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Shear strength prediction of hybrid fiber-reinforced concrete deep beams

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ABSTRACT

The present study aims at developing mathematical equations for predicting the shear strength of Hybrid Fibre Reinforced Concrete (HFRC) deep beams. Parameters considered include split tensile strength, concrete shear strength, fibre factor, and the shear span-to-depth ratio (*a*/*d*) of deep beams. The developed equations are useful for hybrid fibre combinations, particularly steel and polypropylene fibres in concrete. Validation with experimental data and past reported results shows good accuracy in prediction, with shear strength ratios close to unity. The proposed equations provide structural engineers with reliable, cost-effective tools for safe and efficient shear strength prediction in HFRC deep beams.

Keywords: Deep beams; fibrillated polypropylene fiber; hooked end steel fiber; hybrid fiber reinforced concrete; shear strength

1. INTRODUCTION

Many researchers have examined and have contributed to the advancement of fiber-reinforced concrete deep beams' shear strength. Narayan and Darwish (1988), Sachan and Kameswar Rao (1990), Khuntia et al., (1999), Kwak et al., (2002), Slater et al., (2012), Shahanawaz and Alam (2014) and others have presented their equations for shear strength prediction of deep beams. The majority of them are for steel fiber-reinforced deep beams. In view of this, the current work presents a general equation useful for predicting the shear strength of HFRC deep beams. Further, this developed general equation is explicitly modified for the prediction of shear strength of HFRC with steel + Polypropylene (PP) fiber concrete deep beams.

Better-quality concrete is obtained when two or more fiber types are added in concrete (Patel et al., 2012). The addition of hybrid fibers to concrete has shown significant improvement in the shear strength of hybrid fiber-reinforced concrete (HFRC) deep beams (Kulkarni and Halkude, 2022). A lot of evolution has taken place in last decade in study of shear-transfer mechanism of fiber-reinforced concrete. Latest fiber-reinforced studies use mechanisms such as fiber pull-out, study of crack propagation, its bridging, and improvement in energy absorption with delayed failure. The advancement of hybrid fibers, has modified shear transfer, causing better performance, ductility and durability in deep beams (Ma et al., 2018).

Synergy theory suggests that, combination of fibers of different aspect ratios, strengths, and elastic moduli causes complementary effects. One fiber type minimizes crack initiation, while another controls crack propagation. This results in enhanced toughness, ductility, and energy absorption. Size effect in HFRC deep beams is crucial as it influences strength as well as failure mode. Beams with larger dimensions will show reduced strength as a effect of stress redistribution and crack localization. Scaling laws take care of geometric and material non-linearities, making study on smaller specimens possible. These effects allow precise design and consistent performance of prototype HFRC structures (Banthia and Gupta, 2004).

The present work uses Steel and Polypropylene fibers in concrete for casting of HFRC deep beams due to the benefits of these fibers for concrete. The study highlights these benefits and uses them in the development of equations for shear strength enhancement of HFRC deep beams.

Objectives of the Study

1. To analyse and obtain mathematical equations to predict the shear strength of the HFRC deep beams.
2. To obtain the validation of the developed equations through an experimental study undertaken in the current investigation.
3. To compare the prediction of the developed equations with the experimental results and the predictions of other researchers.

2. METHODOLOGY

An extensive experimentation in laboratory is conducted on shear strength evaluation of HFRC Deep beams and the results obtained are published (Kulkarni and Halkude, 2022). In continuation with the experimental work, analytical investigation is carried out and equations are presented for shear strength prediction of HFRC deep beams. Validation of these equations is carried out with the results obtained.

Many factors influence the shear strength of deep beams. One crucial factor is the tensile strength of concrete. Enhancement in a tensile strength improves crack resistance of concrete and contributes to the improvement in the shear strength of deep beams. Tensile strength of concrete and hence shear strength of deep beams will get influenced by enhancement in grade of concrete.

Tensile strength of fiber reinforced concrete improves with increase in steel fiber volume fraction but up to certain limit. The fibers' aspect ratio also has a significant impact. Steel fibers with aspect ratio greater than 80, cause balling effect during mixing and results in reduced strength of concrete. Bond between surface of fiber and the matrix is also crucial factor. Hooked ends of the steel fibers, improve bond between fiber and matrix, which enhances tensile strength of concrete.

All the fiber properties are presented in a standard parameter called fiber factor, which is calculated by multiplication of the fiber volume fraction, fiber aspect ratio, and the extent of bond between the fiber and the matrix. Split tensile strength and the shear strength of fiber reinforced concrete improves in proportion to the fiber factor.

