

# Shear Strength of Beams with Deformed Steel Fibers

Evaluating an alternative to minimum transverse reinforcement

BY GUSTAVO J. PARRA-MONTESINOS

Except for beams with an overall height not greater than 250 mm (10 in.), 2.5 times the flange thickness, or 0.5 times the web width  $b_w$ , Section 11.5.6.1 of ACI 318M-05<sup>1</sup> (ACI 318-05<sup>2</sup>) requires minimum shear reinforcement in the form of stirrups or hoops in beams when the factored shear force  $V_u$  exceeds  $0.5\phi V_c$ . Here,  $\phi$  is the strength reduction factor for shear and  $V_c$  is the nominal shear strength provided by concrete. In most cases,  $V_c$  is taken as  $0.17 \sqrt{f'_c} b_w d$  ( $2 \sqrt{f'_c} b_w d$ ), where  $d$  is the effective depth of the beam.

Besides providing shear strength through truss action  $V_s$ , the addition of minimum shear reinforcement helps control diagonal crack widths and fosters a more uniform distribution of diagonal cracks in the beam webs. Thus, for a given average state of strain, members with minimum shear reinforcement exhibit smaller crack widths and an increase in shear resistance provided by aggregate interlock compared to members without web reinforcement. This is particularly important in large members, where the so-called “size effect” might lead to shear strengths lower than the concrete contribution given in ACI 318.<sup>3</sup>

Although shear reinforcement in beams typically consists of steel bars bent in the form of stirrups or hoops, the addition of deformed steel fibers to the concrete has also

been shown to enhance shear resistance and ductility in reinforced concrete beams.<sup>4</sup> These fibers are typically hooked or crimped, as shown in Fig. 1. When used in reinforced concrete beams without transverse reinforcement, fibers increase shear strength by providing post-cracking diagonal tension resistance. The fibers also enhance cracking distribution, similar to the effect of stirrups. This leads to reduced crack widths, and thus an increase in shear resistance through aggregate interlock. The ability of fibers to foster multiple web diagonal cracks is clearly illustrated in Fig. 2(a) and (b), in which the cracking pattern at failure for a reinforced concrete beam without shear reinforcement is compared with that of an identical fiber-reinforced concrete (FRC)

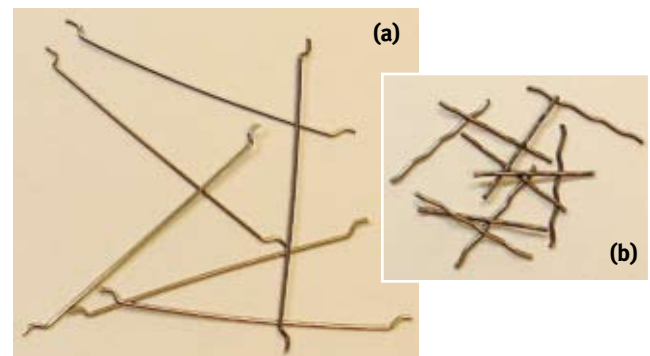


Fig. 1: Typical deformed steel fibers: (a) hooked fibers; and (b) crimped fibers

Note: Coefficients and variables are in SI units, followed by conversion to in.-lb units in parentheses.

beam containing a 1.0% volume fraction of hooked steel fibers.<sup>4</sup> The average shear stress versus deflection responses for these two beams, as well as those for a pair of identical beams (one with and one without steel fibers) tested to evaluate the consistency of the results, are shown in Fig. 3. The addition of hooked steel fibers led to a substantially higher shear resistance and ductility compared with that of the companion beams without fibers.

The ability of fibers to enhance the shear behavior of reinforced concrete flexural members was recently evaluated by ACI Subcommittee 318-F, New Materials, Products, and Ideas. The study evaluated the use of deformed steel fibers as minimum shear reinforcement for beams subjected to shear forces ranging from  $0.085 \sqrt{f'_c} b_w d$  to  $0.17 \sqrt{f'_c} b_w d$  ( $\sqrt{f'_c} b_w d$  to  $2 \sqrt{f'_c} b_w d$ ), which typically correspond to  $0.5V_c$  and  $V_c$ , respectively. These

limits typically define the range where ACI 318<sup>1,2</sup> would require minimum transverse reinforcement, even though the nominal shear strength attributed to the concrete is not exceeded. Results from numerous investigations, compiled into a database, support the use of deformed steel fibers as minimum shear reinforcement in lieu of stirrups or hoops for this range of shear demand. Although the presented data clearly indicate that fibers improve shear resistance in flexural members, they are limited to beams without shear reinforcement. Additional experimental data are required to evaluate the effectiveness of fibers as shear reinforcement in other types of flexural members such as columns or slabs. The information contained in the database is summarized in Table 1. **An electronic copy of the complete database can be obtained by accessing the online version of this article at [www.concreteinternational.com](http://www.concreteinternational.com) or by contacting ACI Headquarters.**

## DATABASE OF BEAM TESTS

As indicated previously, a database was constructed, comprising results from the tests of 147 FRC beams with deformed steel fibers and 45 companion beams without fibers.<sup>4,20</sup> The following parameter ranges were considered:

- Effective beam depth  $d$ : 180 mm (7 in.)  $\leq d \leq$  570 mm (22.5 in.);
- Shear span-to-effective depth ratio  $a/d$ :  $1.0 \leq a/d \leq 6.0$ ;
- Cylinder concrete compressive strength  $f'_c$ : 17.8 MPa (2.6 ksi)  $\leq f'_c \leq$  103.8 MPa (15.1 ksi);
- Fiber volume fraction  $V_f$ :  $0.25\% \leq V_f \leq 2.0\%$  ( $0.19 \text{ kN/m}^3$  [ $33 \text{ lb/yd}^3$ ]  $\leq V_f \leq 1.53 \text{ kN/m}^3$  [ $263 \text{ lb/yd}^3$ ]);
- Steel fiber type: hooked or crimped except for five beams in which a combination of straight and hooked



