FLEXURAL CHARACTERISTICS OF STEEL FIBRE REINFORCED SELF COMPACTING CONCRETE BEAMS

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Abstract. *Fibre reinforced concrete with steel fibres attracted the attention of engineers and researchers during the last five decades. In recent times, self compacting concrete has been accepted as a quality product and are widely used. A large number of studies are available with respect to several parameters viz., flexural strength, load deflection behaviour, toughness, ductility, crack control, effects of beam dimensions, concrete filling sequence, flexural toughness parameters etc., of conventional fibre reinforced concrete. The present study aims to study the flexural behaviour of scc beams with steel fibres. An experimental programme has been designed to cast and test three plain scc beams and six scc beams with steel fibres. The experimental variables were the fibre content (0*v_f*%, 0.5*v_f*% and 1.0*v_f* %) and the tensile steel ratio (0.99%, 1.77% and 2.51%). The type of fibre configuration used was crimped fibre 30mm in length, an equivalent diameter of 0.5mm and with stirrups of 2l-8 mm dia bars* Φ *150mm c/c. The scc design mix was proportioned to obtain a compressive strength of 70 mpa and yield strength of steel used was 595 MPa. The experimental constants were the geometry of the beams (2000x125x250)mm as well as the test set up. A series of trials was made to obtain a suitable mix proportioning of SCC based on "Nan Su et al" method. The cracking, deflection and ultimate failure behaviour were experimentally studied. The available theoretical formulae proposed by Suji et al and Samir for FRC beams with conventional vibrated concrete beams were examined for the case of SFRSCC beams with respect to load deflection behaviour, ultimate moment, deflection and width of crack at service loads. A simplified effective moment of inertia function is proposed for the estimation of deflections of SFRSCC beams at all stages of loading. The results are presented and discussed.*

Key Words: *Beams, Flexure, Self-Compacting, Fibre Reinforced*

1. INTRODUCTION

Self-Compacting concrete offers many benefits to the construction practices i.e., the elimination of the compaction work results in reduced costs of placement, shortening of the construction time and therefore improved productivity. It also overcomes the congestion of steel reinforcement in case of heavily reinforced structures viz., seismic resistant structures. The technical benefits of SCC are extended to crack bridging ability, higher toughness and long-term durability with the use of fibres. Addition of short discrete randomly oriented steel fibres improves many of the engineering properties of conventional concrete. Fibres bridge the cracks and retard their propagation and also decrease the width of cracks, thereby improving the tensile strength or the post cracking behaviour. Steel fibres were incorporated in SCC leading to the development of SFRSCC. The applications include the pre-stressed sheet piles and steel fibre reinforced tunnel segment.

Since the idea of utilizing fibre reinforced cementitious composites in structural elements has been increased exponentially over the past decade, it is necessary to have the concept introduced in the provisions of the concrete codes. In this regard, it is indispensable to conduct laboratory investigations on various types of structural components under different loading conditions to have a precise understanding of their behavior. As on date, there are limited investigations on the flexural behavior of beams cast with steel fibre reinforced self-compacting concrete.

In the present study an attempt has been done with the following objectives:

- To produce M70 grade self-compacting concrete.
- Casting and testing of high-strength SFRSCC reinforced beams under flexure.
- Examining the applicability of the available formulae of FRC to SFRSCC beams.

Literature review

Sonebi et al [1] reported the structural performance of full scale beams cast using ordinary concrete and SCC with steel fibres. A total of eight beams of class C35 and C60 were cast and tested. His investigation showed that the ultimate moment capacity of SCC60 beam was comparable with RC60 beams. The maximum deflection of SCC60 beam was higher than that of RC beam.

Ganesan et al [2] reported an experimental investigation consisted of casting and testing of eighteen SFRSCC flexural elements. Their study showed that all the theoretical models available in the literature were found to underestimate the ultimate strength of SFRSCC beams. They suggested that modifications are required in these models to reduce the range of the predicability of the ultimate moment of SFRSCC members.

