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[1] (ACI 318-05[2]) 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, ϕ 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 $0.17\sqrt{f'_c}b_wd$ ($2\sqrt{f'_c}b_wd$), 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.[3]

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.[4] 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)

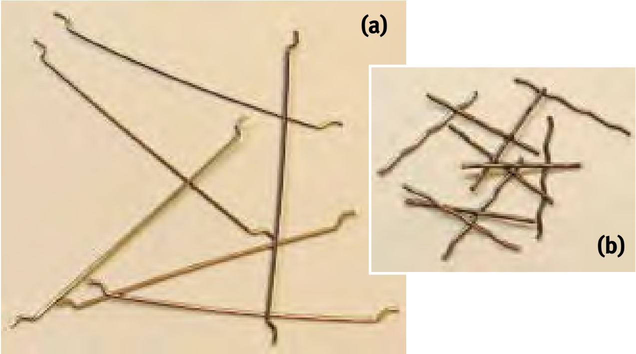

Fig. 1: Typical deformed steel fibers: (a) hooked fibers; and (b) crimped fibers

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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.[4] 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 $0.085\sqrt{f'_c}b_wd$ to $0.17\sqrt{f'_c}b_wd$ ($\sqrt{f'_c}b_wd$ to $2\sqrt{f'_c}b_wd$), which typically correspond to $0.5V_c$ and V_c, respectively. These limits typically define the range where ACI 318[1,2] 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** or by contacting ACI Headquarters.

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

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.[4-20] 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 kN/m^3 [33 lb/yd^3] $\leq V_f \leq$ 1.53 kN/m^3 [263 lb/yd^3]);
- Steel fiber type: hooked or crimped except for five beams in which a combination of straight and hooked

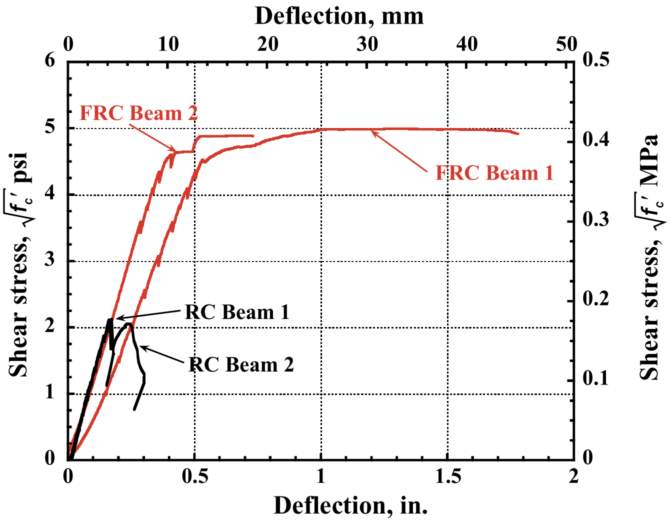

Fig. 3: Normalized shear stress versus deflection behavior for reinforced concrete beams with and without steel fiber reinforcement tested at the University of Michigan[4]

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: $50 \le L_f/d_f \le 100$; and
- Longitudinal tensile reinforcement ratio ρ: $0.37\% \le \rho \le 4.58\%$.

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.[21]

Out of the 147 FRC beams included in the database, 102 beams can be considered slender ($a/d \ge 2.8$), 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 $a/d \ge 2.8$) 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 $V_u \le 0.17\sqrt{f'_c}b_wd$ ($2\sqrt{f'_c}b_wd$). 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

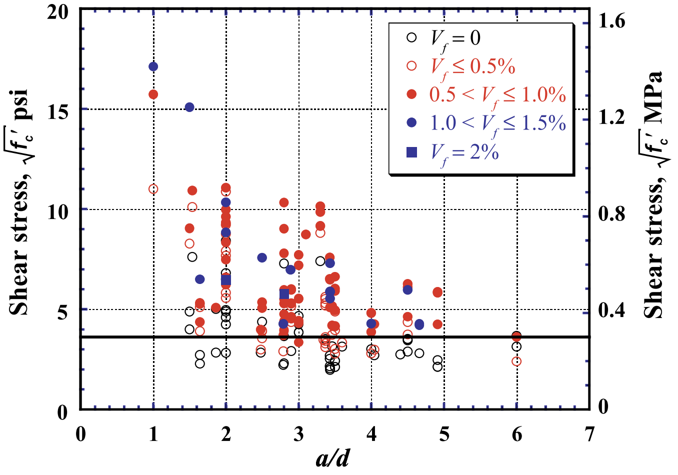

Fig. 4: Normalized shear stress at failure versus shear span-to-effective depth ratio

