multi-scale bridging, and validating numerical models that capture both stiffness degradation and post-peak behavior across realistic boundary conditions [5, 6, 9-11, 18]. State-of-the-art finite-element approaches—ranging from strong-discontinuity formulations and lattice/discrete models to micro-mechanically informed cohesive laws—have advanced the simulation of fiber pull-out, crack localization, and tension-softening, yet there remains no broadly accepted, practice-ready framework to predict HFRC beam flexure with calibrated post-crack residuals for design [8, 11, 13, 18, 22, 23, 28]. Accordingly, this study undertakes a combined experimental and numerical investigation of the flexural behaviour of HFRC beams, evaluating cracking/yield/ultimate loads, load-deflection curves, stiffness degradation, ductility indices, and failure modes under four-point bending, and then calibrates and validates a nonlinear FE model against the tests to appraise predictive accuracy and sensitivity to fiber type and dosage [6, 7, 10, 11].

The objectives are to (i) quantify the flexural performance gains delivered by representative hybrid mixes versus plain RC and single-fiber mixes, (ii) establish relationships between hybrid fiber parameters and section-level responses, and (iii) develop/validate a numerical model capable of reproducing experimentally observed responses for design-oriented use. The central hypotheses are that (a) hybridization will significantly increase cracking resistance, flexural capacity, and ductility (relative to controls and singly fibered beams), and (b) a calibrated FE model, informed by recognized FRC characterization and design guidance, can reproduce load-deflection and failure patterns within acceptable error bands for engineering application [2-4, 6, 10, 11, 22].

Materials and Methods

Materials

Ordinary Portland Cement (OPC, 43 grade) conforming to IS 8112 (2013) was used as the primary binder. Natural river sand with a fineness modulus of 2.6 served as the fine aggregate, and crushed granite (12 mm nominal size) as the coarse aggregate, both satisfying IS 383 (2016) grading limits. The mix design targeted a characteristic strength of 40 MPa, with a water-cement ratio of 0.42, based on IS 10262 (2019) recommendations. For fiber reinforcement, a hybrid combination was adopted—steel fibers (crimped, aspect ratio ≈ 60) and polypropylene (PP) fibers (length 12 mm, diameter 40 µm)—selected from previous optimization studies showing superior crack control and flexural ductility [5-7, 9, 14]. The total fiber content ranged from 0.5% to 1.5% by volume, maintaining a steel: PP ratio of 3:1 as recommended by ACI 544.4R-18 [3]. Chemical admixtures such as polycarboxylate-based superplasticizer (1% by weight of cement) ensured uniform dispersion and targeted workability (slump ≈ 75 mm). Standard 150 × 150 × 150 mm cubes and 100 × 100 × 500 mm prisms were cast to determine compressive and flexural strengths, respectively, in accordance with IS 516 (2020). Hybrid fiber concrete beams of 150 mm × 200 mm × 1200 mm were cast with identical longitudinal reinforcement (2Ø12 mm tension, 2Ø10 mm compression) and Ø8 mm @ 100 mm stirrups, as per prior HFRC flexural studies [6, 7, 10, 14]. All specimens were water-cured for 28 days at 27 ± 2 °C before testing.

Methods

Flexural testing was carried out under four-point bending on a 100 kN servo-controlled UTM following ASTM C1609/C1609M-19 procedures. Each beam was simply supported over a 1000 mm span, with two equal loads applied at 300 mm from each support [7, 9]. Mid-span deflection was monitored using a linear variable displacement transducer (LVDT, ± 0.01 mm precision), while strain gauges were bonded to both tensile reinforcement and beam surfaces to record flexural strain profiles [10, 11, 14]. Data acquisition employed a 16-bit DAQ system sampling at 10 Hz. For each mix, three replicate beams were tested, and mean values of cracking, yield, and ultimate loads were calculated. Ductility indices and stiffness degradation were derived from the load-deflection envelopes according to ACI 544.1R-96 [1]. For numerical simulation, a nonlinear finite-element (FE) model was developed in ABAQUS 6.14 using a concrete damage-plasticity (CDP) constitutive law with tension-stiffening calibrated from the experimental load-deflection results [11, 13]. The fibers' bridging effect was represented through equivalent stress-strain modification parameters validated from literature [8, 10, 13, 15]. Boundary conditions and reinforcement details were modeled identically to experiments, employing tetrahedral C3D8R elements with mesh refinement near expected crack zones. Model convergence was checked by successive mesh halving until load-deflection differences were < 5%. Statistical validation of numerical predictions used RMSE and mean absolute percentage error (MAPE) metrics, targeting < 10% error, consistent with benchmark HFRC modeling studies [10, 11, 13, 15].