Fig. 2: Typical cracking patterns for beams tested at the University of Michigan:<sup>4</sup> (a) reinforced concrete beam without steel fibers; and (b) reinforced concrete beam containing steel fibers

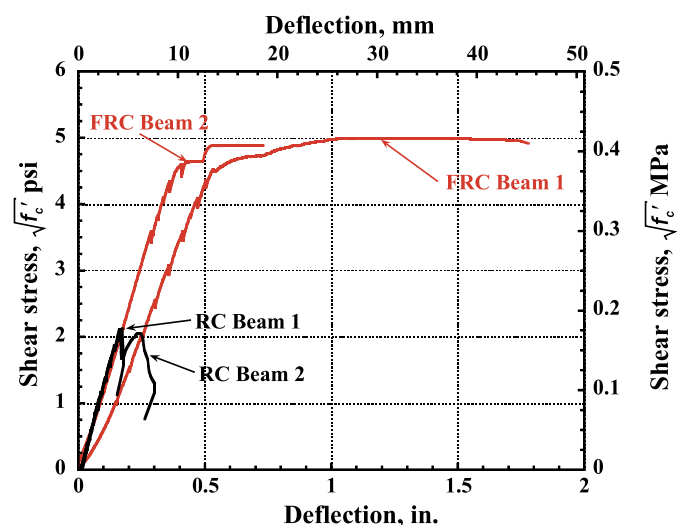


Fig. 3: Normalized shear stress versus deflection behavior for reinforced concrete beams with and without steel fiber reinforcement tested at the University of Michigan<sup>4</sup>

fibers was used, and two beams in which the steel fiber type could not be determined. In most cases, the tensile strength of the fiber wire ranged between 1000 and 1240 MPa (145 and 180 ksi);

- Fiber length-to-diameter ratio  $L_f/d_f$ :  $50 \leq L_f/d_f \leq 100$ ; and
- Longitudinal tensile reinforcement ratio  $\rho$ :  $0.37\% \leq \rho \leq 4.58\%$ .

For cases in which the cube strength of the concrete was reported rather than the cylinder strength, an equivalent cylinder strength equal to 80% of the cube strength was used.<sup>21</sup>

Out of the 147 FRC beams included in the database, 102 beams can be considered slender ( $a/d \geq 2.8$ ), and 78 of them failed in shear, while 40 out of 45 deep FRC beams ( $a/d < 2.8$ ) failed in shear. All beams without fibers reported in the database failed in shear, regardless of  $a/d$ .

## DEFORMED STEEL FIBERS AS MINIMUM SHEAR REINFORCEMENT

The effects of  $a/d$ ,  $d$ ,  $f'_c$ , and  $V_f$  on the shear strength of FRC beams were investigated. For all of the beams in the database that exhibited a shear failure, the average shear stress at failure (normalized by  $\sqrt{f'_c}$ ) is plotted versus  $a/d$  in Fig. 4. Ranges of  $V_f$  are identified through different data markers. Besides the typical trend of a decrease in shear strength with an increase in  $a/d$ , it should be noted that the use of fibers in volume fractions smaller than or equal to 0.5% did not produce shear stresses at failure substantially greater than  $0.17\sqrt{f'_c}$  ( $2\sqrt{f'_c}$ ).

The shear stress data for slender members (again, defined herein as those with  $a/d \geq 2.8$ ) are plotted versus  $d$  and  $f'_c$  in Fig. 5 and 6, respectively. The data for beams with  $a/d < 2.8$  were excluded to reduce the influence of arching action on beam shear strength. As in Fig. 4, ranges for  $V_f$  are identified through various data markers. It should be noted that, for slender beams, no data could be found for  $0.5\% < V_f < 0.75\%$ . No clear trend can be seen in either plot. This suggests that the normalized shear stress at failure of FRC beams does not show a significant correlation with changes in  $d$  and  $f'_c$  for the ranges considered.

All fiber reinforced concrete test beams failed at shear stresses greater than  $0.17\sqrt{f'_c}$  ( $2\sqrt{f'_c}$ ), which could be considered strong enough evidence to support the use of deformed steel fibers in volume fractions greater than or equal to 0.5% as minimum shear reinforcement when  $V_u \leq 0.17\sqrt{f'_c}b_wd$  ( $2\sqrt{f'_c}b_wd$ ). Given the brittle nature and potentially drastic consequences of beam shear failures, however, a much higher lower bound for the shear strength of FRC beams should be used. A lower bound for the shear strength of FRC beams equal to  $0.3\sqrt{f'_c}$  ( $3.5\sqrt{f'_c}$ ) was considered adequate for the purpose of evaluating the use of deformed steel fibers as minimum shear reinforcement. Regardless of  $d$  or  $f'_c$ , the shear stress at

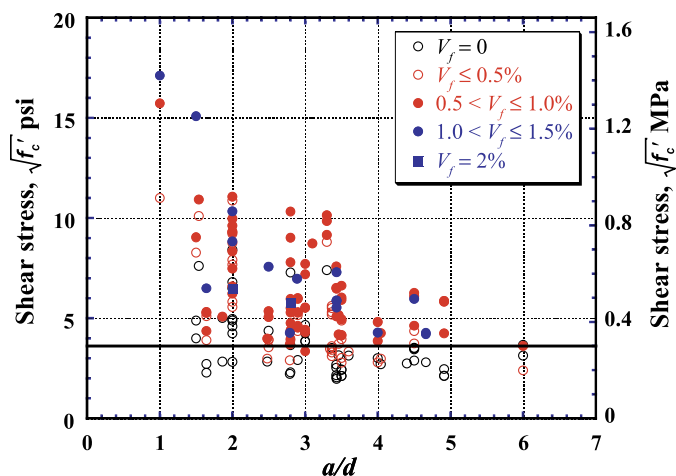


Fig. 4: Normalized shear stress at failure versus shear span-to-effective depth ratio

