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Behaviour of SCFRC Beams under Displacement Reversals

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Abstract: Concrete is a very weak and brittle material in tension. It has been shown that the addition of steel fibers to a concrete matrix can transform this behaviour due to the ability of fibers to control and redistribute stresses after cracking. A review of existing literature shows that the addition of steel fibers enhances concrete's tensile resistance, crack control properties, ductility and damage tolerance. In beams, the addition of fibers can be used to replace the minimum shear reinforcement required by codes. The enhanced shear capacity, ductility and damage tolerance of SFRC can also potentially be used to relax seismic detailing requirements in frames by partially replacing the required transverse reinforcement in the plastic hinge regions of beams. While there is an abundance of research data on the shear behaviour of Steel Fiber Reinforced Concrete (SFRC) beams under monotonic loading, there is limited research on the response of SFRC beams under reverse-cyclic loading. The combined use of Self Consolidating Concrete (SCC) and steel fiber can improve workability of the concrete mix at high fiber contents. This paper presents the results of an experimental and analytical study conducted on several dual-cantilever beam specimens constructed with SCC and steel fibers, tested under reverse-cyclic loading. The test variables included fiber content and transverse reinforcement spacing in the plastic hinge regions. The results confirm improvements in structural response and show that steel fibers can potentially be used to allow for a reduction of transverse reinforcement in beams.

1 Introduction

Concrete exhibits weak and brittle behaviour under tensile loads. Steel Fiber Reinforced Concrete (SFRC) is a composite material whose components include the traditional constituents of Portland cement concrete and a dispersion of randomly oriented short discrete steel fibers.The addition of steel fibers can transform this behaviour due to the ability of fibers to control and redistribute stresses after cracking, resulting in improved tensile resistance, post-cracking strength and toughness. Similarly in compression, the addition of steel fibers improves post-peak strength and ductility. In structural members, addition of steel fibers leads to enhanced shear resistance due to improvements in diagonal tension capacity of concrete. If added in sufficient quantity, steel fibers can be used to replace traditional shear reinforcement and promote flexural failure and ductility (Cohen, 2012). In columns, the addition of fibers enhances confinement and cover spalling (Aoude, 2008). Research has also shown that steel fibers can improve energy dissipation capacity of joints and walls (Parra-Montesinos, 2005). Many studies have been conducted on the effect of steel fibers on behaviour of beams under monotonic loading and there appears to be fairly good agreement between the obtained results; however, limited research has been conducted on the behaviour of SFRC beams under cyclic and reverse-cyclic loading. During earthquakes, flexural members with ductile detailing are required to undergo large inelastic deformations while maintaining strength and stiffness under load reversals. To ensure adequate performance, modern codes require the critical regions in such members to be properly detailed with transverse reinforcement, resulting in congestion of reinforcement. SFRC can potentially be used to relax this detailing requirement. In addition, several studies have shown that addition of steel fibers to a traditional concrete mix can result in poor workability of concrete. In recent years, the combined use of Self Consolidating Concrete (SCC) in and steel fibers has been proposed to obtain workable and uniform fiber reinforced concrete mixtures.

2 Objectives

The primary objective of this research program was to investigate the advantages resulting from the combined use of steel fibers and self consolidating concrete in flexural members subjected to load reversals and to examine the potential of using steel fibers as partial replacement for traditional transverse reinforcement in beams. To improve the placement of concrete, and to allow for high contents of steel fibers without compromising workability, a highly flowable SCC mix was used in this study.

3 Previous Research on behaviour of SFRC Beams under cyclic loading

As noted, there is extensive research available in the literature on the shear behaviour of SFRC beams. Parra-Montesinos (2006) investigated a large test database of beams tested by other researchers which included 147 SFRC and 45 companion RC beams. The test data included beams having a wide range of properties in terms of shear span-to-depth ratio, longitudinal reinforcement ratio, steel fiber content, and steel fiber type. Analysis of the database indicated that specimens with fiber contents greater than or equal to 0.5% and 0.75% failed at applied shear forces corresponding to a shear stress not less than $0.17\sqrt{f_c'}$ [MPa] and $0.30\sqrt{f_c'}$ [MPa], respectively, demonstrating that SFRC can be used to replace minimum shear reinforcement requirements in the ACI 318 code.

