SHEAR BEHAVIOUR OF STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE

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ABSTRACT

In this paper the shear behaviour of Steel Fibre Reinforced SCC (SFRSCC) is investigated and compared to that of traditional Steel Fibre Reinforced Concrete (SFRC). The post cracking shear behaviour is evaluated by means of a modified Japanese standard, namely the JSCE-SF6 standard test method. Several SCC mixtures, steel fibres (with different slenderness (l/d) and length (l)) and dosages were examined. The results obtained for SFRSCC were compared with traditional SFRC. Additionally, four-point bending tests were performed on large scale slender SFRC and SFRSCC beams.
The results obtained within this study, show a similar and in some cases even better mechanical behaviour for SFRSCC compared to SFRC.

Keywords: SFRSCC, SFRC, bending behaviour, shear capacity

INTRODUCTION

Fibre reinforced self-compacting concrete (SFRSCC) is a recent hybrid material that joins two other innovative concrete types. It combines the superior behaviour of self-compacting concrete (SCC) in the fresh state with that of steel fibre reinforced concrete (SFRC) in the hardened state [1]. Modern reinforced concrete structures tend to become increasingly complicated and heavily reinforced. Particularly in critical areas such as column/beam junctions this can lead to execution problems. SFRSCC may ease the pouring of concrete and partially replace the traditional steel reinforcement [2]. Research on concrete reinforced by steel fibres started in the 1950s, originating from

the need to find a material suitable to absorb the tensile forces in concrete. The incorporation of steel fibres in traditionally vibrated concrete can improve its bending capacity [3], this however under the condition that a sufficiently high amount of fibres is introduced into the concrete. These fibres have the ability to bridge cracks, with an improvement of the post cracking behaviour as a result depending on different factors (e.g. slenderness ratio of the fibres, fibre dosage, concrete compressive resistance,…). The small distance between the individual fibres makes them more effective, and even ensures that a redistribution of stresses can occur in hyperstatic elements. A homogenous addition of fibres can increase the ductility, and residual strength of the material, and limit the formation and width of cracks in concrete. A more uniform dispersion of fibres within structural elements can be obtained by incorporating fibres into SFRSCC. Improper compaction and placement of SFRC, can disturb the random dispersion of fibres within structural elements, creating local areas with a reduced fibre dosage triggering early failure and activating unforeseen mechanisms, thus affecting the load bearing capacity and the structural performance as a whole, e.g. in terms of deflection stiffness, fracture toughness etc. SCC is a more recent type of concrete, developed in the late 1980s in Japan. Due to its specific composition, with in general a higher paste and lower coarse aggregate content, is does not require external vibration energy to completely fill the most complex forms and this even when a high reinforcement ratio is adopted. There still exists some concerns regarding to the mechanical performance of this innovative concrete. Shear being one of the topics of concern. The question is if the introduction of steel fibres in SCC could improve its shear capacity to the same extent as for SFRC. One could even argue that the improvement could theoretically be even more important due to a potential (1) better fibre distribution and (2) improved interface between the fibres and the matrix. To answer this question with regard to the shear performance of SFRSCC with this study the shear capacity of SFRSCC was closely evaluated by means of small and large scale experiments and compared with that of SFRC.

LITERATURE OVERVIEW

Failure in shear is considered brittle, and as a result needs to be avoided. In practice, stirrups are generally used to avoid this brittle failure because of their relative ease of placement. Beams failing in shear generally develop a diagonal crack which starts from the support. A lot of research was already devoted to the study of the shear mechanism. Taylor *et al* [4] found that three mechanisms contribute to the shear resistance of a concrete element at the level of the crack: (1) aggregate interlock across the crack (35-50% of the total shear resistance), (2) shear resistance of the compression area (20-40%) and (3) dowel action of the tensile longitudinal reinforcement (15-25%). Aggregate interlock thus is a major contributor to the shear resistance of concrete. Due to the lower coarse aggregate content of SCC some researchers have formulated some concern with regard to its shear resistance. The available literature with regard to the shear resistance of SCC is quite limited and often