The load-carrying capacity of a deep beam is inversely proportional to its shear span-to-depth (a/d) ratio. Due to external loading, cracks appear along the diagonal joining the loading to support points, as the majority of the load is carried by this diagonal in deep beams.

Sample size and statistical power: Around 175 HFRC deep beam samples were cast and tested under the present work. This sample size provided statistical power to utilize results in development of shear strength equations and making them more reliable.

2.1. Development of Equations

Crack propagation in Steel + Polypropylene HFRC includes micro-crack arrest by Polypropylene fibers and macro-crack bridging by Steel fibers. These fibers types distribute stresses uniformly, delay crack initiation and its propagation. Hybrid fiber reinforcement improves strength ductility, toughness, and post-cracking behaviour.

Empirical models for the study of fiber-reinforced concrete make use of experimental data and consequent regression analysis. This may not investigate fiber matrix interaction, crack initiation and loading. Mechanistic models investigate micro-structural principles and material mechanics. For development of underlying equations, both these models are studied, to acquire best results as detailed below.

2.1.1. General Equation for Shear Strength Prediction of Hfrc Deep Beams

Parameters involved in the improvement of shear strength of HFRC deep beams are studied. Considering all parameters, a general equation for shear strength prediction of HFRC deep beams is obtained as follows.

Basically,

$v_{u\,(predict)} = v_u\,(hfrc) + \tau_c$--------- (i)

Where,

$v_{u\,(predict)}$ = Ultimate shear strength of HFRC deep beam

$v_u\,(hfrc)$ = Shear strength contribution of hybrid fiber reinforced concrete,

τ_c = Basic shear strength contribution of plain Concrete

2.1.2. Shear Strength Contribution of HFRC [*Vu (hfrc)*]

Fig. 1 shows a simply supported hybrid fiber-reinforced concrete deep beam subjected to two-point loading and the load redistribution pathways. As a result of two-point loading, the central part of the beam is under pure bending. Shear span regions are subjected mainly to shear.

Consider a shear span region on any one side of the beam. At maximum load P_u, the load transferred to each loading points is $P_u/2$.

If Q_1 = S. F. on faces EH & FG

$$Q_1 = \tau.b.d$$

Also Q_2= S. F. on faces EF & HG

$$Q_2 = \tau.a.b$$

If P_n = Total normal force on the diagonal EG,

$$P_n = Q_1 \sin\theta + Q_2 \cos\theta$$

$$P_n = \tau.b.d.\sin\theta + \tau.a.b.\cos\theta --- (ii)$$

Total normal force on diagonal EG will also be equal to,

$$P_n = f_t.b.L' ----- (iii)$$

Where L' is the length of diagonal EG

Equating (normal force) equations (*ii*) and (*iii*), we get,

$$\tau.b.d\sin\theta + \tau.a.b.\cos\theta = f_t.b.L' ----- (iv)$$

Hence, shear stress, $\tau = \dfrac{f_t.b.L'}{b.d.\sin\theta + a.b.\cos\theta} ---- (v)$

