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Shear strength of steel fiber-reinforced lightweight concrete beams

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ABSTRACT: Experimental data were utilized to investigate the effect of steel fibers on the shear strength of a lightweight concrete beam. Prior tests of steel fiber-reinforced lightweight concrete (SFRLC) beams or small-scale concrete mockups were reviewed. Only two large-scale test programs on SFRLC beams are available to date. The variables studied in these programs included the shear span-to-depth ratio and steel fiber volume fraction. The addition of steel fibers with steel fiber volume fractions of 0.5% to 0.75% increased the shear strength by roughly 25% to 45%. It is also found that the shear-to-depth ratio adversely affected the shear strength. Several models for the shear strength of steel fiber-reinforced concrete beams were evaluated using the re-assessed data to evaluate the shear strength of the SFRLC specimens. Finally, design shear strength equations for SFRLC beams without stirrups have been proposed based on the calibration results.

1 INTRODUCTION

Use of steel fiber-reinforced concrete (SFRC) is increasingly popular in the U.S. and other countries, as it tends to improve mechanical properties and structural performance relative to conventionally reinforced concrete (with the same steel volume fraction). The addition of steel fibers (Fig. 1) to a reinforced concrete (RC) beam is known to improve shear and flexural behavior. The improved behavior of SFRC members is associated with the post-cracking tensile strength of SFRC; thus, the use of SFRC helps in reducing the degree and width of cracking (Fig. 2). Along with these advantages, one of the most useful applications of SFRC is to relieve steel congestion by reducing the amount of shear or confining transverse reinforcement without sacrificing structural performance.

A similar improvement may be anticipated in steel fiber-reinforced lightweight concrete (SFRLC); however, the application of minimum steel fiber volume fraction to lightweight concrete is questionable. To address this question, mechanical properties of SFRLC need to be first identified, and then structural performance needs to be verified through large-scale experimental testing. Finally, a database would be compiled and studied for development or support of design models and provisions. In this paper, these procedures are conducted using previous and current research on SFRLC materials and structural members.

Available studies on the structural behavior for large-scale steel fiber-reinforced members with lightweight concrete are scarce, although a large number of studies on SFRC structural members with normalweight concrete have been conducted by many investigators over the past decades (Narayanan & Darwish 1987, Kwak et al. 2002, Ashour et al. 1992, Swamy et al. 1993, Choi et al. 2007, Kang et al. 2009) (see Fig. 3). Given this gap, a review of experimental studies of the shear behavior of SFRLC beams without stirrups is carried out.

Figure 1. Discrete hooked steel fibers.

Figure 2. Steel fibers that restrain crack opening during shear testing (at Fears Lab of the University of Oklahoma).

The objectives of this study are (1) to verify the effectiveness of steel fibers in lightweight concrete, (2) to assess the shear behavior of SFRLC beams quantitatively, and (3) to develop design shear strength equations for SFRLC beams.

Figure 3. Four-point loading of a steel fiber-reinforced beam (at Fears Lab of the University of Oklahoma).

2 PREVIOUS EXPERIMENTAL PROGRAMS

To date, studies on the use of steel fibers in lightweight concrete have been sparse. Most previous tests of SFRLC materials were performed using approximately 100 x 100 x 360 mm prisms (see Fig. 4), 150 x 300 mm cylinders (see Figs. 4 and 5), and small-scale shear specimens (e.g., 80 x 80 x 155 mm) (Balaguru & Ramakrishman 1987, Balaguru & Dipsia 1993, Balaguru & Foden 1996, Swamy & Jojagha 1982a, b, Kayali et al. 1999, Gao et al. 1997, Higashiyama & Banthia 2008). Only 3 large-scale structural testing programs of SFRLC members were reported (Swamy et al. 1993, Theodorakopoulos & Swamy 1993, Kang & Kim 2009).