While there is an abundance of research data on the behaviour of SFRC beams under monotonic loading there is limited research in the literature on the behaviour of SFRC flexural members under cyclic and reverse-cyclic loads. Campione et al. (2008) conducted an experimental study to evaluate the influence of steel fibers in combination with stirrups in beams tested under cyclic and reverse-cyclic loading. The study on the beams tested under cyclic loads demonstrated that the beams reinforced with steel fibers exhibited higher strength and ductility compared to the control specimens due to the bridging action of steel fibers across main and secondary cracks (Campione et al., 2008). For the beams tested under reverse-cyclic loads the authors noted that the SFRC beams demonstrated enhanced energy dissipation capacity and post-peak ductility when compared to companion beams without fibers.

Chompreda and Parra-Montesinos (2005) investigated the behaviour of fiber reinforced cement composite (FRCC) flexural members under large displacement reversals. The experiments evaluated the displacement capacity and shear strength of members constructed with traditional reinforced concrete and companion specimens constructed with FRCC materials. Eight FRCC specimens were constructed with span to depth ratios of 3.0 and either ultra-high weight polyethylene fibers or hooked-end steel fibers with fiber volume fractions ranging from 1.0% to 2.0%. The study reported that peak shear stress demands in the test specimens without web reinforcement ranged from $0.21\sqrt{f_c'}$ to $0.40\sqrt{f_c'}$ [MPa] and was equal to $0.51\sqrt{f_c'}$ [MPa] for the specimen with web reinforcement. The results suggest that shear resistance, confinement and flexural ductility were improved with addition of fibers. Furthermore, the results indicated that specimens with fiber contents greater or equal to 0.75% failed at applied shear forces corresponding to a shear stress not less than $0.30\sqrt{f_c'}$. Based on the results, the authors suggested that a shear stress level of $0.30\sqrt{f_c'}$ [MPa] can be considered as a lower bound for the shear resistance provided by strain-hardening FRCCs in beams subjected to load reversals.

4 Previous research on the behaviour of SFRC beams constructed with SCC

Greenough and Nehdi (2008) tested thirteen Self Consolidating Fiber Reinforced Concrete (SCFRC) beams constructed with various steel fiber types (hooked-end, flat-end and wavy), fiber contents (0.5% to

1%), and shear span-to-depth ratios (3.0 and above). The results demonstrated that the use of steel fibers enhanced shear strength by up to 128% when compared to companion specimens constructed with plain reinforced concrete. The initial cracking load and ultimate strength of the beams also increased as a result of addition of steel fibers which resulted in higher ductility of the test specimens. It was also reported that the effectiveness of the improvements in shear strength was improved as fiber content increased. It was postulated by the authors that this relative increase in the shear strength of SCFRC beams compared to FRC beams is due to the denser microstructure of the matrix and also due to the SCC's ability in achieving better dispersion of fibers within the concrete matrix. The authors also presented two empirical equations for predicting the shear strength of SCFRC beams and recommended modification to current ACI code provisions for prediction of shear capacity of slender FRC beams by explicitly considering the effect of random orientation of fibers.

Cohen (2012) tested 12 beams under monotonic loading; two series of 6 beams each constructed with different longitudinal reinforcement ratios (2-20M and 2-15M bars) were reinforced with various amounts and types of steel fibers. No transverse reinforcement was used in any of the beams. Normal strength and high strength hooked-end steel fibers at various contents (0.75% to 1.5% by volume of concrete) were used in the test specimens. Ten beams out of twelve used normal strength hooked-end steel fibers whereas 2 beams were constructed with high strength hooked-end steel fibers. A pre-packaged self-consolidating concrete was used in eight of the tested specimens, while the other four beams were constructed using a customized SCC mix developed by the author. It was observed that the addition of 0.5% of steel fibers by volume of concrete increased shear capacity by 47% when compared to the control beam without fibers, however a brittle shear failure was observed. At 1.0% steel fiber content, the brittle shear failure was transformed into a ductile flexural response with 63% increase in shear capacity. The ultimate ductility ratio of the beams with 1.0% steel fiber content was approximately 5.5 times higher than that of the control specimen with no steel fibers. Similar behaviour was observed in beams with 1.5% steel fiber content with 28% increase in the ultimate midspan deflection prior to failure compared to that of the beam with 1.0% steel fiber content. It was also observed that the minimum amount of steel fibers to transform the brittle shear failure behaviour into a ductile manner decreased by 0.25% when high strength hooked-end steel fibers were used.