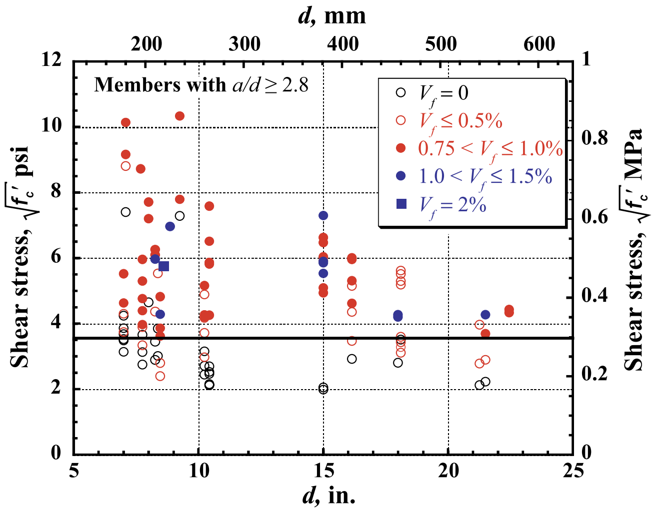

Fig. 5: Normalized shear stress at failure versus beam effective depth (slender beams)

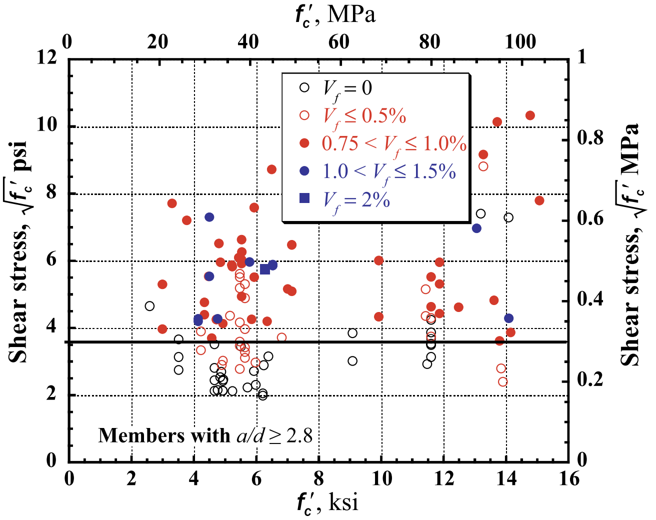

Fig. 6: Normalized shear stress at failure versus concrete compressive strength (slender beams)

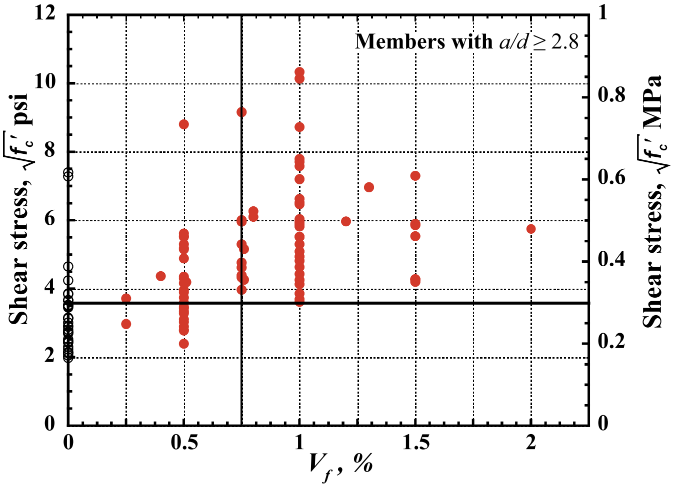

Fig. 7: Normalized shear stress at failure versus fiber volume fraction (slender beams)

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[22] 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 $\sqrt{f'_c}b_wd$ to 0.17 $\sqrt{f'_c}b_wd$ ($\sqrt{f'_c}b_wd$ to 2 $\sqrt{f'_c}b_wd$). 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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Received and reviewed under Institute publication policies.

ACI member **Gustavo J. Parra-Montesinos** is an Associate Professor of Civil Engineering at the University of Michigan, Ann Arbor, MI. He is Secretary of ACI Committee 335, Composite and Hybrid Structures, and a member of ACI Committee 544, Fiber Reinforced Concrete; ACI Subcommittee 318-F, New Materials, Products, and Ideas; and Joint ACI-ASCE Committee 352, Joints and Connections in Monolithic Concrete Structures. His research interests include the seismic behavior and design of reinforced concrete, hybrid steel-concrete, and fiber-reinforced concrete structures.

