

Shearing Resistance of Steel Fiber Reinforced Self Consolidating Concrete Beams Without Stirrups

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Abstract- The objective of this paper is to present the results of shear strength of steel fiber reinforced self consolidating concrete beams as well as normal concrete beams made without stirrups. Totally three mixes representing one for control mix and two for self consolidating concrete with and without steel fiber. The beams were tested under two point loading until shear failure occurred. The experimental test parameters included size of coarse aggregate, percentage of the longitudinal reinforcement and steel fiber content. Shear span to effective depth of beams was kept constant ($a/d=1.36$). The performance of code based design equations in predicting the shear resistance of self consolidating concrete and ordinary concrete is also presented and compared with the experimental results. The beams were tested for ultimate shear failure and experimental shear loads were taken for first flexural crack/diagonal shear crack and ultimate cracking conditions.

Key Words: Self consolidating concrete, steel fiber, shear span to effective depth ratio, shear strength, crack width.

1. INTRODUCTION

SCC means Self-Consolidating Concrete, or Self Compacting Concrete has the property of high flow ability, passing ability and filling ability. Self-compacting concrete is used to cast structural elements very rapidly and promotes faster construction. This type of concrete can be placed in crowded reinforcement zones without any difficulty and reduces the mechanical efforts used for concrete compaction. Self consolidating concrete allows structural designers to provide thin concrete sections and congested reinforcement detailing. It has the better structural performance in terms of bond strength, crushing strength etc. SCC now widely used in all the types of structures all around the world. SCC uses the industrial wastes as a part of making concrete, tends to reduce wastage of industrial wastes and acts as an eco-friendly. Concrete has low tensile strength and has a brittle failure

in nature. Steel fibers in the concrete can enhance the mechanical properties such as ductility and energy absorbing capacity under seismic, impact and blast loading. Steel fibers are also used to increase the compressive strength, shear strength and tensile strength of concrete. Residual shear strength of a beam after shear cracking remained constant as a/d was decreased up to 2.5, then it increased rapidly as a/d was further decreased below 2.5 showing minimum capacity at $a/d = 2.5$. Both ACI code and Zsutty's equations gave conservative value especially for a/d less than 2.5 [1]. Shear strength of rectangular fiber reinforced concrete beams depends mostly on the shear span-to-depth ratio, reinforcement ratio, concrete strength, and fiber properties [3]. Anticipated shear failure of light weight concrete beams without shear reinforcement tended to be brittle; higher the concrete compressive strength, greater the brittleness became. Beams with a/d of 1.5, 2.0, and 2.5, under design loads mostly fail in concrete crushing above the inclined cracks, while beams with a/d of 3.0 may fail by bond failure attributed to splitting of bond along the tension reinforcement [5]. As the longitudinal reinforcement decreased, there was an observed reduction in concrete shear strength [8]. SCC beams showed lower ultimate shear strength than the normal concrete beams. The shear strength reduction was higher in deeper beams with lower reinforcement ratios [9]. Optimum fiber content was governed by the workability requirements of the concrete mix [10]. A significant increase in the shear capacity is observed by providing orthogonal web reinforcement and a desired mode of ductile failure can be achieved through orthogonal web reinforcement [19]. Sudheer Reddy et al [20] studied shearing resistance high strength beams without web reinforcement. An attempt had been made to study shear strength of high strength concrete beams (70 Mpa) with different shear span to depth ratios ($a/d = 1, 2, 3$ & 4) without web reinforcement and compared the test results with the available shear models namely, American Concrete Institute, Canadian Standard, CEPFIP Model, Zsutty Equation and Bazant Equation. The results revealed that the most excellent fit for the test data was provided

by Zsutty's Equation. The authors believed that the factor of safety for shear should be greater than for flexure (when the areas of flexural and shear reinforcement equal that required for strength) as shear failure occurred suddenly with little if any warning [21].