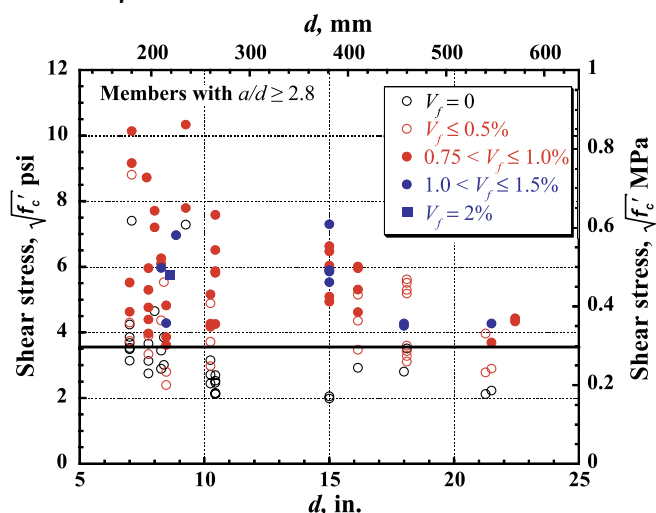


Fig. 5: Normalized shear stress at failure versus beam effective depth (slender beams)

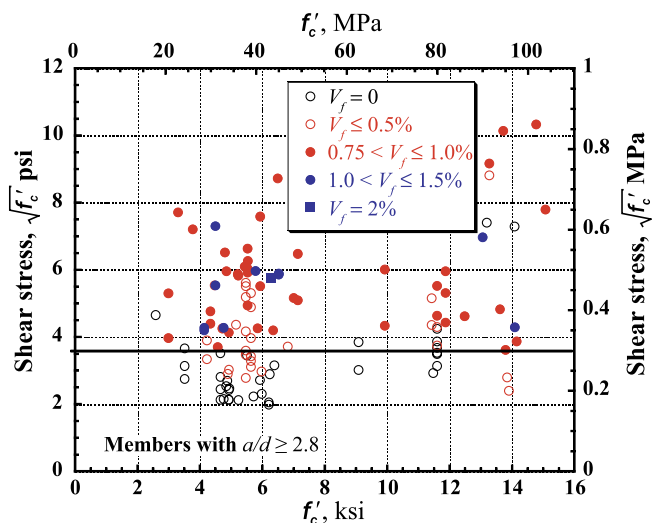


Fig. 6: Normalized shear stress at failure versus concrete compressive strength (slender beams)

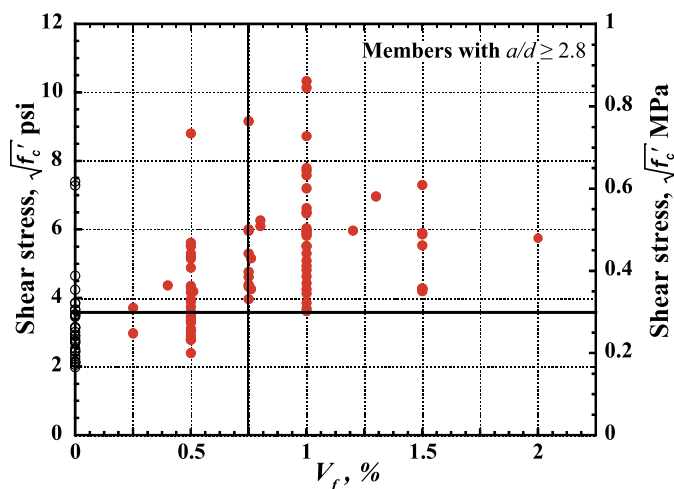


Fig. 7: Normalized shear stress at failure versus fiber volume fraction (slender beams)

failure for beams with  $V_f \geq 0.75\%$  was greater than or equal to  $0.3 \sqrt{f'_c}$  ( $3.5 \sqrt{f'_c}$ ).

To better evaluate the influence of  $V_f$  on beam shear strength, Fig. 7 shows a plot of normalized shear stress at failure versus  $V_f$  for slender beams. The increase in shear strength with an increase in  $V_f$  is clear from Fig. 7. As mentioned earlier, some FRC beams with  $V_f \leq 0.5\%$  exhibited shear strengths close to the code stress value of  $0.17 \sqrt{f'_c}$  ( $2 \sqrt{f'_c}$ ) for the concrete contribution to shear strength. All beams containing deformed steel fibers with  $V_f \geq 0.75\%$ , however, exhibited shear stresses at failure greater than  $0.3 \sqrt{f'_c}$  ( $3.5 \sqrt{f'_c}$ ).

To ensure adequate material performance and account for the use of deformed steel fibers other than those used in the tests included in the database, ACI Subcommittee 318-F has proposed performance criteria that the fiber concrete must meet. The criteria are based on flexural tests per ASTM C 1609<sup>22</sup> that are conducted on FRC beam specimens to determine the first-peak flexural strength and the post-peak strengths at specific midspan deflections. To meet the performance criteria, the strengths at midspan deflections of 1/300 and 1/150 of the span length must be greater than or equal to 90 and 75% of the first-peak, respectively, in any flexural test unit. The first-peak strength should not be taken smaller than the modulus of rupture of concrete  $f_r$  calculated from the equation in ACI 318, Section 9.5.2.3. The proposed performance criteria are based on results from flexural tests (see, for example, Reference 23) of FRC beams containing various types of hooked steel fibers with  $V_f = 0.76\%$ . Regardless of the material performance obtained from ASTM C 1609 beam tests, the use of a minimum  $V_f$  of 0.75% has been recommended by ACI Subcommittee 318-F.