2.1 *Large-scale structural tests*

Swamy et al. (1993) tested seven large-scale specimens of SFRLC I-section beams with a span length of 3 m. The test results indicated that the ultimate shear strength was dependent upon span-to-depth ratio (a/d) and tension reinforcing ratio (ρ), and that SFRLC with a steel fiber volume fraction (V_f) of 1% showed significantly greater shear strength (by 60% to 210%) than equivalent beams without steel fibers.

Kang & Kim (2009) reported monotonic four-point loading tests of nine SFRLC and three SFRC beams, where the parameters of the shear span-to-depth ratio (2, 3, and 4) and steel fiber volume fraction (V_f = 0%, 0.5%, and 0.75%) are evaluated. It was reported that 1) the shear strength of SFRC beams was slightly larger than that of SFRLC beams (failure modes were different); 2) the steel fiber volume fractions (V_f) of both 0.5% and 0.75% increased the shear strength of plain concrete by about 25% and 45%, respectively; and 3) the shear span-to-depth ratio adversely affected the shear strength of SFRLC beams. Here, λ is the modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normalweight concrete of the same compressive strength (as per Ch. 2 of ACI 318-08).

Theodorakopoulos & Swamy (1993) investigated punching shear behavior and strength of SFRLC slab-column connections. Twenty connection specimens were tested under various parameters of steel fiber shapes, V_f (0.5% and 1%), reinforcing ratios of tension and compression slab steel (0.32% and 0.57%), column size (100, 150, and 200 mm), and concrete compressive strength (f'_c = 17.8 to 58.6 MPa). Overall, the addition of all types of steel fibers in SFRLC slab-column connections increased the gravity load at first cracking (by 33% to 50%), at yielding (by 12% to 80%), and at punching (by 30% to 100%). Usage of paddle steel fibers with V_f = 1% resulted in the greatest punching shear strength.

Figure 4. Modulus of rupture testing (per ASTM C1609) and splitting tensile strength testing (per ASTM C496) of concrete mixes (at Fears Lab of the University of Oklahoma).

2.2 *Small-scale materials tests*

Experimental studies were conducted by Balaguru & Dipsia (1993) and Balaguru & Foden (1996) to assess the applicability of discrete steel fibers for improving mechanical properties of normal-strength (42 MPa) and high-strength (62.1 MPa) lightweight concrete. The experimental programs consisted of third-point loading tests of prisms per ASTM C1018, splitting tensile and compressive strength tests of cylinders per ASTM C496/496M, and direct shear tests. In their experimental studies, it was found that the addition of steel fibers to lightweight concrete increased the compressive strength (f'_c) by 30% to 40%, splitting tensile strength (f_{sp}) by 80% to 100%, and modulus of elasticity (E_c) by 5% to 25%. The improved mechanical properties were observed for all combinations of the fiber lengths (30, 50, and

60 mm) and steel fiber volume fractions (0.55%, 0.75%, 0.9%, and 1.1%).

Figure 5. Compressive strength tests of SFRLC cylinders per ASTM C496, with two strain gauges per cylinder to measure strains (at Fears Lab of the University of Oklahoma). Note that red gravels exposed are expanded shale lightweight aggregates.

Similar experiments were conducted for high-strength SFRLC ($\geq$ 70 MPa) by Gao et al. (1997) and for normal-strength SFRLC by Kayali et al. (1999), and similar results were obtained with the fiber length of about 25 mm and the volume fraction of 0.25% to 1.65%.

Higashiyama & Banthia (2008) evaluated relations between shear and flexural toughness for both SFRC and SFRLC. Two fiber volume fractions (V_f = 0.5% and 1%) were selected for third-point loading tests in accordance with ASTM C1609 and for direct shear tests. The results indicated that for a given fiber type and volume fraction, SFRC exhibited better shear and flexural toughness properties than SFRLC.