2. SHEAR CONCEPT

From the theory of mechanics, shear force is nothing but unbalance vertical force acting either to the left or right of the section. Shearing force acts in beams when there is change in bending moment along the span.i.e, this force is equal to the rate of change of bending moment. Normally shear forces are classified into two types i.e. vertical shear force and horizontal shear force. The horizontal shear force occurs in beams when they are subjected to bending stresses. The vertical shear force present in beams when they are subjected to zero bending stresses. From the principle of complementary shear, vertical shear forces are always accompanied with the horizontal shear forces. These forces are very much predominant in beams as they cause severe deformation and lead to cause failure of structures. The main obstacle behind in shear transfer mechanism is the number of parameters involved and these parameters are yet to be known. In the contribution of shear strength of concrete, especially in beam mechanism aggregate interlock mechanism is the for most one resisting shear force. Even in arch action compression strut promotes most of the shear resistance depends on the size of coarse aggregate. Normally, SCC is the type of concrete in which the amount of coarse aggregate content and maximum nominal size of coarse aggregate is less when compared to normal concrete. The above factor has to be studied in SCC in order to predict the shear strength of concrete.

3. DESIGN EQUATIONS FOR SHEAR STRENGTH OF CONCRETE

According to Indian standard (IS) [15] shear strength of concrete members is given by

Design shear strength of concrete,

$$\tau_c = \frac{0.85 \sqrt{(0.8f_{ck}) \sqrt{(1+5\beta)}}}{6\beta} \text{ (N/mm}^2\text{)} \quad [1]$$

$\beta = 0.8f_{ck}/6.89p_t$ or 1 whichever is greater. Where, f_{ck} = characteristic compressive strength of concrete (N/mm²), β = empirical factor, p_t = longitudinal tension steel (%).

According to British Standard (BS) [4] shear strength of concrete members is given by

Design shear stress,

$$v_c = \left(\frac{0.79}{\gamma_m}\right) \left(\frac{100A_s}{b_v d}\right)^{\frac{1}{3}} \left(\frac{400}{d}\right)^{\frac{1}{4}} \left(\frac{f_{cu}}{25}\right)^{\frac{1}{3}} \text{ (N/mm}^2\text{)} \quad [2]$$

$K = \left(\frac{400}{d}\right)^{\frac{1}{4}}$ = size effect factors and should not be less than 0.67 and $p_t\%$ should not be greater than 3.0. This formula gives values of v_c for concrete grade 25. For higher grades of concrete, values should be multiplied by $(f_{cu}/25)^{(1/3)}$. The value of f_{cu} should not be greater than 40. where, γ_m = safety factor for concrete = 1.25, A_s = area of main tension reinforcement (mm²), b_v = width of beam (mm), d = effective depth of beam (mm), f_{cu} = concrete cube compressive strength (N/mm²)

According to Japanese Society of Civil Engineering (JSCE)[17] shear strength of concrete members is given by

Design shear capacity,

$$V_{cd} = \frac{0.2 \beta_d \beta_p \beta_n f_{cy} \left(\frac{L}{D}\right)^{\frac{1}{3}} b d}{\gamma_b} \text{ (kN)} \quad [3]$$

$\beta_d = ((1000/d)^{(1/4)}) \leq 1.5$, $\beta_p = (100p_t)^{(1/3)} \leq 1.5$, $\beta_n = 1$, Where, f_{cy} = compressive strength of cylinder at 28 days (N/mm²), β_n = coefficient to consider effect of axial force on shear capacity, β_d = coefficient to consider effect of effective depth on shear capacity, β_n = coefficient to consider effect of longitudinal reinforcement on shear capacity, d = effective depth of beam (mm), γ_b = member factor = 1.3. b = width of beam (mm)

According to Author's equation, Shear strength of concrete members is given by

$$V_c = \frac{(V_{cs} + V_{ts})}{\beta_b} \text{ (kN) when } 1 < (a/d) < 2.5 \quad [4]$$

Where, $V_{cs} = 0.125 b d_{cz} \sqrt{f_{ck}}$ (kN),

$$V_{ts} = 12.5 A_{st} \left(\frac{L}{D}\right) f_{ck}^{(0.01)} \text{ (kN)}$$

V_c = shear strength of concrete (kN), V_{cs} = shear resistance of compression strut (kN), V_{ts} = shear resistance of tension tie (kN), d_{cz} = depth of compression zone of beam (mm), L = span of beam (mm), D = overall depth of beam (mm), A_{st} = area of main tension reinforcement (mm²), β_b = safety factor for beam = 1.20.