contradictory. In the work of Hassan *et al* [5] a large number of SCC beams with different depths and longitudinal reinforcement ratios were tested in shear. The results of this study revealed a lower shear resistance for SCC than vibrated concrete (VC). This finding was also confirmed by the study of Bugueňo et al [6] in which not only beams were tested but also smaller push-off specimens (S-shaped specimens). Experiments on push-off specimens conducted by Desnerck *et al* [7] on the other hand revealed a slightly higher shear resistance for SCC than for VC. Existing data on mechanical properties of SFRSCC, more specific on shear and bending behaviour, are also limited. Due to the differences in test setups and specimen geometries, comparisons between results are difficult. Greenough *et al* [8] studied the shear capacity of slender SFRSCC beams with longitudinal reinforcement and stirrups and found that steel fibres can replace part of the shear reinforcement. This conclusion was confirmed by Ding *et al* [2]. Helincks *et al* [9] found that if fibre content was increased, higher ultimate shear stresses could be achieved. In comparison with the reference beam (without fibres), beams with 55 kg/m³ of steel fibres demonstrated a 58% higher shear capacity. The SFRSCC beams exhibited also an overall increase in ductility, and a more extensive crack pattern.

EXPERIMENTAL PROGRAMME

As mentioned previously the main goal of this study is to evaluate the shear performance of SFRSCC. Therefore within this research small scale and larger scale experiments were carried out. The experiments were conducted on 2 SCC mixtures and a traditionally VC. In what follows the mix design and test setup will be discussed.

Mix design. The inert skeleton consists of river sand 0/4 and rounded gravel 4/14. For the SCC mixes, limestone filler (calcite, > 98% $CaCO_3$) is added to the mixture. To ensure good workability of the SFRC and the SFRSCC a modified polycarboxylic ether was used as superplasticizer. A mixing time of 6 minutes was maintained (addition of 80% of the superplasticizer after 30 seconds, remaining 20 % after 4 minutes of mixing + addition of the fibres after 3 minutes of mixing).The fresh properties of the mixes are characterized by means of the slump value and the slumpflow value for REF (NBN EN 12350—2) and M1-M2 (NBN 12350-8) respectively. The composition of the SFRSCCs mixes (M1 and M2) and SFRC (REF) are provided in Table 2. M1 and REF are characterized by a similar compressive strength while M2 was designed for a distinctively higher one based on a lower w/c factor. Mixture M2 is also characterized by a higher filler content (thus higher paste volume). Different types of hooked-end steel fibres were used: three types of normal tensile strength steel fibres and two types of high performance fibres. Further information on the steel fibres is provided in Table 1. Two fibre dosages were adopted, 30kg/m³ and 60 kg/m³.

Table 1. Specifications of the steel fibres used

Fibre characteristics	RC65/35 BN	RC65/60 BN	RC80/60 BN	RC80/30 BP	RC80/60 BP
Tensile strength [MPa]		1000		2300	
Length l_f [mm]	35	60	60	30	60
Diameter d_f [mm]	0.55	0.90	0.75	0.38	0.71
l_f/d_f [-]	65	65	80	80	80
Used in		REF and M1		M2	

Table 2. Concrete composition of the mixes used in the research

Component kg/m³	REF (SFRC)	M1 (SFRSCC)	M2 (SFRSCC)
CEM I 42.5R HES	310	336	335
Limestone filler	0	165	335
Round river sand 0/4	755	897	847
Rounded gravel 4/14	1111	736	695
Water	170	185	152
Superplasticizer	2.0-2.2	3.0-3.5	8.0-9.0
Steel Fibres	30	30	30/60
W/C	0.55	0.55	0.45
Slump – Slumpflow [mm]	108 (RC 65/35 BN) 91 (RC 65/60 BN) 83 (RC 80/60 BN)	604 (RC 65/35 BN) 648 (RC 65/60 BN) 723 (RC 80/60 BN)	765 (30 kg/m³ - RC 80/30 BP) 820 (30 kg/m³ -RC 80/60 BP) 707 (60 kg/m³ - RC 80/30 BP) 698 (60 kg/m³ - RC 80/60 BP)
$f_{cube,m}$ [MPa]	47,5 ± 1,3	51,5 ± 2,0	72,1 ± 1,4 (30 kg/m³) 74,0 ± 3,3 (60 kg/m³)