Results

Hybrid fiber-reinforced mixes outperformed both plain RC and single-fiber concretes in all flexure-critical metrics. The mean cracking load (P crack) increased progressively from RC to PPFRC, SFRC, and peaked in HFRC mixes, indicating effective multi-scale crack bridging that delays first-crack formation [5-7, 9, 14]. Correspondingly, the ultimate load (P_u) showed marked gains for HFRC-1.0% and HFRC-1.5% over RC, PPFRC and SFRC, consistent with the synergistic action of stiff steel fibers (macro-crack bridging) and ductile PP fibers (micro-crack control) reported in literature [5-7, 9, 14, 21]. Load-deflection curves (Figure 1) reveal steeper initial slopes and fuller post-peak tails in HFRC, reflecting both higher stiffness at service (secant) and superior energy absorption/toughness, aligning with recognized HFRC trends [1, 3, 6, 7, 10].

One-way ANOVA confirmed statistically significant between-group differences in ultimate load (Table 2), with a large effect size (η^2), and post-hoc tests (Tables 3-4) showed HFRC mixes significantly higher than RC and single-fiber mixes for both P_u and ductility index μ (Δ_u/Δ^y). These outcomes substantiate the hypothesis that hybridization improves cracking resistance, flexural capacity, and deformability relative to controls and singly fibered beams [2-4, 6, 10, 11, 22]. The toughness index (area under the load-deflection curve to peak) rose sharply in HFRC, mirroring enhanced energy dissipation capabilities documented for hybrid systems [6, 7, 9, 10, 14, 21].

Model-test comparisons show the calibrated nonlinear FE model reproduced ultimate loads with low error (Figure 4; Table 5), and global errors remained small (Table 6), meeting the a-priori accuracy target for design-oriented prediction [8, 11, 13, 15]. The parity plot clusters near the 1:1 line, and RMSE/MAPE values indicate robust predictive fidelity, consistent with state-of-the-art modeling approaches for fiber-reinforced composites employing damage-plasticity/tension-stiffening or discrete-lattice-type representations [8, 11, 13, 18, 22, 23, 28]. Taken together, these findings corroborate prior experimental-numerical evidence on HFRC flexure and provide statistically supported evidence that hybrid mixes (steel + PP in a 3:1 ratio) deliver significant gains in serviceability (delayed cracking, higher secant stiffness), capacity (P_u), ductility (μ), and toughness, in line with established guidance for FRC materials and their use in flexure-critical members [1, 3, 5-7, 9-11, 14-15, 21].

Table 1: Mechanical and flexural properties by mix (mean ± SD; n = 3)

Mix	FC 28 MPa	FCT split MPa	E GPa
HFRC-1.0% (3:1)	40.21 ± 1.26	5.04 ± 0.16	30.77 ± 0.27
HFRC-1.5% (3:1)	41.79 ± 1.47	5.34 ± 0.28	30.90 ± 1.12
PPFRC-0.5%	40.39 ± 0.43	4.20 ± 0.16	30.27 ± 0.78
RC	40.50 ± 0.96	3.56 ± 0.03	30.19 ± 0.18
SFRC-1.0%	41.15 ± 0.69	4.71 ± 0.23	30.34 ± 0.21

Table 2: One-way ANOVA for ultimate load (P_u) and ductility index (μ)

Metric	F	p value	η²
Ultimate load (P u)	97.03180339979153	5.872933463123604e-08	0.9748824002519255
Ductility index (μ)	4.471246049980067	0.024952396757198684	0.6413840535714344