Swamy & Jojagha (1982a) performed a variety of workability tests for both SFRC and SFRLC in the fresh state, including inverted slump cone tests, standard slump and flow table tests, and vibrator-based remolding tests. It was concluded that pulverized fuel ash and water-reducing-plasticizing admixture should be added to release inter-locking friction between fibers and aggregates. From similar tests of Balaguru & Ramakrishen (1987), it was concluded that toughness and energy absorption for SFRLC were equivalent to those for SFRC.

Swamy & Jojagha (1982b) experimentally assessed material characteristics of SFRC and SFRLC under impact loads by means of a drop hammer test and a drop ball test in accordance with ACI 544.2R-78. Three and four mixes were tested for normal-weight and lightweight concrete, respectively. Both SFRC and SFRLC with V_f = 1% had greater impact resistance than those without steel fibers by a substantial degree up to a factor of 10. The effects of steel fiber shape and geometry were evident by the fact that the number of shocks needed to fail was 536 and 793 for paddle and hooked shapes, respectively, but much less (124 and 192) for crimped and plain shapes.

Based on the reviews of the prior tests, steel fibers in lightweight concrete appear to be equally effective in improving mechanical properties and structural performance as steel fibers in normal-weight concrete. However, further rational and statistical assessment of the increased properties would be needed to judge whether the λ factor of 0.75 is generally applicable for most cases with relatively small variations. In this study, the variation in λ is not considered for design model simplification and to be consistent with the current ACI 318-08 code provisions (§8.6.1).

3 DEVELOPMENT & CALIBRATION OF DESIGN SHEAR STRENGTH EQUATIONS

In the preceding section, most available previous experimental research on SFRLC was summarized. In this section, the shear strength equations available for SFRC beams were evaluated as to whether or not they are also applicable to SFRLC beams, in consideration of the ACI 318 specified lightweight concrete factor (λ). Results from the prior SFRLC beam tests reported by Swamy et al. (1993) and Kang & Kim (2009) were used for this evaluation.

As part of the analyses, the effect of the dosage rate of steel fibers on shear strength is investigated. According to the new provision of ACI 318-08 (§5.6.6.2(a)), steel fiber-reinforced concrete should be considered acceptable for shear resistance when the dosage rate of deformed steel fibers is not less than 60 kg/m^3. This rate is equivalent to a mix with V_f = 0.75%. Although the specimens investigated (Swamy et al. 1993, Kang & Kim 2009) were built before the inclusion of §5.6.6.2 in the ACI 318 code series, 12 of 15 specimens satisfied this minimum requirement (60 kg/m^3 or V_f = 0.75%).

According to ACI 318-08 (§5.6.6.2), where ASTM C1609 is referred to, a mid-span deflection (δ_{mid}) should also be measured during the modulus of rupture testing if a member is designed for shear resistance (see Fig. 4). The ACI 318 provision specifies that SFRC should be considered acceptable for shear resistance only if the prism flexural strength at $\delta_{mid} = L/300$ is neither less than 90% of the peak nor 90% of cracking moment (M_{cr}), and the strength at $\delta_{mid} = L/150$ is neither less than 75% of the peak nor $0.75M_{cr}$. Here, M_{cr} is calculated using the modulus of rupture (f_r) = $0.63\lambda\sqrt{f'_c}$ MPa per §9.5.2.3 and L is the prism span length.

In order to develop design shear strength model(s) for SFRLC beams without stirrups, the following three steps of the calibration approach were used. First, most available shear strength models for SFRC beams (none lightweight) were extracted from the literature. Detailed equations are not provided in this paper for the sake of brevity. Second, the lightweight concrete modification factor of λ (= 0.75) was accounted for by replacing f'_c with $\lambda^2 f'_c$ for SFRLC beams. Although the constant λ is too simplified for predicting the shear strength of various lightweight concrete, this process is analogous to the application in the current ACI 318-08 code as shown in eqution. (1):

$$\frac{v_c \text{ for lightweight concrete}}{v_c \text{ for normalweight concrete}} = \frac{\lambda\sqrt{f_c'}}{\sqrt{f_c'}} = \frac{\sqrt{\lambda^2 f_c'}}{\sqrt{f_c'}} \quad (1)$$

