

PERFORMANCE OF STEEL FIBER-REINFORCED CONCRETE BEAMS UNDER SHOCK TUBE INDUCED BLAST LOADING

by
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Abstract

This thesis focuses on the dynamic and static behavior of steel fiber-reinforced concrete (SFRC) beams. As part of this study a total of eighteen (18) beams are tested, including fourteen (14) SFRC beams, and a companion set of four (4) beams built without fibers. Seven (7) of the beams are tested under quasi-static (slowly applied) loading with the remaining eleven (11) beams tested under simulated blast loading using the University of Ottawa shock-tube. The variables considered in this study include: concrete type (SFRC vs. conventional concrete), fiber content, fiber type, as well as the effect of transverse reinforcement. The criteria used to evaluate the blast performance of the beams includes: overall blast capacity, maximum and residual mid-span displacement, secondary fragmentation and damage control. Static results confirm the beneficial effect of fibers on improving the shear and flexural capacity of beams. Dynamic results show that use of steel fibers at a sufficient content can increase shear capacity and effectively replace transverse reinforcement in beams tested under blast loads. The results also show that increasing fiber content can improve the blast response of the beams by reducing maximum and residual mid-span displacement, improving damage tolerance and minimizing secondary blast fragments. However, at high fiber contents, problems with workability of the concrete mix can occur, resulting in a reduction of improvements when compared to SFRC specimens with lower fiber content. The analytical research program aimed at predicting the response of the test beams using dynamic inelastic single-degree-of-freedom (SDOF) analysis. Overall the analytical results demonstrate that SDOF analysis can be used to predict the blast response of beams built with SFRC.

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Notations

Symbol	Definition
A	Area impacted by the blast pressure
d_b	Steel reinforcement bar diameter
d_f	Fiber diameter
E_c	Modulus of elasticity, concrete
E_s	Modulus of elasticity, steel
f_{ctf}	Fiber reinforced concrete tensile stress
f_{cu}	Unconfined concrete stress
f_{cuf}	Unconfined fiber reinforced concrete stress
f'_c	Compressive concrete strength
f'_{cu}	Unconfined compressive concrete strength
f'_{cuf}	Unconfined compressive fiber reinforced concrete strength
f'_{dc}	Design compressive concrete strength
f_{du}	Design steel ultimate stress
f_{dy}	Design steel yield stress
$f_{fct,eq}$	Equivalent flexural strength
f_s	Steel stress
f_{sh}	Steel strain hardening stress
f_u	Steel ultimate stress
f_y	Steel yield stress
F_m	Mean load
I_r	Reflected impulse
K_{LM}	Load mass transformation factor
L_d	Driver length
l_f	Fiber length
m	Total mass of the system
P_r	Reflected pressure
P_d	Driver pressure
R	Resistance of the member
RI_v	Reinforcing index
t_p	Positive phase duration
u	Deflection at mid-height
$\ddot{u}$	Acceleration at mid-height
v_f	Fiber volume ratio
ε_{20cu}	Unconfined concrete strain at 20% of peak stress
ε_{50cu}	Unconfined concrete strain at 50% of peak stress
ε_{cu}	Unconfined concrete strain

ε_{cuf}	Unconfined fiber reinforced concrete strain
ε'_{cu}	Unconfined concrete strain at peak stress
ε'_{cuf}	Unconfined fiber reinforced concrete strain at peak stress
ε_s	Steel strain
ε_{sh}	Steel strain hardening strain
ε_u	Steel ultimate strain
ε_y	Steel yield strain
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}_s$	Static strain rate
δ_{anls}	Analytical displacement
δ_{exp}	Experimental displacement
δ_{max}	Maximum displacement
δ_{res}	Residual displacement
θ_{max}	Maximum support rotation
τ_{bond}	Matrix bond strength

Acronyms

Acronym	Definition
ACI	American Concrete Institute
ASTM	American Society of Testing Materials
CSA	Canadian Standards Associations
DIF	Dynamic Increase Factor
HSS	Hollow steel section
LTD	Load transfer device
LVDT	Linear variable displacement transducer
NBCC	National Building Code of Canada
SCC	Self-consolidating concrete
SDOF	Single degree of freedom
SFRC	Steel fiber reinforced concrete
SNFRC	Synthetic fiber reinforced concrete

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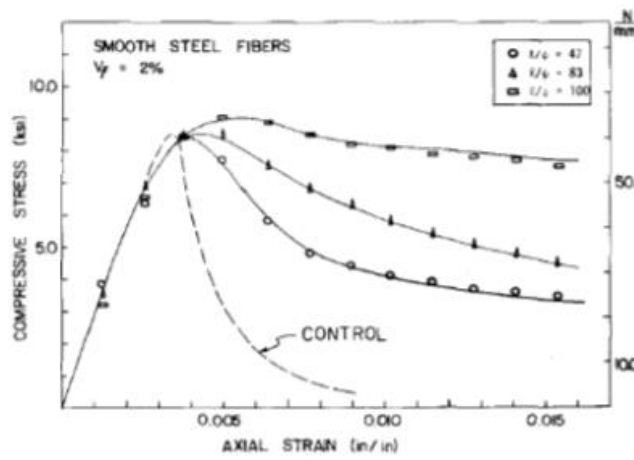
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1 Introduction

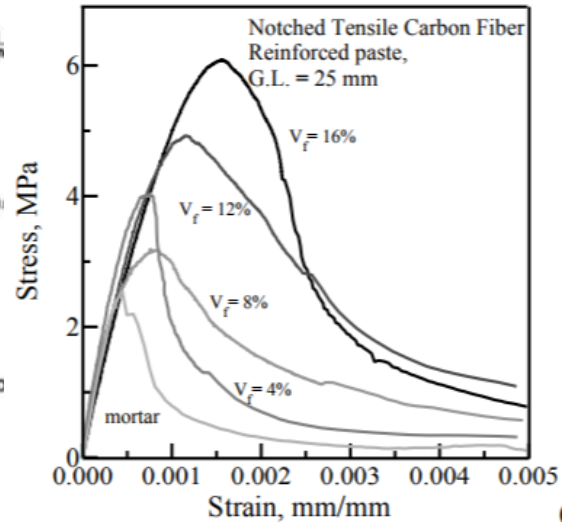
1.1 General Context

The mitigation of blast loads on reinforced concrete structures has become an important issue in today's society to ensure the safety of the people and to build resilient buildings and infrastructure. Recent historical events such as the Lac-Mégantic rail disaster (Canada 2017), the Toronto propane explosion (Canada 2008), Montreal Firework Factory explosion (Canada 2013) and terrorist incidents such as the Oklahoma City bombing (USA 1995) have demonstrated the vulnerability of reinforced concrete buildings against blast loads. Structures, in addition to having sufficient strength, need to be properly detailed to provide ductility and continuity to prevent damage and potentials for brittle failure under extreme blast pressures. Unfortunately, the steel detailing necessary to ensure the required level of performance can lead of overcrowded sections and placement issues. There is a need to develop new technologies to alleviate these problems.

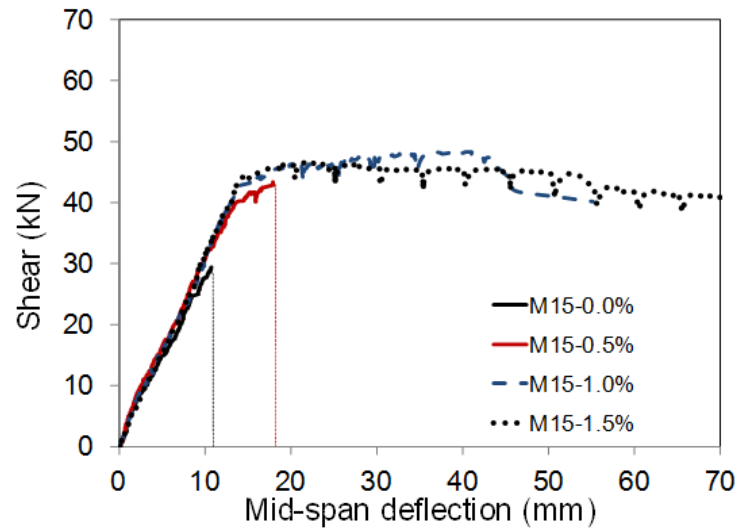
One solution may lie in the use of innovative materials such as fiber-reinforced concrete (SFRC), where short steel fibers are added to improve the performance of concrete. The ability of fibers to arrest and redistribute cracks results in improved tensile resistance, toughness and fragmentation resistance of concrete, and offers new opportunities to improve the resistance of reinforced concrete structures to extreme dynamic loads. Extensive studies on beams tested under quasi-static loads have shown that SFRC can significantly enhance the diagonal tension capacity of concrete, resulting in increased shear resistance, ductility, and flexural performance , with an ability to fully or partially replace transverse reinforcement in flexural members (see Figure 1.1). However, only a limited amount of studies and tests have been conducted on fiber-reinforced concrete beams under blast loading. In order to study the effectiveness of SFRC in blast mitigation, this study aims to provide additional data and observations in regards to the potential benefits of implementing this material in reinforced concrete beams.



(a) Fanella and Naaman (1985), Compression stress-strain Curves



(b) Mobasher and Li (1996), Tension stress-strain curves



(c) Aoude and Cohen (2014), Flexural load-deflection curve

Figure 1.1: SFRC material properties improvement

1.2 Research objectives

The Primary objective of this thesis is to conduct an experimental study in order to investigate the shear and flexural behaviour of steel fiber reinforced concrete (SFRC) beams under static and blast loading. The study investigates the influence of various parameters such as concrete type, fiber content and fiber type, as well as transverse steel ratio on blast performance. The study also examines the suitability of using dynamic inelastic single degree-of-freedom (SDOF) analysis to predict the blast response of the SFRC beams.

1.3 Scope of work

A total of eighteen (18) beams were tested in this study including: fourteen (14) SFRC beams, two (2) companion beams without transverse reinforcement, and two (2) companion specimens with transverse reinforcement. A total of eleven (11) beams were tested under shock tube induced blast loading and seven (7) beams were tested under quasi-static four-point bending. The design parameters investigated in the study includes:

- The effect of concrete type: conventional concrete vs. steel fiber-reinforced concrete
- The effect of transverse reinforcement and ability of fibers to replace such steel
- The effect steel fibers: a selection of three different types of steel fibers with varied fiber tensile strength, length and aspect ratios were studied, at different fiber contents.

The specimens are tested using the University of Ottawa Shock tube under gradually increasing blast pressures. The performance criteria used to evaluate the blast performance of the beams includes: overall blast capacity, maximum and residual mid-span displacement, secondary fragmentation and damage control. These criteria will be used to compare the behaviour of each specimen against their companions to determine the benefits or disadvantage of SFRC over traditional concrete and reinforcement. As part of the research, dynamic inelastic single degree-of-freedom (SDOF) is also conducted to predict the blast response of the SFRC beams.

1.4 Thesis breakdown

This document contains seven chapters and is divided as listed below:

Chapter 1 - Introduction

- Introduces the significance of this research, outlines the objectives and presents the scope of work for this study

Chapter 2 – Literature Review

- Provides background information related to this thesis topic and summarizes previous research on impact and blast performance of SFRC materials and structures

Chapter 3 – Experimental Program

- Describes the static and dynamic experimental program including a description of the materials, specimens, test setup and testing protocols.

Chapter 4 – Experimental Results

- Presents the data obtained from the static and dynamic testing programs.

Chapter 5 - Discussion

- Discusses the effects of transverse reinforcement and the effect of steel fiber content and type in terms of static and blast structural response, with a comparison of overall performance, displacements, damage tolerance and secondary blast fragmentation.

Chapter 6 – Analysis of Dynamic Tests

- Defines material and dynamic increase factors models used in the SDOF analysis.
- Presents the analytic prediction of the beams and compares the experimental to the analytical results.

Chapter 7 – Conclusion and Recommendation

- Presents the final conclusions from this research and proposes recommendations for future research.

2 Literature Review

2.1 Section Overview

This section presents a literature review related to the research topic, which focuses on the blast performance of steel-fiber reinforced concrete (SFRC) beams. The first section summarizes previous research on the effects of high strain-rates on the material response of SFRC, while the second and third sections review previous research relating to the impact and blast behavior of SFRC structures.

2.2 Effect of High-Strain Rates on Material Response of SFRC

Over the years important research has been conducted to study the effects of high strain-rates on the material response of SFRC. Table 2.1 presents a summary of previous studies, with an overview of material properties, specimen details, test setup, strain-rate recorded and a summary of the conclusions drawn from each study. Alongside the summary table, a summary of the acronyms used is presented in Table 2.2. Further details on specific studies are provided below.

Naaman and Gopalaratnam (1983) studied the dynamic bending behavior of steel fiber reinforced mortar using an instrumented drop-weight impact machine. Plain and fiber-reinforced mortar specimens were tested under three-point bending at varied strain rates. Smooth fibers with varied fiber aspect-ratios and fiber contents ranging from 1-3% were used. The authors observed a three-fold increase in the modulus of rupture and energy absorbed by the fiber-reinforced mortars when compared to the results for specimens tested under static and dynamic loading rates. The results also showed that energy absorbed and modulus of rupture under dynamic loading improved with increasing fiber content and fiber aspect-ratio.

Banthia et al. (1996) studied the impact behavior of SFRC at fiber content of 1.5% using a drop-weight machine and found that the addition of fibers resulted in an improvement in terms of fracture energy and toughness. The researchers also found that the behavior was influenced by fiber type and fiber content. The authors noted that the fiber improvement were less pronounced under impact loading than under static loading.