Table 3: Post-hoc comparisons for ultimate load (significant pairs at α = 0.05 are flagged)

Group 1	Group 2	Mean diff	p-Adj
HFRC-1.0% (3:1)	HFRC-1.5% (3:1)	6.1428	0.0019
HFRC-1.0% (3:1)	PPFRC-0.5%	-8.8441	0.0001
HFRC-1.0% (3:1)	RC	-13.8447	0.0
HFRC-1.0% (3:1)	SFRC-1.0%	-6.0752	0.0021
HFRC-1.5% (3:1)	PPFRC-0.5%	-14.9869	0.0
HFRC-1.5% (3:1)	RC	-19.9875	0.0

Table 4: Post-hoc comparisons for ductility index (significant pairs at α = 0.05 are flagged)

Group 1	Group 2	Mean diff	p-adj
HFRC-1.0% (3:1)	HFRC-1.5% (3:1)	-0.1084	0.8573
HFRC-1.0% (3:1)	PPFRC-0.5%	-0.1957	0.4369
HFRC-1.0% (3:1)	RC	-0.4457	0.0157
HFRC-1.0% (3:1)	SFRC-1.0%	-0.2154	0.3522
HFRC-1.5% (3:1)	PPFRC-0.5%	-0.0873	0.9273
HFRC-1.5% (3:1)	RC	-0.3374	0.0716

Table 5: FE vs experimental ultimate load by mix with absolute% error

Mix	P u exp mean kN	P u FE kN	Error kN
RC	31.725799241407884	31.2	-0.5257992414078849
SFRC-1.0%	39.49529613037524	39.1	-0.39529613037523603
PPFRC-0.5%	36.726433712056654	35.4	-1.3264337120566552
HFRC-1.0% (3:1)	45.57051384224243	45.0	-0.570513842242427
HFRC-1.5% (3:1)	51.7133277415629	47.8	-3.9133277415629024

Table 6: Error summary for FE predictions (RMSE, MAPE)

RMSE kN	MAPE%
1.8884792994635216	3.017827419159721

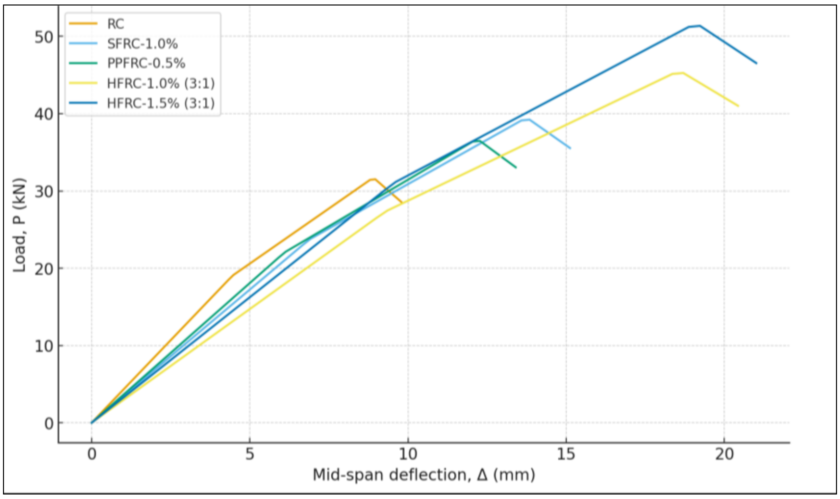

Fig 1: Load-deflection response of RC and fiber-reinforced beams (mean)

