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Shear and Moment Capacities of Steel Fiber Reinforced Concrete Beams

By Roop L. Jindal

Synopsis: Tests were made on 44 beams to study the effect of steel fibers as shear reinforcement and to determine if there was any increase in the shear/moment capacity and change in the mode of failure. Span length of 30 in. (762 mm) was used for shear-span ratios (a/d) of 2.0 and 2.4, and 60 in. (1524 mm) for a/d ratios of 3.6 and 4.8. Steel fibers of 1% by volume were used in all SFRC beams. The variables were type of fibers, aspect ratio (1/d) of the fibers and the shear span ratios. Test results showed that shear and moment capacities of SFRC beams varied from 1.50 to 1.92 and 1.12 to 1.39 times, that of conventional reinforced concrete beam, respectively. Mode of failure changed from shear mode to moment mode when SFRC was used. Steel fibers having aspect ratio of 75 or thin fibers were found to be most effective for increasing the shear capacity of SFRC beams. A design method has been suggested for analysing and designing SFRC beams. Theoretical results based on this method compare favorably with the test results.

Keywords: beams (supports); fiber reinforced concretes; flexural strength; metal fibers; moments; shear properties; structural analysis; structural design.

ACI member Roop L. Jindal is Senior Engineer, Civil & Structures, Bechtel Power Corp. San Francisco. Dr. Jindal worked formerly as Associate Professor of Civil Engineering, Punjab Engineering College, Chandigarh, India, and at University of Sulamaniyah, Iraq. He has published a number of papers on various aspects of concrete and experimental stress analysis.

INTRODUCTION

A number of investigators (1,2) have shown that ultimate tensile strength of SFRC (steel fiber reinforced concrete) varies from 1.5 to 2.5 times that of plain concrete. Various methods have been suggested to predict flexural strength of SFRC (4). Steel fibers can be used effectively in conventional reinforced concrete beams, to increase the flexural and shear strength and crack resistance. Usage of SFRC in sections where shear stresses are very high, can eliminate some congestion of reinforcement. SFRC beams can absorb large amount of energy, which can be very useful in areas of seismic zones. The following investigation was made to study the effect of high strength brass coated and mild strength steel fibers as shear reinforcement, to determine if there was any increase in shear and flexural capacity of SFRC beams as compared to conventional reinforced concrete beam and to propose a suitable, simple method of analysis and design of SFRC beams.

EXPERIMENTAL PROGRAM

Description of the Beams

Tests were conducted on 44 beams. The beam had overall dimensions of 4 x 6 in. (100 x 150 mm) with effective depth of 5 in. (125 mm) and reinforced with 2 bars of 1/2 in. (12 mm) diameter of steel. Yield strength of the main tensile steel was 67.50 ksi (4745 kgf/cm^2). The span of the beams was 30 in. (762 mm) for shear span - depth ratios (a/d) of 2.0 and 2.40, and 60 in. (1524 mm) for a/d ratios of 3.6 and 4.80. No vertical stirrups or bent up bars were used in any beam.

Details of Materials

Steel fibers -- Steel fibers, 1% by volume, were used in all the beams. Two different types of fibers were used in this study. Brass coated plain, high strength, circular steel fibers of sizes 1 x 0.01 in. (25.4 x 0.254 mm), 1 x 0.016 in. (25.4 x 0.406 mm) and 0.5 x 0.006 in. (12.7 x 0.152 mm) were used. These fibers were of tensile strength in the range of 270 to 400 ksi. (19,000 to 28,000 kgf/cm^2). Mild steel fibers of aspect ratios 10, 25, 75, and 100 were obtained by cutting 30 gage i.e. 0.011 in. (0.282 mm) diameter wire. The wire had following properties:

Yield stress	=	54,015 psi (3818 kgf/cm^2)
Ultimate tensile stress	=	69,500 psi (4913 kgf/cm^2)
Percentage elongation	=	14.6
Modulus of Elasticity	=	32.2×10^6 psi (2.27×10^6 kgf/cm^2)

Concrete -- The concrete mix used had water/cement ratio of 0.60 by weight and the ratio of 1:3.0 of cement/sand. Natural river sand of fineness modulus of 3.25 was used. Ordinary portland cement was used.