TABLE 1:
SHEAR TEST DATABASE

Ref. No.	Beam	b_w, mm	h, mm	d, mm	a/d	ρ, %	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†	0.18†
	B-4-1.0-L	125	250	215	4.0	0.37	92.6	H	60	75	1	0.89†	0.09†
	B-6-1.0-L	125	250	215	6.0	0.37	93.7	H	60	75	1	0.56†	0.06†
	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†	0.32†
	B-6-1.0-A	125	250	215	6.0	2.84	100.5	H	60	75	1	1.96†	0.20†
	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†	0.20†
	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	ρ, %	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†	0.57†
	HSFRC3	125	250	225	2.9	2.21	90.0	H	30	60	1.3	3.50†	0.37†
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†	0.48†
	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†	0.54†
	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†	0.23†
	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†	0.54†
	2/1.0/2.5	152	254	221	2.5	1.19	34.0	H	30	60	1	1.79†	0.31†
	2/1.0/3.5	152	254	221	3.5	1.19	34.0	H	30	60	1	1.38†	0.24†
	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	ρ, %	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†	0.23†
	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†	0.29†
	C4	152	229	197	4.4	1.34	29.9	H	30	60	0.75	1.36†	0.25†
	C5	152	229	200	2.8	0.79	29.9	H	30	60	0.75	1.23†	0.22†
	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†	0.56†
	D2	152	229	197	2.8	1.34	30.0	H	30	60	1.0	2.16†	0.39†
	D3	152	229	197	3.6	1.34	30.0	H	30	60	1.0	1.68†	0.31†
	D4	152	229	197	4.4	1.34	30.0	H	30	60	1.0	1.46†	0.27†
	E1	152	229	200	2.8	0.79	20.6	H	30	60	1.0	1.15†	0.25†
	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†	0.27†
	F2	152	229	197	2.8	1.34	33.4	H	30	60	0.75	2.50†	0.43†
	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	ρ, %	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-SRFC-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	ρ, %	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†	0.41†
	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†	0.35†
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†	0.48†
	3TL3	55	300	265	4.9	1.55	33.8	—	—	—	—	1.03	0.18
	3TLF-3	55	300	265	4.9	1.55	32.5	C	50	100	1	2.01†	0.35†
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.