Moncef Nehdi and Jennifer Duquette Ladanchuk [3] investigated the effects of fibre combinations on the workability and ability of SCC to flow around obstructions, its compressive and flexural strengths, flexural toughness and post first crack behaviour. Their aim was not to optimise FRSCC mixtures but rather to identify the synergistic effects of hybrid fibres in FRSCC that can serve for such optimisation in future. Their investigations show that all mixtures containing combinations of steel fibres had higher first crack loads than that of mixtures containing only one type of steel fibre. This is probably because fibres with different shapes and lengths could better control the micro mechanics of crack formation at different strain levels than single type of fibres.

Hemanth et al [4] developed SCFRC for application in pre-stressed concrete beams. SCFRC mixes proved to have greater normalised tensile strength than the traditional fibrous concrete mixes for the same fibre factor.

2. EXPERIMENTAL WORK

Cement conforming to IS was used. Locally available river-sand, free from silt and organic matters and passing through 4.75mm sieve was used. The specific gravity was 2.56, loose density was 1500kg/m^3, packed density was 1651 kg/m^3 and the fineness modulus was 2.43. Locally available crushed granite aggregate passing through 12.5mm and retaining on 4.75mm was used for all of the mixes of SCC and CVC. The specific gravity of CA used was 2.66, loose density was 1373 kg/m^3 and packed density was 1496 kg/m^3. Class F fly-ash from Raichur Thermal Power Plant was used as cement replacement material for SCC mixes. The specific gravity of the fly-ash used was 2.4. Potable water was used for both mixing and curing. Glenium B233, carboxylic ether polymer was used and the dosage was between 0.5 and 0.15 litres per 100 kg of cementitious material. Viscosity Modifying Agent used was Glenium Stream-2. The dosage recommended was between 0.5 to 1.0 litres per cubic meter of binder. The steel crimped fibres used were low carbon drawn flat wires. The length of fibre was 30mm. The aspect ratio was 60. The width was 2 to 2.5mm and the tensile strength was 400 to 600 MPa. 8mm, 10mm, 12mm and 16mm diameter steel rods were used as main reinforcement while 8mm diameter rods were used as stirrups. The yield strength of reinforcement was 569 MPa. Nan Su et al [5-6] method has been used to arrive at the mixing proportion of SCC and steel fibres were incorporated in the same SCC mix for casting SFRSCC specimens with different volume factors.

Designed cylinder compressive strength (f'_c), water cement ratio (w/c), water fly ash ratio (W/f), sand by total aggregate (S/a) ratio, packing factor (PF) ratio, air content in SCC (taken as 1.5%) and percentage of replacement of fly ash by cement. The mixing sequence consisted of introducing both coarse and fine aggregate into the mixer for a minute. Then, cementitious material (cement and fly-ash) was added into the mixer and allowed to mix up for 2 minutes so that a uniform dry blend of the material is reached. Thereafter, 70% of the total required water was introduced into the mixer in five to eight stages (totally about 1.5 minutes). The mixture was allowed to blend the concrete for about 3 minutes to make sure that a completely consistent mixture was achieved. Then, 20% of water mixed with the whole amount of super plasticizer was added to the concrete in five stages, allowing 15 seconds interval in each stage. After adding the SP entirely, the concrete was allowed to mix for one and half minute. Finally, the remaining 10% of water combined with VMA was added to the mix in two stages, considering 15 seconds time interval in between, and was allowed to mix for another 1 minute before testing the fresh properties of the concrete. Therefore, the total time of the wet mixing was about 8.5 minutes. In case of conventionally vibrated concrete all of the mixing process phases will remain the same, except that VMA is not used. The results of the fresh properties of trial mixes are given below.

Table-1(a): Results of the Fresh Properties Tests of SCC

Sl. No	*Slump Flow*		*J-Ring*		*L-Box*	*U-Box*	*V-Funnel*		*Orimet*
	$T_{50(sec)}$	*Dia(mm)*	ΔH	*Dia(mm)*	H_2/H_1	ΔH	$T_{1(sec)}$	$T_{5(sec)}$	*T(sec)*
1	3.15	715	5	660	0.90	27	10.2	12.8	5.8
2	2.68	745	6	685	0.80	28	9.7	16	5.4
3	2.55	770	8	670	1.0	25	10.2	12.0	5.0

Table-1(b): Results of the Fresh Properties Tests of SFRSCC (0.5%Vf)