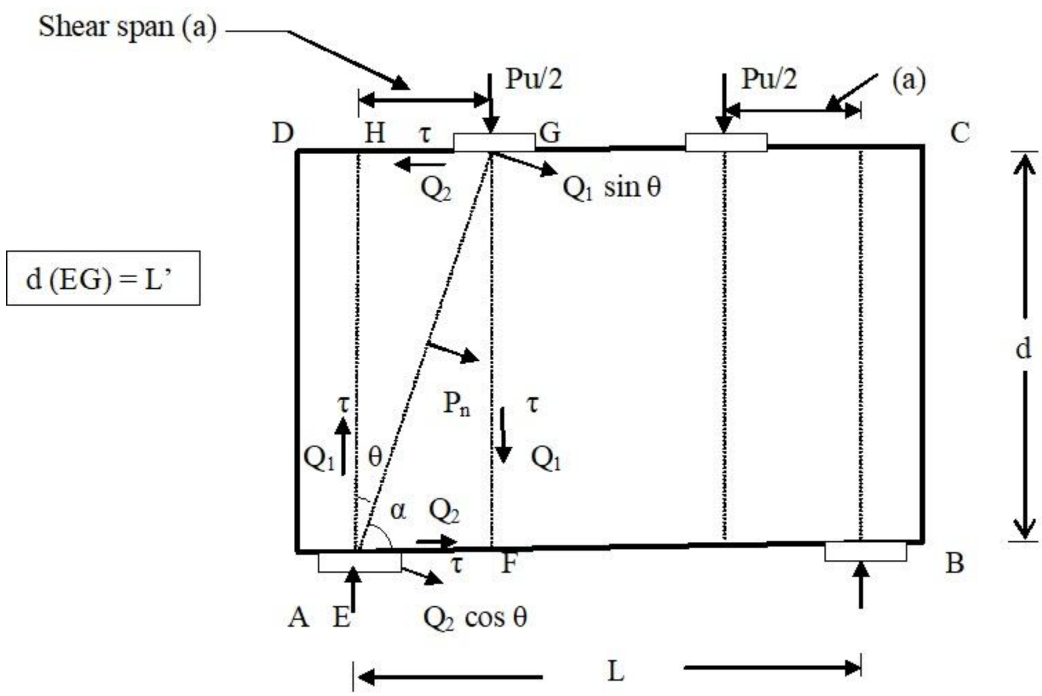

Figure 1: HFRC deep beam under a two-point loading

Total normal force on diagonal EG will also be equal to,

$$P_n = f_t.b.L' - - - - - (iii)$$

Equating (normal force) equations (*ii*) and (*iii*), we get,

$$\tau.b.d\sin\theta + \tau.a.b.\cos\theta = f_t.b.L' - - - - - (iv)$$

Hence, shear stress, $\tau = \dfrac{f_t.b.L'}{b.d.\sin\theta + a.b.\cos\theta} - - - - (v)$

Alternatively, shear stress = Shear load/cross-sectional area

Hence, $\tau = \dfrac{P_u/2}{b.d} = \dfrac{P_u}{2.b.d} - - - - (vi)$

Equating shear stress equations (*v*)& (*vi*), we find,

$$P_u = \frac{2f_t b^2 L' d}{b.d\sin\theta + b.a\cos\theta}$$

$$P_u = \frac{2.f_t b.\frac{L'}{d}d.d}{d\sin\theta + a\cos\theta} - - - (vii)$$

From Fig.1,

$$L'/d = \cos ec\alpha$$

and

$$\theta = (90 - \alpha)^0$$

Substituting in equation (*vii*), we get,

$$P_u = \frac{2.f_t b.d^2.\cos ec\alpha}{d\cos\alpha + a\sin\alpha} --- (viii)$$

Therefore, the maximum shearing load,

$$P_u = \frac{2.f_t b.d \;\; .\cos ec\alpha}{\cos\alpha + \frac{a}{d}\sin\alpha} --- (ix)$$

Hence, Maximum shear stress,

$$\frac{P_u}{2.b.d} = \frac{f_t.\cos ec\alpha}{\cos\alpha + \frac{a}{d}\sin\alpha} --- (x)$$

As is evident,

$$\frac{P_u}{2.b.d} = v_u(hfrc)$$

Hence, the shear strength contribution of HFRC,

$$v_u\,(hfrc) = \frac{f_t.\cos ec\alpha}{\cos\alpha + \frac{a}{d}\sin\alpha} --- (xi)$$

The contribution of HFRC to the shear strength of deep beams is equal to equation (*xi*). Substituting equation (*xi*) in equation (*i*),

$$v_u\,(predict) = \frac{f_t.\cos ec\alpha}{\cos\alpha + \frac{a}{d}\sin\alpha} + \tau_c --- (xii)$$

Equation (*xii*) is the developed general equation for predicting shear strength of HFRC deep beams. It can be used for any fibre reinforced concrete deep beam. The split tensile strength of HFRC is the prerequisite for the use of equation (*xii*). Modification of this general equation in to the specific equation, for steel + polypropylene fibre reinforced concrete deep beams is done as given below.

2.2. Development of Equation for Prediction of Split Tensile Strength of HFRC with Steel and Polypropylene Fibers

The split tensile strengths of M20, M25, and M30 grade concrete reinforced with steel and polypropylene fibres are found through extensive laboratory testing. From the experimental results, a Nomogram is prepared. This data is used for an equation to predict split tensile strength of HFRC with steel +PP fiber.

3. RESULT AND DISCUSSION

3.1. Nomogram

From the experimental results, nomogram of split tensile strength for varying fiber percentages is prepared as shown in Fig. 2. This nomogram is helpful as a general guideline for structural designers to evaluate split tensile strength in the absence of experimental results.