†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_w, in.	h, in.	d, in.	d’, in.	As, in^2	ρ	No. bars	ϕ_b, in.	As’, in^2	ρ’	No. bars’	ϕ_b’, in.	a, in.	a/d	f'_c- cube, ksi	f'_c – cylinder, ksi	Max. aggregate size, in.	Fiber type	L_f, in.	D_f, in.	L_f/D_f	fu_{fiber}	V_f, %	V_u, kips	v_u, psi	v_u, $\sqrt{f_c}$ 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							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	17.12
	B-2-1.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					16.9	2.0		14.02	0.38	H	2.36	0.031	75.0	37.5	1.5	44.3	1046	8.84
	B-4-1.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					33.9	4.0		14.09	0.38	H	2.36	0.031	75.0	37.5	1.5	21.6	509	4.29
	B-6-1.5-A	5.0	10.0	8.5		1.20	0.028	2	0.87					50.8	6.0		14.70	0.38	H	2.36	0.031	75.0	37.5	1.5	12.2	287*	2.37*
	B-2-1.0-M	5.0	10.0	8.5		1.94	0.046	2	1.10					16.9	2.0		13.72	0.38	H	2.36	0.031	75.0	37.5	1	41.3	977	8.34
	B-4-1.0-M	5.0	10.0	8.5		1.94	0.046	2	1.10					33.9	4.0		13.61	0.38	H	2.36	0.031	75.0	37.5	1	23.8	563	4.83
	B-6-1.0-M	5.0	10.0	8.5		1.94	0.046	2	1.10					50.8	6.0		13.79	0.38	H	2.36	0.031	75.0	37.5	1	18.0	425	3.62
7	HSFRC1	5.0	10.0	8.9		1.58	0.036	2	1.00					25.6	2.9		13.06	0.38	H	1.18	0.020	60.0	174.2	1.3	35.3	797	6.97
	HSFRC2	5.0	10.0	8.9		1.58	0.036	2	1.00					25.6	2.9		13.06	0.38	H	1.18	0.020	60.0	174.2	1.3	35.1	791	6.93
	HSFRC3	5.0	10.0	8.9		0.98	0.022	2	0.79					25.6	2.9		13.06	0.38	H	1.18	0.020	60.0	174.2	1.3	22.5	507	4.44
8	A00	5.9	9.8	8.6		0.97	0.019	2	0.79					24.0	2.8		5.98	0.38							9.1	178	2.31
	A10	5.9	9.8	8.6		0.97	0.019	2	0.79					24.0	2.8		5.93	0.38	H	1.18	0.020	60.0	161.7	1	21.6	425	5.52
	A20	5.9	9.8	8.6		0.97	0.019	2	0.79					24.0	2.8		6.27	0.38	H	1.18	0.020	60.0	161.7	2	23.1	455	5.75
	B00	5.9	9.8	8.6		0.97	0.019	2	0.79					17.0	2.0		5.98	0.38							11.1	219	2.83
	B10	5.9	9.8	8.6		0.97	0.019	2	0.79					17.0	2.0		5.93	0.38	H	1.18	0.020	60.0	161.7	1	25.8	508	6.59
	B20	5.9	9.8	8.6		0.97	0.019	2	0.79					17.0	2.0		6.27	0.38	H	1.18	0.020	60.0	161.7	2	25.9	511	6.45
9	FHB1-2	5.0	10.0	8.4		0.62	0.015	2	0.63					16.8	2.0		9.09	0.75							18.4	438	4.60
	FHB2-2	5.0	10.0	8.4		0.62	0.015	2	0.63					16.8	2.0		9.26	0.75	H	1.97	0.031	62.5	156.5	0.5	30.9	739	7.68
	FHB3-2	5.0	10.0	8.4		0.62	0.015	2	0.63					16.8	2.0		9.96	0.75	H	1.97	0.031	62.5	156.5	0.75	33.1	790	7.91
	FHB1-3	5.0	10.0	8.4		0.62	0.015	2	0.63					25.1	3.0		9.09	0.75							15.4	367	3.85
	FHB2-3	5.0	10.0	8.4		0.62	0.015	2	0.63					25.1	3.0		9.26	0.75	H	1.97	0.031	62.5	156.5	0.5	18.8	448	4.66
	FHB3-3	5.0	10.0	8.4		0.62	0.015	2	0.63					25.1	3.0		9.96	0.75	H	1.97	0.031	62.5	156.5	0.75	20.7	493	4.95
	FHB1-4	5.0	10.0	8.4		0.62	0.015	2	0.63					33.5	4.0		9.09	0.75							12.0	287	3.01
	FHB2-4	5.0	10.0	8.4		0.62	0.015	2	0.63					33.5	4.0		9.26	0.75	H	1.97	0.031	62.5	156.5	0.5	14.6	350	3.63
	FHB3-4	5.0	10.0	8.4		0.62	0.015	2	0.63					33.5	4.0		9.96	0.75	H	1.97	0.031	62.5	156.5	0.75	16.7	398	3.99
	FNB2-2	5.0	10.0	8.4		0.62	0.015	2	0.63					16.8	2.0		4.47	0.75	H	1.97	0.031	62.5	156.5	0.5	24.6	586	8.77
	FNB2-3	5.0	10.0	8.4		0.62	0.015	2	0.63					25.1	3.0		4.47	0.75	H	1.97	0.031	62.5	156.5	0.5	15.5	370	5.54
	FNB2-4	5.0	10.0	8.4		0.62	0.015	2	0.63					33.5	4.0		4.47	0.75	H	1.97	0.031	62.5	156.5	0.5	12.2	290	4.34
10		5.0	9.0	8.0		0.88	0.022	2	0.75					24.0	3.0		2.58								9.5	237	4.65
		5.0	9.0	8.0		0.88	0.022	2	0.75					24.0	3.0		3.29		H	1.18	0.020	60.0	170.1	1	17.7	443	7.71
		5.0	9.0	8.0		0.88	0.022	2	0.75					24.0	3.0		3.77		H	1.97	0.020	100.0	170.1	1	17.7	443	7.21
