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EXPERIMENTAL RESULTS ON THE SHEAR BEHAVIOUR OF STEEL FIBRE SELF-COMPACTING CONCRETE (SFSCC) BEAMS

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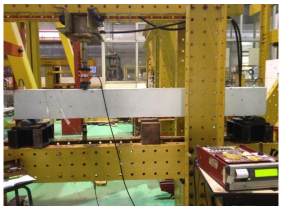
Juli Asni Lamide, Roslli Noor Mohamed*, Ahmad Baharuddin Abd Rahman

Department of Structure and Material, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia

*Corresponding author
roslli@utm.my

Graphical abstract



Abstract

This paper presents an experimental test program that was carried out to investigate the shear performance of steel fibre self-compacting concrete (SFSCC) beams. In this paper, the mechanical performance of results from all mixtures used to cast normal concrete (NC), self-compacting concrete (SCC) and steel fibre self-compacting concrete (SFSCC) were also investigated. In total, 27 cubes, 9 cylinders, 9 prisms and 9 beams were prepared for the assessment of mechanical properties of three different mixtures. Four beams (125 mm x 250 mm x 2200 mm) were tested and cast using three different concrete mixtures, having two different spacing of stirrups as a result of 50% reduction of the stirrups amount. Three beams with different mixtures having similar stirrups spacing 125mm while the fourth beam with SFSCC mixes having 250mm stirrups spacing. The results show that the mechanical properties were positively affected with steel fibres inclusion. The addition of steel fibres showed an increment up to 40% in the shear load capacity for B-SFSCC125 compared to B-NC125 and B-SCC125. In addition, the crack pattern of B-SFSCC was found better than B-NC and B-SCC.

Keywords: Shear behaviour, Mechanical properties, SCC, SFSCC

Abstrak

Kertas ini menunjukkan ujian eksperimen yang dijalankan untuk menyiasat prestasi ricih untuk rasuk yang dihasilkan menggunakan gentian keluli dan konkrit mampat sendiri. Dalam kertas ini, hasil kajian prestasi mekanikal bagi semua campuran untuk menyediakan konkrit biasa, konrit mampatan sendiri, dan konkrit mampatan sendiri bersama gentian keluli juga disiasat. Secara keseluruhannya, 27 kiub, 9 silinder, 9 prisma dan 9 rasuk telah disediakan untuk ujikaji ciri mekanikal berdasarkan tiga campuran konkrit yang berbeza. Empat rasuk (125 mm x 250 mm x 2200 mm) diujikaji dan disediakan menggunakan tiga campuran konkrit yang berbeza tetapi mempunyai dua jarak besi ricih yang berlainan disebabkan oleh pengurangan 50% jumlah besih ricih yang digunakan. Tiga rasuk yang dibuat daripada konkrit yang berbeza mempunyai jarak besi ricih yang sama iaitu 125 mm manakala rasuk keempat yang dibuat menggunakan konkrit mampatan sendiri bersama gentian keluli mempunyai jarak besi ricih 250 mm. Hasil kajian menunjukkan bahawa penambahan gentian keluli memberi kesan positif kepada ciri mekanikal konkrit. Penambahan gentian keluli menunjukkan peningkatan keupayaan ricih sehingga 40% untuk rasuk B-SFSCC125 berbanding rasuk B-NC125 dan B-SCC125. Tambahan lagi, corak retakan bagi rasuk B-SFSCC adalah lebih baik berbanding B-NC dan B-SCC.

Kata kunci: Sifat ricih, ciri mekanikal, SCC, SFSCC

1.0 INTRODUCTION

Self-compacting concrete (SCC) is one of the most recent development in concrete technology, well known with its high flowability that permits the concrete to flow under its own weight with no efforts of vibrators. SCC achieves good level of compaction without segregation even in a very congested structural member with huge number of reinforcing bars. Particularly, there are few designers that show some anxiety regarding SCC which perhaps not strong enough in resisting shear due to the small proportion of coarse aggregates compared to normal concrete (NC) which can lead to the lesser friction forces and development of weak aggregate interlock [1]. Some parameters that have been identified to influence shear performance of structural members are member dimensions, existence of axial forces, load conditions, number of reinforcing bars, compressive strength of concrete, cross section shape, the shear span/depth ratio (a_v/d) and residual flexural tensile strength of fibre reinforced concrete [2, 3].