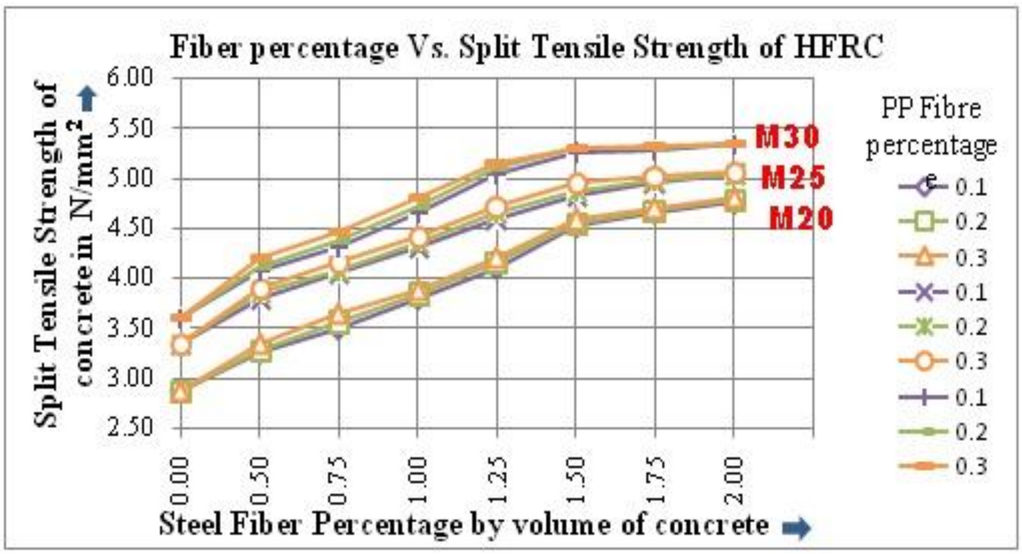

Figure 2: Nomogram: Steel & PP fiber content Vs. Concrete's Split tensile strength

Regression analysis for split tensile strength of HFRC is performed as given below.

Split Tensile strength of HFRC with Steel+ PP fibers = (Split Tensile strength of conventional concrete) + Contribution of (Steel fibers+ PP fibers) in split tensile strength

Hence,

$$f_{t(sf+ppf)} = f_{sp} + 1.72F_{sf} + 0.34F_{ppf} - 0.12 - - - - - (xiii)$$

Equation (*xiii*) is helpful in predicting the Split Tensile Strength of Steel + PP fibres concrete, especially when laboratory test data is not available.

3.1.1. Specific Shear Strength Equation for Steel and Polypropylene Hfrc Deep Beams from General Equation

The developed general equation is further modified to obtain a specific equation suitable for shear strength prediction of (Steel+PP) fiber HFRC deep beams.

Substituting equation (*xiii*) for the split tensile strength of HFRC for 'f_t' in general equation (*xii*),
we get,

$$v_{u\ predict(steel+PP)} = \frac{(f_{sp} + 1.72F_{sf} + 0.34F_{ppf} - 0.12).\cos ec\alpha}{\cos\alpha + \frac{a}{d}\sin\alpha} + \tau_c - - - (xiv)$$

Equation *(xiv)* is a specific equation developed for shear strength prediction of HFRC deep beams with steel +PP fiber reinforced concrete, from the general equation (*xii*).

3.2. Validation of the Developed Shear Strength Equations

An extensive testing work is performed in the laboratory and the test results are recorded (Kulkarni and Halkude, 2022). Validation of the shear strength prediction of the developed equations is made by comparing the results obtained. Confidence intervals: Shear strength ratio close to unity ensures precise prediction of shear strength.

The shear strength predictions of HFRC deep beams using the developed general equation and the specific equation for steel & PP fiber reinforced concrete deep beams are considered. Using them, the following two shear strength ratios are calculated.

$$(\mu_g) = \frac{\text{Vu expt. work undertaken}}{\text{Vu (Estimated by developed general HFRC equation for deep beams)}}$$

$$(\mu_s) = \frac{\text{Vu expt. work undertaken}}{\text{Vu (Estimated by Modified specific equation for steel + PP fiber concrete deep beams)}}$$

Table 1 compares the shear strength ratios (μ_g) and (μ_s) for M20 HFRC deep beams.