11	2/0.5/1.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38	H	1.18	0.020	60.0		0.5	24.0	460	6.55
	2/0.5/2.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	22.0	2.5		4.93	0.38	H	1.18	0.020	60.0		0.5	13.0	250	3.56
	2/0.5/3.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38	H	1.18	0.020	60.0		0.5	10.2	195	2.77
	2/0/1.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38							14.7	281	4.00
	2/0/3.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38							8.9	170	2.43
	2/1.0/1.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38	H	1.18	0.020	60.0		1	23.9	458	6.53
	2/1.0/2.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	22.0	2.5		4.93	0.38	H	1.18	0.020	60.0		1	13.5	259	3.69
	2/1.0/3.5	6.0	10.0	8.7		0.62	0.012	2	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38	H	1.18	0.020	60.0		1	10.4	200	2.85
	4/0.5/1.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38	H	1.18	0.020	60.0		0.5	30.3	581	8.28
	4/0.5/2.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	22.0	2.5		4.93	0.38	H	1.18	0.020	60.0		0.5	14.3	274	3.91
	4/0.5/3.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38	H	1.18	0.020	60.0		0.5	11.1	213	3.03
	4/0/1.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38							17.9	344	4.89
	4/0/3.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38							7.8	149	2.13
	4/1.0/1.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	13.0	1.5		4.93	0.38	H	1.18	0.020	60.0		1	33.1	635	9.04
	4/1.0/2.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	22.0	2.5		4.93	0.38	H	1.18	0.020	60.0		1	18.6	356	5.06
	4/1.0/3.5	6.0	10.0	8.7		1.25	0.024	4	0.63	0.24	0.470	2	0.39	30.0	3.5		4.93	0.38	H	1.18	0.020	60.0		1	15.1	290	4.13
12	A1	6.0	9.0	7.8		0.62	0.013	2	0.63					15.5	2.0		3.51	0.38**							13.5	290	4.89
	A2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		3.51	0.38							10.1	217	3.67
	A3	6.0	9.0	7.8		0.62	0.013	2	0.63					27.9	3.6		3.51	0.38							8.7	186	3.14
	A4	6.0	9.0	7.8		0.62	0.013	2	0.63					34.1	4.4		3.51	0.38							7.6	163	2.75
	B1	6.0	9.0	7.8		0.62	0.013	2	0.63					15.5	2.0		4.22	0.38	H	1.18	0.020	60.0	183.0	0.5	16.9	362	5.57
	B2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		4.22	0.38	H	1.18	0.020	60.0	183.0	0.5	11.8	254	3.90
	B3	6.0	9.0	7.8		0.62	0.013	2	0.63					27.9	3.6		4.22	0.38	H	1.18	0.020	60.0	183.0	0.5	10.1	217	3.34
	B4	6.0	9.0	7.8		0.62	0.013	2	0.63					34.1	4.4		4.22	0.38	H	1.18	0.020	60.0	183.0	0.5	8.5	184*	2.82*
	C1	6.0	9.0	7.8		0.62	0.013	2	0.63					15.5	2.0		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	19.1	410	6.23
	C2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	13.5	290	4.40
	C3	6.0	9.0	7.8		0.62	0.013	2	0.63					27.9	3.6		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	10.7	229*	3.48*
	C4	6.0	9.0	7.8		0.62	0.013	2	0.63					34.1	4.4		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	9.2	198*	3.01*
	C5	6.0	9.0	7.9		0.37	0.008	3	0.39					22.0	2.8		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	8.4	178	2.71
	C6	6.0	9.0	7.8		0.93	0.020	3	0.63					21.7	2.8		4.34	0.38	H	1.18	0.020	60.0	183.0	0.75	14.6	314	4.76
	D1	6.0	9.0	7.8		0.62	0.013	2	0.63					15.5	2.0		4.35	0.38	H	1.18	0.020	60.0	183.0	1	20.9	449*	6.81*
	D2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		4.35	0.38	H	1.18	0.020	60.0	183.0	1	14.6	314*	4.76*
	D3	6.0	9.0	7.8		0.62	0.013	2	0.63					27.9	3.6		4.35	0.38	H	1.18	0.020	60.0	183.0	1	11.3	244*	3.70*
	D4	6.0	9.0	7.8		0.62	0.013	2	0.63					34.1	4.4		4.35	0.38	H	1.18	0.020	60.0	183.0	1	9.9	212*	3.22*
	E1	6.0	9.0	7.9		0.37	0.008	3	0.39					22.0	2.8		2.99	0.38	H	1.18	0.020	60.0	183.0	0.75	7.9	166*	3.04*