5 Experimental and Analytical Program on SCFRC Beams

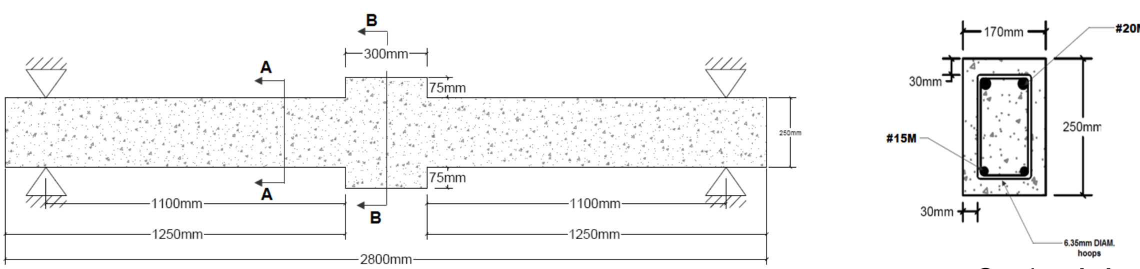
As part of this experimental program, several Steel Fiber Reinforced Concrete (SFRC) dual-cantilever beams were constructed using SCC and tested under reverse-cyclic loading in order to investigate the performance enhancements gained from using steel fibers combined with SCC. The test variables included fiber content and transverse reinforcement spacing in the plastic hinge regions, and included two control beams constructed without fibers. This paper presents results from four of the specimens tested in the experimental program.

5 .1 Description of Specimens

All specimens had a total length of 2800 mm and were simply supported over a span of 2500 mm, with a middle loading block having length of 300 mm. The middle block had larger cross-sectional dimensions of 400 mm x 170 mm, with 75 mm protruding at the top and bottom with respect to the beams. The two cantilever beams had clear spans of 1100 mm and cross-sectional dimensions of 250 mm x 170 mm. For each cantilever section the negative moment reinforcement (top) consisted of 2-20M (d_b = 20 mm, A_s = 300 mm^2) reinforcing bars, while the positive moment reinforcement (bottom) consisted of 2-15M (d_b = 16 mm, A_s = 200 mm^2) reinforcing bars. The longitudinal reinforcement details were chosen in accordance with cl. 21.3.2.2 of the CSA A23.3-04 (CSA, 2004); this clause requires the positive bending reinforcement in flexural members to be at least 50% of the negative moment reinforcement at beam-column joints locations. The beam sections had a top and bottom clear cover of 30 mm to the reinforcing bars resulting in an average effective depth, d of 204 mm. Table 1 summarizes properties of the four tested specimens; two test series D/2 and D/4 are discussed in this paper each consisting of beams with different steel fiber contents and hoops spacings. Beam specimens were named D/2-0.0% and D/2-1.5%, D/4-0.0% and D/4-1.0%, indicating the spacing of hoops in the plastic hinge regions (in terms of the effective depth of the section d – D/2 and D/4) followed by the steel fiber content in % by volume of concrete. Figure 1 shows the properties of a typical beam specimen while Figure 2 shows the details of the specimens in the D/4 series (the details of the other specimens were the same with the exception of the hoop spacing in the plastic hinge regions). Figure 3 shows the load setup used in testing the dual-cantilever specimens. The same loading protocol was used in testing all specimens. According to a reverse cyclic loading convention, each beam was loaded at 0.5% drifts up to 3.0% drift and loaded by 1.0% drift after this point until the failure of the specimen in both the positive and negative bending directions. Loading was cycled three times in each drift stage.