Sl. No	*Slump Flow*		*J-Ring*		*L-Box*	*U-Box*	*V-Funnel*		*Orimet*
	$T_{50(sec)}$	*Dia(mm)*	ΔH	*Dia(mm)*	H_2/H_1	ΔH	$T_{1(sec)}$	$T_{5(sec)}$	*T(sec)*
1	4.98	650	-	-	-	-	17.4	22.5	22.0
2	4.76	655	-	-	-	-	18.2	26.0	19.7
3	3.98	678	-	-	-	-	17.5	22.0	20.0

Table-1(c): Results of the Fresh Properties Tests of SFRSCC (1.0%Vf)

Sl. No	*Slump Flow*		*J-Ring*		*L-Box*	*U-Box*	*V-Funnel*		*Orimet*
	$T_{50(sec)}$	*Dia(mm)*	ΔH	*Dia(mm)*	H_2/H_1	ΔH	$T_{1(sec)}$	$T_{5(sec)}$	*T(sec)*
1	7.95	600	-	-	-	-	30.6	36.4	33.4
2	6.80	615	-	-	-	-	30.1	35.2	33.2
3	6.50	618	-	-	-	-	29.5	34.4	32.8

3. BEAM SPECIMENS

Size of the beam specimens were fixed based on the loading frame dimensions, capacity of the hydraulic jack used for loading the beams, applicable distance between supports in the loading frame, available measurement equipments capability and capacity of the proving ring. Accordingly, the beam dimensions were fixed as (2000x125x250)mm. All beams were singly reinforced. The percentage of steel was varied from ρ_{min}=0.32% to ρ_{max}=2.22% as specified by ACI 318 [7].

Table-2: Details of tested beams

Sl. No	Beam Designation	Tensile reinforcement	Steel ratio (%)	Compressive Strength, MPa	Modulus of Rupture, MPa	Volume fraction (%)	P_{cr} kN	Δcr mm	P_u kN	Δu mm
1	SCC 1	2Φ8 + 2Φ10	0.98	59.12	4.95	0.0	22	1.62	94	22.56
2	SCC 2	2Φ12 + 2Φ12	1.77	61.11	7.38	0.0	22	1.20	162	18.82
3	SCC 3	2Φ12 + 2Φ16	2.51	59.12	7.01	0.0	20	0.76	216	14.01
4	SFRSCC 4	2Φ8 + 2Φ10	0.98	62.00	6.93	0.5	22	1.02	108	29.85
5	SFRSCC 5	2Φ12 + 2Φ12	1.77	57.12	8.65	0.5	22	0.99	162	19.90
6	SFRSCC 6	2Φ12 + 2Φ16	2.51	57.79	8.71	0.5	20	0.78	224	17.13
7	SFRSCC 7	2Φ8 + 2Φ10	0.98	61.34	6.17	1.0	20	0.64	100	21.63
8	SFRSCC 8	2Φ12 + 2Φ12	1.77	63.78	7.38	1.0	20	1.12	158	17.72
9	SFRSCC 9	2Φ12 + 2Φ16	2.51	61.79	6.99	1.0	22	1.00	222	13.93

All the beams were tested in a loading frame of 50 tonnes capacity [Figure-1]. The beams were simply supported having an effective span of 1700mm and loaded symmetrically at 700mm from the support. Two of 25mm diameter rods were placed symmetrically at 150mm from each end of the beam, providing a free rotation at the ends. The load was applied by means of a 500kN hydraulic jack, through a steel I-section, supported on two steel rollers covering the entire width of the beam and placed symmetrically with respect to mid-span section. Measurements of applied load, deflection, surface strain, and crack width were done at various load intervals. Auxillary specimens of cubes and prisms were tested on the same day of testing of SFRSCC beams to determine the mean compressive strength and modulus of rupture of the concrete respectively. Figure 2 shows the load deflection curves for carrying percentage of fibres.