Test set-ups. To determine the shear capacity of the steel fibre reinforced mixes, a modified JSCE-SF6 configuration was used. The authors of [10] believed that this test procedure allows for the introduction of a pure shear failure. Finite element software revealed that other test setups often fail due to bending or mixed-modes [11]. For the JSCE-SF6 test setup, 150 mm x 150 mm x 600 mm prisms are equipped with 2 all round notches with a depth of 15 mm, creating as such a cube with side 150 mm in the middle of the prism (see Figure 1). The prism is placed on two steel blocks, 155 mm apart of each other, so as not to support the cube element of the prism. A loading block with two knife-edges is placed on top of the cube part of the prism. This configuration allows the cube to be pushed out of the middle of the prism. During preliminary experiments it was decided to equip the prisms with special holders at both ends to restrict the movement of the prism and as a result eliminate undesired bending of the specimens (as was proposed by [10] as a modification of the standard test method). The cube's slide off displacement with regard to the rest of the prism is monitored during the experiment and this on each side of the prism. At predefined values of the cube's push off displacement (1/2/3/4 mm), the residual shear strength is determined. The experiment is executed in displacement control.
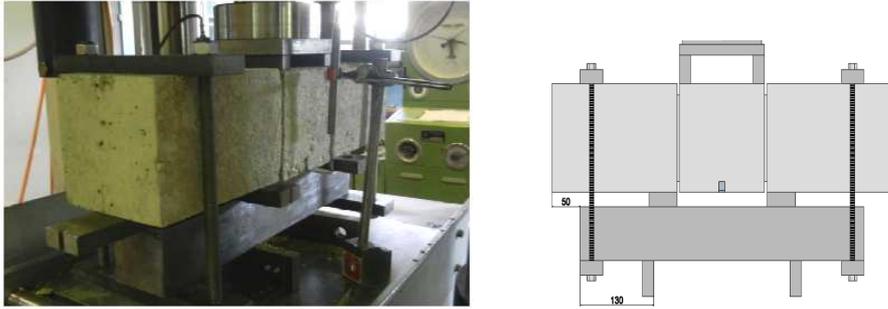
Figure 1. Modified JSCE-SF6 test set-up for the determination of the shear behaviour

In addition to the small scale experiment, 8 larger beams (2300 mm x 160 mm x 250 mm) were also tested in a four-point bending setup (see Figure 2). Three beams were made of SFRC with 30 kg/m³ RC65/60BN (REF-type), three contained SFRSCC (M1-type) with the same type and amount of fibres and two were manufactured with the M1 mixture without addition of steel fibres. The M2 mixture was not examined within this context. The distance between load and support was 650 mm, leading to a shear-span-to-depth ratio (a/d-ratio) of approximately 3. No stirrups were used between the supports (in the tested area). Two bars with a diameter of 20 mm were used as longitudinal reinforcement. A sufficient anchorage and cover was provided.