Table 1 Properties of the tested concrete beam specimens

Series	*Beams*	*Concrete Type*	*Cross-section* (mm x mm)	*Reinforcement*	*Fiber type*	*Shear span to depth ratio, a/d*	Transverse reinforcement spacing, s (mm)	*Fiber content* (% by volume)
D/2	D/2-0.0%	KING SCC	170 x 250	Bottom (M+): 2 - 15M; Top(M-): 2 - 20M	ZP-305	5.4	103 (d/2)	0
	D/2-1.5%						103 (d/2)	1.5
D/4	D/4-0.0%						51 (d/4)	0
	D/4-1.0%						51 (d/4)	1.0



Section A-A

Figure 1 Typical beam geometric properties

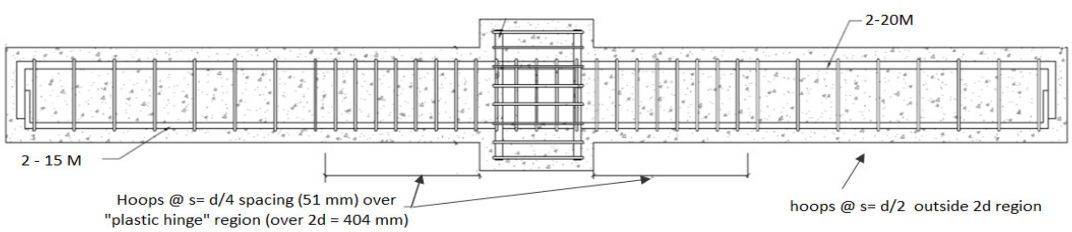


Figure 2 Reinforcement details for the beams in the D/4 series

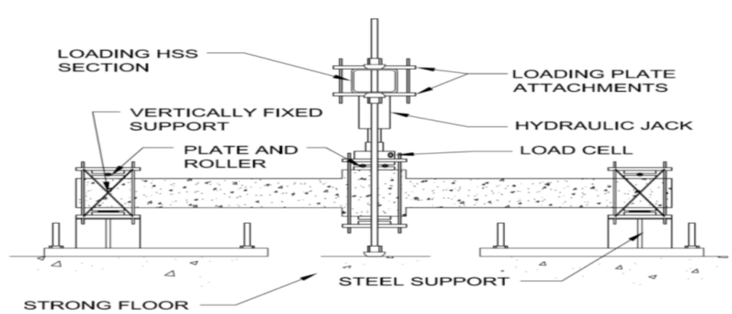
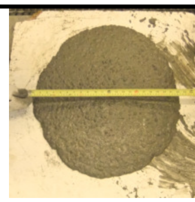


Figure 3 Schematics of the beam loading setup

5 .2 Material Properties

Self-consolidating concrete was used to improve the workability of the fiber reinforced concrete mixtures. The concrete consisted of a pre-packaged self-consolidating mix with a specified strength of 50 MPa (MS Self-Consolidating Concrete, KING Packaged Materials Company). The mix contained a maximum aggregate size of 10 mm with a sand-to-aggregate ratio of approximately 0.45 and a water-cement ratio of approximately 0.42. An air-entraining admixture, a super-plasticizer and a VMA were incorporated into the mix in the form of dry powder. It was previously shown by Aoude (2008) that 1.5% by volume of concrete is the upper limit for use of steel fibers for producing workable SFRC hence steel fiber content was limited to 1.5%. It should be noted that despite the use of SCC, the concrete that contained 1.0% or higher steel fiber content, although exhibiting excellent workability, did not exhibit full self-consolidating properties. All specimens were constructed using hooked-end steel fibers. The Dramix ZP305 fibers had a tensile strength of 1100MPa, length of 30mm, diameter of 0.55mm and aspect ratio (Lf/Df) of 55. The concrete was mixed using a pan mixer as shown in. The workability of each batch of concrete was tested using slump flow test after each mixing. The concrete was also inspected for segregation, bleeding and other concrete fresh state defects. It was observed that workability reduced as the steel fiber content increased. At fiber contents of below 1.0% very minimal vibration was required, however at fiber contents of 1.0% and higher vibration was required to achieve proper consolidation of concrete. Standard size cylinders (100mm dia. by 200mm height) were tested at 28 days after casting. Table 2 presents slump flow test results and average compressive strengths for the various concrete mixes used in the beams.

Table 2 Effect of steel fiber content on slump flow

Slump Flow Photos			
Batch	0.0%	1.0%	1.5%
Slump flow (mm)	600	480	405
f'co (MPa)	53.0	59.7	60.8

5 .3 Results of Experimental Program

In order to examine the effects of steel fibers on structural performance, the hysteretic load-displacement response of the specimens, flexural strength, post-peak ductility, energy dissipation capacity, crack control and damage tolerance of the beams are compared.