The weakness of SCC in tensile strength and crack resistance has been widely acknowledged [4]. These weaknesses could be overcomed by the inclusion of fibres as fibres are greatly enhanced the bridging effect of the cracks and thus, retarding the crack propagation [5–7]. The possibility of using steel fibres with short length and small diameter as reinforcement improves the strength and ductility performance of concrete matrices. Special properties of fibrous concrete can be very useful to enhance the behaviour of conventional reinforced concrete members [8]. Steel fibres may be used to substitute part of the conventional reinforcement requires high number of labour consumption to be handled and reduces reinforcement congestion [8, 9]. At the shear region of reinforced concrete beams, the presence of main reinforcement and shear links results to the congestion of reinforcement. This situation will lead to the compaction problem which results to development of honeycombs. Amongst all means of replacement materials, steel fibre has known as the least cost/strength ratio [10].

Having lacking of comprehensive guidelines of fibre reinforced concrete in building codes has covered the full ability of fibre reinforced concrete as potential material to be practised in construction [11]. Comprehensive design of civil engineering structures have resulted to high volume usage reinforcement to avoid shear failure [11]. These will then lead to the difficulties of concrete placement during construction and resulted to poor construction quality. The application of short fibre would be one of the proper methods in overcoming this problem. Therefore, numerous researchers have stated that the application of steel fibres can be used to enhance the shear strength and ductility of reinforced members owe to its fibre-bridging characteristic and delaying the propagation of cracks [12, 13].

2.0 METHODOLOGY

2.1 Materials

The type of cement used in this study was Ordinary Portland Cement (OPC) with maximum size of aggregate used was 10 mm. Special additive was used as the superplasticizer named as Glenium ACE 389 RM. The aspect ratio (*l/d*) of end hooked steel fibres used in this study was 60 with length of 35mm. Class F fly ash produced by coal-burning electric utilities obtained from Tanjung Bin Power Plant was used. Longitudinal steel bars, 16 mm diameter as tensile steel, 8 mm diameter as compression steel, and 6 mm diameter were used as stirrups.

2.2 Specimens

The experimental program consists of testing four rectangular reinforced concrete beams with the dimension of 125 x 250 mm. The length of all the beams is 2200 mm, having a_v/d of 2.3. The variables considered in this experiment are the type of concrete and the spacing of shear stirrups. For the assessment of mechanical properties, 100 x 100 x 100 mm concrete cube specimens were prepared for compressive test, 150 mm diameter and 300 mm height cylinder specimens for splitting tensile test, 100 x 100 x 500 mm prism specimens for flexural tensile test and 150 x 150 x 600 mm beam specimens for residual flexural tensile strength test were also cast. Table 1 depicts the details of the beams tested while Figure 1 shows the reinforcement detailing of the beams.

Table 1 Details of the beams

Identification of beams	**Types of concrete**	**Stirrups**		**Fibres (*l/d* = 60)**
		Spacing (mm)	**ρ_s (%)**	**v_f (%)**
B-NC125	Normal concrete	125	100	0
B-SCC125	Self-compacting concrete	125	100	0
B-SFSCC125	Steel fibre self-compacting concrete	125	100	1
B-SFSCC250	Steel fibre self-compacting concrete	250	50	1

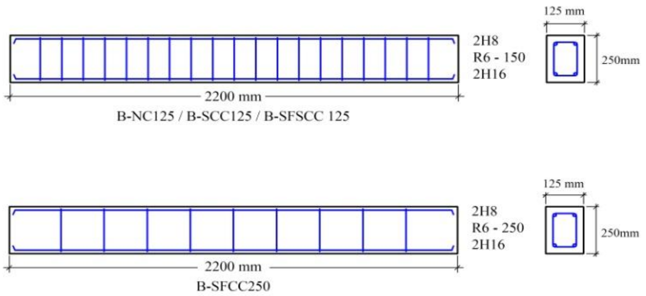


Figure 1 Reinforcement detailing of test specimens

2.3 Admixture Design

Control specimens NC mixture was designed based on Department of Environment (DoE) method [14]. For SFSCC mixture, it was prepared with the addition of 30% of fly ash as cement replacement as this type of filler is able to reduce the cost and enhance the workability of SCC [15] and 1.0% steel fibres by volume. SCC and SFSCC mixtures were designed based on the modification of previous research and referring the guideline provide by European Federation [16]. This guideline shows initial range of certain parameters as a guide to achieve self-compactability characteristics even with the addition of fibres. Modifications to the mixtures were made throughout the mixing process until a satisfactory mix was obtained based on the results of fresh concrete properties. Table 2 shows the composition materials for all mixes.