Figure 2. Test setup used for the study of the shear in beams.
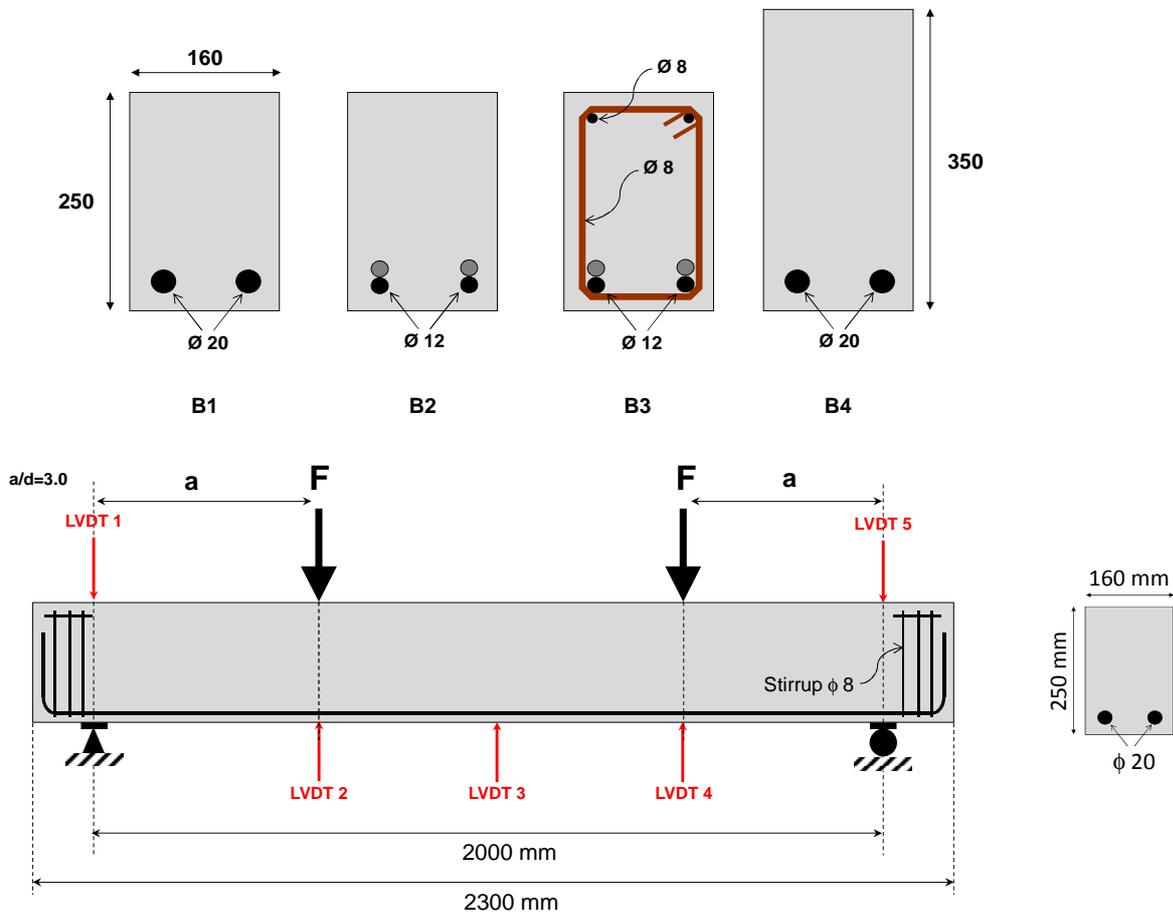
RESULTS AND DISCUSSION

Small scale experiments. As an overall conclusion, SFRSCC-M1 and SFRC-REF show similar ultimate and residual shear strength on the small shear experiments, with only one exception for the shorter fibre (RC 65/35 BN). For this combination, the residual shear strength of SFRC-REF was found to be 2.5 MPa higher compared to SFRSCC-M1 for a cube displacement of 1 mm. This difference decreases with increasing cube displacement: 1.5 MPa, 0.8 MPa and 0.6 MPa respectively for displacements equal to 2 mm, 3 mm and 4 mm. It should however be mentioned that the ultimate shear strength is substantially higher for this SFRSCC-M1 mixture.

Table 3. Residual shear strength and maximum shear strength for the different studied mixtures (REF, M1 and M2).

				τ_{max}	τ_{R1}	τ_{R2}	τ_{R3}	τ_{R4}
M1	30kg/m³	RC 65/35 BN	Average *[MPa]*	10.2	4.5	1.4	0.6	0.3
			COV* *[%]*	15.7	61.5	37.7	45.7	43.3
		RC 65/60 BN	Average *[MPa]*	8.3	6.0	2.3	1.3	1.0
			COV *[%]*	22.9	38.8	47.6	45.9	58.0
		RC 80/60 BN	Average *[MPa]*	8.6	4.6	1.7	0.8	0.5
			COV *[%]*	12.6	14.1	23.0	14.3	23.6
REF	30kg/m³	RC 65/35 BN	Average *[MPa]*	7.7	7.0	2.9	1.4	0.9
			COV *[%]*	9.6	16.6	31.5	18.3	16.3
		RC 65/60 BN	Average *[MPa]*	7.3	6.2	2.6	1.4	0.9
			COV *[%]*	5.8	14.5	21.8	23.0	26.9
		RC 80/60 BN	Average *[MPa]*	8.8	4.8	1.8	0.9	0.6
			COV *[%]*	9.7	21.2	12.3	22.8	30.9
M2	30kg/m³	RC 80/30 BP	Average *[MPa]*	12.3	8.6	4.1	1.8	0.9
			COV *[%]*	2.9	7.8	5.2	10.2	9.7
		RC 80/60 BP	Average *[MPa]*	12.9	9.8	6.0	3.6	2.5
			COV *[%]*	12.6	17.8	22.8	23.2	26.0
	60kg/m³	RC 80/30 BP	Average *[MPa]*	15.5	14.5	9.2	4.5	2.6
			COV *[%]*	14.3	18.5	25.1	27.1	27.1
		RC 80/60 BP	Average *[MPa]*	15.8	14.6	9.6	6.0	4.5
			COV *[%]*	11.9	17.3	20.7	23.0	19.9