	E2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		2.99	0.38	H	1.18	0.020	60.0	183.0	0.75	10.1	217	3.97
	E3	6.0	9.0	7.8		0.93	0.020	3	0.63					21.7	2.8		2.99	0.38	H	1.18	0.020	60.0	183.0	0.75	13.5	290	5.30
	F1	6.0	9.0	7.9		0.37	0.008	3	0.39					22.0	2.8		4.85	0.38	H	1.18	0.020	60.0	183.0	0.75	10.5	223*	3.20*
	F2	6.0	9.0	7.8		0.62	0.013	2	0.63					21.7	2.8		4.85	0.38	H	1.18	0.020	60.0	183.0	0.75	16.9	362*	5.20*
	F3	6.0	9.0	7.8		0.93	0.020	3	0.63					21.7	2.8		4.85	0.38	H	1.18	0.020	60.0	183.0	0.75	19.3	415	5.96
13	1 type A	7.9	9.8	7.1		2.51	0.045	8	0.63					23.6	3.3		13.19	0.63							47.4	851	7.41
	4 type A	7.9	9.8	7.1		2.51	0.045	8	0.63					23.6	3.3		13.72	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	66.3	1188	10.14
	5 type A	7.9	9.8	7.1		2.51	0.045	8	0.63					23.6	3.3		13.27	0.63	H	2.36	0.028	86.0	319.3	0.5	56.7	1015	8.81
	6 type A	7.9	9.8	7.1		2.51	0.045	8	0.63					23.6	3.3		13.27	0.63	H	2.36	0.028	86.0	319.3	0.75	58.9	1056	9.16
	9 type A	7.9	9.8	7.7		1.87	0.031	6	0.63					23.6	3.1		6.50	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	42.5	703	8.73
	1 type B	7.9	11.8	9.3		3.13	0.043	10	0.63	0.24	0.003	2	0.39	25.6	2.8		14.08	0.63							62.9	865	7.29
	3 type B	7.9	11.8	9.3		3.13	0.043	10	0.63	0.24	0.003	2	0.39	25.6	2.8		15.07	0.63	H	1.18	0.024	50.0	159.7	1	69.7	957	7.80
	5 type B	7.9	11.8	9.3		3.13	0.043	10	0.63	0.24	0.003	2	0.39	25.6	2.8		14.77	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	91.5	1256	10.33
	1 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		11.48	0.63							39.8	314	2.93
	5 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		11.87	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	82.5	650	5.96
	6 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		11.87	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	73.5	579	5.31
	7 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		11.43	0.63	H	2.36	0.028	86.0	319.3	0.5	59.4	466	4.36
	8 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		11.43	0.63	H	2.36	0.028	86.0	319.3	0.5	70.1	551	5.16
	9 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		9.93	0.63	H	2.36	0.028	86.0	319.3	0.75	76.2	599	6.01
	10 type C	7.9	19.7	16.1		3.81	0.030	8	0.79	0.62	0.005	2	0.63	47.2	2.9		12.48	0.63	H	2.36	0.028	86.0	319.3	0.75	65.6	516	4.62
	3 type D	11.8	27.6	22.4		7.69	0.029	10	0.98	0.62	0.002	2	0.63	66.9	3.0		11.87	0.63	S-H	1.18	0.024	50.0	159.7	0.5/0.5	134.0	483	4.43
	4 type D	11.8	27.6	22.4		7.69	0.029	10	0.98	0.62	0.002	2	0.63	66.9	3.0		9.93	0.63	H	2.36	0.028	86.0	319.3	0.75	114.4	432	4.34
14	1.2/1	7.9	11.8	10.2		2.87	0.036	3	1.10					35.4	3.5		6.39								20.3	252	3.16
	1.2/2	7.9	11.8	10.2		2.87	0.036	3	1.10					35.4	3.5		6.81		H	2.36	0.035	66.7	145.1	0.25	24.7	307	3.72
	1.2/3	7.9	11.8	10.2		2.87	0.036	3	1.10					35.4	3.5		6.35		H	2.36	0.035	66.7	145.1	0.51	27.0	335	4.20
	1.2/4	7.9	11.8	10.2		2.87	0.036	3	1.10					35.4	3.5		7.00		H	2.36	0.035	66.7	145.1	0.76	34.8	432	5.16
	2.2/1	7.9	11.8	10.2		1.46	0.018	3	0.79					15.8	1.5		5.93								47.2	586	7.61
	2.2/2	7.9	11.8	10.2		1.46	0.018	3	0.79					15.8	1.5		5.98		H	2.36	0.035	66.7	145.1	0.25	62.9	781	10.10
	2.2/3	7.9	11.8	10.2		1.46	0.018	3	0.79					15.8	1.5		5.85		H	2.36	0.035	66.7	145.1	0.76	67.4	836	10.94
	2.3/1	7.9	11.8	10.3		0.93	0.012	3	0.63					25.6	2.5		5.82								17.6	217	2.85
	2.3/2	7.9	11.8	10.3		0.93	0.012	3	0.63					25.6	2.5		5.81		H	2.36	0.035	66.7	145.1	0.25	18.5	228	2.99
	2.3/3	7.9	11.8	10.3		0.93	0.012	3	0.63					25.6	2.5		5.61		H	2.36	0.035	66.7	145.1	0.76	24.3	299	3.99