Table 2 Composition materials

Components	**Content (kg/m³)**		
	NC	**SCC**	**SFSCC1.0%**
C (kg)	392.35	416.82	416.82
F.A (kg)	0	178.64	178.64
C.Ag (kg)	1042	729	729
F.Ag (kg)	802.28	783.16	783.16
Sp (L)	2.07	4.13	6.25
W (L)	188.33	200	200
W/C	0.48	0.34	0.34
SF (kg)	0	0	78.5

2.4 Mechanical properties of SCC and SFSCC

Testing on the hardened concrete was conducted to confirm the mechanical properties such as cube compressive strength, splitting tensile strength, flexural strength and also residual flexural tensile strength. The cube compressive test is carried out based on BS EN 12390-3:2009 [17]. A total of 27 concrete cubes with dimension of 100 x 100 x 100 mm were prepared and tested at the age of 7 days, 14 days and 28 days. The splitting tensile strength test was carried out in accordance to BS EN 12390-6:2009 [18]. Total of 9 concrete cylinders with 150mm in diameter and 300mm height were tested after 28 days of casting. Flexural test was done in accordance with BS EN 12390-5:2009 [19] using 9 numbers of prisms. The size of prism is 100 x 100 x 500 mm. Another test namely residual flexural tensile strength test was conducted is in accordance with BS EN 14651:2005 [20]. This test investigates the ability of steel fibre in contributing tensile strength of SFSCC. For this test, 9 numbers of beams were prepared and tested at the age of 28 days. The size of beam is 150 x 150 x 550 mm. The specimens were loaded under three points loading until failure and result of vertically ultimate load was recorded. Generally, flexural test was conducted based on the deflection control. For this procedure, a notch with 3 mm x 10 mm in size was made at the mid span of the specimen. Deflection was measured at the mid span of the beams by using LVDT. The residual flexural tensile strength of the SFRC test beam, $f_{RK,4}$ is calculated in terms of the centre-span load, FL as follows:

$$f_{Rj} = 3F_jL/2bh_{sp}^{\;2} \tag{1}$$

where:

$f_{R,j}$ (N/mm²) is the residual flexural tensile strength corresponding with $\delta = \delta_j$ (j = 1,2,3,4), F_j (N) is the load corresponding with $\delta = \delta_j$ (j = 1,2,3,4), l (mm) is the span length, b (mm) is the width of the specimen, h_{sp} (mm) is the distance between the tip of the notch and the top of the specimen.

2.5 Structural Testing

The right end and left end of each beam specimens were tested at two different effective span lengths under three-point loading condition. The vertical load was applied at a distance of shear span-to-depth ratio of 2.3. After the right end beam that was first tested at 2000 mm span length, the beam was turned to test the left end. The formation of shear failure and cracks from the right end beam had affected the span length for the left end beam. The span length of left end beam was determined by considering the previous failure region because the support needs to be placed at a new point that was free from cracks and failure. LVDT was used to measure the deflection under the point of applied load. As the test was conducted to investigate the shear behaviour of the beams, steel strain gauges were attached to the stirrups in order to assess the contribution and effectiveness of stirrups in resisting shear load. The presence of steel strain gauge at the stirrups was chosen at the intersection of an angle between 22° to 45° between the load and support. This position is seen as the best location which will determine whether the stirrup yielded or not. Demec disc were attached at a distance of 150 mm for monitoring strains in concrete. Details of the schematic test diagram are shown in Figure 2. Figure 3 shows the experimental set-up of beam shear test. The load was applied in stage at increment of 5 kN up to the ultimate load. All measurements were automatically scanned and stored in digital format at each loading stage. At the end of each stage, propagation of cracks was sketched and marked on the specimen.