Finally, the ratio (v_u/v_n) of measured peak shear stress to shear stress capacity calculated based on the existing model, except for the replacement of f'_c by $\lambda^2 f'_c$, was determined for each specimen to make a direct comparison between the models. Here, as-measured material properties are used for the calculation of v_n, and v_u and v_n are defined as the maximum shear force (V_u) and the nominal shear strength (V_n), divided by the beam web width (b_w) and effective depth (d), respectively. Thus, (v_u/v_n) is the same as (V_u/V_n). The mean, standard deviation, and minimum and maximum values of the ratios, as well as the slope of the linear regression lines were compared in this study (Tables 1 and 2). It is noted that this analysis is based on limited data (only 2 test programs and 15 SFRLC specimens). The lack of data warrants additional large-scale experimental studies.

Table 1. Comparisons of measured peak stresses (vu) and shear stress capacities (vn) based on the available SFRC shear strength models except the replacement of f'c by 2f'c for SFRLC beams.

Model		Mean	Stdev.	Max.	Min.
Narayanan et al. (1987)		1.37	0.22	1.87	1.05
Ashour et al.	[model A]	1.33	0.14	1.57	1.11
(1992)	[model B]	1.16	0.22	1.79	0.86
Kwak et al. (2002)		1.30	0.25	1.79	1.02
Khuntia et al. (1999)		2.05	0.70	3.40	1.19
Sharma (1986)		1.60	0.62	2.72	0.72
Imam et al. (1997)		1.38	0.36	2.02	0.75
Shin et al. (1994)		1.16	0.14	1.34	0.84
Li et al. (1992)		1.32	0.43	2.01	0.69
Choi et al. (2007)		1.39	0.71	2.88	0.54

Stdev.: Standard deviation of (vu/vn)'s for 15 SFRLC beams.
Max: Maximum of (vu/vn)'s for 15 SFRLC beams.
Min: Minimum of (vu/vn)'s for 15 SFRLC beams.

The standard deviation is a good statistical indicator of consistent accuracy. The models by Narayanan & Darwish (1987), Ashour et al. (1992), Kwak et al. (2002), and Shin et al. (1994) showed lower standard deviations (average = 0.19) relative to other models (Table 1). The mean values of (v_u/v_n) indicate that the models by Narayanan & Darwish (1987), Ashour et al. (model A; 1992), and Kwak et al. (2002) have reasonable safety margins (about 30%), whereas the models by Ashour et al. (model B; 1992) and Shin et al. (1994) have small safety margins of 16%, on average. Even the (v_u/v_n) ratios for about 15% of the specimens are below 1.0 (minimum: 0.86 and 0.84 for Ashour et al. (model B; 1992) and Shin et al. (1994), respectively). The rather unconservative models may not be appropriate for the development of the shear strength model for an SFRLC beam, given the brittleness nature of the shear failure modes. On the other hand, the model by Narayanan & Darwish (1987) somewhat overestimates the shear strength (20% of specimens ≥ 1.64, with maximum of 1.87), and the models by Khuntia et al. (1999), Sharma (1986), and Choi et al. (2007) are overly conservative or provide substantial scatter in their predictions (Table 1).

Table 2. Steepness (slope) of the linear regression line for the ratio of measured peak shear stress (vu) to calculated shear stress capacity (vn), with the consideration of lightweight concrete factor (λ= 0.75) (see Fig. 4).