Wang et al. (1996) conducted drop-weight impact tests on a series of flexural beams reinforced with hooked-end and crimped steel fibers at fiber contents ranging from 0.25-1.5%. Modest

increase in fracture energy was observed at low fiber contents ($\leq 0.5\%$), while a more important increase in fracture energy was observed at higher fiber contents until a critical point is reached (0.75%) with the failure mode transitioning from fiber fracture to fiber pullout. The authors noted that beyond the critical point, the increase of fiber content only led to small increase in fracture energy.

Xu et al. (2006) studied the impact response of normal and high-strength SFRC round panels under quasi-static and dynamic drop-weight impact loading. The panels were reinforced with deformed steel fibers with at contents ranging from 0.5 to 1%. For the normal-strength panels, toughness improved with increased drop-height, while no significant improvement in toughness was observed for the high-strength panels. The results demonstrated that the effect of fibers in improving toughness was reduced in high-strength concrete specimens. The results also demonstrated that high-strength SFRC may be less strain-rate sensitive when compared to normal-strength SFRC. Finally, the authors noted that the round panel impact test is suitable for assessing the impact behavior of fiber reinforced concrete.

Mohammadi et al. (2009) conducted a series of drop weight tests on SFRC to study the effect of fiber content (1% - 2%) and aspect ratio (20 vs. 40) also using a drop-weight setup. The increase in length and aspect ratio both improved the impact resistance of the specimens in terms of numbers of blows required to produce the first crack and ultimate failure.

Nia et al. (2012) studied the drop-weight impact resistance on a series of cylinders reinforced with hooked-end steel fibers at fiber content ranging from 0.5% to 1%. A significant increase in tensile and compressive strength was observed for SFRC specimens. Impact resistance, first crack initiation resistance and final fracture were also improved for SFRC.

Cadoni et al. (2009) examined the behavior of high-strength FRC under high-velocity impact loads using Split-Hopkinson bar test setup. The authors observed a remarkable increase in dynamic increase factor (DIF) with increasing strain-rate, although the authors found SFRC showed more brittle behavior at higher strain-rates.

Table 2.1: Summary of previous research on the effect of high-strain rate on material response of SFRC

Study	Testing method	Strain Rate Range (s ⁻¹)	Specimen type	Property investigated	f'_c (Mpa)	Fiber type	Fiber property	Fiber content (%)	Aspect Ratio (L_f/d_f)	Conclusions
Naaman and Gopalaratnam (1983)	Drop weight	$0.5 \times 10^{-5} - 1.2$	Beam	Flexure	56-64.7	SFRC	S	1-3	47-100	➤ Increase in modulus of rupture and energy absorbed by the fiber-reinforced mortars when compared to the results for specimens tested under static and dynamic loading rates. ➤ Energy absorbed and modulus of rupture under dynamic loading improved with increased fiber content and fiber aspect-ratio.
Banthia et al. (1987)	Drop weight	M = 345 kg DH = 1-2.4 m V = 0.15 msec ⁻¹	Beam	Flexure	42 - 82	SFRC SNFRC	H PP	0.5 - 1.5	83	➤ It was observed that Fiber-reinforced concrete was a better material for dynamic situation because of its increased ductility. ➤ Steel fibers behaved better than polypropylene fibers
Benthia & al. (1996)	Swinging Pendulum	0.08	Cube	Compression	38 - 90	SFRC	H C	40kg/m ³	60 - 75	➤ Plain and fiber reinforced concrete were sensitive to strain rate and were stronger and tougher under impact loading when compared to static loading. ➤ Fiber reinforcement improved energy absorption but was dependent on fiber type and geometry
Wang et al. (1996)	Drop weight	M = 60.3 kg DH = 150 mm	Beam	Flexure		SFRC SNFRC	F H C	0.25 - 1	50 - 60	➤ Increased fiber content of hooked steel fiber increased fracture energy of the beams. ➤ Beyond a critical fiber content (.75%), the increased content only lead to small increase of fracture energy.
Xu et al. (2006)	Drop weight	M = 578 kg V = 1.9 msec ⁻¹	Round panel	Fracture energy	80	SFRC SNFRC	PP	0.5 - 1		➤ Increased fiber content for both SRFC and the synthetic fiber reinforced concrete (PPNFRC) specimens resulted in increased toughness. ➤ Steel fibers were more effective then synthetic fibers at increase the toughness for high strength concrete.
Cadoni et al. (2009)	Modified Hopkinson Bar	50, 100 & 200	Cylinder	Tension	160 - 185	SFRC SNFRC	PVA	2.5	120 - 666	➤ Tensile strength increased with strain rate but was more brittle. ➤ Optimal mix was different for synthetic fibers than for steel fibers.
Mohammadi et al. (2009)	Drop weight	M = 5.54 kg DH = 457 mm	Beam	Flexure	57.8 - 72.8	SFRC	C	1 - 2	20 - 400	➤ The incorporation of steel fibers improved impact resistance when compared to plain concrete. ➤ Increased fiber content increased impact resistance with the best results observed at 2%.
Nia et al. (2012)	Drop weight	M = 4.54 kg DH = 457 mm	Cylinder	Compression Tension	41.3 - 58.45	SFRC SNFRC	H PP	0.2 - 1	80	➤ The addition of fibers increased compressive and tensile strength. ➤ The addition of fibers increased impact strength. ➤ Steel fibers with hooked-ends exhibited a better performance that the synthetic fiber reinforced concrete specimens

Xu et al. (2012)	Drop weight	M = 12.5 kg DH = 4 m V = 8.85 m/sec 37 - 113	Cylinder	Tension	49.7 – 53.3	SFRC	H SP	1	63 - 70	➤ The use of steel fibers increased tensile strength and fracture energy under both static and dynamic test.
Zhang et al. (2014)	Drop weight	10^{-3} mm/s ⁻¹ to 10^3 mm/s ⁻¹	Beam	Bending	76 - 92	SFRC	H	0.8	67	➤ Peak load and fracture energy are load rate sensitive
Ulzurum & Zanuy (2017)	Drop weight	1 – 10	Beam	Bending	60 – 80	SFRC	S, H, P	0.5 - 1	48.5 – 64.7	➤ Higher Peak load and fracture energy was observed with higher fiber volume ➤ Rate sensitivity of peak load measured in terms of DIF increased with the increase of fiber content with both smooth and prismatic fibers but decreases with hooked fibers. ➤ The DIF of fracture energy decreased with fiber content.

Table 2.2: Acronym summary

Fiber type		Fiber properties	
S	Straight	SFRC	Steel fiber-reinforced concrete
H	Hooked	SNFRC	Synthetic fiber-reinforced concrete
P	Prismatic		
F	Fibrillated		
C	Corrugated/Crimped		
SP	Spiral		
T	Twisted		
PP	Polypropylene fiber		
PVA	Polyvinyl fiber		

2.3 Impact Behavior of SFRC Structures

This section presents a summary of previous research in the literature which has been conducted to study the impact behaviour of SFRC structures. A summary of previous studies, with information of material properties, specimen details, test method and fiber types/properties used in each study, is presented in Table 2.3. Further details on these studies are provided below.

Banthia (1987) conducted a study on the effect of fiber content and fiber type on the impact response of beams. A large set of unreinforced (plain) and conventionally reinforced beams were tested using an instrumented drop-weight impact machine and were compared to fiber-reinforced specimens. The use of fibers reduced the brittleness of the concrete, particularly at high strengths and lead to increased ductility and energy absorption capacity. The effect of fibers on increasing energy absorption capacity was found to be greater for high strength concrete when compared to normal strength concrete, particularly at higher drop-heights.

Miyamoto et al. (1989) presented an analytical and experimental study that examined the effect of loading rate, concrete strength ($f'_c = 38\text{-}84$ MPa), high-strength steel ($f_y = 350\text{-}650$ MPa) and fibers on the behaviour of beams tested under impulsive loading. The study found that increasing concrete strength on its own can decrease impact resistance, however the authors noted that this can be overcome by incorporating the use fibers.

Luo et al. (2000) conducted a series of projectile tests on high strength concrete targets to study the effect of varying fiber content (7 – 10%) and fiber type on resistance. The use of steel fibers improved the impact resistance by preventing failure of the specimens. The study found that the projectile would crush the plain concrete specimens, while the projectile reflected off the surface or embedded itself in the surface of the SFRC specimens. Improvements to impact resistance were noted with increased fiber aspect ratio and the specimens with fibers showed reduced crack widths.

Hrynyk and Vecchio (2014) studied the effect of fiber content ranging from 0% to 1.5% by volume in two-way slabs under drop weight impact tests. The addition of sufficient fiber content ($\geq 1.5\%$) prevented punching shear of the specimen, whereas control specimens, as well specimens with low fiber contents, failed in shear under dynamic impact loads (compared to flexure under quasi-static loads). At all contents, the use of fibers reduced crack spacing and crack widths, while

also increasing stiffness and impact capacity of the slabs. A correlation between fiber content and increased impact performance was noted in the study.

Hao et al. (2015) studied the effect of different fiber types on the impact performance of beams. A series of six (6) specimens were tested using a drop weight machine and the results indicated that the use of fibers increased the ability of the concrete to absorb impact damage. It was noted that spiral steel fibers increased the post cracking load-bearing capacity of the beams while also increasing contributions in terms of absorbing impact damage when compared to hooked fibers.

Ulzurrin et al. (2017) conducted a study on the effect steel fiber type and steel fiber ratio for beams subjected to drop hammer tests. The bending strength and fracture energy increased at higher strain rates for every type of fiber although, it was reported that the dynamic increase factor (DIF) for smooth and prismatic fibers increased with strain-rate but decreased for hooked-end steel fibers. The author also noted that prismatic and hooked-end fibers performed better than the smooth fibers at both 0.5% and 1% fiber content in terms of both peak load and fracture energy.

Table 2.3 Summary of previous research on the impact behavior on SFRC structures

Study	Testing method	Specimen type	No. of Specimens	Dimensions	f_c (MPa)	Fiber type	Fiber property	Fiber content (%)	Aspect Ratio (L_f/d_f)
				b x h x L t x b x L (mm)					
Banthia (1987)	Drop weight	Beam	360	100 x 125 x 1400 100 x 125 x 1525	42 - 82	SFRC SNFRC	H S PP	0.5-1.5	50
Miyamoto et al. (1989)	Drop weight	Beam	19	150 x 160 x 1300 150 x 160 x 1600	--*	--	--	--	--
Luo et al. (2000)	Projectile Impact	Blocks	12	300 x 400 x 400	72 - 116	SRFC	S	7 - 10	35 - 60
Hrynyk & Vecchio (2014)	Drop weight	Slab	7	130 x 1800 x 1800	50 - 70	SFRC	H	80	0 - 1.5
Hao et al. (2015)	Drop Weight	Beam	6	100 x 100 x 350		SFRC	H SP	1%	63 - 70
Ulzurrin et al. (2017)	Drop Weight	Beam	7	150 x 150 x 600	48 - 65	SFRC	H S P	60 - 80	0.5, 1

*Not specified by authors

2.4 Blast Behavior of SFRC Structures

When compared to impact a fewer number of studies have examined the blast performance of SFRC structural members, however some research has been conducted on slabs, beams and columns. Published research in this area is summarized in Table 2.4. It is noted that the majority of testing has been conducted on slabs and panels.

Lok and Xiao (2000) tested a series of one-way and two-way SFRC panels under varying charge weights of TNT. The fiber-reinforced concrete slabs were reinforced with steel fibers having different aspect-ratios at ratios varying between 0.5% and 1.5% by volume of concrete. The study did not report detailed test data comparing the performance of control and SFRC panels, however the authors noted damage was significantly reduced for the fiber-reinforced panels. In both the simply-supported and fixed slab series, residual displacements reduced as the fiber content increased from 0.5% to 1.0%, however no further improvement was observed as fiber content increased further to 1.5%.

Lan et al. (2004) conducted live blast testing on a large set of composite structural panels which included conventional reinforced concrete slabs, steel fiber reinforced concrete slabs, profiled steel sheeting reinforced concrete slabs, steel–air–steel sandwich panels and steel–concrete–steel sandwich panels, with a total 72 panels tested. Charge weights were varied between 8 and 100 kg of explosive at a stand-off distance of 5m. Parameters investigated included concrete and construction type as well as slab thickness. The SFRC panels included specimens with different boundary conditions and fiber types, with fiber contents ranging from 0.5% to 1.5%. Fiber type and content affected damage and cracking in the slabs, with the authors noting the positive effect of fibers which prevented breaching of the slabs. Optimum results were obtained at a fiber content of 1%, with the authors noting that 0.5% yields favourable results while being cost-effective.

Yosof et al. (2010) conducted close-in live explosive testing on a set of 8 one-way normal-strength SFRC panels. Hooked end fibers at contents of 0.5%-1.5% were used in this study. Blast loading was generated by detonation of 1kg of explosive charge at a 0.6m standoff. The specimen with 0.5% fibers showed similar failure mode to the control slab (no enhancement), with improvements in blast performance observed at 1% fibers and optimal results at 1.5% fiber content.

Yi et al. (2012) tested the blast performance of three two-way slabs under the effects of close-in ANFO blasts. The specimens included one panel made of normal strength concrete, one panel made of ultra-high-strength concrete (UHSC), and one panel made of reactive powder concrete (RPC), a type of ultra-high performance FRC. The results showed that the UHSC and RPC showed better blast performance when compared to the normal-strength concrete panel, with reduced cracking, spalling and damage and energy absorption capacity.