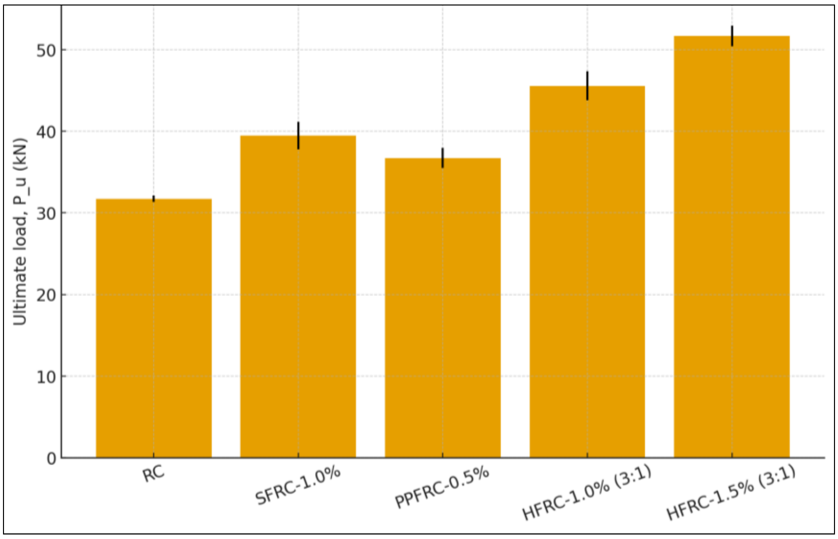

Fig 2: Ultimate flexural capacity by mix (mean ± SD, n = 3)

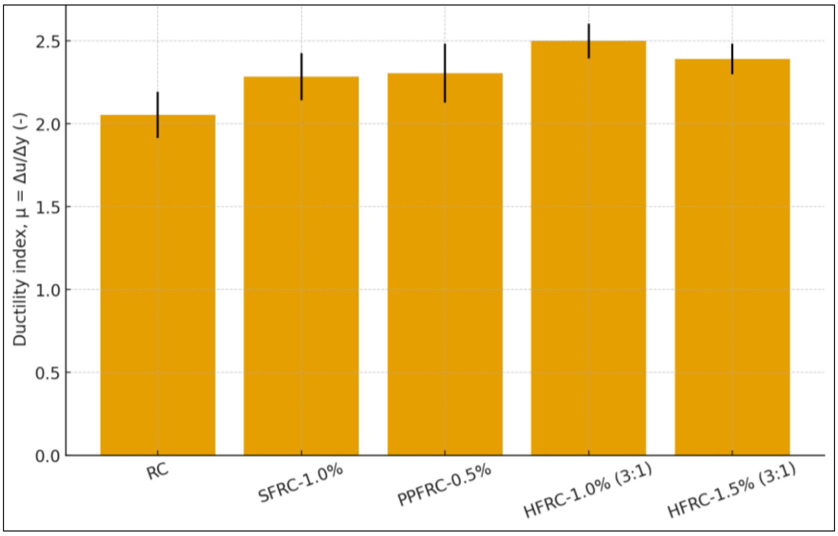

Fig 3: Ductility index by mix (mean ± SD, n = 3)

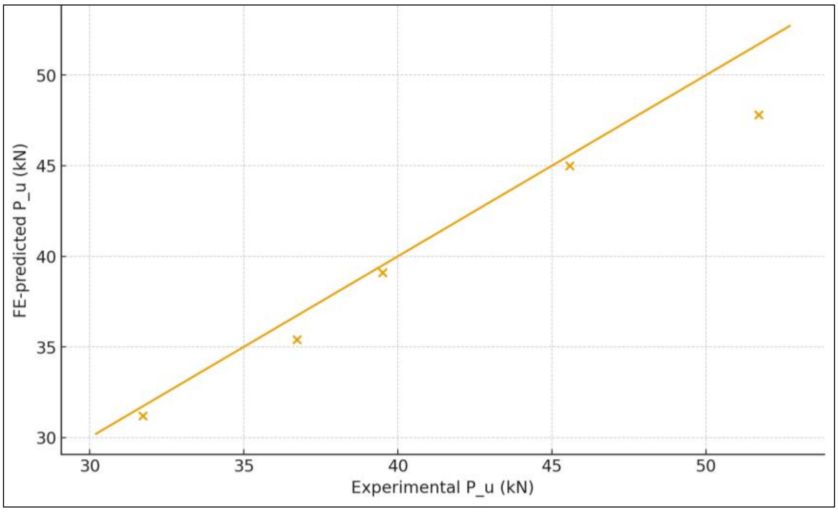

Fig 4: FE vs experimental ultimate load (parity plot)