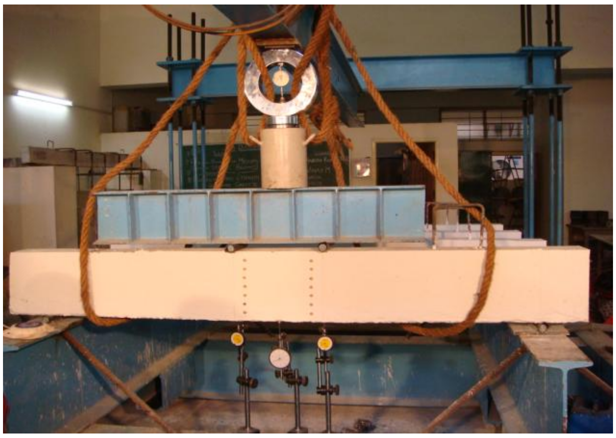

Figure-1: Test Setup of a Typical Beam

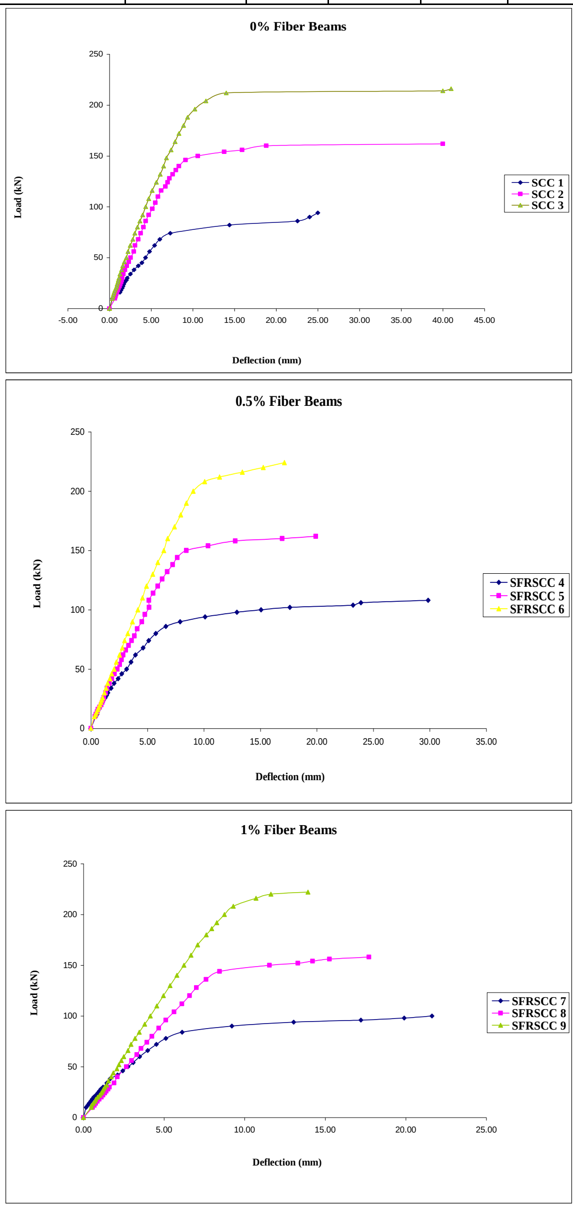

Figure-2: Experimental Load deflection curves by varying fibre %

It was observed that, deflection was linear up to the cracking stage and it deviated to non-linear after cracking for all of the beams. It was observed that the very first crack formed had the maximum width in all stages of loading. It was noted that the beams with higher percentage fibres showed less number of cracks. The deflection at ultimate ranges from 0.06 to 0.12 times the depth of beam.

4. ULTIMATE LOADS OF SFRSCC BEAMS

Method 1:
Suji et al [8] proposed the formula for the Ultimate moment equation as,

$$M_{uth} = (\sigma_u b(D - k_1 D) + A_s f_y) \times (d - 0.475 k_1 D) \tag{1}$$

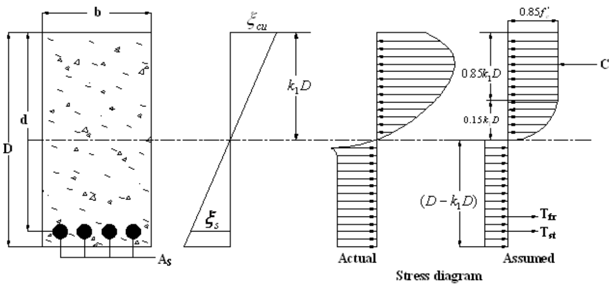

Figure-3: Stress and Strain distribution

$$k_1 = \frac{\sigma_u \times b \times (D - k_1 D) + A_s f_y}{0.8075 f_c' \times b \times D} \tag{2}$$