Foglar et al. (2013) tested the blast behaviour of five one-way RC panels reinforced with polypropylene (PP) fibers. Blast loads were applied by detonating 25 kg of TNT in close proximity of the slabs. The performance was evaluated based on the level of breach in the slabs. The experiments showed the benefits of using PP fibers which reduced the amount of breaching, spalling and amount of flying debris. The tests also showed the benefits of increased concrete compressive strength in the FRC panels, with the higher strength specimens showing less damage and reduced deformations. In a follow-up study, **Foglar et al. (2015)** studied the effect of using waste steel fibers on the blast performance of similar panels. In this study better performance was observed for specimens with higher fiber contents (1% vs. 0.5%), although the authors noted that the low-ductility waste steel fibers had only limited effect on blast resistance. Specimens with a combination of fiber types (waste steel + poly-propylene) showed greater crushing of concrete when compared to specimens containing only propylene fibers. Finally, the authors noted that concrete strength had a greater effect on the extent of puncture while the fiber properties affect the extent of spalling.

Magnusson and Hallgren (2010) studied the performance of a series of FRC beams having different concrete strengths (40-200 MPa), fiber contents and types under static and blast loading using a shock-tube. Blast loads were generated by detonating an explosive placed within the shock-tube. The tests showed that beam load capacity increased under dynamic loading when compared to static loads. However, the authors noted that dynamic loads affected failure mode in some cases, with the failure changing from flexure to shear under blast. The study noted that the use of steel fibers was effective in preventing such brittle shear failures and improved the ductility and overall blast performance of the beams. The study also found that the longer fibers were less effective when compared to the shorter fibers in the beams tested under blast loads.

Burrell et al. (2015) studied the blast performance of a series of reinforced concrete and SFRC columns under the effects of simulated blast loading using the shock-tube facility at the University of Ottawa. The columns in this study were tested under combined axial and blast loads. The study showed clear benefits associated with the use of steel fibers, which reduced the displacements recorded by the columns while also significantly reducing the amount of damage and secondary fragmentation at failure. The authors also demonstrated that dynamic-inelastic SDOF analysis can be used to predict the blast performance of SFRC columns tested under shock-tube loads.

Table 2.4: Summary of previous research on the blast behavior on SFRC structures

Study	Testing method	Specimen type	No. of Specimens	Dimensions	f_c (MPa)	FRC type	Fiber property	Fiber content (%)	Aspect Ratio (L_f/d_f)
				b x h x L t x b x L (mm)					
Lok & Xio (2000)	Live explosives	Panel	42	50 x 500 x 810 50 x 810 x 810 356 x 1200 x 1200	29- 44	SFRC	T+C, H	0.5- 1.5	33.4 - 75
Lan et al. (2005)	Live explosives	Panel	72	50 x 500 x 810 50 x 810 x 810 50 x 960 x 960 150 x 1200 x 2200 200 x 1200 x 2200 250 x 1200 x 2200 300 x 1200 x 2200	35- 43	SFRC	T+C H	0.5- 1.5	33.4 - 75
Yusof et al. (2010)	Live explosives	Panel	2	100 x 600 x 600	35- 40	SFRC	H	0.5-1.5	80
Yi et al. (2012)	Live explosives	Two-way slab	3	150 x 1000 x 1000	35- 40	RPC	S	2.0	--
Foglar et al. (2013)	Live explosives	Panel	5	300 x 1500 x 6000	30- 55	SNFRC	PP	0.5-1.0	--
Foglar et al. (2015)	Live explosives	Panel	11	300 x 1500 x 6000	46- 83	SNFRC Waste-SFRC	PP	0.5-1.0	--
Magnusson et al. (2010)	Shock tube	Beam	49	160 x 300 x 1720	40-200	SFRC	S	1-2.4	80
Burrell et al. (2015)	Shock tube	Column	8	152 x 152 x 2468	46-56	SFRC	H	0.5-1.5	55-80

2.5 Summary

This section presented a literature review related to the effect of fibers on the dynamic material properties of concrete. It also reviewed previous research which has focused on the impact and

blast performance of steel-fiber reinforced concrete (SFRC) structures. Key conclusions from the literature can be summarized below:

- Material studies on SFRC tested under high strain-rates shows that the use of fibers increases the toughness and energy absorption capacity of concrete, although some authors report a reduction in fiber efficiency under dynamic loading when comparing to static testing. In general, the amount of energy absorbed under dynamic impact loading increases with fiber content and aspect ratio, although some research shows that there may be a critical fiber content (limit of $\sim 1\%$) after which further improvements are not observed. Previous research on the effect of fiber properties shows that hooked-end fibers may be better suited for impact applications when compared to smooth fibers.
- A limited number of studies have investigated the dynamic performance of large-scale SFRC structural components under impact loads. Previous research on one-way and two-way panels shows that the use of fibers significantly enhances the impact and fragmentation resistance of slabs, with the amount of energy absorbed increasing with increased fiber content (although some studies report a reduction of fiber efficiency beyond 1% fiber content). Some limited studies also show the beneficial effects of fibers in beams tested under impact loading.
- Limited research (mostly on slabs subjected to close-in blasts) shows that SFRC improves the blast performance of concrete members, reducing damage and enhancing blast capacity. Only limited blast studies have been conducted on SFRC flexural members subjected to far-field blasts, however these studies show the fibers reduce blast damage and improve overall blast performance.

Despite existing studies, there is a need for further investigations focussing on the blast performance on SFRC beams subjected to far-field type blasts. There is a need to study whether the use of fibers can increase the shear capacity and flexural resistance of beams subjected to blast shockwaves. There is also a need to study whether the use of fibers can allow for a relaxation of steel transverse reinforcement detailing in beams. Moreover, there is a need to investigate the effect the effect of such parameters as fiber content, and fiber type on beam blast performance.

This research aims to fill these gaps in knowledge and develop further experimental data related to the effect of steel fibers on the shear and flexural performance of SRFC beams subjected to extreme blast loading.

3 Experimental program

3.1 General

This experimental program aims at studying the behaviour of steel fiber reinforced concrete (SFRC) beams subjected to simulated blast loads using the University of Ottawa Shock Tube. The experimental program involves the construction and testing of eighteen beam specimens, seven of which were tested under static load and eleven of which were subjected to simulated blast loads. This section summarizes the details regarding specimens, material properties, test setup and testing procedures.

3.2 Description of Test specimens

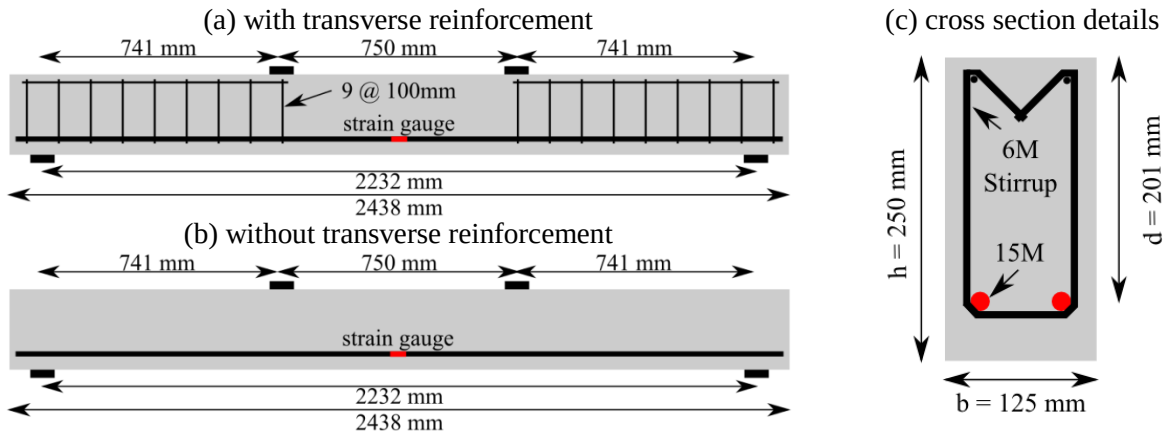
A total of eighteen beams were tested in this experimental program, with eleven beams tested under dynamic loading and seven companion beams tested under static loading. Four control beams were constructed with plain self-consolidating concrete (SCC) while the remaining fourteen SFRC beams constructed using a combination SCC and steel fibers, with fiber contents ranging from 0.5% to 1.5% by volume of concrete (40 to 120 kg/m³). All beams had a cross-sectional dimension of 125 mm x 250 mm and had longitudinal reinforcement which consisted of 2-15M bars (bar diameter = 16 mm and bar area = 200 mm²) on the tension face with a clear cover of 35 mm. Transverse reinforcement made with 6.3 mm diameter wire was provided in two of the control beams. Figure 3.1 illustrates the reinforcement layout for both types of beams and the typical cross-section of the beams reinforced with transverse steel. Nomenclature used for the beams includes concrete type, fiber content (in % by volume of concrete), fiber type and stirrup spacing if applicable. For Example, Beam SCC 1% ZP indicates a beam built using SCC and 1% of the ZP-305 steel fiber. Three types of steel fibers were used in this experimental study, including: Dramix ZP-305, Dramix 5D, Dramix BP80/30 which are abbreviated to ZP, 5D and BP respectively. Table 3.1 summarizes the design properties of the various beams included in this experimental program.

Table 3.1 Properties of test specimens

Beam I.D.	Concrete mix	Cross-Section	Transverse Reinforcement Spacing	Transverse Reinforcing Steel Stirrups	Longitudinal Reinforcing Steel Bars	Fiber Type	Fiber Content (%)	
SCC 0% 100 mm*	King SCC	150 mm x 250 mm	100 mm	6.3 mm dia. f _y = 600 Mpa	2 – 15M Bars f _y = 400 MPa	N/A	0.00	
SCC 0%*							0.00	
SCC 0.5% ZP*			N/A	N/A		ZP-305	0.5	
SCC 0.75% ZP							0.75	
SCC 1% ZP*							1.00	
SCC 1.5% ZP*							1.50	
SCC 0.5% 5D							5D	0.50
SCC 0.75% 5D								0.75
SCC 1% 5D			1.00					
SCC 1.5% 5D*			1.50					
SCC 0.75% BP*						BP-80/30	0.75	

All beams were tested under shock tube induced blast loading

* A second beam was constructed and tested under static loading



3.3 Materials

3.3.1 Reinforcing Steel

The longitudinal deformed reinforcing bars used in this experimental program were 15M bars for all the beams. Transverse stirrups were constructed out of 6.3 mm steel wire. A 600 kN universal testing machine (UTM) was used to perform standard tension tests on three samples of the 15M bars and 6.3 mm wire as shown in Figure 3.2. The average stress-strain relationships are shown in

Figure 3.3 and the average properties of both the 15M bars and 6.3 mm wire are presented in Table 3.2 and Table 3.3 respectively.

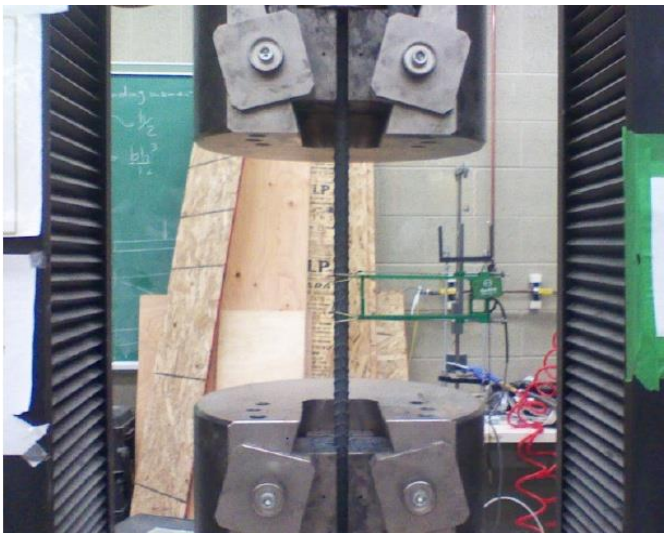


Figure 3.2 University of Ottawa UTM

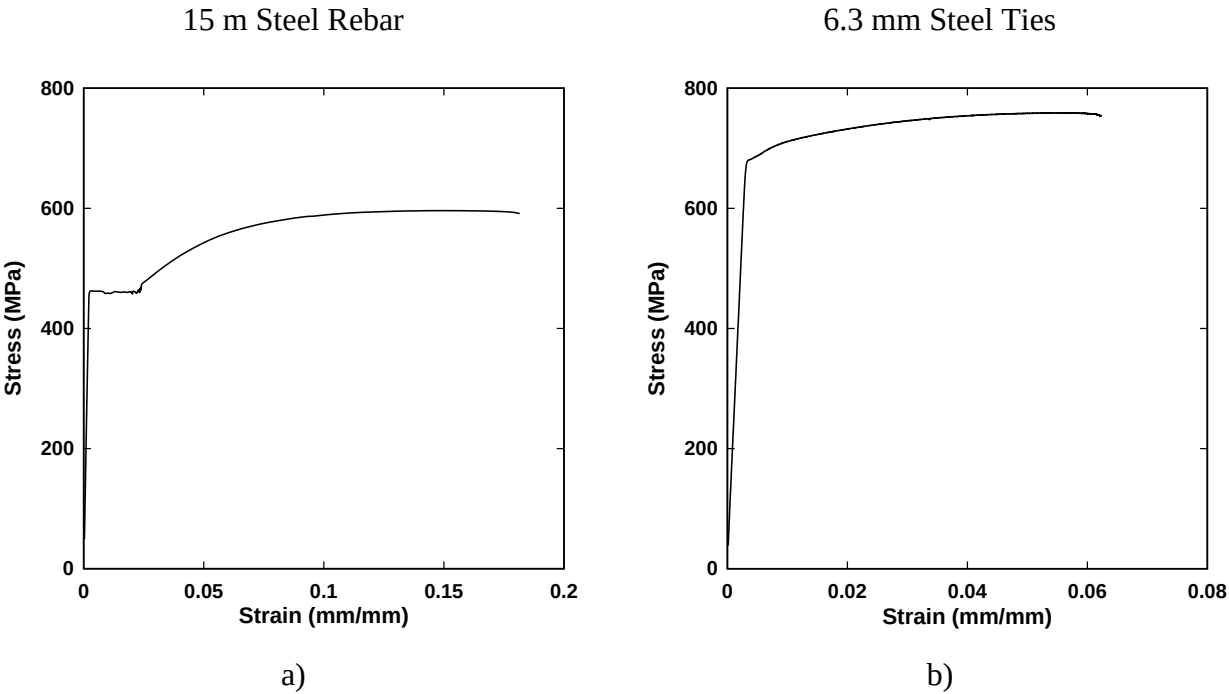


Figure 3.3 a) Average Stress-strain relationship for 15M bars, and b) stress-strain relationship for 6.3 mm diameter steel wire