Figure 4 shows the hysteretic load-displacement response curves for various beams tested in this experimental program and Table 3 shows the flexural capacities of the various specimens. Test parameters consisted of the amount of steel fibers and hoop spacings used in the beams. A comparison of the flexural strengths shows that addition of steel fibers increases flexural strength slightly in most cases. It was noted that at higher steel fiber contents, the increase in flexural strength was more significant. The results showed that varying hoop spacing generally does not have a major impact on flexural strength; this was expected as the tested beams were flexure-dominant and hence additional shear reinforcement did not contribute to increasing flexural capacity significantly. The effect of test parameters on ductility and energy dissipation capacity of the tested beams can be investigated by comparing the hysteretic responses of the beams. In all test series, it was observed that ductility increased significantly with the increase of steel fiber content. By comparison of Figures 4c and 4d, it can be seen that addition of 1.5% of steel fibers by volume of concrete in D/2 series results in significant increase in post-peak ductility. A similar pattern was observed in the D/4 series. Comparison of the hysteretic curves for beams with the same amount of steel fiber content and varying hoop spacing indicates that reduced spacing (higher transverse reinforcement ratio) increases ductility slightly. Energy dissipation capacity was quantified as the area enclosed by the load-deflection envelope as shown in Figure 5 and Figure 6. Table 4 presents a comparison between the energy dissipation capacities for the tested specimens in the D/2 and D/4 series at their failure. As seen in this table, the energy dissipation capacity of beam D/4-1.0% is significantly greater than that of beam D/4-0.0%. Similar results were obtained for the two beams in the D/2 series. A similar pattern was observed when comparing beams with same amounts of steel fiber and varying hoop spacing as seen in Figure 6. This figure shows that at 1.0% steel fiber content, beam D/4-1.0% with d/4 hoop spacing shows significant improvement in energy dissipation capacity compared to beams with 1.0% steel fiber content and larger hoop spacings.

Comparing hysteretic response of beam D/4-0.0%, which had no steel fiber but had the required hoop spacing for ductile frames (corresponding to s= d/4), with beam D/2-1.5%, which had 1.5% fiber content and minimum hoop spacing (corresponding to s = d/2) shows that the combined use of fibers and transverse reinforcement in beam D.2-1.5% results in performance which matches or exceeds the flexural strength, energy dissipation capacity, ductility, damage tolerance and crack control of the heavily congested D/4-0.0% specimen.

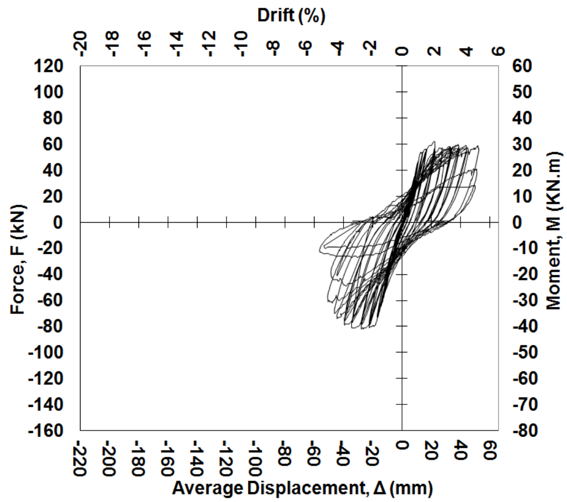
Table 5 shows photos of the beams at failure for positive and negative bending**.** As seen in this table, beams reinforced with steel fibers demonstrated the ability to control cover spalling, concrete crushing and cracking. For example, the addition of 1.5% of steel fibers in beam D/2-1.5% and 1% steel fibers in beam D/4-1.0% resulted in major improvements in crack control and reduced spalling and crushing when compared to the companion beams constructed without fibers. In contrast, beam D/2-0.0%, which contained no fibers, experienced severe spalling of concrete cover and crushing of core concrete in the hinging regions. Several major cracks were observed within the hinge region, which progressed as displacements increased. Increased shear and flexural stresses eventually led to complete loss of concrete material in this region. Beam D/4-0.0% showed similar behaviour, although crushing was better controlled in this beam due to the higher ratio of transverse reinforcement.