Independent variable		f'c MPa	a/d -	Vf %	%
Narayanan et al. (1987)		0.0077	0.1237	0.1827	0.0010
Ashour et al.	[model A]	0.0106	0.0002	0.2418	0.0210
(1992)	[model B]	0.0225	0.0997	0.5945	0.1431
Kwak et al. (2002)		0.0006	0.1524	0.0474	0.0274
Khuntia et al. (1999)		0.0318	0.4688	1.0577	0.2575
Sharma (1986)		0.0759	0.1845	2.2406	0.3732
Imam et al. (1997)		0.0346	0.2397	0.5747	0.0283
Shin et al. (1994)		0.0046	0.0115	0.1108	0.0307
Li et al. (1992)		0.0348	0.2258	1.1878	0.1704
Choi et al. (2007)		0.0868	0.1262	2.5708	0.5114

The slope (steepness) of the linear regression line for (v_u/v_n) ratios is one of the most robust statistical indicators to evaluate the sensitivity of the dependent variable (v_u/v_n) to each independent variable. Table 2 indicates that the models by Narayanan & Darwish (1987), Ashour et al. (model A; 1992), Kwak et al. (2002) and Shin et al. (1994) are overall satisfactory in this aspect. Based on the review in this and previous paragraphs, the models by Ashour et al. (model A; 1992) and by Kwak et al. (2002) are chosen to propose design shear strength model(s) for SFRLC beams. Figure 6 illustrates the distributions of (v_u/v_n) ratios against four different independent variables. It is shown that these selected models are not overly sensitive to the variation of these four main variables, compared with the other models that are quite sensitive to each variable (Figs 6(c), 6(f), 6(i) and 6(l); right column).

The first design shear strength equation proposed for SFRLC beams is the modified version of the

SFRC shear strength equations developed by Ashour et al. (model A; 1992), as given in equtions. (2) and (3).

$$v_n = \left(2.11\sqrt[3]{\lambda^2 f_c'} + 7F\right)\sqrt[3]{\left(\rho\frac{d}{a}\right)} \quad \text{(MPa)} \qquad (2)$$

for $(a/d) \geq 2.5$.

$$v_n = [\text{Eq. (2)}]\left(2.5\frac{d}{a}\right) + v_b\left(2.5 - \frac{a}{d}\right) \quad \text{(MPa)} \qquad (3)$$

for $(a/d) < 2.5$.

here, f'_c is the cylinder concrete strength of SFRLC in MPa; A_s is the area of tension flexural reinforcement; v_b is the fiber pullout stress (= $0.41\tau F$); and τ is the average fiber matrix interfacial bond stress, tentatively taken as 4.15 MPa based on the recommendations by Li et al. (1992), Swamy et al. (1993), and Kwak et al. (2002). The lightweight concrete modification factor (λ) of 0.75 was applied as per the ACI 318-08 code provisions (§8.6.1). The fiber factor (F) is equal to $(L_f/D_f)V_f d_f$, where L_f is the steel fiber length; D_f is the steel fiber diameter; V_f is the steel fiber volume fraction; and d_f is the bond factor (= 0.5 for circular section plain fiber, 0.75 for crimped fiber or hooked fiber, and 1 for indented fiber (Narayanan & Darwish 1987).

Alternatively, the second design shear strength equation for SFRLC beams is proposed based on the SFRC shear strength equation developed by Kwak et al. (2002), as given in eqution (4).

$$v_n = 3.7e\left(f_{spfc}\right)^{2/3}\sqrt[3]{\left(\rho\frac{d}{a}\right)} + 0.8v_b \quad \text{(MPa)} \quad (4)$$

here, e is the arch action factor, taken as 1.0 if $(a/d) > 3.4$, otherwise taken as $3.4(d/a)$; v_b is the fiber pullout stress (= $0.41\tau F$); and f_{spfc} is the splitting tensile strength computed using eqution (5).