Table 3.2 Average properties of 15M bars

Yield		Strain Hardening		Ultimate		Rupture	
f_y (MPa)	ϵ_y (mm/mm)	f_{sh} (MPa)	ϵ_{sh} (mm/mm)	f_u (MPa)	ϵ_u (mm/mm)	f_r (MPa)	ϵ_r (mm/mm)
459	0.0023	460	0.024	596	0.15	591	0.18

Table 3.3 Average properties of 6.3 mm non-deformed steel wire

Yield		Ultimate		Rupture	
f_y (MPa)	ϵ_y (mm/mm)	f_u (MPa)	ϵ_u (mm/mm)	f_r (MPa)	ϵ_r (mm/mm)
616	0.0033	691	0.058	685	0.066

3.3.2 Steel fibers

Three type of steel fibers were used in this experimental program. ZP-305 fibers are made from normal strength steel wire with a 1100 MPa tensile strength, have a length of 30 mm with an aspect ratio (L_f/d_f) of 55 and are hooked at the ends. BP 80/30 fibers have the same 30 mm length and hooked ends, but have a higher tensile strength of 2300 MPa and aspect-ratio of 80. Finally, the 5D fibers have a tensile strength of 2300 MPa, a length of 60 mm with an aspect ratio of 65 and an optimized hook shape (two bends in the end hooks to increase pullout strength). The three types of fibers are shown in Figure 3.4.

All steel fibers where manufactured by Bekaert Corporation (Belgium). The properties of the steel fiber used in this study are presented in Table 3.1 Different amounts of fibers were used in reinforcing the specimens in order to examine the effect of varying fiber content on blast resilience and shear strength of the beams.

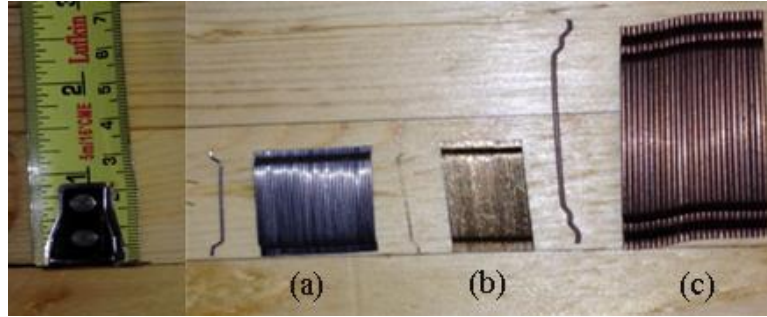


Figure 3.4 Hooked-end steel fibers considered in this study: (a) ZP305; (b) BP80/30; and (c) 5D fibers.

Table 3.4 Steel Fiber Properties

Fiber type	Length l_f (mm)	Diameter d_f (mm)	Aspect ratio l_f/d_f (mm/mm)	Tensile strength f_{fy} (MPa)	Note.
ZP-305	30	0.55	55	1100	Hooked-end Low Carbon
BP-80/30	30	0.38	79	2300	Hooked-end High Carbon
5D	60	0.93	65	2300	Improved Hooked-end High Carbon

3.3.3 Concrete

The concrete for every specimen was mixed at the University of Ottawa using a large pan mixer. One of the disadvantages associated with the use of SFRC is the loss of workability that can occur with the addition of fibers, especially when using higher content of fibers. To improve workability, a self-consolidating concrete (SCC) mix was selected for this study. The SCC mix consisted of a pre-packaged concrete with an average compressive strength of 50 MPa (manufactured by KING Packaged Materials Company). The mix contained a maximum aggregate size of 10 mm with a sand-to-aggregate ratio of 0.55 and a water-cement ratio of approximately 0.42. Furthermore, the mix contained an air-entraining admixture, a super-plasticizer and a viscosity modifying admixture (VMA). The admixtures are incorporated into the blend in the form of dry powder. Table 3.5 lists the mix properties as specified by the manufacturer. This mix was used for all eighteen beams of the experimental program; four “control” specimens did not contain any fibers, while the remaining beams were constructed using a mix of SCC and steel fibers with contents ranging from 0.5% to 1.5% fibers by volume of concrete (40 to 120 kg/m³).

Table 3.5 KING SCC composition

Component	Content
HSF Cement	500 (kg/m ³)
Water-cement ratio	0.42
Coarse Aggregate	765 (kg/m ³)
Fine Aggregate	915 (kg/m ³)
Ratio Fine/Total Aggregate	0.55
Mass Density	2300 (kg/m ³)
Air Content	7 (%)

3.4 Construction of Test Specimens

The construction of the beams was completed over five steps. These steps included bending of the steel stirrups, installation of electrical resistance strain gauges, building of the cages, building of the formwork and casting of the concrete. Both the reinforcing steel and the dry concrete mix were provided by local companies. The stirrups were constructed using a hand jig designed to provide the exact dimension needed. The 6.3 mm wire was first cut to the exact length required. Two 135° bends and two 90° bends were provided for each stirrup. The strain gauges were installed at mid-span on both longitudinal bars as seen in Figure 3.7. Assembly of the steel cages were done by first marking out stirrup spacing on both longitudinal reinforcing bars per beam. The transverse reinforcement was then placed on the steel bars and tied in place using quick tie wires. The longitudinal bars for beams without any transverse reinforcement were tied together using handmade spacers using 6.3 mm wire in order to keep the spacing even. Figure 3.5 and Figure 3.6 show typical cages with transverse reinforcement after construction. Formwork was constructed using 3/4" thick plywood and assembled in a manner such that the beams could be cast horizontally.

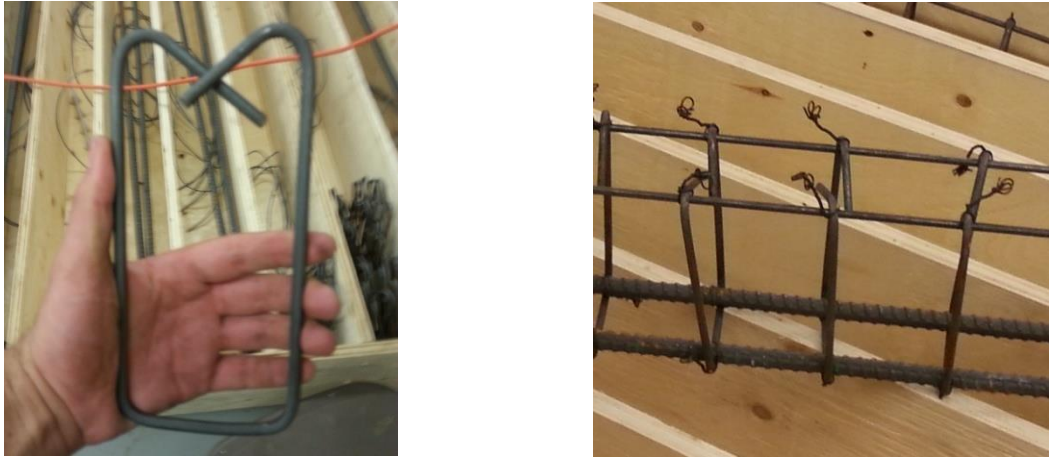


Figure 3.5 Typical stirrup (left) and spacing of stirrups (right)



Figure 3.6 typical cage with stirrups



Figure 3.7 Typical bars sowing strain gauge instrumentation

3.4.1 Casting

All the beams were casted using a large electric multi-flow pan mixer (as shown in Figure 3.8) that uses three fix paddles blade that are arranged to in such a way as to create a mixing action as the pan revolves at high velocity. A series of side scrapers ensures that material does not build up on the side wall. The pan mixer is the ideal mixer for SFRC due to its ability to force materials in a designed flow path at high velocity to achieve a consistent mix even with a high volume of steel fibers (e.g. 1-1.5%) in the mix.



Figure 3.8 Pan mixer

3.4.1.1 Mixing procedure

The SFRC mixes were prepared by adding the right amount of pre-packaged KING SCC mix in the mixer, dry mixing for 30 seconds and then adding the first half of the water over the course of a minute. The second half of the water was added gradually in four intervals, every 60 seconds. After the initial stage of the mixing, the fibers were added gradually and mixed until a uniform mix was achieved.

3.4.1.2 Casting and Curing

After mixing was complete, the concrete was poured in a wheelbarrow and then transferred from the wheelbarrow to the formwork using plastic buckets. Figure 3.9 shows the placing procedure used in this experimental program. Due to confined areas, all beams were vibrated using a 1 in. (25.4mm) diameter poker vibrator until the concrete was visibly consolidated. Once the placement and vibrating was complete, the surface of the beam was levelled using a trowel, and then covered with wet burlap and a plastic film. The beams were allowed to wet cure for seven days at which points they were removed from the formwork and air-cured until the day of testing.



Figure 3.9 Placing of the beams

3.4.1.3 Fresh state properties

The slump flow for each concrete mix in this program was measured by following the *ASTM C1611* “Slump Flow test for Self-Consolidating Concrete” Standard in order to examine the workability of the mixes. Visual inspection was used to examine the concrete for uniformity of the mix and to assess if any segregation occurred. The spread of concrete was measured in two orthogonal directions, averaged and recorded as “slump flow”. Figure 3.10 lists the measured slump flow diameters for all the mixtures. As expected, the content of fibers affected the slump-flow diameter, and consequentially workability of the concrete mixtures. In general, increasing the fiber content resulted in a loss of workability. Nonetheless, most mixes were suitably workable for typical construction, but mixes which used higher fiber contents (1% and above) were no longer self-consolidating. Aoude et al. (2009) determined that 1.5% is an upper limit for a semi-workable self-consolidating mix using the KING-SCC material. The flowability was also affected by fiber type, as recorded by the loss of slump-flow values in mixtures using steel fibers with a higher aspect ratio (l_f/d_f) such as in the case of Dramix BP 80/30 fiber. While good workability was attained by normal fibers at moderate levels (up to 1.5%), the use of 0.75% of BP 80/30 significantly reduced workability owing to the higher aspect ratio of this fiber.

			
SCC 0% 560 mm	SCC 0.5% ZP 450 mm	SCC 0.75% ZP 550 mm	SCC 1% ZP 510 mm
			
SCC 1.5% ZP 350 mm	SCC 0.5% 5D 495 mm	SCC 0.75% 5D 485 mm	SCC 1% 5D 455 mm
			
	SCC 1.5% 5D 390 mm	SCC 0.75% BP 340 mm	

Figure 3.10 Picture of slump flow test including average slump flow diameter

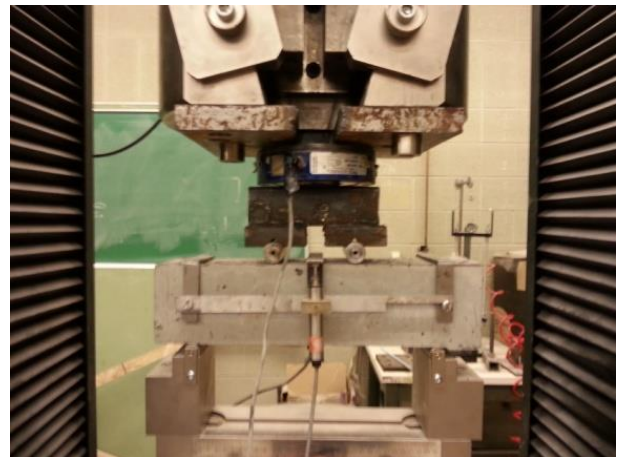
3.4.2 Hardened State of Concrete Properties

A series of concrete cylinders and flexural prisms were prepared during the mixing of the concrete, and cured in similar conditions as the beam specimens themselves. The cylinders which had a diameter of 100 mm and a height of 200 mm were cast alongside each batch to determine the compressive strength of the concrete in the beams. The average compressive strength was determined by testing a minimum of 2 cylinders using a 1000 kN cylinder testing machine at the Structures Laboratory at University of Ottawa [Figure 3.11 (a)] in accordance with CSA 23.2-14 “Test methods and standard practices for concrete” and the results are presented in Table 3.6. Additional compressive tests were carried out on companion cylinders using an LVDT setup to plot the full stress-strain curve of the material under compression. The resulting compressive stress-strain curves are shown in Figure 3.12. Four-point bending tests were used to determine the flexural toughness of SCC and SFRC batches, in accordance with ASTM C1609 standard. When batch yields were sufficient, flexural prisms were cast with dimensions of 100 mm by 100 mm by

400 mm. The prisms were subjected to third-point loading over a span of 300 mm, with displacement captured using an LVDT jig as shown in Figure 3.11 (b). The results as defined in the ASTM C1609 Standard are presented in Table 3.7. The load deflection-relationships are presented in Figure 3.13, and the figure shows that the addition of fibers improves flexural toughness, and allows the concrete to have post-cracking ductility.