	2.4/1	7.9	11.8	10.2		1.46	0.018	3	0.79					25.6	2.5		5.82								27.0	334	4.38
	2.4/2	7.9	11.8	10.2		1.46	0.018	3	0.79					25.6	2.5		5.81		H	2.36	0.035	66.7	145.1	0.25	24.3	301	3.95
	2.4/3	7.9	11.8	10.2		1.46	0.018	3	0.79					25.6	2.5		5.61		H	2.36	0.035	66.7	145.1	0.76	32.4	401	5.36
	2.6/1	7.9	11.8	10.2		1.46	0.018	3	0.79					41.4	4.0		5.93								16.9	209	2.72
	2.6/2	7.9	11.8	10.2		1.46	0.018	3	0.79					41.4	4.0		5.98		H	2.36	0.035	66.7	145.1	0.25	18.5	230	2.98
	2.6/3	7.9	11.8	10.2		1.46	0.018	3	0.79					41.4	4.0		5.85		H	2.36	0.035	66.7	145.1	0.76	26.3	326	4.27
	20x30-Plain Series 1	7.9	11.8	10.2		2.28	0.028	3	0.98					35.8	3.5		4.66	0.98							13.5	167	2.45
	20x30-SFRC Series 1	7.9	11.8	10.2		2.28	0.028	3	0.98					35.8	3.5		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	24.9	308	4.17
	20x45-SFRC Series 1	7.9	17.7	16.1		3.91	0.031	3	1.26					53.9	3.3		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	32.7	257	3.47
	20x60-Plain Series 1	7.9	23.6	21.3		4.57	0.027	6	0.98					74.4	3.5		4.66	0.98							24.3	145	2.13
	20x60-SFRC Series 1	7.9	23.6	21.3		4.57	0.027	6	0.98					74.4	3.5		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	34.5	206	2.78
	T10x50-SFRC Series 1	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	38.0	266	3.60
	T15x50-SFRC Series 1	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	59.3	416	5.62
	T15x75-SFRC Series 1	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	58.2	408	5.51
	T15x100-Plain Series 1	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		4.66	0.98							34.2	240	3.52
	T15x100-SFRC Series 1	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.47	0.98	H	2.36	0.035	66.7	145.1	0.5	54.8	384	5.19
	20x30-SFRC Series 2	7.9	11.8	10.2		2.28	0.028	3	0.98					35.8	3.5		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	29.6	367	4.90
	20x50-SFRC Series 2	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	33.3	233	3.11
	20x60-SFRC Series 2	7.9	23.6	21.3		4.57	0.027	6	0.98					74.4	3.5		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	49.9	298	3.97
	T10x50-SFRC Series 2	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	35.2	247	3.29
	T15x50-SFRC Series 2	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	36.7	258	3.43
	T23x50-SFRC Series 2	7.9	19.7	18.1		3.74	0.026	3	1.26					61.0	3.4		5.63	0.98	H	2.36	0.035	66.7	145.1	0.5	56.7	398	5.30
15	I	12.0	24.0	21.5		4.74	0.018	6	1.00					60.0	2.8		5.72	0.38							43.5	169	2.23
	II	12.0	24.0	21.5		4.74	0.018	6	1.00					60.0	2.8		4.89	0.38	C	3.00	0.035	80.0	100.0	0.5	52.3	203	2.90
	III	12.0	24.0	21.5		4.74	0.018	6	1.00					60.0	2.8		4.57	0.38	C	3.00	0.035	80.0	100.0	1	64.5	250	3.70
	IV	12.0	24.0	21.5		4.74	0.018	6	1.00					60.0	2.8		4.76	0.38	C	3.00	0.035	80.0	100.0	1.5	76.1	295	4.28
16	S1	6.0	12.0	10.9	1.1	0.93	0.014	3	0.63	0.10	0.002	2	0.25	20.0	1.8		6.14								14.3	220	2.81
	S2	6.0	12.0	10.9	1.1	0.93	0.030	3	0.63	0.10	0.002	2	0.25	20.0	1.8		6.27								25.6	393	4.96
	S3F	6.0	12.0	10.9	1.1	0.93	0.045	3	0.63	0.10	0.002	2	0.25	20.0	1.8		7.05		H	2.00	0.024	83.3		0.9	27.6	423	5.03
17	B51	6.9	9.8	8.3		2.28	0.040							37.2	4.5		5.52	0.38							14.6	256	3.45
	B52	6.9	9.8	8.3		2.28	0.040							37.2	4.5		5.16	0.38	C	1.97	0.020	100.0	152.0	0.4	17.9	314	4.37
	B53	6.9	9.8	8.3		2.28	0.040							37.2	4.5		5.43	0.38	C	1.97	0.020	100.0	152.0	0.8	25.6	450	6.10
	B54	6.9	9.8	8.3		2.28	0.040							37.2	4.5		5.78	0.38	C	1.97	0.020	100.0	152.0	1.2	25.8	454	5.97