## CONCLUSION

The data presented in this article support the use of deformed steel fibers as an alternative to minimum

transverse shear reinforcement (stirrups or hoops) for beams subjected to factored shear forces ranging from  $0.085 \sqrt{f'_c} b_w d$  to  $0.17 \sqrt{f'_c} b_w d$  ( $\sqrt{f'_c} b_w d$  to  $2 \sqrt{f'_c} b_w d$ ). These values typically correspond to  $0.5V_c$  and  $V_c$ , respectively. All slender FRC beams that contained  $V_f \geq 0.75\%$  exhibited a shear stress at failure greater than the conservative lower bound value of  $0.3 \sqrt{f'_c}$  ( $3.5 \sqrt{f'_c}$ ). To ensure adequate material performance and to account for the use of deformed steel fibers other than those used in the tests included in the database, performance criteria should be used for acceptance of steel fibers as minimum shear reinforcement. Until further data become available, a minimum  $V_f$  of 0.75% is recommended.

## Acknowledgments

The data presented in this paper were compiled by the author as part of an effort undertaken by ACI Subcommittee 318-F to evaluate the use of deformed steel fibers as minimum shear reinforcement in reinforced concrete flexural members. The contribution of H.H. Dinh, graduate student at the University of Michigan, in the development of the database is greatly appreciated.

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**TABLE 1:**  
**SHEAR TEST DATABASE**

Ref. No.	Beam	$b_w$ , mm	$h$ , mm	$d$ , mm	$a/d$	$\rho$ , %	$f'_c$ , MPa	Fiber type*	$L_f$ , mm	$L_f/d_f$	$V_f$ , %	$v_u$ , MPa	$v_u/\sqrt{f'_c}$ MPa
4	1	152	457	381	3.5	1.96	38.1	H	30	60	1	3.03	0.49
	2	152	457	381	3.5	1.96	38.1	H	30	60	1	3.09	0.50
	3	152	457	381	3.5	2.67	38.1	H	30	60	1	3.46	0.56
	4	152	457	381	3.5	2.67	38.1	H	30	60	1	2.53	0.41
	5	152	457	381	3.4	2.67	42.8	—	—	—	—	1.12	0.17
	6	152	457	381	3.4	2.67	42.8	—	—	—	—	1.08	0.17
	7	152	457	381	3.4	2.67	31.0	H	30	60	1.5	2.56	0.46
	8	152	457	381	3.4	2.67	31.0	H	30	60	1.5	3.37	0.61
	9	152	457	381	3.4	2.67	44.9	H	30	60	1.5	3.28	0.49
	10	152	457	381	3.4	2.67	44.9	H	30	60	1.5	3.26	0.49
	11	152	457	381	3.4	2.67	49.2	H	60	80	1	2.97	0.42
	12	152	457	381	3.4	2.67	49.2	H	60	80	1	3.77	0.54
5	FC1	152	610	558	1.6	2.12	60.0	—	—	—	—	1.75	0.23
	FC2	152	610	558	1.6	2.12	54.1	H	30	60	0.75	3.24	0.44
	FC3	152	610	558	1.6	2.12	49.9	H	30	60	1.5	3.81	0.54
	FC7	152	610	558	1.6	2.12	57.0	—	—	—	—	1.43	0.19
	FC8	152	610	558	1.6	2.12	54.8	H	30	60	0.4	2.40	0.32
	FC9	152	610	558	1.6	2.12	56.5	H	30	60	0.6	2.73	0.36
	FC10	152	610	558	1.6	2.12	46.9	H	50	100	0.4	2.90	0.42
	FC11	152	610	558	1.6	2.12	40.8	H	50	100	0.6	2.79	0.44
6	B-2-1.0-L	125	250	215	2.0	0.37	92.0	H	60	75	1	1.68 <sup>†</sup>	0.18 <sup>†</sup>
	B-4-1.0-L	125	250	215	4.0	0.37	92.6	H	60	75	1	0.89 <sup>†</sup>	0.09 <sup>†</sup>
	B-6-1.0-L	125	250	215	6.0	0.37	93.7	H	60	75	1	0.56 <sup>†</sup>	0.06 <sup>†</sup>
	B-1-0.5-A	125	250	215	1.0	2.84	99.0	H	60	75	0.5	9.09	0.91
	B-2-0.5-A	125	250	215	2.0	2.84	99.1	H	60	75	0.5	4.82	0.48
	B-4-0.5-A	125	250	215	4.0	2.84	95.4	H	60	75	0.5	2.27	0.23
	B-6-0.5-A	125	250	215	6.0	2.84	95.8	H	60	75	0.5	1.95	0.20
	B-1-1.0-A	125	250	215	1.0	2.84	95.3	H	60	75	1	12.74	1.31
	B-2-1.0-A	125	250	215	2.0	2.84	95.3	H	60	75	1	6.06	0.62
	B-4-1.0-A	125	250	215	4.0	2.84	97.5	H	60	75	1	3.17 <sup>†</sup>	0.32 <sup>†</sup>
	B-6-1.0-A	125	250	215	6.0	2.84	100.5	H	60	75	1	1.96 <sup>†</sup>	0.20 <sup>†</sup>
	B-1-1.5-A	125	250	215	1.0	2.84	96.4	H	60	75	1.5	13.95	1.42
	B-2-1.5-A	125	250	215	2.0	2.84	96.6	H	60	75	1.5	7.21	0.73
	B-4-1.5-A	125	250	215	4.0	2.84	97.1	H	60	75	1.5	3.51	0.36
	B-6-1.5-A	125	250	215	6.0	2.84	101.3	H	60	75	1.5	1.98 <sup>†</sup>	0.20 <sup>†</sup>
	B-2-1.0-M	125	250	215	2.0	4.58	94.5	H	60	75	1	6.73	0.69
	B-4-1.0-M	125	250	215	4.0	4.58	93.8	H	60	75	1	3.88	0.40
	B-6-1.0-M	125	250	215	6.0	4.58	95.0	H	60	75	1	2.93	0.30