Table 1: Shear strength ratios for M20 HFRC with varying steel + 0.3% PP fiber deep beams

Steel fiber Percentage by volume of concrete	Shear span to depth ratio (*a*/*d*)	*Vu* (Expt. work undertaken) N/mm²	*Vu* (Estimated by developed General Equation for HFRC deep beams) N/mm²	*Vu* (Estimated by Modified Specific equation for steel+ PP fiber deep beams) N/mm²	*Shear strength ratio* μ_g	*Shear strength ratio* μ_s
0.50	0.45	4.88	4.61	4.80	1.05	1.01
	0.50	4.63	4.28	4.47	1.08	1.03
	0.55	4.54	4.10	4.28	1.10	1.06
0.75	0.45	5.54	5.01	5.14	1.10	1.07
	0.50	5.00	4.66	4.79	1.07	1.04
	0.55	4.88	4.45	4.59	1.09	1.06
1.00	0.45	6.08	5.31	5.49	1.14	1.10
	0.50	5.54	4.94	5.11	1.12	1.08
	0.55	5.21	4.72	4.89	1.10	1.06
1.25	0.45	6.50	5.75	5.83	1.13	1.11
	0.50	5.92	5.35	5.43	1.10	1.09
	0.55	5.58	5.12	5.20	1.09	1.07
1.50	0.45	6.88	6.25	6.17	1.10	1.11
	0.50	6.42	5.81	5.75	1.10	1.11
	0.55	6.04	5.55	5.50	1.09	1.09

1.75	0.45	7.04	6.41	6.52	1.09	1.07
	0.50	6.63	5.96	6.07	1.11	1.09
	0.55	6.38	5.70	5.81	1.11	1.09
2.00	0.45	7.17	6.54	6.86	1.09	1.04
	0.50	6.75	6.08	6.39	1.11	1.05
	0.55	6.54	5.81	6.11	1.12	1.07

From Table 1, it is found that both the shear strength ratios are near unity. Predictions of general equation are lower than experimental results in the range of 5% to 10%, depending upon fiber content. The predictions by the specific equation are lower than experimental results in the range of 1% to 7%. The predictions of the particular equation are more precise by @ 3% in comparison with general equation. Narrower confidence intervals show higher precision, offering safer HFRC designs.

3.3. Comparison of Predictions of the Developed Equations with Experimental Results of the other Researchers

Literature study shows that, majority of the researchers have investigated shear strength of SFRC deep beams. Therefore, PP fiber content is substituted as 0 % in the equation for the prediction of shear strength using the developed equation (*xiii*).

The following shear strength ratios are computed for comparison of current shear strength predictions with experimental results of other researchers.

$$(\eta_g) = \frac{\text{Vu researchers expt. work}}{\text{Vu (Prediction of the Developed general HFRC equation)}}$$

$$(\eta_s) = \frac{\text{Vu researchers expt. work}}{\text{Vu (Prediction of the Developed specific steel + PP fiber equation)}}$$

Table 2 presents a comparison of shear strength ratios of developed equations with other researchers' experimental results.

Table 2: Comparison of Shear Strength Ratios of developed Equations with other Researchers' Experimental Results for M20 HFRC Deep Beams

Researcher	Fiber Type & Content	Shear Span-to-Depth Ratio (*a*/*d*)	Comparison with Experimental Results	
			Shear strength ratio η_g	*Shear strength ratio* η_s
Narayan and Darwish, (1988)	1% steel fiber	0.50	0.92	0.92
Sachan and Kameswar Rao, (1990)	1% steel fiber	1.00	0.97	0.98
Kwak et al., (2002)	0.5% steel fiber	2.00	1.14	1.14

The results (Table 2) show that the predictions of the developed shear strength equations are in good agreement with experimental results of other researchers also.

3.4 Comparison with Predicted Results of other Researchers

Comparison of the shear strength forecasts of the developed equations with predictions of other researchers is done by using following shear strength ratios.

$$(\psi g) = \frac{\text{Vu researchers prediction (equation)}}{\text{Vu (Prediction of theDeveloped general HFRC equation)}}$$

$$(\psi s) = \frac{\text{Vu researchers prediction (equation)}}{\text{Vu (Prediction of the Developed specific steel + PP fiber equation)}}$$

Table 3 presents a comparison of shear strength ratios of developed equations with predicted results of the other Researchers.

Table 3: Comparison of Developed Equations' Predictions with those of other Researchers for M20 SFRC Deep Beams with 1% Steel Fibre at 0.5 *a/d* ratio.