In general, when compared to the beams constructed without fibers, the crack widths in the SFRC specimens were generally very well controlled and remained as hairline cracks until the end of the tests, with the exception of one major crack at the face of the middle block on each side. In addition to observations discussed above, examination of the cracking patterns indicates that the length of the plastic hinge zone is reduced in the case of beams with fibers. This behaviour has also been observed by Burrell et al. (2012) in columns tested under lateral blast loads.

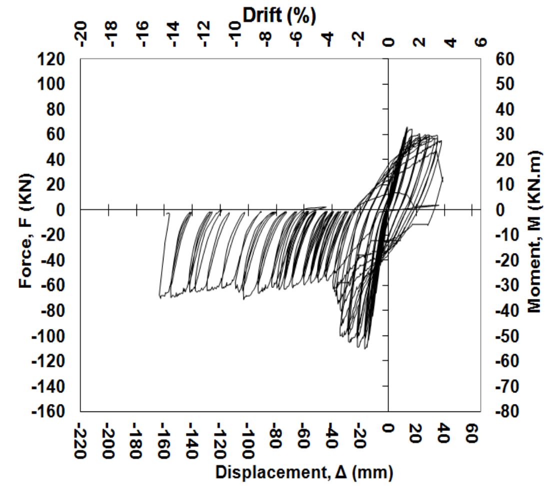
Despite the enhancements in structural behaviour, it is noted that the performance of the SFRC specimens was limited due to the early rupture of the positive moment reinforcing bars (2-15M) during the positive bending cycles. For the specimens with steel fibers, rupture of positive bending reinforcement was observed at average drift of 5.0%. In the case of negative bending, the 20M reinforcing bars ruptured at much higher drift stages. The early rupture of the 15M bars in positive bending was primarily due to the effect of steel fibers in enhancing toughness of concrete in compression; this increased toughness enabled longitudinal steel reinforcement bars to undergo rupturing strains at earlier drift stages compared to the case of beams with no steel fibers.

Table 3 Flexural capacities of tested specimens

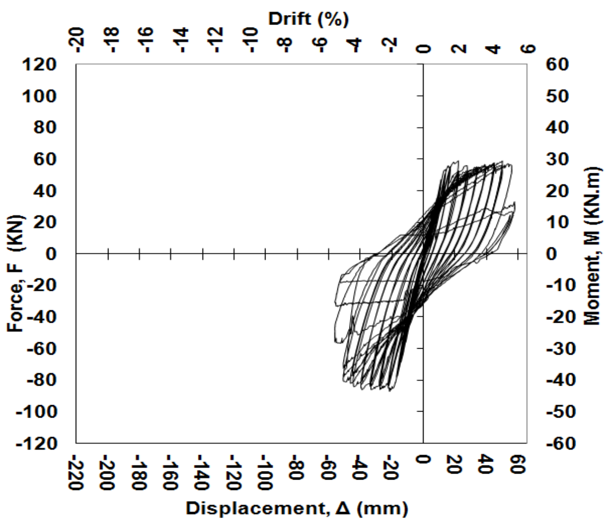
Beam Specimen	Flexural Capacity in positive bending (KN.m)	Flexural Capacity in negative bending (KN.m)
D/2-0.0%	34.1	-45.1
D/2-1.5%	36.1	-60.7
D/4-0.0%	32.5	-47.9
D/4-1.0%	34.9	-50.6