3.1 Flexural cracking moment

According to American concrete constitute (ACI) [2] flexural cracking moment is given by Cracking moment, $M_{cr} = \frac{(0.62 (f_{cy})^{0.51} I_g)}{y_t}$ (Nmm) [5]

Where, I_g = moment of inertia of gross section (mm⁴), y_t = distance of centroidal axis of gross section (mm). f_{cy} = compressive strength of cylinder at 28 days (N/mm²)

According to Canadian Standards Association (CSA) [6] flexural cracking moment is given by,

$$M_{cr} = \frac{(0.6 (f_{cy})^{0.5} I_g)}{y_t} (\text{Nmm}) \quad [6]$$

According Indian standard[15] flexural cracking moment is given by

$$M_{cr} = \frac{(0.7 (f_{ck})^{0.5} I_g)}{y_t} (\text{Nmm}) \quad [7]$$

4. EXPERIMENTAL PROGRAM

In this work, totally three mixes were adopted in which NC represents Normal Concrete, SCC means Self Consolidating Concrete and SCCF means Steel Fiber Reinforced Self Consolidating Concrete. In the normal concrete, coarse aggregate size of 20mm was used. In the first mix of self consolidating concrete, coarse aggregate size of 12.5mm was used and the steel fiber added self consolidating concrete coarse aggregate size of 20mm was used. For every mix, both rheological properties and mechanical properties were found out. For finding of compressive strength, totally eighteen cubes of side 150mm were cast and test carried out at 7th and 28th day. Similarly, for finding of indirect tensile strength of concrete, totally nine cylinders of size 150mm diameter and 300mm height were cast and test carried out at 28th day. For computing shear strength of concrete, totally nine beams of size 1000mmx150mmx250mm were cast and test carried out at 28th day. For every mix, three beams were cast and with three different reinforcement ratios ranging from 0.25, 0.5 and one %. All the specimens were cast in steel moulds and in a single batch. The inside faces of the moulds were applied with grease to prevent water absorption and for providing better surface finishability. The control specimens were compacted using needle vibrator and the SCC specimens compacted without any mechanical devices. The reinforcement was carefully placed inside the mould and concrete was filled from one side. The specimens were cured for a period 28 days after stripping of specimens from moulds.

4.1 Materials

The cement used in all mixes was Ordinary Portland Cement (OPC) had the compressive strength of 43N/mm². The specific gravity of the cement was found out to be as 3. The initial and final setting times were found as 80 minutes and 620 minutes respectively. The fine and coarse aggregates conform to IS 383 [13] standards used in this work. The sand passed through 4.75mm Indian Standard (IS) sieve was used. The specific gravity and fineness modulus of fine aggregate were found as 2.65 and 3.18. The water absorption and moisture content of fine aggregate were found as 0.8% and 2%. The coarse aggregate passed through 75mm IS sieve was used. The specific gravity and fineness modulus of coarse aggregate were found as 2.8 and 6.75. The water absorption and moisture content of coarse aggregate were found as 0.6%

and 1%. Class F type Fly ash used as a powder material conform to IS 3812[14] and obtained from Tuticorin thermal power plant, Tamil Nadu, India was used in this study. Class F type fly ash had the specific gravity of 2. Enfiq Super Plast-400 was used with a specific gravity of 1.19 as a super plasticizer. Cera Hyper Plast XR W-40 was used in this study with a specific gravity of 1.11 as a viscosity modifying admixture. Shaktiman MSH 10050 steel fiber of diameter 1 mm, fiber had a tensile strength 1100 Mpa. The aspect ratio of fibers was 50. Tulsyanec Fe 415 High Yield Strength Deformed bars (HYSD) was used with a yield and ultimate strength of 415N/mm² and 710N/mm².

4.2 Mix design

In this study, two types of concrete were used. The mixes were designed for M30. The normal concrete mix design was carried out by IS 10262:2009[16]. The ratio of normal concrete, 1:1.76:3.45:0.42. The Self compacting concrete mix design was carried out by European guidelines as per European Federation for Specialist Construction Chemicals and Concrete Systems [7]. The powder content (cement and fillers) was fixed as 450kg/m³. Fly ash occupied 20% of powder content. The super plasticizer and stabilizer dosages were fixed at 1.5% and 1% of powder content. The initial mix design ratio was to be 1:1.81:1.6:0.38. After that, several trials were conducted on SCC in order to ensure both fresh and mechanical properties. The fiber addition added in last SCC mix, also optimized as a one percent of cement content. The final ratio of SCC, 1:2:1.9:0.42.