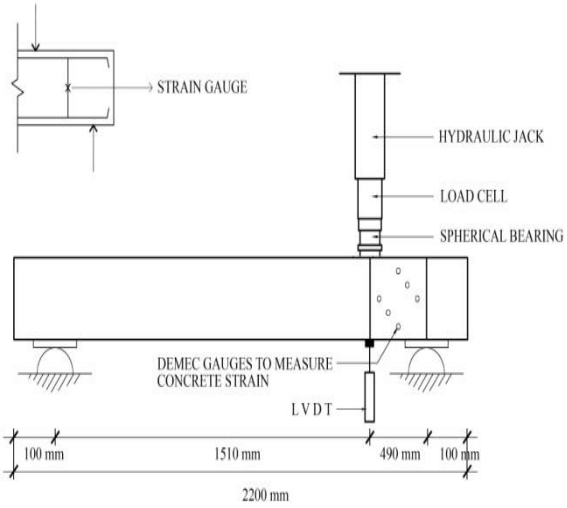


Figure 2 Schematic diagram for shear test

Figure 3 Test setup for shear test

3.0 RESULTS AND DISCUSSION

3.1 Mechanical Properties of Mixtures

Table 3 summarizes the mechanical properties results for NC, SCC and SFSCC mixes in term of compressive, tensile and flexural strength. Comparison of all strength properties is shown in Figure 4. Compressive strength of concrete increased about 15% when 1.0% by volume fibres was introduced into the mixtures. From Figure 4, it was observed that SFSCC showed the highest compressive strength. In term of flexural strength, steel fibre has significantly enhanced the flexural strength of concrete by 57% as compared to the NC. Addition of steel fibre has showed great energy absorption and ductility. It can also be seen that splitting tensile strength was increased significantly by 69% when 1.0% fibre volume was added to SFSCC. As reported earlier, these results were inline with the findings from previous researchers [5–7], where the inclusion of steel fibre has improved the resistance to cracking by retarding the propagation of cracks. Figure 5 shows the results from residual flexural tensile strength test for all three mixes. The results clearly showed that the incorporation of 1.0% by volume of steel fibres has effectively increased the residual flexural tensile strength up to 168%. Figure 6 presents the load-deflection curves for all three mixes taken from residual tensile strength test. The deflection of the plain and steel fibre concrete beam are relatively linear with the increasing load until the first flexural cracking load. SFSCC beam was found to be able to absorb more loads even after the ultimate load compared with the NC beam. The results showed double post-cracking achievement with the presence of steel fibres. Steel fibre has ability in providing ductility and contributes to the post crack behaviour of the concrete. Due to significant enhancement in residual flexural tensile strength, the shear beam test is expected to benefit the strength increment.

Table 3 Mechanical characteristics of three different mixtures

Types of concrete	Percentage of fibres (%)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Residual flexural tensile strength	
					(kN)	(MPa)
NC	0	41.44	3.94	5.97	15.9	4.87
SCC	0	42.75	4.44	6.73	16.9	5.17
SFSCC	1	47.66	6.66	9.38	42.7	13.07