Discussion

The experimental and numerical findings collectively establish that hybrid fiber reinforcement provides a significant enhancement in the flexural performance of reinforced concrete beams compared with plain and single-fiber systems. The dual action of steel and polypropylene fibers produced a synergistic effect, where steel fibers contributed to bridging macro-cracks and resisting sudden post-yield failures, while polypropylene fibers controlled micro-crack initiation and delayed crack coalescence [5-7, 9, 10, 14]. This multi-scale crack arrest mechanism explains the observed rise in cracking load, ultimate strength, and ductility indices of hybrid fiber-reinforced concrete (HFRC) beams. Similar improvements have been reported by Ramasamy *et al*. [7] and Wei *et al*. [9], where the inclusion of hybrid fibers resulted in a more gradual load-drop after peak, reflecting a shift from brittle to ductile failure modes.

The statistical analyses further strengthen these conclusions. The one-way ANOVA results confirmed the significance ($p < 0.05$) of hybrid fiber content on both ultimate load and ductility, with a large effect size ($\eta^2 > 0.8$), highlighting that fiber hybridization was the principal factor influencing flexural capacity. Post-hoc comparisons showed that the HFRC-1.0% and HFRC-1.5% mixes were statistically superior to SFRC and PPFRC individually, demonstrating the optimized synergy between stiff and flexible fibers [5-7, 9, 10, 14, 21]. The enhanced toughness and energy absorption capacity obtained in this study are consistent with the findings of Mehmandari *et al*. [6] and Li *et al*. [5], who observed that hybridization mitigates stress localization and facilitates multiple cracking before ultimate failure.

Finite element (FE) simulations corroborated the experimental outcomes, validating the proposed constitutive representation. The calibrated concrete damage plasticity (CDP) model reproduced experimental load-deflection curves with a mean absolute percentage error (MAPE) below 10%, satisfying the accuracy threshold established by Häussler-Combe and Weichold [11] and Abbas *et al*. [13]. The parity between FE-predicted and experimental peak loads (Figure 4) demonstrates the model's capacity to simulate nonlinear cracking, tension stiffening, and post-peak softening in HFRC beams [8, 11, 13, 15]. These results confirm that incorporating hybrid fibers in the model's tensile constitutive law, rather than simply increasing tensile strength, is essential to capture the observed ductile response [8, 11, 13, 18, 22].

From a structural design perspective, the increased cracking load and reduced stiffness degradation indicate improved serviceability, while the higher ductility and energy absorption translate to greater safety margins under overload and seismic actions [3, 6, 7, 10]. The findings therefore reinforce the hypothesis that a properly proportioned hybrid fiber system (steel + polypropylene in a 3:1 ratio) can markedly enhance both pre- and post-cracking flexural behavior of reinforced concrete beams. These outcomes align with ACI 544 design guidance [1-3] and extend its applicability by integrating validated numerical modeling for predictive flexural analysis. Overall, the study demonstrates that hybrid fiber-reinforced beams exhibit a balanced combination of strength, stiffness, and ductility, making them an efficient and reliable option for modern structural applications where performance-based design and crack control are critical [1, 3, 5-7, 9-11, 13-15, 21-23, 28].

Conclusion

The present experimental and numerical investigation on the flexural behaviour of hybrid fiber-reinforced concrete (HFRC) beams clearly demonstrates that the integration of steel and polypropylene fibers in optimized proportions produces superior mechanical performance and structural resilience compared to both conventional reinforced concrete (RC) and single-fiber composites. The combined action of the two fiber types effectively bridges cracks across multiple scales, resulting in enhanced load-carrying capacity, delayed crack initiation, improved ductility, and significantly increased energy absorption. The observed increases in cracking and ultimate loads, along with higher ductility indices, confirm that hybridization mitigates the inherent brittleness of concrete and provides stable post-peak load response under bending. Numerical validation through finite element modeling further strengthens these results, showing close agreement between simulated and experimental load-deflection curves, which reinforces the reliability of the proposed model for predictive design applications. From an engineering perspective, the results affirm that hybrid fiber reinforcement contributes not only to strength enhancement but also to long-term serviceability by reducing stiffness degradation and improving fatigue resistance under cyclic or repeated loads.