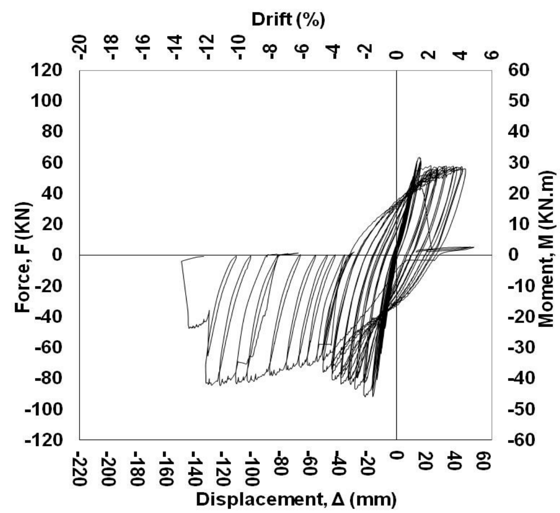
(a) D/2-0.0%



(c) D/2-1.5%



(d) D/4-0.0%



(e) D/4-1.0%

Figure 4 Load-displacement responses for tested specimens

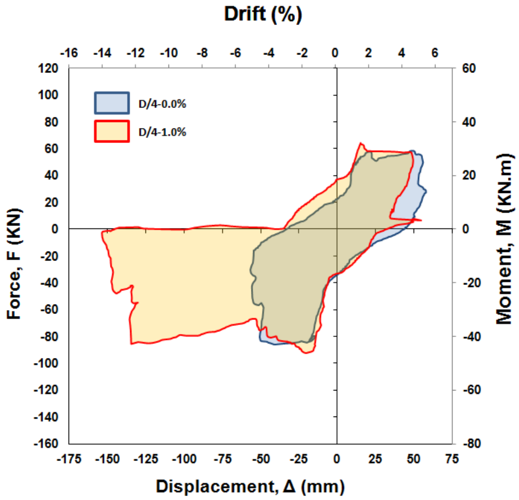


Figure 5 Areas enclosed by hysteresis loops for specimens in D/4 series

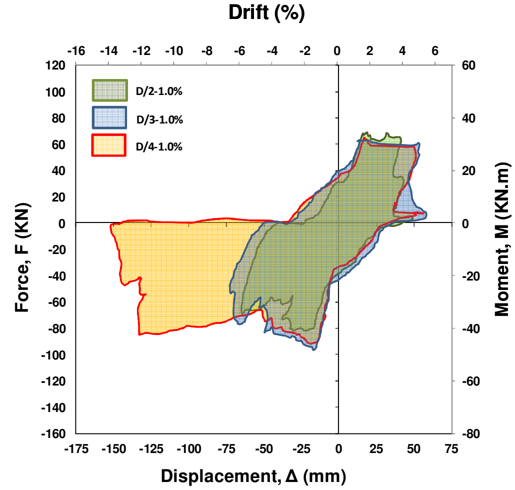
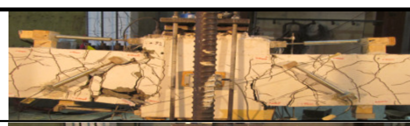
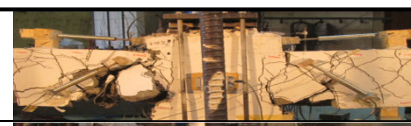
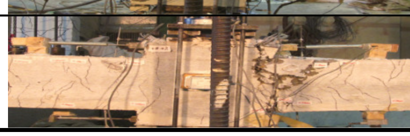
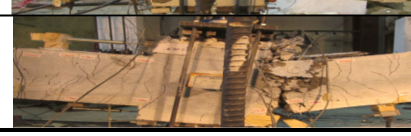


Figure 6 Areas enclosed by hysteresis loops for specimens with 1.0% steel fiber content

Table 4 Energy dissipated at failure of tested specimens

Specimen series	0.00%	1.0%	1.50%
D/2	6.30	-	13.93
D/4	7.49	12.9	-

Table 5 Comparison of damage tolerance and cracking patterns for tested specimens

Beam Label	Damage at failure in positive bending	Damage at failure in negative bending
D/4-0.0%		
D/4-1.0%		
D/2-0.0%		
D/2-1.5%		