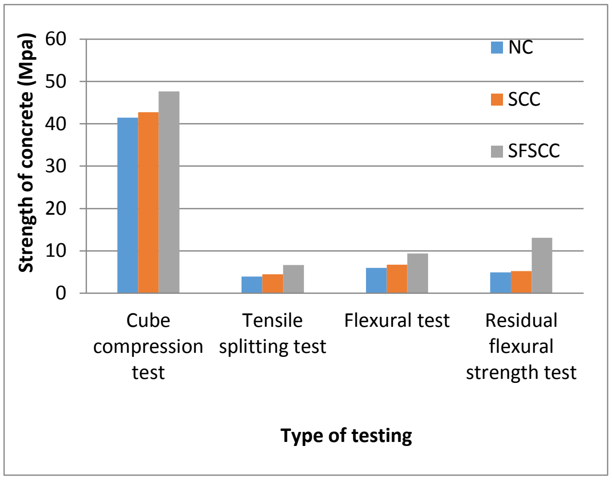


Figure 4 Mechanical strength of three different mixtures

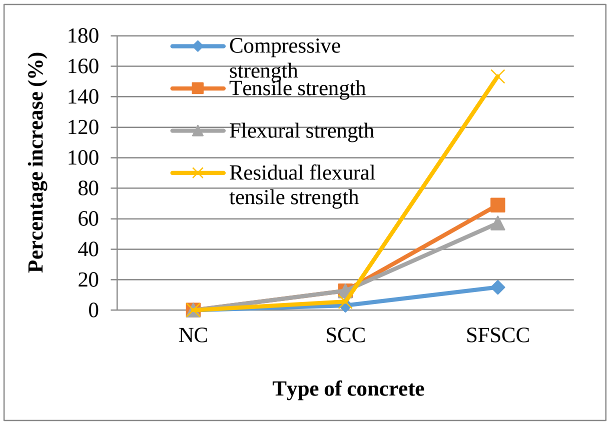


Figure 5 Percentage increment of SCC and SFSCC

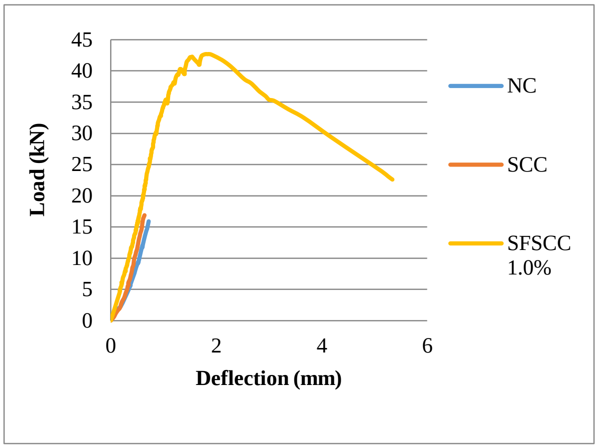


Figure 6 Load-deflection curves for unreinforced beam

3.2 Structural Testing

3.2.1 Failure Modes and Crack Pattern

Table 4 summarizes the data obtained from shear test of all beams. As in Figure 7(a) to 7 (d) and Figure 8(a) to 8(d), all beams failed in diagonal shear as expected. Figure 7(a) to Figure 8(d) show that few vertical flexural cracks were formed first followed by the formation of diagonal shear cracks from the supports towards the point of applied load before failed ultimately. For B-NC125 and B-SCC125, a large opening to the diagonal shear crack was noticed due to the sudden failure of aggregate interlock. Meanwhile, B-SFSCC125 and B-SFSCC250 which contain steel fibres were able to bridge the formation of cracks and thus preventing the sudden failure of the beams. Based on observation, these beams also showed more closer crack distance together with the vertical flexural cracks compared to beam without steel fibres and the number of cracks increased for SFSCC beams as shown in Table 4. The appearance of more cracks in SFSCC beams represents a good warning prior to ultimate failure compare to NC beam and SCC beam. SFSCC beams showed an improved ductile behaviour with larger deflections at recorded ultimate load due to presence of steel fibres. Figure 7(a) to 7(d) depicts the cracking behaviour of beams for the right end where Figure 8(a) to 8(d) for the left end of tested beams. Both sides were found to have the similar crack pattern, yet, the left end seem able to sustain higher applied load compared to the right end. In comparison with the B-NC125, the shear capacities of B-SCC125, B-SFSCC125 and B-SFSCC250 increase with 6.67%, 60.67% and 40% respectively. The lower increment in shear capacity for B-SCC125 which contains no steel fibres can be explained by the lower tensile strength recorded for mechanical properties of B-SCC125. Comparing NC ad SCC, they produced almost similar strength level and brittleness.

Table 4 Shear characteristics of beams

Beam	Load at first crack (kN)	Ultimate load (kN)	Percentage increment of ultimate load (%)	No of cracks
B-NC125	9	90	-	6
B-SCC125	12	96	6.67	6
B-SFSCC125	14.6	144.6	60.67	9
B-SFSCC250	12	126	40	9