Researchers	Equations by Researchers	Comparison of predicted results	
		ψ_g	ψ_s
Narayan and Darwish, (1988)	$V_u = C_1(1-0.35\frac{x_a}{h_a})f_{spf}.b.h_a + C_2\sum A_{st}\frac{y}{h_a}\sin^2\alpha$	0.85	0.86
Sachan and Kameswar Rao, (1990)	$P = \pi bL'tan\theta\left[0.41\,\pi d_f\frac{l_f}{2}v_f\tau + \sigma_0\right]$	1.02	1.01
Khuntia et al., (1999)	$v_u = [0.167\left(2.5.\frac{d}{a}\right) + 0.25\,F]\sqrt{f'c}$	0.94	0.942
Kwak et al., (2002)	$v_u = Aef_{spfc}^{exp1}\left(p\frac{d}{a}\right)^{exp2} + Bv_b^{exp3}$	1.20	1.16
Slater et al., (2012)	$v_u = \frac{7}{500} + \frac{176}{5}f_c'^{-\frac{22}{25}} - \frac{11}{50}\rho^{-\frac{27}{50}} + 545\rho.\frac{d}{a} - \frac{23}{5}F^{-\frac{3}{20}}$	1.07	1.08
Shahnewaz and Alam, (2014)	$v_u = 0.2 + 0.034f'_c + 19\rho^{0.087} - 5.8(a/d)^{1/2} + 3.4V_f^{0.4} - 800(l_f/d_f)^{-1.6} - 12((a/d)V_f)^{0.05} - 197((a/d)(l_f/d_f))^{-1.4} + 105(V_f(l_f/d_f))^{-2.12}$	0.87	0.88

Table 3 shows that the predictions of the developed shear strength equations are in good agreement with the results obtained from the equations developed by other researchers. Both the developed equations are capable of predicting the shear strength for HFRC deep beams with reasonable accuracy. Shear mode of failure is observed in all HFRC deep beams (Kulkarni and Halkude, 2022). This is common when sufficient main steel reinforcement is provided as per structural design.

Reliability-based design considerations: These ensure structural safety and behaviour under varying loading conditions, materials, and construction quality. In HFRC deep beams, fiber effectiveness is based upon random orientation and interaction in the mix. By using partial safety factors, concrete technologists can attain strength, ductility and using optimum fiber contents suggested in the present work. Controlled quality of work will ensure strength as well as durability.

4. CONCLUSION

The general equation developed for predicting shear strength of HFRC deep beams, is quite versatile, since it applies to HFRC as well as SFRC deep beams. Shear strength ratios using derived equations and experimental results, as well as results from equations of other researchers, are close to unity. The specific equation for the shear strength of steel and PP fibre HFRC deep beams predicts more precisely than the general HFRC equation. The equation presented for the split tensile strength of HFRC is helpful in the absence of experimental results and for predicting the shear strength of HFRC deep beams.

List of Abbreviations

Symbol	***Meaning***	***Symbol***	***Meaning***
A_s	*Area of steel bar reinforcement*	f_{sp}	*Basic split tensile strength of concrete (without fibers)*
a	*Shear span*	f_t	*Split tensile strength of concrete, MPa*
a/d	*Shear span to depth ratio*	$f_{t(sf+ppf)}$	*Split tensile strength of HFRC with steel fiber and PP fiber*
d	*depth of beam*	f_{ck}	*Characteristic comp. strength of concrete, MPa*
b	*width of beam*	F_{sf}	*Hooked end steel Fiber factor*
l	*span of beam*	F_{ppf}	*Polypropylene Fiber factor*
d_f	*fiber diameter*	α	*Inclination of the diagonal from loading to support point*
l_f	*length of fiber*	τ	*Shear stress, MPa*
V_f	*Volume fraction of fibers*	P_u	*Ultimate load of deep beam*
V_{sf}	*Volume fraction of steel fibers*	$V_{u\ pred}$	*Predicted shear strength of deep beam*
V_{ppf}	*Volume fraction of Polypropylene fibers*	$V_{u\ expt}$	*Experimental shear strength, MPa*
		$Vu_{\ hfrc}$	*Shear strength contribution of hybrid fiber reinforced concrete.*

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Author Contributions

Author 1 conducted the experimental and analytical studies, validated the results, and prepared the manuscript. Author 2 supervised the research and reviewed the manuscript.

Ethical issues

Not applicable. This study does not involve any experiments on humans or animals. Hence, ethical approval was not required.

Informed consent

Not applicable.

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Conflict of Interest

The authors declare that they have no conflicts of interests, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and materials availability

Data that support the findings of this study are embedded within the manuscript.

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