(a) Cylinder testing machine



(b) Flexural beam testing machine

Figure 3.11 Testing apparatus used to asses concrete strength in this test program

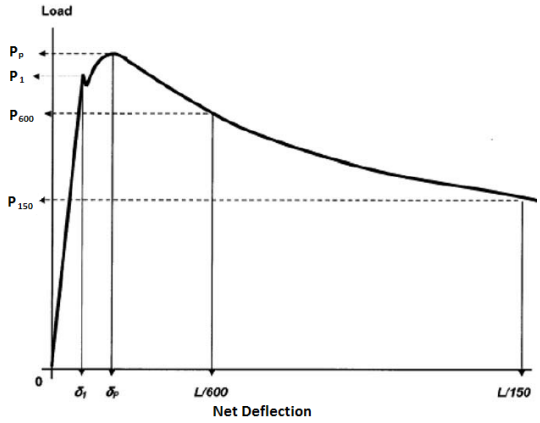
Table 3.6 Concrete Properties

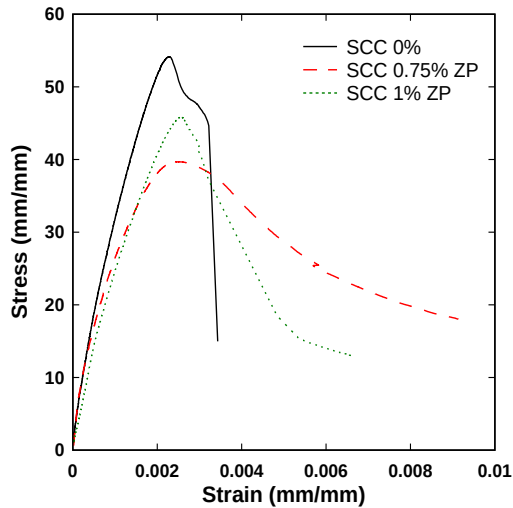
Beams	Fiber type	Fiber Content V_f (%)	Average Compressive Strength f'_c (MPa)
SCC 0%	--	0.00	47.6
SCC 0% 100mm	--	0.00	46.8
SCC 0.5% ZP	ZP-305	0.50	44.3
SCC 0.75% ZP	ZP-305	0.75	41.5
SCC 1% ZP	ZP-305	1.00	45.7
SCC 1.5% ZP	ZP-305	1.50	39.7
SCC 0.5% 5D	5D	0.50	46.3
SCC 0.75% 5D	5D	0.75	47.8
SCC 1% 5D	5D	1.00	47.9
SCC 1.5% 5D	5D	1.50	39.0
SCC 0.75% HS	BP 80/30	0.75	41.0

Table 3.7 ASTM C1609 Toughness results

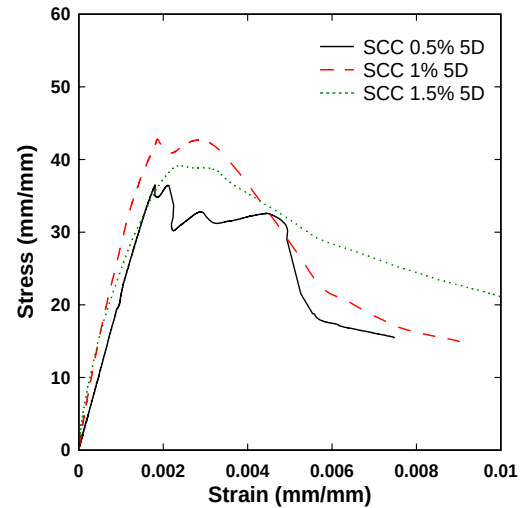
Mixture Name	P_1	δ_1	P_p	δ_p	f_1	f_p	P_{600}	f_{600}	P_{150}	f_{150}	T_{150}
SCC 0 %	25.4	--	25.4	-	--	7.63	--	--	--	--	--
SCC 0.5 % ZP	22.5	0.073	22.5	0.073	--	6.75	13.2	3.96	7.7	2.31	23.1
SCC 0.75 % ZP	19.6	0.065	19.6	0.065	--	5.88	16.7	5.03	13.38	4.01	31.0
SCC 1 % ZP	21.8	0.269	21.8	0.269	--	6.55	21.0	6.32	13.11	3.93	35.8
SCC 1.5 % ZP	24.6	0.145	24.6	0.145	--	7.40	22.9	6.87	10.95	3.28	35.2
SCC 1.5 % 5D	16.8	0.044	27.2	1.281	5.052	8.17	20.4	6.14	24.24	7.27	42.9
SCC 0.75 % BP	17.1	0.091	19.9	0.461	5.118	5.99	19.9	5.97	15.16	4.54	35.2

L = Span Length (300 mm), ($L/600 = 0.5$, $L/150 = 2$)
 P_1 = First-Peak Load (kN)
 δ_1 = Net Deflection at First-Peak Load (mm)
 P_p = Peak Load (kN)
 δ_p = Net Deflection at Peak Load (mm)
 f_1 = First-Peak Strength (kN)
 f_p = Peak Strength (MPa)
 P_{600} = Residual Load at net deflection of $L/600$ (kN)
 f_{600} = Residual Strength at net deflection of $L/600$ (MPa)
 P_{150} = Residual Load at net deflection of $L/150$ (kN)
 f_{150} = Residual Strength at net deflection of $L/150$ (MPa)
 T_{150} = Area under load vs. net deflection curve (0 to $L/150$), (kN*mm)



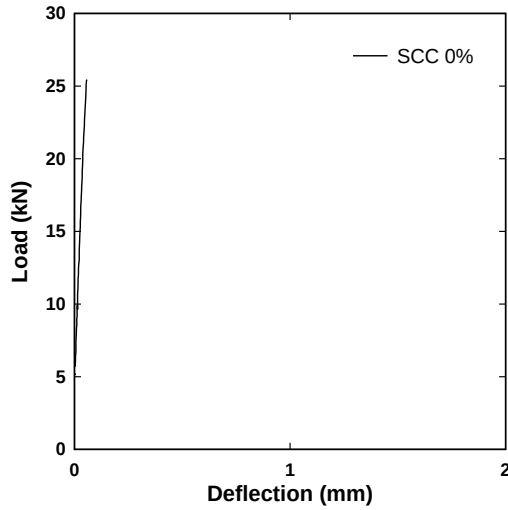


(a) Concrete cylinder compression stress-strain relationship SCC 0%, 0.75% ZP, 1% ZP

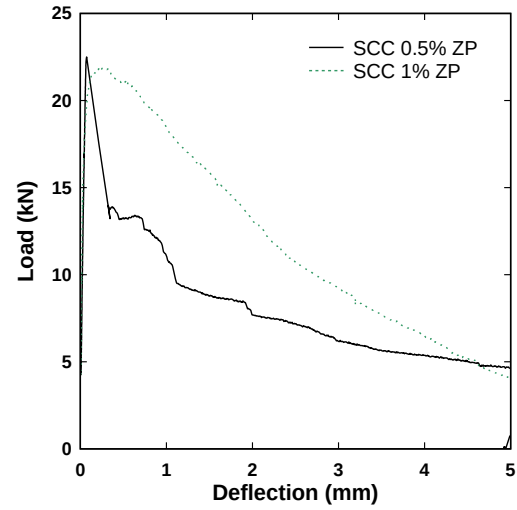


(b) Concrete cylinder compression stress-strain relationship SCC 0.5% 5D, 1% 5D and 1.5% 5D

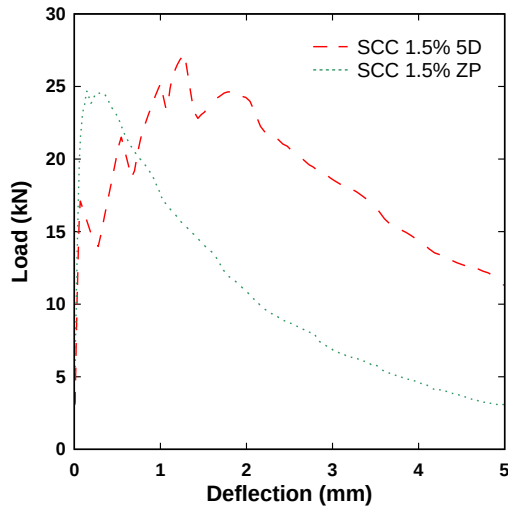
Figure 3.12 Typical concrete cylinder stress-strain curves



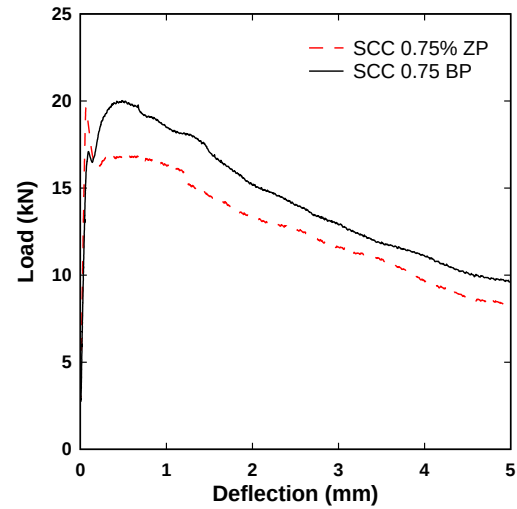
(a) Flexural beam load-deflection curve
SCC 0%



(b) Flexural beam load-deflection curve
SCC 0.5%, 1% ZP



(c) Flexural beam load-deflection curve
SCC 1.5% ZP, 1.5% 5D



(d) flexural beam load-deflection curve
SCC 0.75% ZP, 0.75% BP

Figure 3.13 Typical Load-Deflection for prisms (when specimens available)

3.5 Test procedure and instrumentation

3.5.1 Test setup

Two types of setup were used in this experimental study. One was used to conduct static tests on seven specimens and the other was used to conduct dynamic loading tests on the remaining eleven specimens. Both setups were used to test the beams under the same 4-point bending configuration.

Figure 3.14 shows a typical static test setup while Figure 3.15 shows a typical dynamic test setup using the University of Ottawa shock tube.

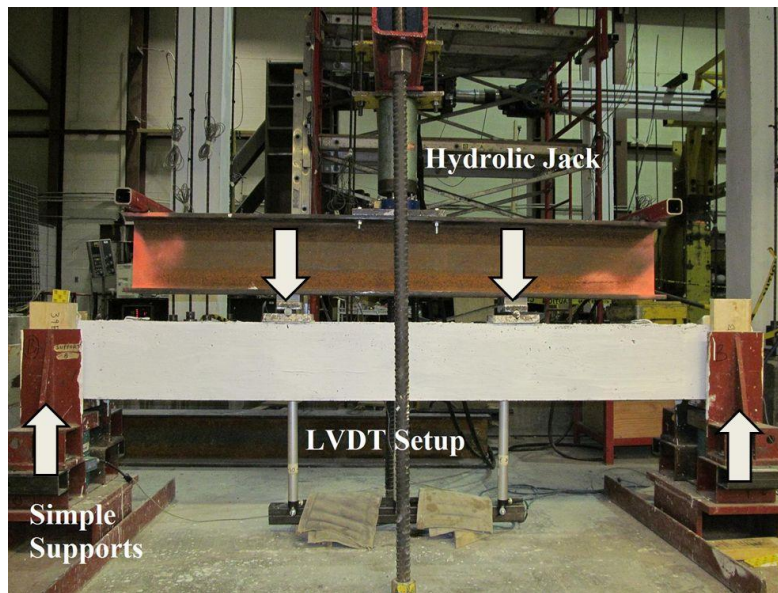


Figure 3.14 Typical Static Test Setup

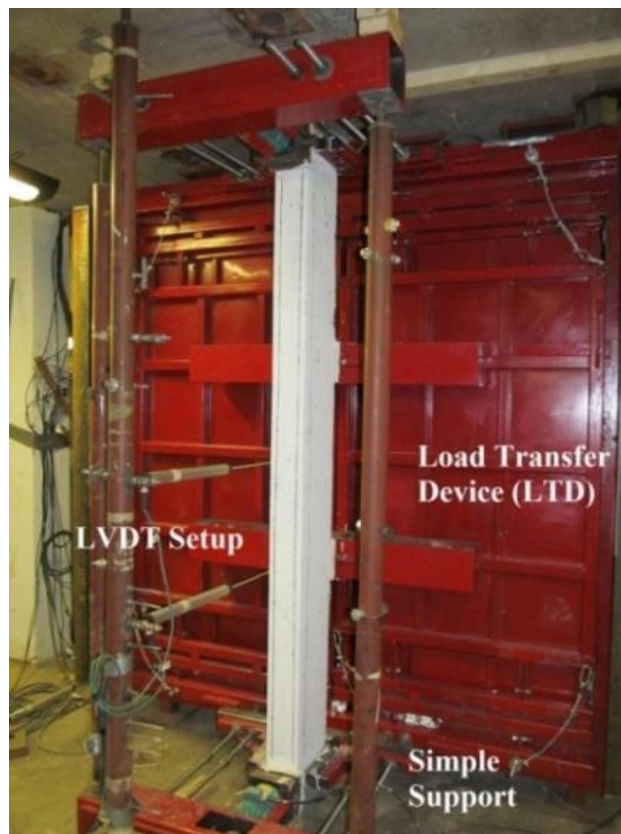


Figure 3.15 Typical Dynamic Test Setup

3.5.2 Static test setup

The beams were simply supported over a span of 2232 mm and were subjected to four-point loading with shear spans of 737 mm from the face of the supports, and a constant moment region of 750 mm. The beam rested on a series of notched 152 mm x 152 mm x 38 mm bearing plates and a roller to allow rotation of the beams at each support (the notched plates and roller setup for dynamic testing is shown in Figure 3.19 (b) and closely replicates the one used for static testing). A transfer beam was used to transfer the load from the hydraulic jack as two-point loads onto the beams. Another set of notched bearing plates and rollers were used at each point load to allow rotation at the load application points.