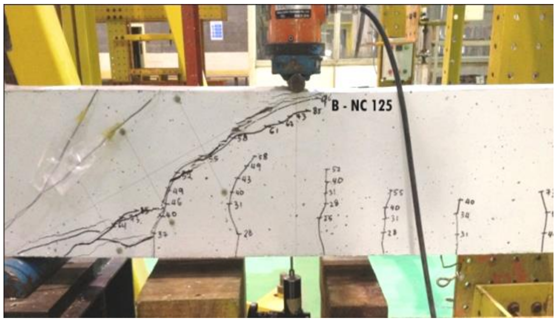


Figure 7 (a) Ultimate cracking behaviour of right end beams for B-NC125

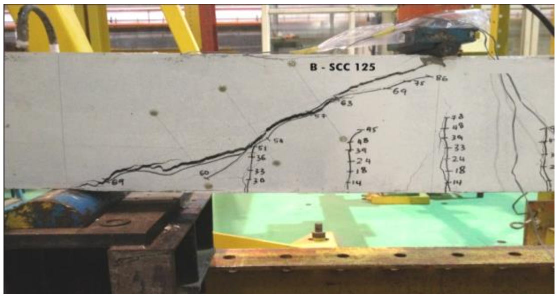


Figure 7 (b) Ultimate cracking behaviour of right end beams for B-SCC125

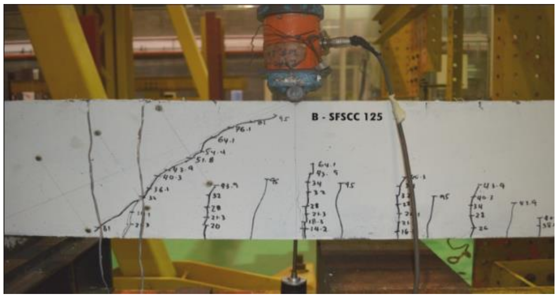


Figure 7 (c) Ultimate cracking behaviour of right end beams for B-SFSCC125

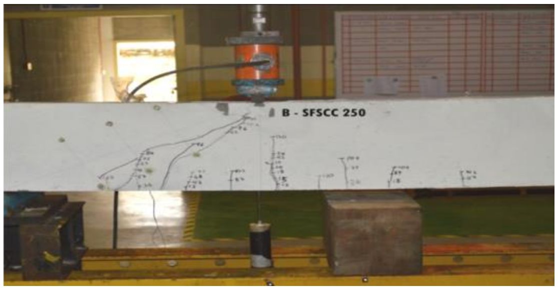


Figure 7 (d) Ultimate cracking behaviour of right end beams for B-SFSCC250

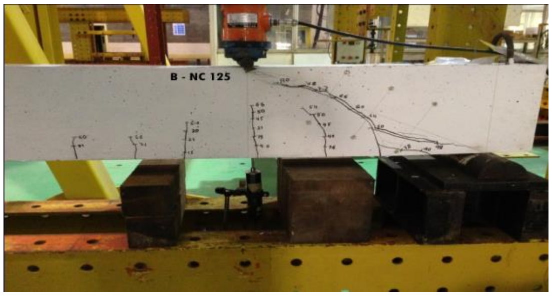


Figure 8 (a) Ultimate cracking behaviour of left end beams for B-NC125

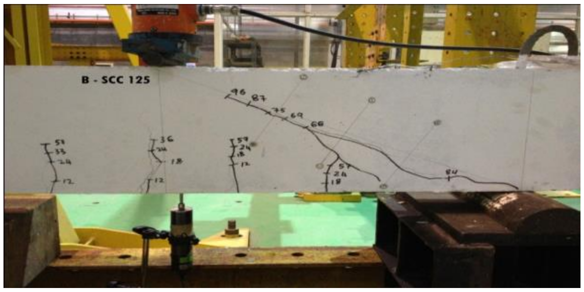


Figure 8 (b) Ultimate cracking behaviour of left end beams for B-SCC125

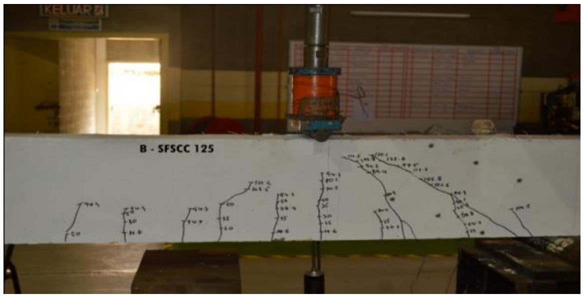


Figure 8 (c) Ultimate cracking behaviour of left end beams for B-SFSCC125

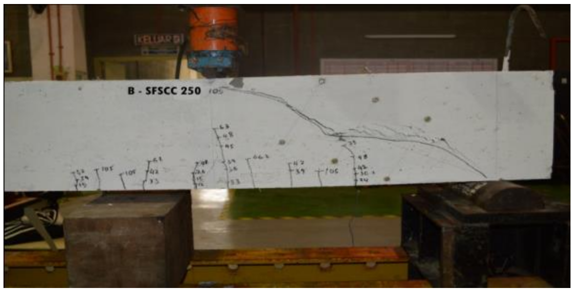


Figure 8 (d) Ultimate cracking behaviour of left end beams for B-SFSCC250

3.2.2 Load-deflection Characteristics

The load-deflection curves for all the beam specimens are shown in Figure 9 and Figure 10 respectively. Figure 9 presented the load-deflection curves for right end of all beams while for the left end was illustrated in Figure 10. For beams B-SFSCC125 and B-SFSCC250, the main observation was increment of shear load due to fibre inclusion. The main reason for this increment is due to the performance of randomly distributed steel fibres which provide bridging forces across micro cracks and thus prevents them from growing[7]. It should be noted that, B-SFSCC250 which have 50% reduction of stirrups performed even better than that of B-NC125 and B-SCC125. With the reduction of shear reinforcement, the B-SFSCC250 matched with able to matched with B-NC125 and B-SCC125 in terms of ultimate shear load capacity. In contrast, B-SFSCC125 was able to perform up to 60% of the maximum shear load exhibited by B-

NC125. The increment is caused by the high residual tensile strength.

The deflection increase linearly with load almost until the ultimate failure occurs. For both left end beams and right end beams, this occurs mostly with the plain concrete members which shows that the shear deformation generally brittle in nature and thus leads to a sudden failure without advance warning. With the addition of steel fibres, B-SFSCC125 and B-SFSCC250 exhibit an extended deformation compare to B-NC125 and B-SCC125 which shows improvement in the ductility behaviour of the concrete. The small deflection characterized by left end beams is mainly caused by the short span length. Compare with beams having long span length, the stiffness of beams generally increase with the decrease in span length. Therefore, the deflection found for all right end beams are relatively small as high stiffness behaviour could leads in high brittleness level. In addition, during the left end tests, the LVDT was taken out earlier before the failure due to shorter effective span. However, it was ensured that the beam has cracked before the disattachment of LVDT.