Ref. No.	Beam	$b_w$ , mm	$h$ , mm	$d$ , mm	$a/d$	$\rho$ , %	$f'_c$ , MPa	Fiber type*	$L_f$ , mm	$L_f/d_f$	$V_f$ , %	$v_u$ , MPa	$v_u/\sqrt{f'_c}$ , MPa
7	HSFRC1	125	250	225	2.9	3.57	90.0	H	30	60	1.3	5.49	0.58
	HSFRC2	125	250	225	2.9	3.57	90.0	H	30	60	1.3	5.45 <sup>†</sup>	0.57 <sup>†</sup>
	HSFRC3	125	250	225	2.9	2.21	90.0	H	30	60	1.3	3.50 <sup>†</sup>	0.37 <sup>†</sup>
8	A00	150	250	219	2.79	1.92	41.2	—	—	—	—	1.23	0.19
	A10	150	250	219	2.79	1.92	40.9	H	30	60	1	2.93	0.46
	A20	150	250	219	2.79	1.92	43.2	H	30	60	2	3.14 <sup>†</sup>	0.48 <sup>†</sup>
	B00	150	250	219	2.0	1.92	41.2	—	—	—	—	1.51	0.24
	B10	150	250	219	2.0	1.92	40.9	H	30	60	1	3.50	0.55
	B20	150	250	219	2.0	1.92	43.2	H	30	60	2	3.52	0.54
9	FHB1-2	125	250	212	2.0	1.48	62.6	—	—	—	—	3.02	0.38
	FHB2-2	125	250	212	2.0	1.48	63.8	H	50	63	0.5	5.09	0.64
	FHB3-2	125	250	212	2.0	1.48	68.6	H	50	63	0.75	5.44	0.66
	FHB1-3	125	250	212	3.0	1.48	62.6	—	—	—	—	2.53	0.32
	FHB2-3	125	250	212	3.0	1.48	63.8	H	50	63	0.5	3.09	0.39
	FHB3-3	125	250	212	3.0	1.48	68.6	H	50	63	0.75	3.40	0.41
	FHB1-4	125	250	212	4.0	1.48	62.6	—	—	—	—	1.98	0.25
	FHB2-4	125	250	212	4.0	1.48	63.8	H	50	63	0.5	2.41	0.30
	FHB3-4	125	250	212	4.0	1.48	68.6	H	50	63	0.75	2.74	0.33
	FNB2-2	125	250	212	2.0	1.48	30.8	H	50	63	0.5	4.04	0.73
	FNB2-3	125	250	212	3.0	1.48	30.8	H	50	63	0.5	2.55	0.46
	FNB2-4	125	250	212	4.0	1.48	30.8	H	50	63	0.5	2.00	0.36
10		127	229	203	3.0	2.20	17.8	—	—	—	—	1.63	0.39
		127	229	203	3.0	2.20	22.7	H	30	60	1	3.05	0.64
		127	229	203	3.0	2.20	26.0	H	50	100	1	3.05	0.60
11	2/0.5/1.5	152	254	221	1.5	1.19	34.0	H	30	60	0.5	3.17 <sup>†</sup>	0.54 <sup>†</sup>
	2/0.5/2.5	152	254	221	2.5	1.19	34.0	H	30	60	0.5	1.72	0.30
	2/0.5/3.5	152	254	221	3.5	1.19	34.0	H	30	60	0.5	1.34 <sup>†</sup>	0.23 <sup>†</sup>
	2/0/1.5	152	254	221	1.5	1.19	34.0	—	—	—	—	1.93	0.33
	2/0/3.5	152	254	221	3.5	1.19	34.0	—	—	—	—	1.17	0.20
	2/1.0/1.5	152	254	221	1.5	1.19	34.0	H	30	60	1	3.16 <sup>†</sup>	0.54 <sup>†</sup>
	2/1.0/2.5	152	254	221	2.5	1.19	34.0	H	30	60	1	1.79 <sup>†</sup>	0.31 <sup>†</sup>
	2/1.0/3.5	152	254	221	3.5	1.19	34.0	H	30	60	1	1.38 <sup>†</sup>	0.24 <sup>†</sup>
	4/0.5/1.5	152	254	221	1.5	2.39	34.0	H	30	60	0.5	4.00	0.69
	4/0.5/2.5	152	254	221	2.5	2.39	34.0	H	30	60	0.5	1.89	0.32
	4/0.5/3.5	152	254	221	3.5	2.39	34.0	H	30	60	0.5	1.47	0.25
	4/0/1.5	152	254	221	1.5	2.39	34.0	—	—	—	—	2.37	0.41
	4/0/3.5	152	254	221	3.5	2.39	34.0	—	—	—	—	1.03	0.18
	4/1.0/1.5	152	254	221	1.5	2.39	34.0	H	30	60	1	4.38	0.75
	4/1.0/2.5	152	254	221	2.5	2.39	34.0	H	30	60	1	2.45	0.42
	4/1.0/3.5	152	254	221	3.5	2.39	34.0	H	30	60	1	2.00	0.34