Test details

Series A beams were conventional reinforced concrete. Beams B, C, D, E and F had mild steel wire fibers of aspect ratios 10, 25, 50, 75 and 100 respectively. Beams G, H and J had circular brass coated high strength steel fibers of sizes 1 x 0.01 in. (25 x 0.25 mm), 1/2 x 0.006 in. (12.5 x 0.15 mm) and 1 x 0.016 in. (25 x 0.4 mm) respectively. The beams were cast in steel molds and compacted by internal vibration. The beams were tested at age of 28 days under two point loading. Deflections and strain measurments were made at two sections of the beams as shown in Figure 1, at various stages of loading.

TEST RESULTS AND DISCUSSION

Table 1 gives the test results of different beams. The shear and flexural strength of Series A beams (conventional RCC test beam) were found to be 4.4 kips (2000 kgf) and 96 inch-kips (110.4 m-kgf) respectively. Shear and flexural strength ratios of SFRC beams were determined by dividing ultimate shear and ultimate moment of test beams by 4.4 kips and 96.0 in-kips respectively. Maximum shear stress was calculated as follows:

$$v = VQ/Ib$$

where
- V = maximum shear
- b = width of beam
- Q = first moment of the area about n.a.
- I = moment of inertia of uncracked transformed section

Shear Strength Ratio

Shear strength of SFRC beams increased up to maximum of 2.05 times that of conventional beams. M.S. (mild steel) wire fibers were quite effective in shear. Maximum shear strength ratio of 1.44 was obtained in case of series D and E beams having M.S. wire fibers of aspect ratios 50 and 75 respectively. In the case of high strength brass coated fibers, maximum shear strength ratio of 2.05 was obtained with SFRC beam having 1/2 x 0.006 in. (12.5 x 0.15 mm) size fibers.

Flexural Strength Ratio

Maximum flexural strength ratio of 1.59 was obtained in case of beams series D and E having M.S. wire fibers of aspect ratios 50 and 75 respectively. In the case of beams having high strength brass coated fibers, maximum flexural strength ratio of 1.38 was obtained in series H beams having 1/2 x 0.006 in. (12.5 x 0.15 mm) fibers.

Mode of Failures

Shear failure -- Plain conventional RCC beams having a/d of 2.0, 2.4 and 3.6 failed in shear. In this case cracks developed along the compressive stress trajectories in the shear-span. The shear crack appeared suddenly and upper portion of the shear-span was violently ejected upwards.

Initial moment and ultimate failure in shear -- SFRC beams of series C of a/d = 3.6, G of a/d 2.4, and H of a/d =2.0, 3.6 and 4.8 failed in this mode. In these cases, number of moment cracks formed in the inital stage of loading, but finally the beams failed due to formation of sudden shear crack.

Initial shear and final moment failure -- SFRC beam of series J of a/d = 2.0 failed in this mode. In this case there was formation of diagonal shear crack in the beginning somewhere in the shearspan, but subsequently moments cracks appeared and the beam finally failed in flexure. The initial shear crack did not propogate further.

Moment failure -- Most of the SFRC beams failed in flexure. A number of cracks formed in the central region. Near the failure there was an increase in the deflection with little or no increase in the load. The test was stopped at this stage.

Mode of failure changed from shear to moment in most of the beams as steel fibers were used. This shows that steel fibers are very effective as shear reinforcement.