$$f_{spfc} = \frac{\lambda^2 f_{cuf}}{\left(20 - \sqrt{F}\right)} + 0.7 + \sqrt{F} \quad \text{(MPa)} \qquad (5)$$

here, f_{cuf} is the cube strength of SFRLC. The cylinder strength (f'_c) is typically 0.75% to 0.95% of the cube strength; thus, a value of f_{cuf} equal to $1.2f'_c$ is recommended as was used by Kwak et al. (2002). This model empirically considers the arch action, which tends to occur when (a/d) is less than about 3.4. In the first design model of equations (2) and (3), the extra shear strength due to the arch action is conservatively considered when (a/d) is less than 2.5. Note that quantification of the effect of arch action for steel fiber-reinforced beams was part of the previous studies (Ashour et al. 1992, Kwak et al. 2002), and this work was limited to evaluating the performance of the SFRLC beams and the feasibility of using the readily available design shear models and lightweight concrete modification factor (λ).

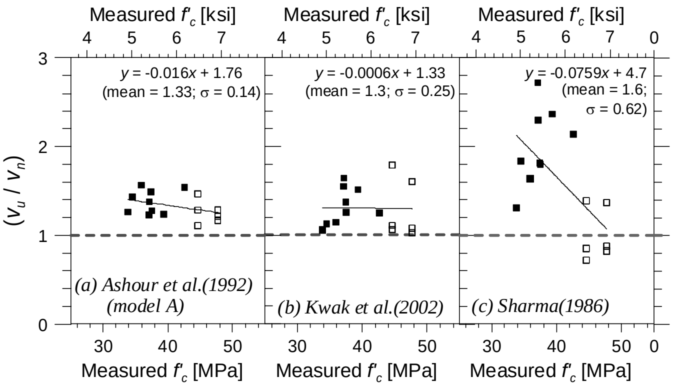

Figure 6. The ratio of (vu/vn) vs. measured f'c (continued).

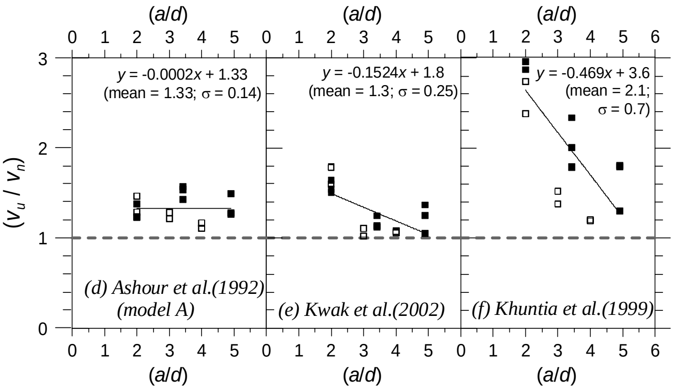

Figure 6. The ratio of (v_u/v_n) vs. (a/d) (continued).

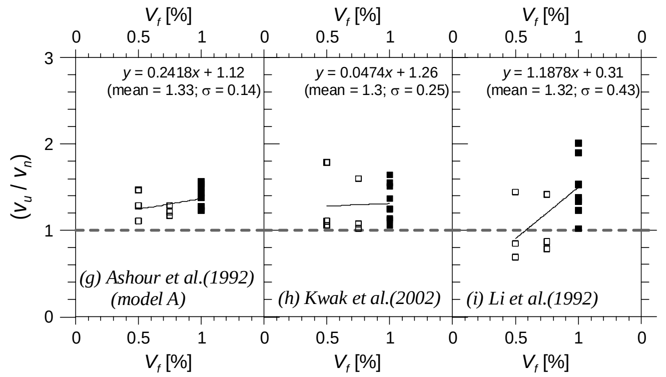

Figure 6. The ratio of (v_u/v_n) vs. V_f (continued).