3.5.2.1 Instrumentation

Each beam was instrumented using two electric resistance strain gauges, located on the longitudinal bars at mid span (one strain gauge per bar). The 350 ohms linear strain gauges were 6 mm in length. Complete displacement time histories were recorded using linear variable differential transducer (LVDT) with a 300 mm stroke which were placed at $\frac{1}{2}$ (mid-span) and $\frac{1}{3}$ rd distance along the clear span of the beam (see Figure 3.16 (b)). With a clear span of 2232 mm, the LVDT's were placed at 1488mm, 1162 mm and 744 mm measured from the supports. Two load cells were used to measure the reaction loads at the supports (see Figure 3.16 (a)). A third load cell was used to measure the load acting on the transfer beam.



(a) Load cells



(b) LVDT's

Figure 3.16: Static setup: Instrumentation

3.5.2.2 Static Test procedure

All the specimens were subjected to the same loading sequence. Initially the specimens were tested under a deformation-control with an interval of 4 mm mid-span deflection. This interval represents the mid-span deflection estimated to cause the strain in longitudinal reinforcement to reach 0.001 mm/mm (half yield). At a mid-span deflection of 48 mm, the deflection interval stage was increased to 8 mm until 72 mm or failure of the beam. In some cases the beams continued to carry significant load at 72 mm; in these cases testing continued until the loading mechanism interfered with the beam, at which point the testing was stopped.

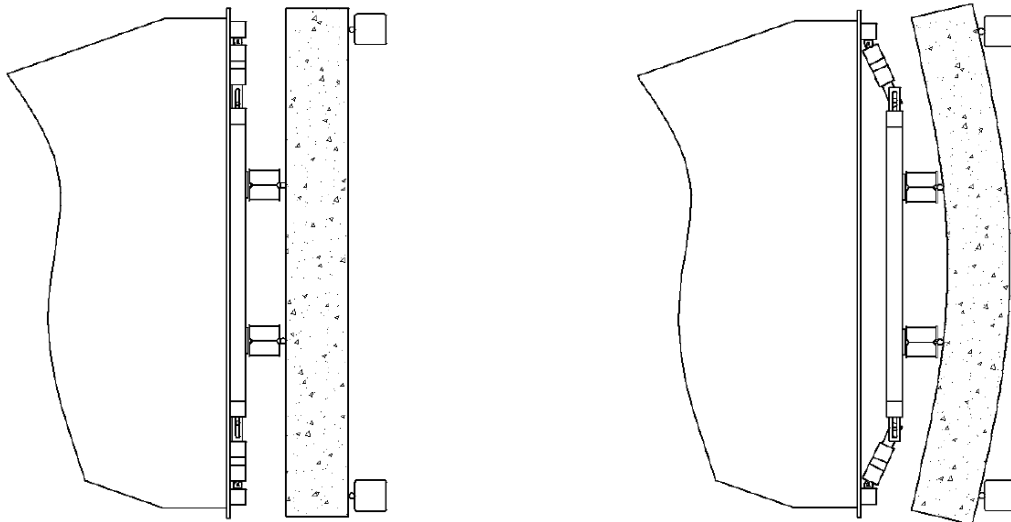
3.5.3 Dynamic test setup

3.5.3.1 Lateral Load Transferring Mechanism

In order to transfer the shockwave pressure created by the shock tube to the non-planar beams, a load transfer device (LTD) was used. In the setup used in this research program, the LTD collects the shock wave pressure and distributes it as two-point loads acting at 1/3 and 2/3 height of the span, resulting in four-point loading. The LTD consists of a series of ten panes made with light gage sheet metal and hollow steel sections, connected by sliders and bolts as seen in Figure 3.17. Five panels cover each half of the shock tube and are connected together by two W150x30 wide flange sections which then transfers the load to the specimen. The wide flange uses four stiffeners added for extra strength, one at each end and two in the middle. An HSS located at the top and the bottom of the shock tube connects the panels to the shock tube. The HSS sections are bolted to the shock tube and connected to the panels with eight hinges to allow rotation. The LTD covers the entire opening of the shock tube and weighs a total of 283.6 kg. Figure 3.18 illustrates the load transfer device before and during testing.



Figure 3.17: Photographs of the Load Transfer Device



(a) LTD configuration prior to testing

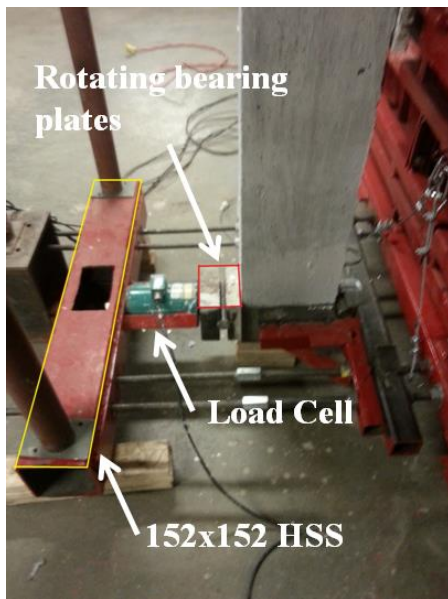
(b) LTD configuration during testing

Figure 3.18 Details of the Load Transfer Device

3.5.3.2 Supports

For all the tests, the beams were attached to the shock tube using simple supports at the top and the bottom that were intended to provide lateral restraint while still allowing the beam to rotate. Figure 3.19 (a) shows the support configuration used at the top and bottom supports. To connect the beams and measure the reactions a 152mm x 152mm HSS was bolted to the shock tube using four 15.9 mm bolts. A load cell was bolted to the HSS and a set of two steel bearing plates with v-notches and a pin was placed in between load cell and the beam to allow rotation as seen in Figure 3.19 (b). In order to keep the supports from sagging due to their own weight, shoring jacks were

provided to keep the supports at the required height as seen in Figure 3.19 (c). Blocks of wood were laid down on the floor until the bottom support was at the desired height, then the shoring jacks were inserted between the top and bottom support and adjusted until the top support was at the desired height. Wood was then inserted between the top support and the ceiling and finally the jacks were readjusted to keep everything tight during testing as shown in Figure 3.19 (c).



(a) Bottom support



(b) Bearing plate and roller



(c) Shoring jack setup

Figure 3.19 Simply Supported Lateral Restraint Setup

3.5.3.3 Instrumentation

Each beam was instrumented using two electric resistance strain gauges, both located on the longitudinal bar at mid span (one strain gauge per bar). The same type of 350 ohm 6 mm strain gauges used in the static tests were used in the dynamic tests. Complete displacement time histories were recorded using linear variable differential transducer (LVDT) with a 300 mm stroke which were placed at $\frac{1}{2}$ (mid height) and $\frac{1}{3}$ rd distance along the clear span of the beam. With a clear

span of 2232 mm, the LVDT's were place at 1162 mm and 744 mm measured at the base of the clear span (Figure 3.20). A third LVDT was connected to the base of the shock tube and the floor to record the shock tube movement during testing. Two load cells were used to measure the reaction loads at the supports. The reflected blast pressures were measured at the base and on the side of the shock tube end frame using voltage differential high resolution pressure probes with 14.5 mV/kPa sensitivity capable of reading a maximum pressure of 345 kPa (5000 mV) (Lloyd, 2010).



Figure 3.20 LVDT Setup

3.5.3.4 Data Acquisition

Two digital oscilloscopes recording at 100,000 Hz (samples per seconds) were used as the data acquisition system (DAC) during the dynamic tests. Two channels recorded strain readings, three recorded displacement, two recorded reaction forces and the last two recorded pressure. The DAC continuously measured and recorded strain, displacement and pressure in an overwriting loop until the side pressure sensor triggered the system. When the pressure at the face of the load transferring system reached the pre-set level, the system began recording the required data, and initiated the recording of the high speed camera (Lloyd, 2010). The high-speed camera was placed on the side of the beam for each test. It was triggered by the DAC and recorded the beam behavior at a frame rate of 500 frames per second.

3.5.3.5 Test Procedure and Loading program

Each beam was subjected to a series of shock-tube induced shockwaves increasing in force until failure. The chosen pressure parameters aimed at testing the beams under elastic (blast 1), yield

(blast 2) and ultimate loading condition until failure (blast 3,4,5). Figure 3.22 illustrates the strain-time history for blast 1,2 & 3 of a sample specimen. Failure was defined as either a shear failure or a full flexural failure when a support rotation of around 3.5 degrees was achieved. For all the shots, the driver length was kept constant at 1828 mm (6 ft) with the driver pressures increased until failure. The driver pressures selected were 138 kPa (20 psi), 276 kPa (40 psi), 414 kPa (60 psi), 552 kPa (80 psi) and 621 kPa (90 psi) representing Blasts 1 to 5 respectively. The blast load properties, including the average reflected pressure, reflected impulse and positive phase duration, for each test are presented in Table 3.8.

Table 3.8 Blast load properties

Blast Load	Targeted Driver Pressure	Driver Length	Average Reflected Pressure,	Average Reflected Impulse,	Average Positive Phase Duration,
	(kPa)		(kPa)	(ms)	(kPa*ms)
Blast 1	138	1828	30.5	232	14.3
Blast 2	279	1828	49.9	352	15.1
Blast 3	414	1828	62.4	475	16.1
Blast 4	552	1828	73.6	564	16.7
Blast 5	621	1828	74.4	648	18.3

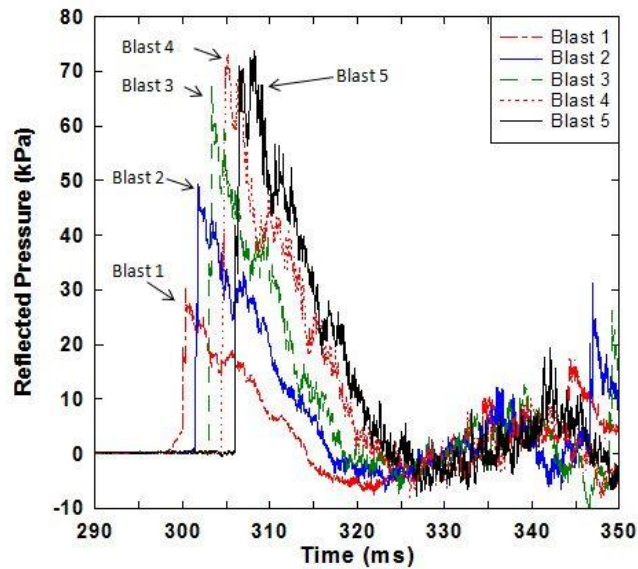


Figure 3.21 Sample pressure time histories

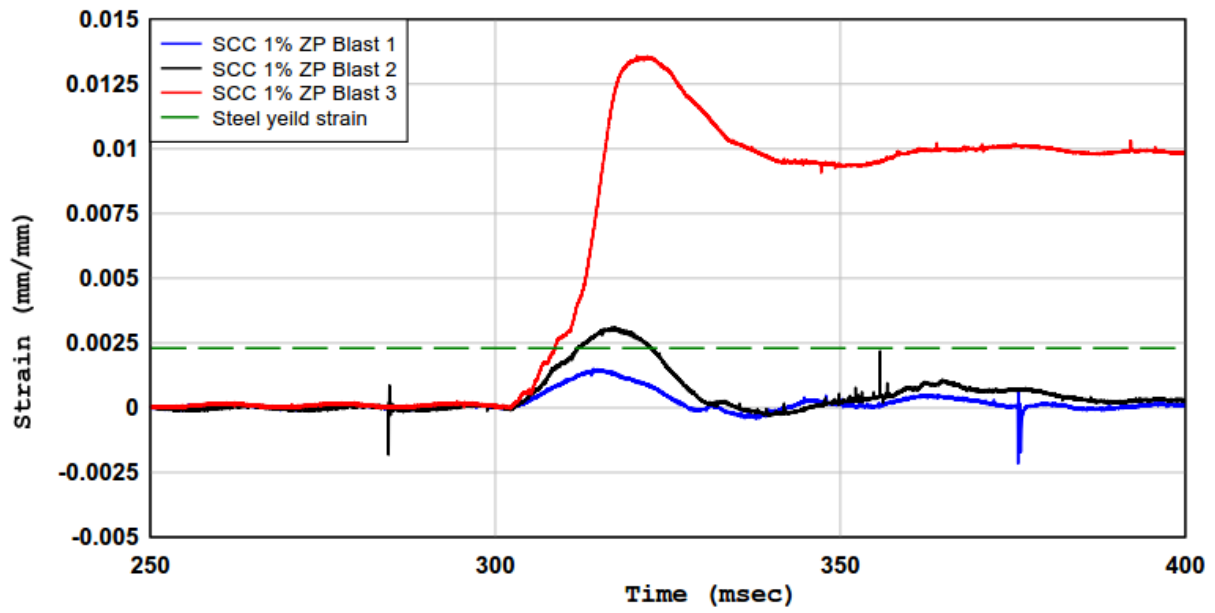


Figure 3.22 Sample strain-time history

4 Experimental Results

4.1 Static testing

This section compares the result from the seven beams tested under static loading in this experimental program. The response of these beams in terms of load-deflection response, cracking behaviour, major events during testing and failure mode will be discussed. While Section 4.1.2 presents the detailed response of each beam, the results are compared and discussed on Chapter 5.