Effect of Aspect Ratio and Type of Fibers

Figure 2 shows the effect of aspect ratio on ultimate shear stress, for M.S. wire fibers for shear span ratios of 3.6 and 4.8. Though most of these beams failed in flexure, maximum shear stress increased from 352 psi (24.8 kgf/cm^2) to 622 psi (43.79 kgf/cm^2) when aspect ratio was increased from 10 to 75. There was decrease in the maximum shear stress when aspect ratio was increased to 100. The beams having brass coated high strength steel fibers, indicated similar behavior. The maximum shear stress occured in SFRC beam having 1/2 x 0.006 in. fibers of aspect ratio of 83.3. There was decrease in the maximum shear stress value when fibers of size 1 x .01 in. having aspect ratio of 100 were used. If aspect ratio is less number of wires increase in a section, for the same amount of fibers. Thus the shear strength of SFRC beams should increase with the decrease in the aspect ratio of the fibers. However, the efficiency of the fiber decreases with the decrease in length due to poor anchorage. Therefore, there has to be some optimum value of the aspect ratio for the maximum shear strength. Based on the limited test data of this study, it seems that the optimum value of aspect ratio is near about 75 for maximum shear strength.

Mild steel wire fibers seems to be quite effective in increasing shear/ flexural capacity of the SFRC beams. These fibers are cheaper and can be fabricated easily in any workshop, in India or in any other developing country.

Load vs Deflection

Typical load-deflection curves of the conventional RCC beams and SFRC beams having 1/2 x 0.006 fibers, for shear span ratios of 3.6 and 4.8, are shown in Fig. 3. The ultimate deflections of SFRC beams were about 3-4 times that of conventional RCC beams, for shear-span ratios of 3.6 and 4.8. It can be concluded from these curves that SFRC beams have higher toughness. The toughness is defined as the area under the load-deflection curve. Toughness ratio vs shear-span ratio is shown in Fig. 4. The toughness ratio is the ratio of toughness of SFRC beams to that of conventional RCC beam. The maximum toughness ratio of 7.85 was observed in SFRC beam having 1/2 x 0.006 in. fibers, with shear-span ratio of 3.6.

DESIGN METHOD

It can be concluded from the test results that there is considerable increase in moment and shear capacity of beams when SFRC is used. Swamy and Al-Ta'an (3) also reported similar test results. It has been observed that there is difficulty in obtaining uniform SFRC mix if the fiber content is more than 2% by volume (2). It is suggested that the fiber content should be limited to 1% fiber by volume of the concrete. Since the shear failure is primarily a diagonal tension failure, steel fibers increase the shear strength of FRC considerably. Number of methods have been suggested for the design/ analysis of SFRC beams (3). These methods are quite complicated. A new simple method is proposed herein. The ultimate tensile strength of SFRC in flexure can be obtained by using the following equations given by Swamy and Mangat (4):

$$\sigma_{ut} = 0.97\ \sigma_m (1-V_f) + 3.41\ V_f(l/d)$$

This equation is in N/mm^2 units.

The following equation is obtained in psi units.

$$\sigma_{ut} = 0.97\ \sigma_m\ (1-V_f) + 495\ V_f\ (l/d) \quad \text{......... (1)}$$

where,

σ_{ut} = ultimate flexural tensile strength of SFRC

σ_m = ultimate flexural tensile strenght of plain concrete

V_f = volume fraction of the fibers

l/d = aspect ratio of the fiber

Method of Analysis

Assumptions

1. The strain diagram is linear.

2. The tensile stress block is rectangular and its depth is 0.85 times the distance between neutral axis and the bottom fiber of the beam. This assumption is similar to the assumption made by Whitney (5) for the compressive stress block for calculating the ultimate strength of rectangular reinforced concrete section. The stress in SFRC is taken as 0.85 σ_{ut}. The assumed stress block is shown in Figure 5.

3. There is no increase in compressive strength of SFRC as compared to plain concrete.

4. Ultimate shear stress of SFRC is equal to 0.41 σ_{ut}, because effective length of any fiber in any direction = 0.41 (length of fiber) as found by Romualdi and Mandel (6).

This method was applied to determine shear and moment capacities of SFRC test beam having the following section:

b	=	4.0 in.	d	=	5.0 in.
D	=	6.0 in.	A_s	=	0.352 $in.^2$
f_y	=	70.4 ksi	f'_c	=	3 ksi
σ_m	=	0.2 ksi			

The calculated values of ultimate moment and shear were 106.2 inch kips and 5.3 kips, respectively. The test result values of ultimate moment and ultimate shear were 117.0 inch-kips and 6.6 kips, respectively. The test results of moment and shear values are fairly close to the calculated values.