Where, k_1 =neutral axis depth factor; b,d = width and effective depth of the beam respectively; D = overall depth of the beam; f_t = direct tensile strength of concrete (MPa); η = 0.405 for beam element; V_f = percentage volume fraction of fibres; τ_d = bond stress; L_f / d_f =aspect ratio; σ_u = ultimate fibre concrete strength given by Lok and Xiao [9]. A modification has been done by using,

$$\sigma_u = 1.34 f_t + (0.0016 + 0.84 \eta V_f) \tau_d (L_f / d_f) \tag{3}$$

in Equation (1).

Method 2:
Samer and Hsu [10] proposed an empirical formula for computation of ultimate moment capacity as,

$$M_n = A_s f_y \left(d - \frac{a}{2}\right) + \sigma_t b \left(h - \frac{a}{\beta_1}\right)\left(\frac{h}{2} + \frac{a}{2\beta_1} - \frac{a}{2}\right) \tag{4}$$

$$a = \frac{\dfrac{A_s f_y}{b} + \sigma_t h}{0.85 f_c' + \dfrac{\sigma_t}{\beta_1}} \tag{5}$$

$$\sigma_t = 1.12 F_{be} \left(\frac{l}{d_f}\right) \rho_f \tag{6}$$

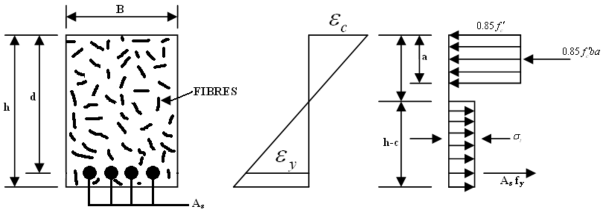

Figure-4: Stress and Strain distribution

where, M_n = ultimate flexural strength of beam; A_s = area of tension reinforcing bar; f_y = yield stress of reinforcing bar; a = depth of rectangular stress block; σ_t = tensile stress in fibrous concrete; b = beam width; d = distance from extreme compression fibre to reinforcing bar centroid; h = beam depth; β_1 = factor of 0.65-0.85, depending on the concrete compressive strength; F_{be} =bond efficiency of fibres; l = fibre length; d_f = diameter of fibre; ρ_f = percent by volume of steel fibres.

The ultimate moments of tested beams were calculated using above methods and are compared in Table 3. Also the investigations of others were used to calculate the same. It is inferred from Table 3 that Samer's method underestimates the Ultimate moment of resistance by 11% on an average while 'modified' Suji et al method over estimates by 32%.

5. LOAD DEFLECTION BEHAVIOUR OF SFRSCC BEAMS

Central deflection of the beam is calculated by using the expression,

$$\delta = \frac{P L_1}{48 E_c I}\left(3L^2 - 4L_1^2\right) + \frac{P_a h^2 L_1}{20 G_c I} \tag{7}$$

where, P = total applied load (N); L = effective span of the beam (mm); L_1 = distance from support to one of the loads (mm); h = overall depth of section (mm); E_c = modulus of elasticity of concrete (MPa); G_c = shear modulus of elasticity of concrete (MPa); I = moment of inertia (mm^4).

Proposed formula for the effective moment of inertia I_{eff}:
A semi-empirical formula is proposed to estimate the deflection using the effective moment of inertia on lines similar to ACI 318 [7] as,

$$I_{eff} = \left(\frac{M_{cr}}{M_a}\right)^m \times I_g + \left(1 - \left(\frac{M_{cr}}{M_a}\right)^m\right) \times I_{cr} \quad (8)$$

and the value of 'm' is obtained using regression analysis of test data as,

$$m = \frac{2.1}{1 + 0.66 \times V_f \times \sqrt{a/d}} \quad (9)$$

Where, 'm' is a power coefficient; V_f = volume fraction; a/d = aspect ratioThe deflection calculated using the proposed semi-empirical in comparison with the experimental ultimate moment is shown in Table 3. Figure 4 shows the comparison between the experimental and proposed load deflection curves for SCC 3 (0% V_f); SFRSCC 6 (0.5% V_f) and SFRSCC 9 (1.0% V_f). It is inferred that the proposed method predicts satisfactorily the load deflection behaviour at all stages of loading.