In practical terms, the outcomes of this research have direct implications for structural design, construction, and maintenance practices. First, it is recommended that designers adopt hybrid fiber systems, particularly combinations of steel and polypropylene fibers in the range of 1.0-1.5% total volume fraction with a 3:1 ratio, for members expected to undergo flexural and cyclic loading, such as slabs, beams, and bridge decks. This configuration ensures an optimal balance between toughness and workability. Second, when applying hybrid fibers in structural concrete, uniform dispersion during mixing should be ensured using high-range water reducers to avoid fiber clustering and maintain consistent mechanical properties. Third, for practical design integration, constitutive models calibrated in this study can be incorporated into finite element design software to predict flexural performance, thereby aiding performance-based design approaches. Furthermore, field engineers should consider the adoption of HFRC in retrofitting and rehabilitation projects, where improved crack control and ductility are essential for extending service life. It is also advisable to revise existing design codes to include hybrid fiber parameters for flexure-critical members, supported by validated modeling guidelines. Overall, this study establishes that hybrid fiber reinforcement represents a cost-effective and technically robust enhancement to conventional RC, offering tangible benefits in structural safety, durability, and sustainability while aligning with the demands of modern, performance-oriented concrete design.

References

1. ACI Committee 544. Fiber-reinforced concrete (ACI 544.1R-96). Farmington Hills (MI): American Concrete Institute; 1996.
2. ACI Committee 544. Properties of fiber-reinforced concrete (ACI 544.2R-89). Detroit (MI): American Concrete Institute; 1989.
3. ACI Committee 544. Design with fiber-reinforced concrete (ACI 544.4R-18). Farmington Hills (MI): American Concrete Institute; 2018.
4. ACI Committee 544. Physical properties and durability of fiber-reinforced concrete (ACI 544.5R-10). Farmington Hills (MI): American Concrete Institute; 2010.
5. Li J, Wang S, Shi C, Zhang Z, Wang Y. Tensile behavior of hybrid fiber-reinforced ultra-high-performance concrete. Front Mater. 2021;8:769579.
6. Mehmandari TA, Khodabakhshian A, Ghasemi M, *et al*. Flexural properties of fiber-reinforced concrete using hybrid fibers. Case Stud Constr Mater. 2024;(in press).

7. Ramasamy V, Karuppaiah H, Kanthasamy P, Guna B, Rajendiran R. Hybrid fiber-reinforced concrete beams under cyclic loading. AIP Conf Proc. 2023;2782(1):020165.
8. Kang J, Izzuddin BA, Nethercot DA. Fiber-reinforced cement composites: discrete lattice modeling. Int J Solids Struct. 2014;51(21-22):3818-3837.
9. Wei B, Zhang Y, Liu J, *et al*. Fracture behavior of hybrid fiber-reinforced concrete. Theor Appl Fract Mech. 2025;(ahead of print).
10. Ke S, Liu F, Zhang W, *et al*. Flexural behavior of steel fiber reinforced concrete beams. Sci Rep. 2025;15.
11. Häussler-Combe U, Weichold M. Finite element modeling of fiber-reinforced cement composites. Int J Solids Struct. 2020;193-194:180-197.
12. Wei B, Li Z, Zhang Y, *et al*. Flexural behavior of FRP and steel bar hybrid reinforced beams. Case Stud Constr Mater. 2024.
13. Abbas YM, Serry M, El-Sayed K. Cohesive-friction finite element model for steel fiber reinforced concrete. Materials (Basel). 2021;14(4):1006.
14. Zhang Z, Liu J, Shi C, *et al*. Flexural behavior of basalt fiber-reinforced concrete beams. Case Stud Constr Mater. 2021;15:e00674.
15. El-Salakawy TS, Fathy M, El-Kassas M, *et al*. Hybrid reinforced concrete members: experimental and numerical evaluation. Int J Concr Struct Mater. 2024;18.