Design Method

A SFRC beam for given ultimate shear and moment capacities can be designed as follows:

1. Knowing the tensile strength of the plain concrete, fiber size, and content, determine:

$$\sigma_{ut} = 0.97 \quad \sigma_m (1-V_f) + 495\ V_f(l/d) \ \ldots\ldots\ (1)$$

$$\sigma_{us} = 0.41 \quad \sigma_{ut} \ \ldots\ldots\ (2)$$

2. Knowing M_u and V_u for the beam to be designed we have the following relationship.

$$V_u = bjd\ (0.41 \quad \sigma_{ut}) \ldots\ldots (3)$$

$$M_u = 0.261\ bd^2\ f'_c \ldots\ldots (4)$$

The width of beam in general lies between d/2 to 2/3 d. From equations (3) and (4) determine b and d. Take higher of values of b and d.

3. Maximum value of 'a' depends upon values of f'_c and f_y. ACI 31877(7) limits maximum values of a/d for given values of f'_c and f_y. Assume a value slightly less than this value. From the following equation calculate area of tensile steel (A_s):

$$M_u = A_s\ f_y\ (d - a/2) + bg(0.85\ \sigma_{ut})\ (D - a/2 - g/2) \ldots\ldots (5)$$

4. Knowing A_s, calculate depth of n.a. and determine moment capacity of the section. Revise the section and area of main tensile steel if required.

Application to Other Test Beams

The method of calculating ultimate flexural strength of SFRC beams was applied to SFRC beams reported by Swamy and Al-Taan (3), where crimped steel fibers of size 0.02 x 2.0 in. (0.50 x 50 mm) were used. The calculated and test results values were very close as shown in Table 2.

CONCLUSIONS

The following conclusions can be made.

1. Steel fibers are very effective as shear reinforcement. The maximum shear strength ratios were 1.44 and 2.05 in beams having mild steel fibers of aspect ratio of 75 and brass coated fibers of size 1/2 x 0.006 in respectively.

2. There was increase in flexural strength of SFRC beams. The maximum flexural stregnth ratios were 1.59 and 1.38 in SFRC beams having M.S. fibers of aspect ration 75 and brass coated fibers of size 1/2 x 0.006 in respectively.

3. The mode of failure changed from shear in conventional RCC beam to moment or moment - shear failure in SFRC beams.

4. The maximum increase in shear and moment capacity of the beams were obtained using fibers of aspect ratio 75.

5. The ultimate deflection in SFRC beams was 2-3 times that of conventional beams. The maximum toughness ratio of 7.85 was obtained in beam having 1/2 x 0.006 in. fibers, tested for shear-span ratio of 3.6.

6. A method for analysis and design of steel fibers reinforced concrete beam has been suggested. This method is simple and values of moment and shear capacities were fairly close to the test results.

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NOTATION

A_s = Area of main tension steel
a = Shear-span or depth of the rectangular compressive stress block

b = Width of the beam

d = Effective depth of the beam

D = Overall depth of the beam

f'_c = Ultimate compressive strength of the concrete at age of 28 days

f_y = Yield strength of steel

g = Depth of rectangular tensile stress block for fiber reinforced concrete beam

l = Length of the fiber

M_u = Ultimate moment

M_{uo} = Ultimate moment capacity of RCC beam

M_{uf} = Ultimate moment capacity of SFRC beam

V_f = Volume fraction of the fiber

V_u = Ultimate shear

V_{uo} = Ultimate shear capacity of conventional RCC beam

V_{uf} = Ultimate shear capacity of SFRC beam

σ_m = Flexural tensile stress of the plain concrete

σ_{us} = Ultimate shear stress of SFRC

σ_{ut} = Ultimate flexural tensile stress of the steel fiber reinforced concrete.