Comparing the strain value in shear links, SFSCC beam was observed to produce promisable post-cracking behaviour at large strain values. The ductility at large strains was observed to be best for the B-SFSCC125. The beam was expected to sustain high load capacity due to the configuration of the fibres having hook at both ends [21]. These hooks at both ends generally can increase the bond between the fibre and the matrix of the concrete. These fibres acting like a bridge that intercepts the cracks forming when the load was applied. After the formation of cracks, all beams exhibited nonlinear load-deflection characteristic which obviously describe the behaviour of steel fibres concrete in absorbing the load applied.

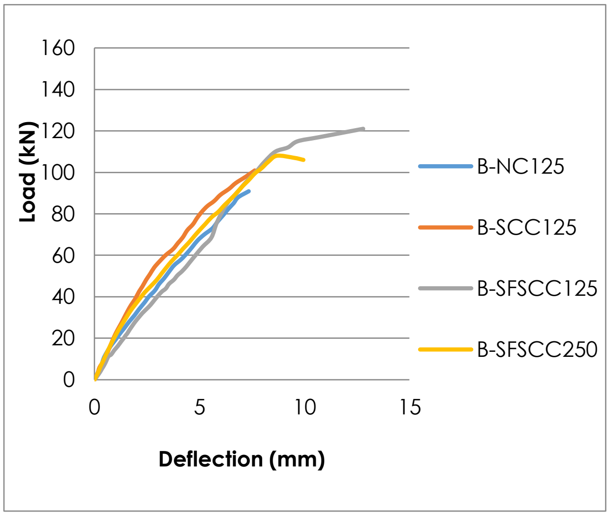


Figure 9 Load-deflection curve for right end beams

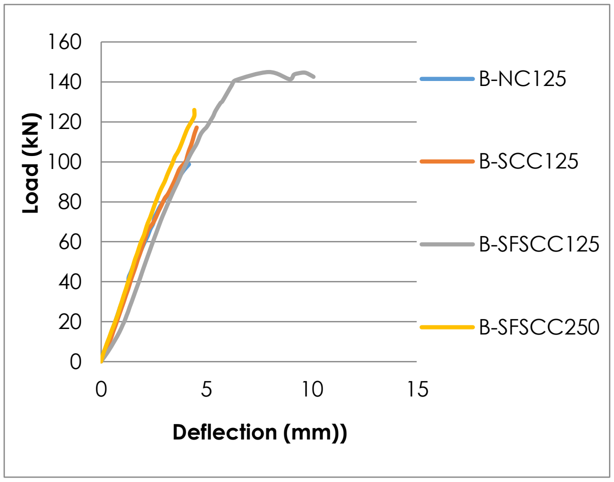


Figure 10 Load-deflection curve for left end beams

3.2.3 Load-strain Relationship for Shear Reinforcing Bar

In general, the shear resistance of all beams mainly contributed by the shear links. This is proven from the strain reading obtained throughout the test. Figure 11 and Figure 12 illustrate the results of steel strain reading of all beams. Most of the shear links yielded at about 2000με unless for B-SFSCC125 where the shear link does not yield ultimately. This is due to the effective combination of steel fibres within the concrete matrix and shear link in resisting shear load. At the same shear load carried by each beam, the shear link of SFSCC beams is not fully yielding where as the shear link for NC and SCC beams were totally yielded. This is due to effectiveness of steel fibres that help in absorbing the energy, thus distributing the stress between shear links and steel fibres [22].