4.1.1 Summary of results

Overall summaries of the test results for the SFRC beams under static loading are presented in Table 4.1 and Table 4.2. The tables includes parameters such as load and displacement at yield (P_y and Δ_y), initial beam stiffness (k), maximum load carrying capacity (P_{max}), displacement when the load reached 80% of the peak load (Δ_{80}) ultimate displacement when testing was stopped (Δ_{ult}), ductility, defined by Δ_{80}/Δ_y and Δ_{ult}/Δ_y , and toughness (area under the load-displacement curves up to $2\Delta_y$, $3\Delta_y$, $4\Delta_y$ and Δ_{ult}). Figure 4.1 illustrates how the parameters were determined for each test. Comparisons of these parameters in the form of bar charts are shown in Figure 4.3 and Figure 4.4 along with notes on failure modes. Table 4.3 summarises the failure mode of each specimen.

The overall test result for the SFRC beams can also be found in Figure 4.2. The graph presents the load vs. displacement plot for every specimen. The load P represents the load measured by the load cell at the transfer beam. The load at each reaction is then $P/2$. The displacement represents the mid-span displacement measured by the LVDT.

Initially the specimens were tested under a deformation-control with an interval of 4 mm mid-span deflection. This interval represents the mid-span deflection at the point where the strain in longitudinal reinforcement was 0.001 mm/mm (half yield). At 48 mm, the deflection interval stage was increased to 8 mm until 72 mm. At which point the beam was tested until the loading mechanism interfered with the beam. In this case, the beam was considered a flexural failure.

Table 4.1 Summary of static test results (1/2)

Beam	Load		Displacement			Stiffness $K \left(\frac{N}{mm} \right)$
	P_y (kN)	P_{max} (kN)	Δ_y (mm)	Δ_{80} (mm)	Δ_{ult} (mm)	
SCC 0%	--	87.6	15.0	17.1	--	5836
SCC 0% 100 mm	91.0	101.3	13.1	46.3	43.3	7733
SCC 0.5% ZP	100.2	106.4	14.5	51.9	50.3	7338
SCC 1% ZP	111.4	113.9	15.7	47.3	112.1	7255
SCC 1.5% ZP	111.0	113.9	15.9	96.0	101.0	7164
SCC 1.5% 5D	120.0	126.3	16.0	62.8	82.3	7894
SCC 0.75% BP	101.7	109.1	14.7	116.2	116.3	7422

Δ_{ult} = maximum displacement, Δ_y =displacement at yield, P_y =Load at yield, P_{max} = Maximum Load

Table 4.2 Summary of static test results (2/2)

Beam	Ductility		Toughness (kN-mm)				
	$\frac{\Delta_{80}}{\Delta_y}$	$\frac{\Delta_{ult}}{\Delta_y}$	$2\Delta_y$	$3\Delta_y$	$4\Delta_y$	Δ_{ult}	Δ_{80}
SCC 0%	--	--	--	--	--	--	--
SCC 0% 100 mm	3.53	3.31	1814	3146	--	3619	3619
SCC 0.5% ZP	3.58	3.47	2258	3728	--	4406	4517
SCC 1% ZP	3.01	7.14	2615	4176	5492	8541	4240
SCC 1.5% ZP	6.04	6.35	2659	4461	6182	9699	9172
SCC 1.5% 5D	3.93	5.14	3025	4891	6499	7309	6347
SCC 0.75% BP	7.90	7.91	2322	3916	5437	10909	10728

Table 4.3: Summary of failure mode

Beam	Failure Type
SCC 0%	Shear
SCC 0% 100mm	Flexure: Concrete crushing; steel yielding
SCC 0.5% ZP	Flexure: Concrete crushing with fiber pullout; steel yielding
SCC 1% ZP	Flexure: Concrete crushing with fiber pullout; steel yielding
SCC 1.5% ZP	Flexure: Concrete crushing with fiber pullout; steel yielding
SCC 1.5% 5D	Flexure: Concrete crushing with fiber pullout; steel yielding
SCC 0.75% BP	Flexure: Concrete crushing with fiber pullout; steel yielding

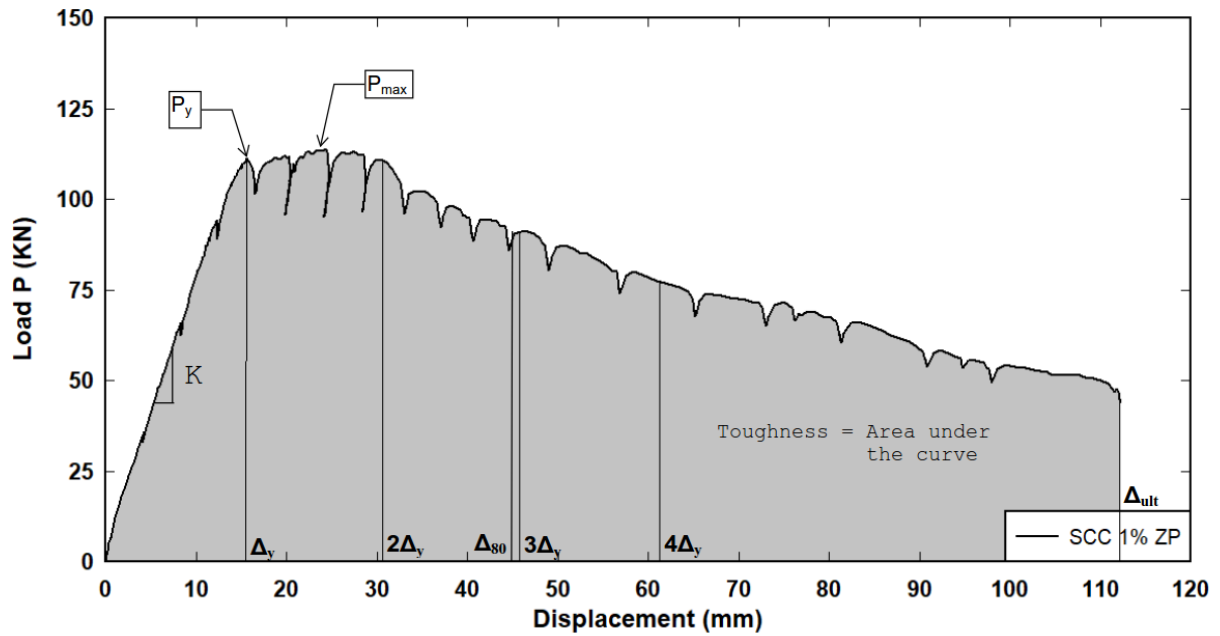


Figure 4.1: Static results: definition of load-deflection parameters

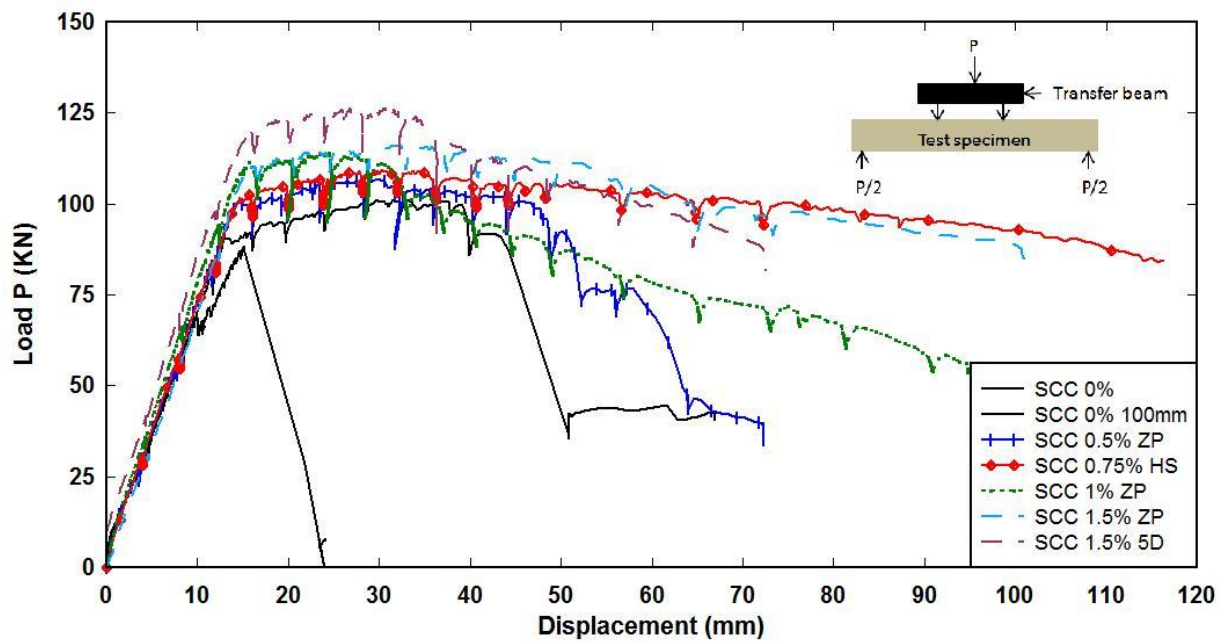


Figure 4.2 Load vs. Displacement curves for all beams

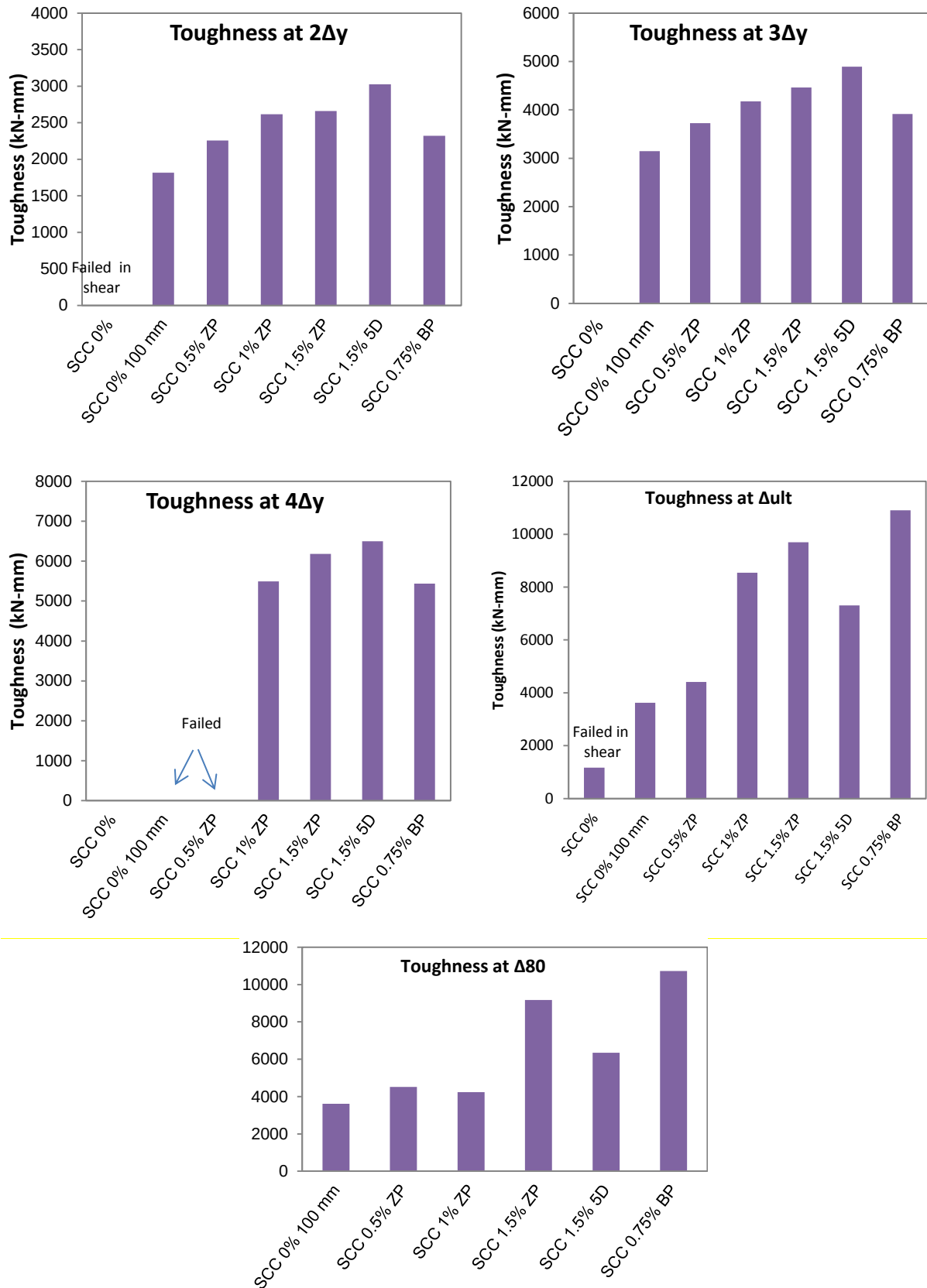


Figure 4.3 Toughness for each beam up to $2\Delta_y$, $3\Delta_y$, $4\Delta_y$, Δ_{ult} and Δ_{80}