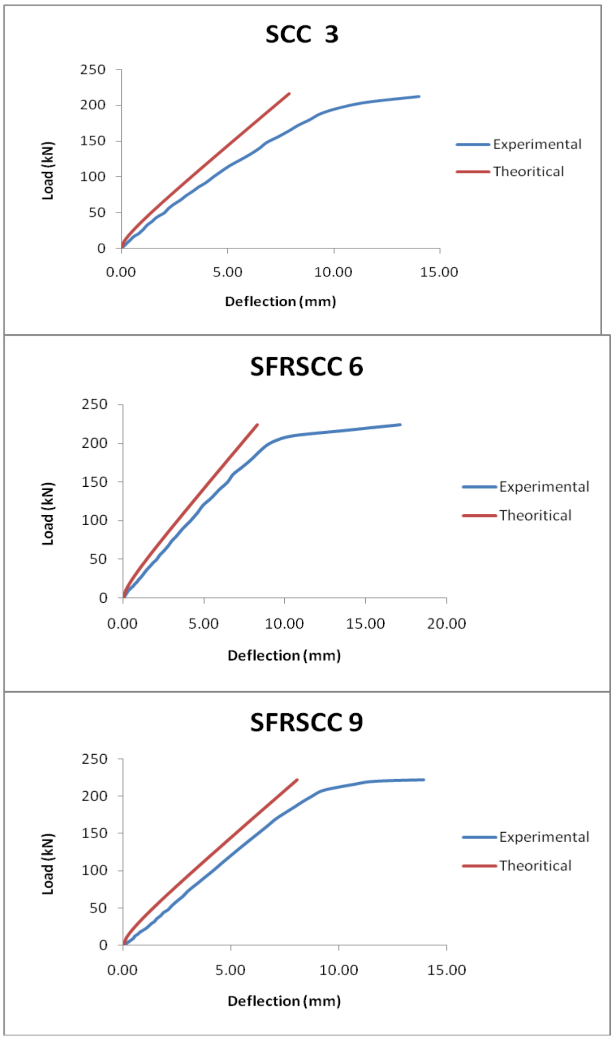

Figure-4: Comparison of experimental to computed load deflection curves

6. COMPUTATION OF CRACK WIDTH OF SFRSCCBEAMS

Rilem [11] gives a semi empirical formula as follows,

$$W_m = \varepsilon_{sm} \times S_{rm} \quad (10)$$

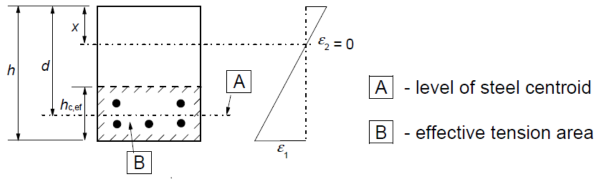

Figure-5: Cross sectional details of beam [10]

where, S_{rm} = maximum crack spacing (mm); ε_{sm} = mean strain in the reinforcement

$$S_{rm} = \left(50 + 0.25 k_1 k_2 \frac{\phi_b}{\rho_r}\right)\left(\frac{50}{L_f/\phi_f}\right) \quad (11)$$

where, k_1 = coefficient which takes into account the bond properties of Bond Reinforcement=0.8;

k_2 = coefficient which takes into account distribution of strain=0.5;

L_f = length of the fibre;

ϕ_f / ϕ_b = diameter of the fibre/ bar used;

ρ_r = effective reinforcement ratio

$$\rho_r = \frac{A_s}{A_{c)eff}} \quad (12)$$

$$A_{c)eff} = b \times h_{c)eff} \quad (13)$$

where, b = width of the beam;
h = overall depth of the section;
x = depth of neutral axis;

$$h_{c,eff} = min\left(2.5 \times (h-d), \frac{h-x}{3}, \frac{h}{2}\right)$$

$$\varepsilon_{sm} = \frac{\sigma_S}{E_s}\left[1 - \beta_1 \beta_2 \left(\frac{\sigma_{sr}}{\sigma_s}\right)^2\right] \quad (14)$$

where, E_s = modulus of tensile steel reinforcement;