5 .4 Analytical comparison of results

This section briefly discusses the analysis of the beams tested in the experimental program. Analytical predictions of beam responses were carried out using inelastic static analysis (push-over analysis). Sectional and member analyses using material models and beam member properties were used to derive moment-curvature relationships and moment-displacement responses for the beams. For the RC beams, the well-established model proposed by Legeron and Paultre (2003) was used for confined and unconfined plain concrete. Models proposed by Aoude (2008) were used to predict the stress-strain behaviour of unconfined and confined SFRC. Steel stress-strain relationships were obtained from standard coupon tests performed for the tested specimens. Buckling of reinforcement was taken into account by using the model proposed by Yalcin and Saatcioglu (2000). This model modifies the stress-strain behaviour based on bar aspect ratio, which is defined as the ratio between the unsupported bar length and diameter. For aspect ratios greater than 8.0 the model assumes stability of the reinforcing bar is lost upon reaching yield. Deflections due to anchorage slip of the longitudinal reinforcement were incorporated into the analysis by using a model developed by Alsiwat and Saatcioglu (1992). This model is based on construction of the stress-strain diagram along the embedment length of the reinforcement to obtain stress and strain in the reinforcement at the that location by first performing sectional analysis of the critical section and then using the elastic and inelastic bond stresses to compute the length of each region within the embedment length.

Analytical calculation of force-displacement relationship consisted of sectional analysis and member analysis. In sectional analysis, beam member and material properties were incorporated using the models for concrete, SFRC and reinforcement steel allowing for the derivation of moment-curvature relationships. In the member analysis, it was assumed that the length of the plastic hinge region remains constant throughout the test. This assumption is not entirely true for reinforced concrete beams, however due to its small impact on the analytical results and in order to simplify the analysis, this assumption was made. As noted previously, plastic hinging in SFRC beams starts with multiple hairline cracks, and one major crack that widens throughout the test and hence limits the length of the plastic hinge when compared to traditional reinforced concrete beams; this effect requires further research. Figure 7 compares the analytical and experimental load-deflection envelopes obtained for a sample of the beams tested in the experimental program (similar results were obtained for the other beams tested in the experimental program). In general, the results demonstrate that the inelastic-static analysis provides good agreement between experimental and analytical results for both the reinforced concrete and SFRC beams tested in this experimental program.

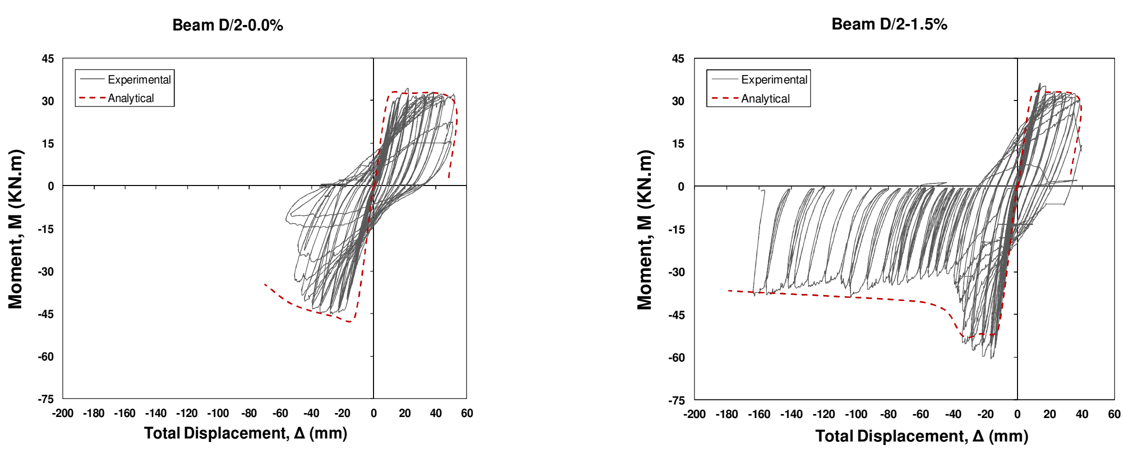


Figure 7 Analytical predictions vs. experimental results for beams D/2-0.0% and D/2-1.5%

6 Conclusion

The following conclusions are drawn from the study presented in this paper: (1) the combined use of SCC and steel fibers results in adequately workable mixtures at moderate fiber contents; (2) the combined use of SCC and steel fibers in beams subjected to load reversals improves ductility, enhances energy dissipation capacity, damage tolerance and improves crack control (3) steel fibers can potentially be used to partially replace transverse reinforcement requirements for seismic detailing and reduce reinforcement congestion in highly reinforced areas (i.e. beam-column joints), however, minimum transverse reinforcement is required to prevent bar buckling; (4) Static-inelastic analysis and were used to predict the behaviour of RC and SFRC beams tested in this study with good accuracy.

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