* COV = Coefficient Of Variation

For the SFRSCC-M2 series it can be clearly seen that a higher fibre dosage and fibre length lead to a better performance in shear (both for residual strength and ultimate strength). The effect of the fibre content is more prominent compared to the influence of the length of the fibres, especially at limited push off displacement of the cube (1 mm or 2 mm) during the test.

Beam tests

In Table 4 a summary can be found of the beam experiments. The results clearly show the beneficial impact of the steel fibres on the shear behaviour of SCC, with an increase of 37% of the shear capacity by adding only a limited amount of 30kg/m³ to the mixture. Taking into account the dispersion on the results, the ultimate shear strength of SFRSCC was also found to be slightly higher (on average 12%) than that recorded for SFRC. Furthermore, the amount of bending cracks was found to be

slightly higher for SFRSCC compared to SFRC. One can state that for the mixes used in this study, the mechanical performance of SFRSCC is slightly better compared to SFRC: with a slightly higher ductility (formation of more cracks, see figure 3) and bearing capacity for SFRSCC.

Table 4. Summary of the beam experiments for mixtures M1 and REF.

	$f_{cube,m}$* [MPa]	V_E** [kN]	$V_{E,m}$*** [kN]
SCC-M1-B1	48.0	55.4	55.0
SCC-M1-B2		54.6	
SFRSCC-M1-B1	49.3	85.0	75.6
SFRSCC-M1-B2		64.6	
SFRSCC-M1-B3		77.3	
SFRC-REF-B1	50.4	70.0	67.2
SFRC-REF-B2		72.2	
SFRC-REF-B3		59.4	

* $f_{cube,m}$ is the mean cube compressive strength
** V_E is the experimentally obtained ultimate shear capacity
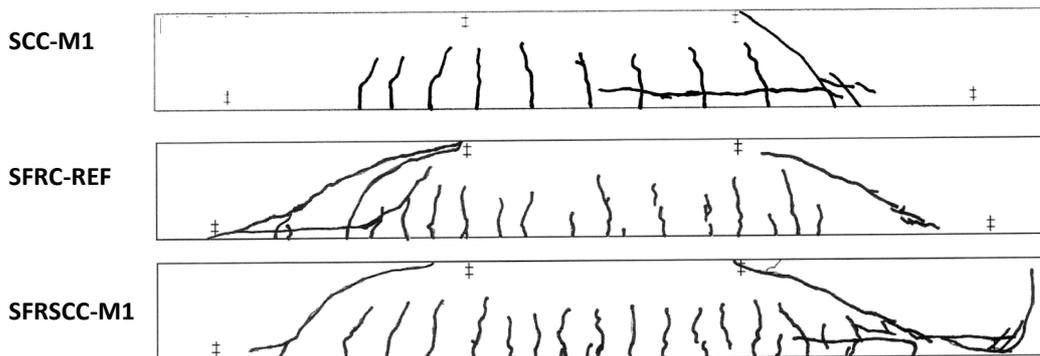*** $V_{E,m}$ is the average experimentally obtained ultimate shear capacity

SCC-M1

SFRC-REF

SFRSCC-M1

Figure 3. Typical crack patterns observed for the different mixtures

CONCLUSIONS

The general results of this limited study seem to indicate that the shear resistance of SFRSCC is similar to or slightly better than that observed for traditional SFRC of a comparable strength class. Furthermore, regarding the pure shear response of the concrete, a similar behaviour for SFRC and SFRSCC is found. Large scale beam experiments, where a mixed shear/bending mode is applied to the concrete, seem to indicate a slightly better shear behaviour for the SFRSCC in comparison with the studied SFRC. The beam experiments also revealed a more ductile behaviour (more observed cracks along the length-axis) for the SFRSCC beams than for SFRC.

AKNOWLEDGEMENTS

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