Ref. No.	Beam	$b_w$ , mm	$h$ , mm	$d$ , mm	$a/d$	$\rho$ , %	$f'_c$ , MPa	Fiber type*	$L_f$ , mm	$L_f/d_f$	$V_f$ , %	$v_u$ , MPa	$v_u/\sqrt{f'_c}$ , MPa
12	A1	152	229	197	2.0	1.34	24.2	—	—	—	—	2.00	0.41
	A2	152	229	197	2.8	1.34	24.2	—	—	—	—	1.50	0.30
	A3	152	229	197	3.6	1.34	24.2	—	—	—	—	1.28	0.26
	A4	152	229	197	4.4	1.34	24.2	—	—	—	—	1.12	0.23
	B1	152	229	197	2.0	1.34	29.1	H	30	60	0.5	2.50	0.46
	B2	152	229	197	2.8	1.34	29.1	H	30	60	0.5	1.75	0.32
	B3	152	229	197	3.6	1.34	29.1	H	30	60	0.5	1.50	0.28
	B4	152	229	197	4.4	1.34	29.1	H	30	60	0.5	1.26 <sup>†</sup>	0.23 <sup>†</sup>
	C1	152	229	197	2.0	1.34	29.9	H	30	60	0.75	2.83	0.52
	C2	152	229	197	2.8	1.34	29.9	H	30	60	0.75	2.00	0.37
	C3	152	229	197	3.6	1.34	29.9	H	30	60	0.75	1.58 <sup>†</sup>	0.29 <sup>†</sup>
	C4	152	229	197	4.4	1.34	29.9	H	30	60	0.75	1.36 <sup>†</sup>	0.25 <sup>†</sup>
	C5	152	229	200	2.8	0.79	29.9	H	30	60	0.75	1.23 <sup>†</sup>	0.22 <sup>†</sup>
	C6	152	229	197	2.8	2.00	29.9	H	30	60	0.75	2.16	0.40
	D1	152	229	197	2.0	1.34	30.0	H	30	60	1.0	3.09 <sup>†</sup>	0.56 <sup>†</sup>
	D2	152	229	197	2.8	1.34	30.0	H	30	60	1.0	2.16 <sup>†</sup>	0.39 <sup>†</sup>
	D3	152	229	197	3.6	1.34	30.0	H	30	60	1.0	1.68 <sup>†</sup>	0.31 <sup>†</sup>
	D4	152	229	197	4.4	1.34	30.0	H	30	60	1.0	1.46 <sup>†</sup>	0.27 <sup>†</sup>
	E1	152	229	200	2.8	0.79	20.6	H	30	60	1.0	1.15 <sup>†</sup>	0.25 <sup>†</sup>
	E2	152	229	197	2.8	1.34	20.6	H	30	60	0.75	1.50	0.33
	E3	152	229	197	2.8	2.00	20.6	H	30	60	0.75	2.00	0.44
	F1	152	229	200	2.8	0.79	33.4	H	30	60	0.75	1.53 <sup>†</sup>	0.27 <sup>†</sup>
	F2	152	229	197	2.8	1.34	33.4	H	30	60	0.75	2.50 <sup>†</sup>	0.43 <sup>†</sup>
	F3	152	229	197	2.8	2.00	33.4	H	30	60	0.75	2.86	0.50
13	1 Type A	200	250	180	3.3	4.50	90.9	—	—	—	—	5.86	0.61
	5 Type A	200	250	180	3.3	4.50	91.4	H	60	86	0.5	6.99	0.73
	6 Type A	200	250	180	3.3	4.50	91.4	H	60	86	0.75	7.27	0.76
	9 Type A	200	250	195	3.1	3.10	44.8	S-H			1	4.85	0.72
	1 Type B	200	300	235	2.8	4.30	97.0	—	—	—	—	5.96	0.61
	3 Type B	200	300	235	2.8	4.30	103.8	H	30	50	1	6.60	0.65
	5 Type B	200	300	235	2.8	4.30	101.8	S-H			1	8.65	0.86
	1 Type C	200	500	410	2.9	3.00	79.1	—	—	—	—	2.16	0.24
	5 Type C	200	500	410	2.9	3.00	81.8	S-H			1	4.48	0.50
	6 Type C	200	500	410	2.9	3.00	81.8	S-H			1	3.99	0.44
	7 Type C	200	500	410	2.9	3.00	78.7	H	60	86	0.5	3.21	0.36
	8 Type C	200	500	410	2.9	3.00	78.7	H	60	86	0.5	3.80	0.43
	9 Type C	200	500	410	2.9	3.00	68.4	H	60	86	0.75	4.13	0.50
	10 Type C	200	500	410	2.9	3.00	86.0	H	60	86	0.75	3.56	0.38
	3 Type D	300	700	570	3.0	2.90	81.8	S-H			1	3.33	0.37
	4 Type D	300	700	570	3.0	2.90	68.4	H	60	86	0.75	2.98	0.36



Ref. No.	Beam	$b_w$ , mm	$h$ , mm	$d$ , mm	$a/d$	$\rho$ , %	$f'_c$ , MPa	Fiber type*	$L_f$ , mm	$L_f/d_f$	$V_f$ , %	$v_u$ , MPa	$v_u/\sqrt{f'_c}$ , MPa
14	1.2/1	200	300	260	3.5	3.56	44.0	—	—	—	—	1.74	0.26
	1.2/2	200	300	260	3.5	3.56	46.9	H	60	67	0.25	2.11	0.31
	1.2/3	200	300	260	3.5	3.56	43.7	H	60	67	0.51	2.31	0.35
	1.2/4	200	300	260	3.5	3.56	48.3	H	60	67	0.76	2.98	0.43
	2.2/1	200	300	260	1.5	1.81	40.8	—	—	—	—	4.03	0.63
	2.2/2	200	300	260	1.5	1.81	41.2	H	60	67	0.25	5.38	0.84
	2.2/3	200	300	260	1.5	1.81	40.3	H	60	67	0.76	5.76	0.91
	2.3/1	200	300	262	2.5	1.15	40.1	—	—	—	—	1.50	0.24
	2.3/2	200	300	262	2.5	1.15	40.0	H	60	67	0.25	1.57	0.25
	2.3/3	200	300	262	2.5	1.15	38.7	H	60	67	0.76	2.06	0.33
	2.4/1	200	300	260	2.5	1.81	40.1	—	—	—	—	2.30	0.36
	2.4/2	200	300	260	2.5	1.81	40.0	H	60	67	0.25	2.07	0.33
	2.4/3	200	300	260	2.5	1.81	38.7	H	60	67	0.76	2.77	0.44
	2.6/1	200	300	260	4.0	1.81	40.8	—	—	—	—	1.44	0.23
	2.6/2	200	300	260	4.0	1.81	41.2	H	60	67	0.25	1.58	0.25
	2.6/3	200	300	260	4.0	1.81	40.3	H	60	67	0.76	2.25	0.35
	20x30-Plain-1	200	300	260	3.5	2.83	32.1	—	—	—	—	1.15	0.20
	20x30-SFRC-1	200	300	260	3.5	2.83	37.7	H	60	67	0.5	2.13	0.35
	20x45-SFRC-1	200	450	410	3.3	3.08	37.7	H	60	67	0.5	1.77	0.29
	20x60-Plain-1	200	600	540	3.5	2.73	32.1	—	—	—	—	1.00	0.18
	20x60-SFRC-1	200	600	540	3.5	2.73	37.7	H	60	67	0.5	1.42	0.23
	T10x50-SFRC-1	200	500	460	3.4	2.80	37.7	H	60	67	0.5	1.84	0.30
	T15x50-SFRC-1	200	500	460	3.4	2.80	37.7	H	60	67	0.5	2.86	0.47
	T15x75-SFRC-1	200	500	460	3.4	2.80	37.7	H	60	67	0.5	2.81	0.46
	T15x100-Plain-1	200	500	460	3.4	2.80	32.1	—	—	—	—	1.65	0.29
	T15x100-SFRC-1	200	500	460	3.4	2.80	37.7	H	60	67	0.5	2.65	0.43
	20x30-SFRC-2	200	300	260	3.5	2.83	38.8	H	60	67	0.5	2.53	0.41
	20x50-SFRC-2	200	500	460	3.4	2.41	38.8	H	60	67	0.5	1.61	0.26
	20x60-SFRC-2	200	600	540	3.5	2.73	38.8	H	60	67	0.5	2.05	0.33
	T10x50-SFRC-2	200	500	460	3.4	2.80	38.8	H	60	67	0.5	1.70	0.27
	T15x50-SFRC-2	200	500	460	3.4	2.80	38.8	H	60	67	0.5	1.78	0.28
	T23x50-SFRC-2	200	500	460	3.4	2.80	38.8	H	60	67	0.5	2.74	0.44
15	I	305	610	546	2.8	1.84	39.4	—	—	—	—	1.16	0.19
	II	305	610	546	2.8	1.84	33.7	C	76	80	0.5	1.40	0.24
	III	305	610	546	2.8	1.84	31.5	C	76	80	1	1.72	0.31
	IV	305	610	546	2.8	1.84	32.8	C	76	80	1.5	2.03	0.35
16	S1	150	305	276	1.8	1.44	42.3	—	—	—	—	1.53	0.24
	S2	150	305	276	1.8	2.99	43.2	—	—	—	—	2.74	0.42
	S3F	150	305	276	1.8	4.54	48.6	H	51	83	0.9	2.94	0.42