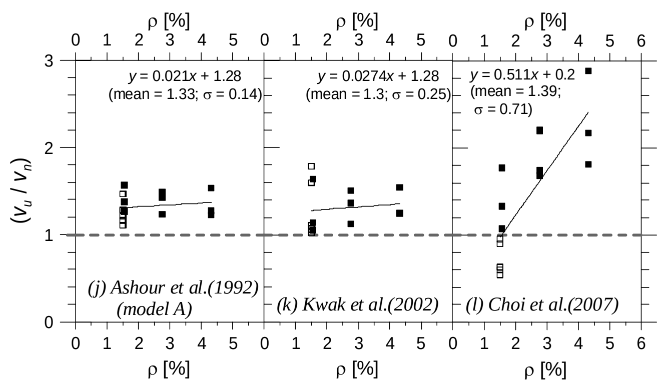

Figure 6. The ratio of (v_u/v_n) vs. ρ.

Figure 6 (left and center columns) depicts that these two modified models correspond well to the current and prior data of SFRLC beams in terms of the prediction (mean), consistency (standard deviation), random variation (slope of linear regression line), safety (minimum greater than unity) and structural efficiency (maximum less than 1.8). These models are only applicable to the SFRLC beams without stirrups.

The measured peak shear forces of the tested SFRLC beams (Kang & Kim, 2009) are at least 30% larger than the ACI 318 shear strengths (V_n) of imaginary beams with the same details but without steel fibers, also assuming that the ACI 318 specified minimum amount of shear stirrups are provided. Here, the minimum amount is determined based on ACI 318-08, §11.6.4.1(f), and V_n is calculated from equations (11-2), (11-3) and (11-15) of ACI 318-08. The results signal that all the conventional stirrups could be replaced by use of steel fibers for lightweight concrete (as permitted for SFRC by ACI 318-08, §11.6.4.1(f)); however, it is recommended that this study not be considered conclusive on this point due to the lack of data and the absence of comparative studies between SFRLC beams with and without stirrups. This study also signals that the limitation of f'_c (41.4 MPa) in Section 11.4.6.1(f) could be increased. For these expansions, more experimental data on SFRLC beams both with and without stirrups would be very useful.

4 SUMMARY & FINDINGS

The study herein was comprised of a re-assessment of data from previous structural and material tests, and model calibrations using the prior data. The data were evaluated mainly in terms of the steel fiber volume fraction and the shear span-to-depth ratio. Other variables related to steel fibers, material and reinforcing properties, or unit weight of concrete were also examined. Based on the study, the following were found:

1) The shear strength of the steel fiber-reinforced normalweight concrete beam is slightly larger than that of the steel fiber-reinforced lightweight concrete beam; however, for design models, the lightweight concrete modification factor (λ) of 0.75 is conservatively applicable to the steel fiber-reinforced beam. This is mainly due to the brittle nature of shear failure and the lack of available experimental data.

2) The addition of steel fibers with V_f of 0.5% to 0.75% improves the resistance to structural damage and ultimate shear strength in SFRLC by roughly 25% to 45% (based on the research by Kang & Kim 2009).

3) The shear span-to-depth ratio adversely affects the shear strength of the lightweight fiber-reinforced beam. Thus, a term associated with the moment-shear interaction (e.g., a/d) should be included in the shear strength equation of SFRLC beams.

4) The ACI 318 minimum requirement of 0.75% (i.e., 60 kg/m^3) for shear resistance (§5.6.6.2(a)) could be reduced to improve concrete workability, when (a/d) is 3 or less.

5) Two shear strength models for SFRLC beams without stirrups [eqution (2) & (3) and eqution (4) & (5)] have been proposed based on available SFRC research and in accordance with the ACI 318-08 (§11.2) provision for the lightweight concrete modification factor ($\lambda = 0.75$). These models correspond well to the existing data with reasonable precision and repeatability. Perhaps these two models could be conservatively used for precast, prestressed SFRLC girders, which are increasingly popular in the United States.

6) The reported results signal that all the conventional stirrups could be replaced by use of steel fibers for lightweight concrete (as permitted for SFRC by ACI 318-08, §11.6.4.1(f)); however, it is recommended that this study not be considered conclusive on this point due to the lack of data and the absence of comparative studies between SFRLC beams with and without stirrups.

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