	B55	6.9	9.8	8.3		1.74	0.031							37.2	4.5		5.54	0.38	C	1.97	0.020	100.0	152.0	0.8	26.6	466	6.27
	B56	6.9	9.8	8.3		1.11	0.020							37.2	4.5		6.07	0.38	C	1.97	0.020	100.0	152.0	0.8	21.7	380	4.88
	B61R	6.9	9.8	8.3		1.11	0.020							37.2	4.5		6.24	0.38							13.0	228	2.89
	B63R	6.9	9.8	8.3		1.11	0.020							37.2	4.5		5.10	0.38	C	1.97	0.020	100.0	152.0	0.8	17.0	298	4.17
18	1TL-1	2.2	12.0	10.4		0.98	0.043							20.9	2.0		5.14	0.55							11.1	488	6.81
	1TLF-1	2.2	12.0	10.4		0.98	0.043							20.9	2.0		5.17	0.55	C	2.00	0.020	100.0	227.9	1	18.0	796	11.07
	1TL-2	2.2	12.0	10.4		0.98	0.043							35.8	3.4		4.88	0.55							4.3	188	2.70
	1TLF-2	2.2	12.0	10.4		0.98	0.043							35.8	3.4		5.93	0.55	C	2.00	0.020	100.0	227.9	1	13.3	585	7.59
	1TL-3	2.2	12.0	10.4		0.98	0.043							51.2	4.9		4.95	0.55							3.9	173	2.47
	1TLF-3	2.2	12.0	10.4		0.98	0.043							51.2	4.9		5.22	0.55	C	2.00	0.020	100.0	227.9	1	9.6	421	5.83
	2TL-1	2.2	12.0	10.4		0.63	0.028							20.9	2.0		5.29	0.55							8.2	362	4.97
	2TLF-1	2.2	12.0	10.4		0.63	0.028							20.9	2.0		5.48	0.55	C	2.00	0.020	100.0	227.9	1	16.2	712	9.62
	2TL-2	2.2	12.0	10.4		0.63	0.028							35.8	3.4		4.84	0.55							4.0	176	2.53
	2TLF-2	2.2	12.0	10.4		0.63	0.028							35.8	3.4		4.81	0.55	C	2.00	0.020	100.0	227.9	1	10.2	452	6.52
	2TL-3	2.2	12.0	10.4		0.63	0.028							51.2	4.9		5.24	0.55							3.5	154	2.12
	2TLF-3	2.2	12.0	10.4		0.63	0.028							51.2	4.9		5.21	0.55	C	2.00	0.020	100.0	227.9	1	9.6	424	5.87
	3TL-1	2.2	12.0	10.4		0.35	0.016							20.9	2.0		5.42	0.55							7.1	312	4.24
	3TLF-1	2.2	12.0	10.4		0.35	0.016							20.9	2.0		5.18	0.55	C	2.00	0.020	100.0	227.9	1	15.2	672	9.33
	3TL-2	2.2	12.0	10.4		0.35	0.016							35.8	3.4		4.76	0.55							3.4	149	2.15
	3TLF-2	2.2	12.0	10.4		0.35	0.016							35.8	3.4		5.00	0.55	C	2.00	0.020	100.0	227.9	1	9.3	411*	5.81*
	3TL3	2.2	12.0	10.4		0.35	0.016							51.2	4.9		4.91	0.55							3.4	150	2.13
	3TLF-3	2.2	12.0	10.4		0.35	0.016							51.2	4.9		4.71	0.55	C	2.00	0.020	100.0	227.9	1	6.6	292*	4.26*
19	1	2.4	14.8	13.4		1.20	0.034	6	0.50					26.8	2.0		4.76	0.75							28.4	449	6.50
	2	2.4	14.8	13.4		1.20	0.034	6	0.50					26.8	2.0		5.08	0.75	H	1.20	0.020	60.0		0.5	49.0	775	10.87
	3	2.4	14.8	13.4		1.20	0.034	6	0.50					26.8	2.0		4.79	0.75	H	1.20	0.020	60.0		0.75	40.7	643	9.29
	4	2.4	14.8	13.4		1.20	0.034	6	0.50					26.8	2.0		5.22	0.75	H	1.20	0.020	60.0		1	47.3	747	10.34
	5	2.4	14.8	13.4		1.20	0.034	6	0.50					33.5	2.5		5.22	0.75	H	1.20	0.020	60.0		1	34.7	548	7.58
	6	2.4	14.8	13.4		1.20	0.034	6	0.50					20.1	1.5		5.22	0.75	H	1.20	0.020	60.0		1	69.0	1091	15.09
20	1	12.0	21.5	18.0		5.50	0.025	7	1.00					83.9	4.7		4.66	0.35							41.5	192	2.81
	3	12.0	21.5	18.0		5.50	0.025	7	1.00					83.9	4.7		4.14	0.35	NA					1.5	59.4	275	4.28
	4	12.0	21.5	18.0		5.50	0.025	7	1.00					83.9	4.7		4.14	0.35	NA					1.5	58.4	270	4.20

*Beam failed in flexure

**There is an inconsistency in the values reported in the original reference. The number shown corresponds to the value reported in US units. However, 20 mm was the reported value in metric units

C: Crimped fiber; H: hooked fiber

h: beam height; *d’*: distance from centroid of compression reinforcement to extreme compression fiber; A_s’: area of compression longitudinal reinforcement

No. Bars: number of tension reinforcing bars; No. Bars’: number of compression reinforcement bars

ϕ_b: tensile reinforcing bar diameter; ϕ_b’: compression reinforcing bar diameter; ρ’: compression reinforcement ratio

v_u: ultimate shear stress; fu_{fiber}: tensile strength of fiber wire; other variables are defined in article