Ref. No.	Beam	$b_w$ , mm	$h$ , mm	$d$ , mm	$a/d$	$\rho$ , %	$f'_c$ , MPa	Fiber type*	$L_f$ , mm	$L_f/d_f$	$V_f$ , %	$v_u$ , MPa	$v_u/\sqrt{f'_c}$ , MPa
17	B51	175	250	210	4.5	4.00	38.0	—	—	—	—	1.77	0.29
	B52	175	250	210	4.5	4.00	35.5	C	50	100	0.4	2.16	0.36
	B53	175	250	210	4.5	4.00	37.4	C	50	100	0.8	3.10	0.51
	B54	175	250	210	4.5	4.00	39.8	C	50	100	1.2	3.13	0.50
	B55	175	250	210	4.5	3.05	38.2	C	50	100	0.8	3.21	0.52
	B56	175	250	210	4.5	1.95	41.8	C	50	100	0.8	2.62 <sup>†</sup>	0.41 <sup>†</sup>
	B61R	175	250	210	4.5	1.95	43.0	—	—	—	—	1.57	0.24
	B63R	175	250	210	4.5	1.95	35.1	C	50	100	0.8	2.05 <sup>†</sup>	0.35 <sup>†</sup>
18	1TL-1	55	300	265	2.0	4.31	35.4	—	—	—	—	3.37	0.57
	1TLF-1	55	300	265	2.0	4.31	35.6	C	50	100	1	5.48	0.92
	1TL-2	55	300	265	3.4	4.31	33.6	—	—	—	—	1.30	0.22
	1TLF-2	55	300	265	3.4	4.31	40.9	C	50	100	1	4.03	0.63
	1TL-3	55	300	265	4.9	4.31	34.1	—	—	—	—	1.19	0.20
	1TLF-3	55	300	265	4.9	4.31	36.0	C	50	100	1	2.90	0.48
	2TL-1	55	300	265	2.0	2.76	36.5	—	—	—	—	2.49	0.41
	2TLF-1	55	300	265	2.0	2.76	37.8	C	50	100	1	4.91	0.80
	2TL-2	55	300	265	3.4	2.76	33.4	—	—	—	—	1.22	0.21
	2TLF-2	55	300	265	3.4	2.76	33.1	C	50	100	1	3.11	0.54
	2TL-3	55	300	265	4.9	2.76	36.1	—	—	—	—	1.06	0.18
	2TLF-3	55	300	265	4.9	2.76	35.9	C	50	100	1	2.92	0.49
	3TL-1	55	300	265	2.0	1.55	37.4	—	—	—	—	2.15	0.35
	3TLF-1	55	300	265	2.0	1.55	35.7	C	50	100	1	4.63	0.77
	3TL-2	55	300	265	3.4	1.55	32.8	—	—	—	—	1.02	0.18
	3TLF-2	55	300	265	3.4	1.55	34.5	C	50	100	1	2.83 <sup>†</sup>	0.48 <sup>†</sup>
19	1	60	375	340	2.0	3.44	32.8	—	—	—	—	3.09	0.54
	2	60	375	340	2.0	3.44	35.0	H	30	60	0.5	5.34	0.90
	3	60	375	340	2.0	3.44	33.0	H	30	60	0.75	4.43	0.77
	4	60	375	340	2.0	3.44	36.0	H	30	60	1	5.15	0.86
	5	60	375	340	2.5	3.44	36.0	H	30	60	1	3.78	0.63
	6	60	375	340	1.5	3.44	36.0	H	30	60	1	7.52	1.25
20	1	305	546	457	4.7	2.54	32.1	—	—	—	—	1.32	0.23
	3	305	546	457	4.7	2.54	28.5	NA	NA	NA	1.5	1.90	0.36
	4	305	546	457	4.7	2.54	28.5	NA	NA	NA	1.5	1.86	0.35

\*C = Crimped fiber; H = hooked fiber; S-H = combination of straight and hooked fibers; NA = unknown fiber type.