4.3 Test procedure

Once the beam specimens were taken out from the curing, the test beams were cleaned and white washed to assist for crack detection. The specimens were tested under two point loading until shear failure occurred. Fig.1 shows test setup for beams under two point loading. The center to center distance between the bottoms beds assemblies of rollers kept constant at 900mm. The loading configuration was arranged keeping the shear span constant at 300 mm yielding a shear span-to-depth ratio of 1.36. In order to avoid the sudden shear failure the reinforcement was provided with L-bend as shown in Fig.1. The load was applied to the specimens gradually with the help of hydraulic jack. The loads were taken for first flexural, diagonal and ultimate cracking conditions. The tests also gave information about development of cracks, crack widths, crack pattern, shear transfer mechanism and failure modes.

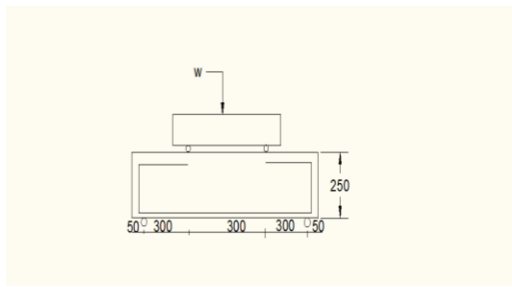


Fig-1: Test setup (dimensions are in mm)

5. TEST RESULTS AND DISCUSSION

The fresh properties as well as hardened properties were found out by conducting both workability tests and shear test. The test results are given below with detailed explanations.

5.1 Rheological properties

Table 1 shows the workability of concrete mixes. The fresh properties for both ordinary and self consolidating concrete mix were taken. For control concrete slump value and compaction factor tests were carried out as per normal concrete procedures. The results for controlled concrete based on slump value and compaction factor showed medium degree of workability. For self consolidating concrete, the workability tests were carried out as per European mix design guide lines. The test results showed better workability for SCC mixes. The SCC mix had a very good slump flow and V-funnel values due to addition of appropriate percentage of fly ash and super plasticizer content. The mix of SCC without steel fiber showed better workability than SCC with steel fiber. The steel fiber affects the self consolidating concrete workability namely slump and V-funnel. The fresh properties of steel fiber reinforced self consolidating concrete was not affected too much by the steel fiber due to the lesser addition of fiber content.

Table- 1: Workability of concrete mixes

Mix type	Slump value (mm)	Compaction factor	Slump flow (mm)	V-Funnel Time (s)
NC	80	0.87	-	-
SCC	-	-	730	5.8
SCCF	-	-	690	6.6

5.2 Mechanical properties

Table 2 shows the stiffened properties of concrete. The test results showed compressive strength and split tensile strength of concrete. The rate of strength development of 7 days to 28 days ranged from 0.5 to 0.7 for all the mixes. The rate of strength development in SCC mixes was slow when compared to normal concrete. This was due to addition of filler material of fly ash retarded the compressive strength growth rate. It was also observed that SCCF mix showed compressive strength as very close to ordinary concrete. It was due to increase in size of aggregate in the SCCF mix from 12.5 mm to 20mm. But the SCC mixes showed considerable amount of increase in compressive strength at 28 days. The steel fiber addition in SCC contributed sufficient amount of split tensile strength as closer to normal concrete. The plain mix of SCC showed less amount of split tensile strength.

Table- 2: Compressive and split tensile strength of mixes

Mix	Average 7 days compressive strength (N/mm ²)	Average 28 days compressive strength (N/mm ²)	Average 28days split tensile strength (N/mm ²)
NC	23.5	35	2.3
SCC	16.8	31	1.9
SCCF	19	33	1.1

5.3 Shear strength

Table 3, 4 and Chart 1 show the experimental and theoretical shear loads of concrete. The analytical results obtained based on various code provisions and also with the proposed empirical formulae without considering safety factors. The proposed empirical equation suggested based on empirical analysis. The loads obtained from experiment were converted into shear loads. The loads obtained for first flexural crack (V_{fc}) diagonal shear crack (V_{sc}) and ultimate cracking conditions (V_u). The numerical numbers indicated on the mixes i.e. 1, 2, 3 denoted the reinforcement ratios from 0.25, 0.5 and one. The results indicated shearing resistance of concrete. Shearing resistance of concrete is the resistance of concrete up to formation of diagonal shear crack. From, chart 1 the experimental results clearly showed that, the post cracking shear resistance of concrete beams more or less same with the diagonal shearing resistance. This showed that concrete did not have the ultimate shear resistance when compared with shearing resistance of concrete. The