σ_S = stress in tensile reinforcement calculated on basis of cracked section;

σ_{sr} = stress in tensile reinforcement calculated on basis of cracked section under loading conditions causing first crack;

β_1 = a coefficient which takes into account the bond properties of bar;

β_2 = a coefficient which takes into account of the duration of the load.

$$E_c = 3750\sqrt{f_{ck}} \text{ (given in reference 12)} \quad (15)$$

where, f_{ck}=cube strength of concrete

$$\sigma_S = \frac{M_w (d-x) E_s}{E_c I_{cr}} \quad (16)$$

$$\sigma_{sr} = \frac{M_{cr}}{A_s\left(d - x/3\right)} \quad (17)$$

Table 3: Comparison of Ultimate moments (M_u), deflection (δ) and crack width(w)

INVESTIGATOR	BEAM DESIGNATION	$M_{u,exp}$	$M_{u,th}$/ $M_{u,Suji}$	$M_{u,th}/M_{u,Samer}$	δ_{exp} (mm)	$\delta_{PRED}/\delta e$	$W_{c,cal}$ (mm)	$W_{c,cal}/W_{c,exptl}$
AUTHOR	SFRSCC 4	37.80	1.45	0.82	4.94	0.95	0.17	1.66
	SFRSCC 5	56.70	1.14	0.87	5.14	1.02	0.13	1.32
	SFRSCC 6	78.40	0.96	0.85	6.41	0.95	0.13	0.67
	SFRSCC 7	35.00	1.58	0.90	4.04	1.06	0.15	0.51
	SFRSCC 8	55.30	1.24	0.92	5.70	0.88	0.13	0.43
	SFRSCC 9	77.70	1.00	0.88	6.15	0.97	0.13	1.34
HARISH	HSF1	35.70	1.26	0.82	4.52	1.09	0.16	0.80
	HSF2	28.90	1.84	1.53	2.47	1.17	0.07	0.33
	HSF3	62.90	1.06	0.90	5.95	0.91	0.11	0.36
	HSF4	37.40	1.40	0.82	4.51	1.04	0.17	0.83
	HSF5	53.83	1.09	0.86	6.80	0.81	0.13	0.42
	HSF6	63.75	1.00	0.88	5.47	1.03	0.11	0.55
GANESAN AND INDIRA	GS1	10.80	1.26	0.89	3.40	0.87	-	-
	GS2	11.00	1.31	0.87	3.50	0.90	-	-
	GS3	10.40	1.44	0.92	3.25	0.86	-	-
	GS4	11.00	1.35	0.88	3.50	0.86	-	-
	GS5	11.20	1.47	0.87	3.30	0.90	-	-
	GS6	10.60	1.54	0.92	3.20	0.87	-	-
	GS7	10.60	1.34	0.92	3.20	0.91	-	-
	GS8	12.20	1.20	0.79	4.00	0.91	-	-
	GS9	10.60	1.47	0.92	3.30	0.85	-	-
SONEBI	SF	110.00	1.54	0.65	11.00	1.72	-	-
		$\overline{X}$	1.32	0.89	-	0.98	-	0.77
		CV	0.17	0.17	-	0.21	-	0.58

Comparison of calculated to experimental crack width is as shown in Table 3. Results show that the crack width formula suggested in RILEM is not able to predict crack width and requires modification.

7. SUMMARY AND CONCLUSIONS

An experimental program has been designed to cast and test nine Self Compacting Fibre Reinforced Concrete beams with three steel ratios (0.98, 1.77 and 2.51) and three different volume fractions of fibres (0%, 0.5% and 1.0%) under flexure.

The ultimate moment carrying capacity of the beams was calculated using 'modifying' Suji et al's method and Samer's method. It is noted that the former method over estimates the Ultimate moments and the average ratio of $M_{u)thr}$ to $M_{u)exp}$ was 1.32 with a CV 0.16 while in the later method the respective values were 1.90 and 0.17 respectively.

An effective moment of inertia function has been proposed and is able to predict the short term deflection satisfactorily at all stages of loading.

The available formula for FRC beams given by RILEM has been examined for SFRSCC beams and is found that it requires modification and as such is unable to predict the width of crack satisfactorily.

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