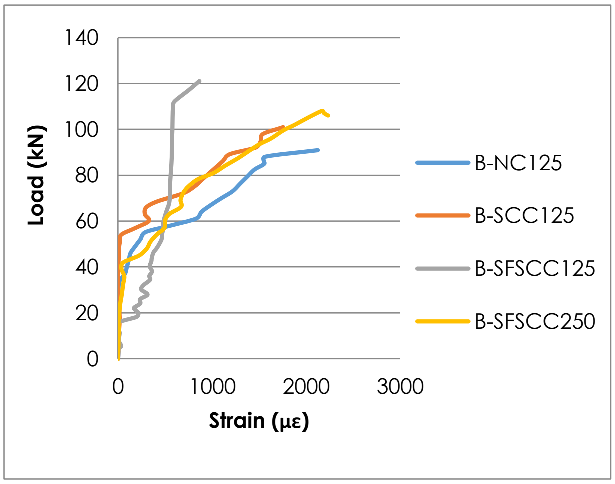


Figure 11 Load-strain curve for right end beams

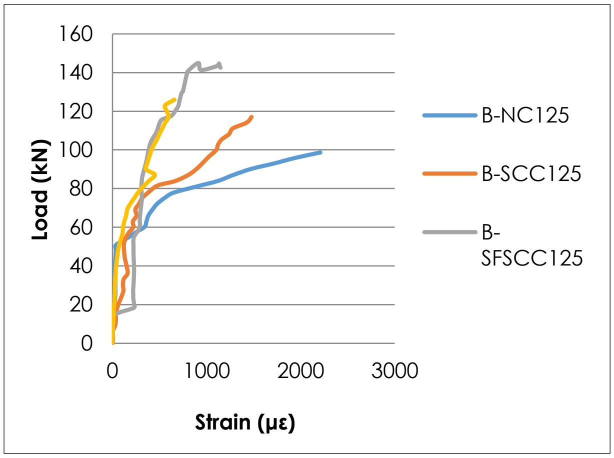


Figure 12 Load-strain curve for left end beams

3.2.4 Comparison between Theoretical and Experimental Results

According to RILEM [3], the theoretical shear stress V_{theo} consists of V_c which combined the shear resistance of concrete matrix and shear links, as shown in Equation 2. This formula is typically formulated for conventional vibrated concrete. The addition of steel fibres forms shear resistance contribution, V_f which increased the shear resistance of beams. RILEM [3] proposed Equation 6 to be used to determine the shear stress developed by steel fibres.

$$V_{RILEM} = [0.12\,k\,(\,100\rho_1 f_{ck})^{1/3} + 0.15\,\sigma_{cp}]\,b_w d + \frac{A_{sw}}{s}\,0.9\,d\,f_{ywd} \tag{2}$$

Where:

$$k = 1 + \sqrt{\left(\frac{200}{d}\right)} \leq 2 \tag{3}$$

$$\rho_1 = A_s/b_w d \leq 0.02 \tag{4}$$

$$\sigma_{cp} = N_{ed}/A_c \tag{5}$$

A_{sw} = area of stirrups

s = stirrups spacing

f_{ywd} = design yield strength of stirrups

b_w = width of web

d = effective depth

where:

N_{ed}=axial force due to load or prestress

$$V_f = 0.7 \,.\, k_f \,.\, k \,.\, \tau_{fd} \,.\, b_w \,.\, d \tag{6}$$

where:

$$k_f = 1 + n(h_f/b_w)(h_f/d) \text{ and } k_f \leq 1.5 \tag{7}$$

$$n = (b_f - b_w)/h_f \leq 3 \text{ and } n \leq 3b_w/h_f \tag{8}$$

$$\tau_{fd} = 0.12 f_{Rk4} \tag{9}$$

Table 5 clearly shows the comparison between experimental and theoretical shear for both right end and left end beams. As can be seen in Table 4, the results indicated that the percentage error between V_{Exp} and V_{Theo} is ranging from 5% to 30% for both right end and left end beams. Thus, it can be concluded that the proposed equations given by RILEM could be used in predicting the shear strength capacity of reinforced concrete beams made of SFSCC.

Table 5 Comparison between experimental shear and theoretical shear

Beam	**$V_{c,RILEM}$ (kN)**	**V_f (kN)**	**$V_{Theo} = V_{RILEM} + V_{fd}$ (kN)**	**V_{Exp} (kN) Right End**	**V_{Exp}/V_{Theo}**	**V_{Exp} (kN) Left End**	**V_{Exp}/V_{Theo}**
B-NC125	107.44	0	107.44	90.9	0.85	98.7	0.92
B-SCC125	107.44	0	107.44	101	0.94	126	1.17
B-SFSCC125	107.44	57.59	165.03	121	0.73	142.5	0.86
B-SFSCC250	78.77	57.59	136.36	106	0.78	126	0.92

4.0 CONCLUSION

From this study, it was found that the performance of SFSCC is better compared to NC and SCC. For the compressive strength test, only 15% increment was achieved with the addition of 1.0% fibres. In spite of little increment observed to the compressive strength of SFSCC, it offered a great contribution to the tensile splitting strength, flexural strength and residual flexural strength of concrete with 69%, 57% and 168% increment respectively which significantly helps in resisting the shear load. The use of steel fibres has improved the residual flexural tensile strength behaviour of concrete beam due to the fibre-bridging effect, thus enhanced the tensile strength of concrete. In the case of non-fibrous beams, the shear performance of B-NC125 and B-SCC125 was almost similar. Therefore, SCC is highly recommended to be used because this type of concrete offers easy handling and placement for beam construction. The application of SCC with the incorporation of steel fibres is capable to combine two advantages in terms of fresh and hardened properties of concrete. B-SFSCC250 which was prepared with only 50% stirrups provided the same shear strength as B-SCC125 and even higher than that of B-NC125. Hence, it can be concluded that, steel fibres plays the role as a particular substitution of conventional shear reinforcement bars where the addition of steel fibres can significantly increase the shear strength and ductility of reinforced concrete members. At the same time, steel fibres are able to delay the propagation of cracks due to the internal bridging effect in reinforced concrete beams.

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