variation between the experimental shear loads of first flexural crack and diagonal crack of all beams also less but mainly varied due to the increase in amount of main tension reinforcement as well as increase in size of coarse aggregate. The SCCF mix had higher ultimate shear strength when compared with all the mixes. All the major codes safely predicted the shear strength of concrete even without safety factors. The Indian code estimated shear strength slightly higher when compared with the JSCE and author's empirical equation. When compared to IS code, BS code estimated shear strength of concrete slightly higher and at the same time BS code estimated shear strength value closer to experimental results. Japanese code also predicted ultimate shear strength of concrete was at the slower rate. The proposed equation for the arch-rib mechanism formed to yield lower bound solutions, in which rate of shear strength prediction was slow when compared to code predictions and yielding safer results for the experimental results. This proposed equation estimated results very close to Japanese code and also predicted test results at slower rate.

Table- 3: Experimental shear loads (kN)

Beam	V_{fc}	V_{sc}	V_u
NC-1	19.6	20.87	25.68
NC-2	22.05	26.46	27.17
NC-3	23.03	29.89	36.27
SCC-1	18.13	18.64	23.03
SCC-2	19.6	21.06	25.51
SCC-3	22.05	27.94	28.94
SCCF-1	19.62	20.11	23.54
SCCF-2	24.53	25.9	29.4
SCCF-3	26.95	31.85	36.6

Table- 4: Theoretical shear loads (kN)

Beam	IS	BS	JSCE	Author's
NC-1	14.85	22.74	18.81	17.57
NC-2	23.10	30.36	23.58	23.68
NC-3	32.67	34.14	29.85	28.32
SCC-1	16.5	21.84	18	18
SCC-2	23.10	29.02	22.65	24.06
SCC-3	32.64	32.80	28.67	28.73
SCCF-1	16.5	22.31	18.44	18.38
SCCF-2	23.10	29.55	23.13	24.46
SCCF-3	32.63	33.50	29.27	29.13

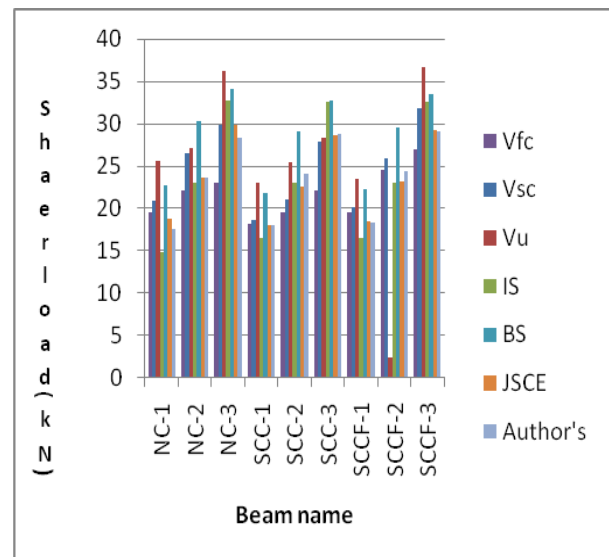


Chart-1: Experimental and theoretical loads

5.4 Flexural cracking moment

Table 5 shows the experimental and theoretical cracking moments. The cracking moment results obtained from the experiments compared with the code predictions. The following table shows the cracking moment results of various mixes. The experimental loads converted into shear loads to predict the experimental cracking moment. The moment is obtained for first flexural cracking load and ultimate cracking load. As similar to the case of shear strength, flexural cracking moment directly increased with increase in area of longitudinal reinforcement, size of

coarse aggregate and characteristic compressive strength of concrete. The test results showed gradual increment of moment values of cracking and ultimate moment. The normal and self consolidating concrete beams with higher percentage of main tension reinforcement had the maximum ultimate moment. The standardized codes predicted initial cracking moment based upon the compressive strength of concrete. The Canadian code estimated flexural cracking moment very less. Indian code predicted flexural cracking moment better than other codes. At the same time American code safely predicted flexural cracking moment.