<sup>†</sup>Beam failed in flexure.

Notes:  $h$  = beam height;  $v_u = V_u/b_w d$  = ultimate shear stress; other variables are defined in article. 1 mm = 0.0394 in.; 1 MPa = 145 psi.

Ref.	Beam No.	b <sub>c</sub> , in.	h, in.	d, in.	d', in.	A <sub>s</sub> , in <sup>2</sup>	ρ	No. bars	φ <sub>s</sub> , in.	A <sub>s</sub> ', in <sup>2</sup>	ρ'	No. bars'	φ <sub>s</sub> ', in.	a, in.	a/d	f' <sub>c</sub> - cube, ksi	f' <sub>c</sub> - cylinder, ksi	Max. aggregate size, in.	Fiber type	L <sub>c</sub> , in.	D <sub>c</sub> , in.	L <sub>t</sub> /D <sub>t</sub>	f <sub>u, fiber</sub>	V <sub>c</sub> %	V <sub>s</sub> , kips	v <sub>c</sub> , psi	v <sub>s</sub> , √f <sub>i</sub> , psi	
4	1	6.0	18.0	15.0		1.76	0.020	4	0.75	0.40	0.004	2	0.50	52.5	3.5		5.53	0.38		H	1.18	0.020	60.0	174.2	1	39.6	440	5.92
	2	6.0	18.0	15.0		1.76	0.020	4	0.75	0.40	0.004	2	0.50	52.5	3.5		5.53	0.38		H	1.18	0.020	60.0	174.2	1	40.4	449	6.04
	3	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	52.5	3.5		5.53	0.38		H	1.18	0.020	60.0	174.2	1	45.2	502	6.75
	4	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	52.5	3.5		5.53	0.38		H	1.18	0.020	60.0	174.2	1	33.1	368	4.94
	5	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		6.21	0.38							1	14.6	162	2.06
	6	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		6.21	0.38								14.1	157	1.99
	7	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		4.50	0.38		H	1.18	0.020	60.0	160.0	1.5	33.4	371	5.54
	8	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		4.50	0.38		H	1.18	0.020	60.0	160.0	1.5	44.1	490	7.30
	9	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		6.52	0.38		H	1.18	0.020	60.0	160.0	1.5	42.9	476	5.90
	10	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		6.52	0.38		H	1.18	0.020	60.0	160.0	1.5	42.6	473	5.86
	11	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		7.14	0.38		H	2.36	0.020	80.0	152.0	1	38.8	431	5.10
	12	6.0	18.0	15.0		2.40	0.027	4	0.88	0.40	0.004	2	0.50	51.5	3.4		7.14	0.38		H	2.36	0.020	80.0	152.0	1	49.2	547	6.47
5	FC1	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		8.71	0.55								33.5	254	2.72
	FC2	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		7.85	0.55		H	1.18	0.020	60.0	174.2	0.75	62.0	471	5.31
	FC3	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		7.24	0.55		H	1.18	0.020	60.0	174.2	1.5	72.8	553	6.50
	FC7	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		8.27	0.55								27.4	208	2.29
	FC8	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		7.95	0.55		H	1.18	0.020	60.0	174.2	0.4	45.8	348	3.90
	FC9	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		8.20	0.55		H	1.18	0.020	60.0	174.2	0.6	52.1	396	4.37
	FC10	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		6.81	0.55		H	1.97	0.020	100.0	174.2	0.4	55.5	421	5.11
	FC11	5.9	24.0	21.9	2.1	2.92	0.023	6	0.79	2.92	0.023	6	0.79	36.0	1.6		5.92	0.55		H	1.97	0.020	100.0	174.2	0.6	53.3	404	5.26
6	B-2-1.0-L	5.0	10.0	8.5		0.16	0.004	2	0.31					16.9	2.0		13.35	0.38		H	2.36	0.031	75.0	37.5	1	10.3	244*	2.11*
	B-4-1.0-L	5.0	10.0	8.5		0.16	0.004	2	0.31					33.9	4.0		13.44	0.38		H	2.36	0.031	75.0	37.5	1	5.5	130*	1.12*
	B-6-1.0-L	5.0	10.0	8.5		0.16	0.004	2	0.31					50.8	6.0		13.60	0.38		H	2.36	0.031	75.0	37.5	1	3.4	81*	0.70*
	B-1-0.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					8.5	1.0		14.37	0.38		H	2.36	0.031	75.0	37.5	0.5	55.8	1319	11.01
	B-2-0.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					16.9	2.0		14.38	0.38		H	2.36	0.031	75.0	37.5	0.5	29.6	700	5.83
	B-4-0.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					33.9	4.0		13.85	0.38		H	2.36	0.031	75.0	37.5	0.5	13.9	329	2.80
	B-6-0.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					50.8	6.0		13.90	0.38		H	2.36	0.031	75.0	37.5	0.5	12.0	283	2.40
	B-1-1.0A	5.0	10.0	8.5		1.20	0.028	2	0.87					8.5	1.0		13.83	0.38		H	2.36	0.031	75.0	37.5	1	78.3	1849	15.72
	B-2-1.0-A	5.0	10.0	8.5		1.20	0.028	2	0.87					16.9	2.0		13.83	0.38		H	2.36	0.031	75.0	37.5	1	37.2	880	7.48
	B-4-1.0-A	5.0	10.0	8.5		1.20	0.028	2	0.87					33.9	4.0		14.15	0.38		H	2.36	0.031	75.0	37.5	1	19.5	460*	3.87*
	B-6-1.0-A	5.0	10.0	8.5		1.20	0.028	2	0.87					50.8	6.0		14.59	0.38		H	2.36	0.031	75.0	37.5	1	12.0	284*	2.36*
	B-1-1.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					8.5	1.0		13.99	0.38		H	2.36	0.031	75.0	37.5	1.5	85.7	2025	17.17