Table-5: Experimental & theoretical cracking moments

Beam	M_{cr} (kNm)	M_u (kNm)	Theoretical cracking moment M_{cr} (kNm)		
			ACI	CSA	IS
NC-1	5.88	7.70	5.27	5.11	5.96
NC-2	6.62	8.15	5.27	5.11	5.96
NC-3	6.91	10.88	5.27	5.11	5.96
SCC-1	5.44	6.91	4.96	4.8	5.61
SCC-2	5.88	7.65	4.96	4.8	5.61
SCC-3	6.62	8.68	4.96	4.8	5.61
SCCF-1	5.88	7.06	5.12	4.96	5.78
SCCF-2	7.36	8.82	5.12	4.96	5.78
SCCF-3	8.08	10.98	5.12	4.96	5.78

5.5 Cracking study and mode of failure

Table 6 shows details of cracks in beams. Cracks developed for every beam in terms of its height, number of cracks, maximum crack width and maximum crack height at failure stages were noted. The beams with higher longitudinal reinforcement generated cracks more when compared to beams with lower reinforcement content. Self consolidating concrete beams developed less cracks as compared to normal concrete beams. The propagation of cracks from its originating point towards loading point were increased with increase in size of coarse aggregate and percentage of longitudinal reinforcement. But in case of anchorage failure, the height of crack at failure contrast to the other failure mode conditions. The crack width at failure stage reduced with increase in longitudinal reinforcement. Generated crack width in the SCC with fiber added was less as compared to normal concrete. It proved that steel fibers were better crack arresters.

Table-6: Details of cracks in beams

Beam	No. of cracks at failure	Maximum height of crack at failure (mm)	Maximum width of crack at failure (mm)	Mode of failure
NC-1	4	202	20	DT
NC-2	7	208	10	SC
NC-3	10	220	7.5	SC
SCC-1	3	223	5	BF
SCC-2	4	230	3.5	BF
SCC-3	4	238	2.3	BF
SCCF-1	5	212	14	SC
SCCF-2	6	230	10	SC
SCCF-3	6	240	8	SC

DT-Diagonal tension, SC-Shear compression, BF-Bearing failure

5.6 Failure behavior

The failure behavior beams under shear failure are described in a detail manner as given below. The failure modes also play an important role in predicting shearing strength capacity of beams.

5.6.1 Diagonal tension failure

This kind of failure observed in NC-1 beam. Initially flexural cracks are appeared and then flexure shear cracks originate from the final flexural crack. Due to the increase in load this type of crack propagates gradually until it reaches the loading point. While no web-shear cracks were observed, the outer most flexure crack in the shear span propagated diagonally towards the loading point. This type of failure crack pattern usually has greater crack width and originates either left or right end support of beam.

5.6.2 Bearing failure

This kind of failure observed in three beams of SCC without fiber. In this case, the shear crack is carried as an inclined between load and reaction that almost eliminates ordinary diagonal tension concepts. Normally an inclined crack travelled from loading point to the supporting point.

5.6.3 Shear compression failure

This kind of failure observed in remaining beams. This type failure takes place either by crushing of reduced concrete section above the tip of the crack under combined shear and compression is known as shear compression failure. In this failure, the beam behaved like a tied arch. The load was carried by direct compression between the load and the reaction point and by tension in the longitudinal steel.

6. CONCLUSIONS

The compressive strength for SCC mixes increased as the size of coarse aggregate changed from 12.5mm to 20mm. The workability properties for SCC mixes slightly reduced due to increase in coarse aggregate size and also addition of steel fiber. Shear strength self consolidating concrete beams were gradually increased due to the increase in percentage of longitudinal reinforcement, size of coarse aggregate and steel fiber content. The British code estimated shear strength of concrete slightly higher and yielding good results when compared to other codes. The shear strength results obtained from proposed empirical equation were closed to Japanese code equation results. The prediction of flexural cracking moment has high accuracy in Indian code as compared with Canadian and American codes. Crack growths in normal concrete beams were more as compared to self compacting beams. The failure pattern in terms of the shear was not same mode in all beams. It was observed that, perfect arch-rib mechanism was formed in five out of nine beams. Bearing failure was observed in SCC beams without steel fiber. Diagonal tension failure occurred in a single beam associated with large crack width. These types of shear failures always revealed that shear transfer mechanisms in concrete complex criteria, can't be predicted with high accuracy.

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