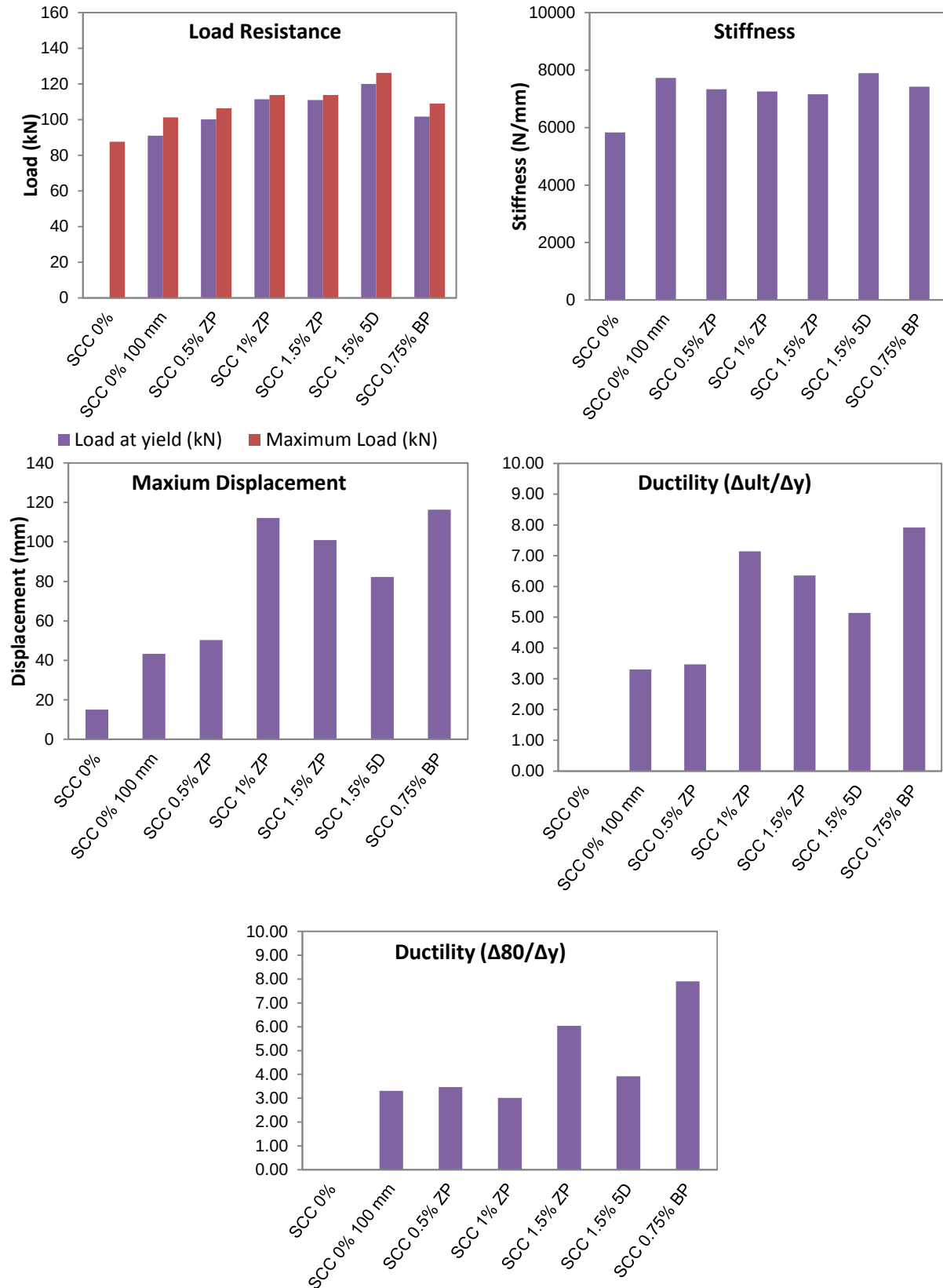


Figure 4.4 Comparative results resistance loads and displacements for each beam

4.1.2 SCC 0% 100mm

This beam is the first of two “control specimens” built with plain SCC (without fibers) and conventional transverse reinforcement spaced at 100 mm in the shear spans. It serves as a baseline for comparison with the other fiber-reinforced concrete beams in the study.

The first hairline crack in the form of flexural crack occurred at an applied load of 24 kN in the center of the beam on the tension side. The first shear cracks appeared on both sides of the beams at an applied load of 79 kN. Crushing was first observed near the east point load within the constant moment region of the beam at an applied load of 96 kN. The peak applied load recorded during testing was 101 kN and shortly thereafter, substantial crushing occurred and the test was ended when the applied load dropped to 36 kN. Figure 4.5 (a) shows a plot of the load that was applied to the specimen versus mid-span deflection. The mid-span deflection recorded before the rapid degradation of the crushing zone was 48 mm. Figure 4.5 (b) shows a plot of the crack widths versus load. The maximum shear crack width observed was 0.3 mm and the flexural crack width increased over 2 mm at an applied load of 95 kN. Figure 4.6 includes photographs detailing the state of the beam at various load stages

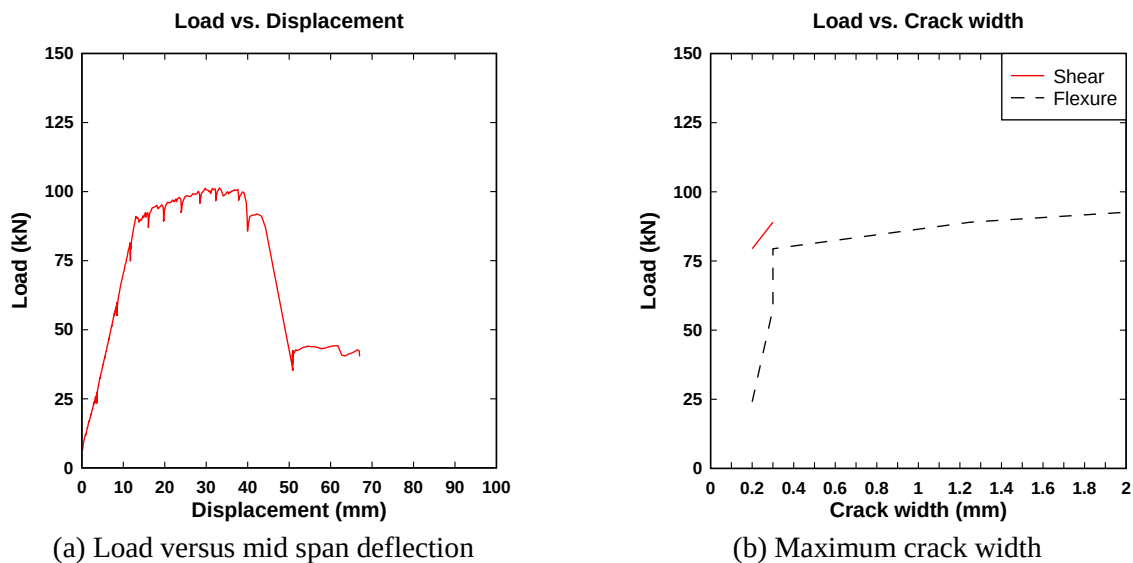


Figure 4.5 Experimental results for Beam SCC 0% 100 mm

Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	24	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	79	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	95	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	96	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L10	36	53
		

Figure 4.6 Beam SCC 0% 100 mm during various load stages of static testing

4.1.3 SCC 0 %

This beam is the second of two “control specimens” in the test series. As with the previous specimen, the beam was built with plain SCC, but was designed without conventional transverse reinforcement. It serves as a baseline of comparison with the other fiber-reinforced beams in this experimental test series, which were also built without transverse reinforcement.

The first hairline crack in the form of flexural crack occurred at an applied load of 30 kN in the center of the beam on the tension side. The first shear crack appeared on both sides of the beam at an applied load of 66 kN. Before the next load stage, the beam failed in shear with the formation of a diagonal shear crack on the west side of the beam. A Maximum applied load of 88 kN and a displacement of 15 mm was measured immediately before failure. Figure 4.7 (a) shows a plot of

the total load that was applied versus mid-span deflection. Figure 4.7 (b) shows a plot of the crack widths versus load. The maximum flexural crack width measured was 0.5 mm at a load of 88 kN. Figure 4.8 include photographs detailing the state of the beam at various load stages

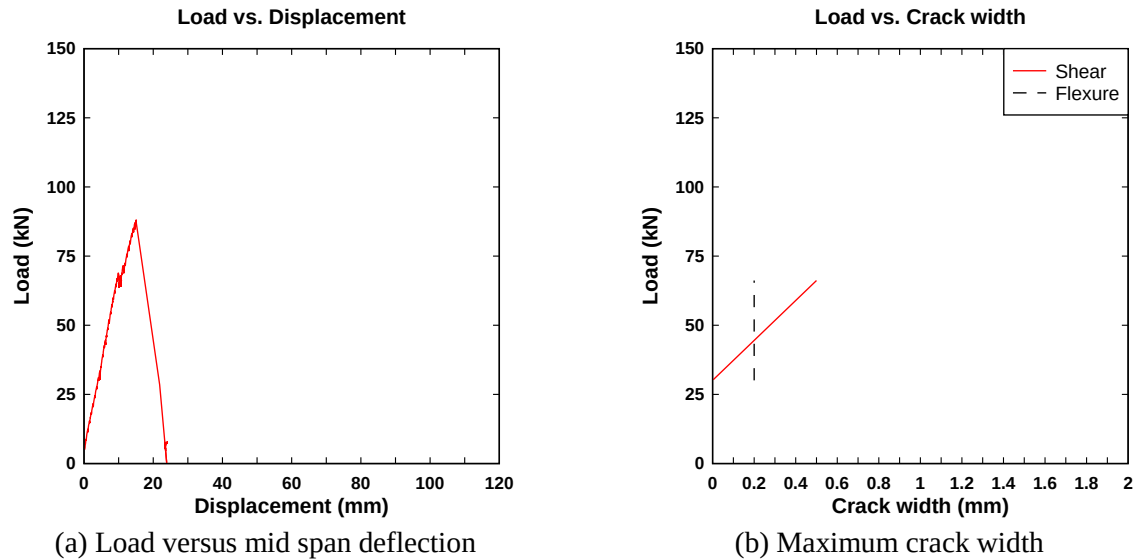


Figure 4.7 Experimental results for Beam SCC 0%

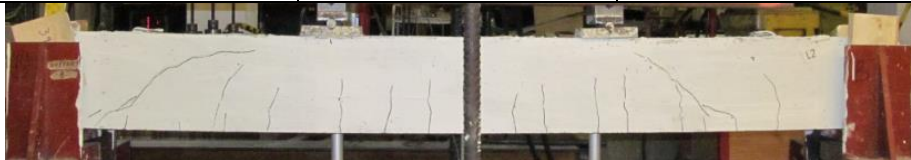
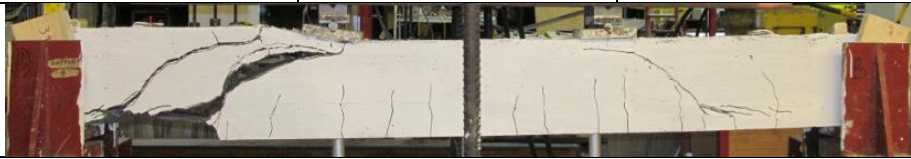
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	30	5
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L2	66	9
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	0	24
		

Figure 4.8 Beam SCC 0% during various load stages of static testing

4.1.4 SCC 0.5% ZP

This beam is the first of the SFRC specimens tested to study the effect of combined use of SCC and steel fibers on beam performance. It contained 0.5% (40 kg/m^3) fiber content by volume of the normal strength ZP fiber. It was constructed to have identical geometrical properties as the SCC 0% control beam.

The first hairline crack occurred at an applied load of 28 kN in the center of the beam on the tension side. The first shear cracks appeared on both side of the beams at an applied load of 83 kN. Crushing was first observed near the east point load, within the constant moment region of the beam, at an applied load of 101 kN (30mm mid-span deflection). The test was stopped at a mid-span deflection of 72 mm when the applied load dropped to 36 kN. Figure 4.9 (a) shows a plot of the total load applied versus mid-span deflection. A peak applied load of 106 kN was recorded. The mid-span deflection recorded before the rapid degradation of the crushing zone was 56 mm. Figure 4.9 (b) illustrates the crack widths versus load. The maximum shear crack width observed was 0.5 mm and the flexural crack width increased over 2 mm at a beam load of 101 kN. Figure 4.10 include photographs detailing the state of the beam at various load stages.

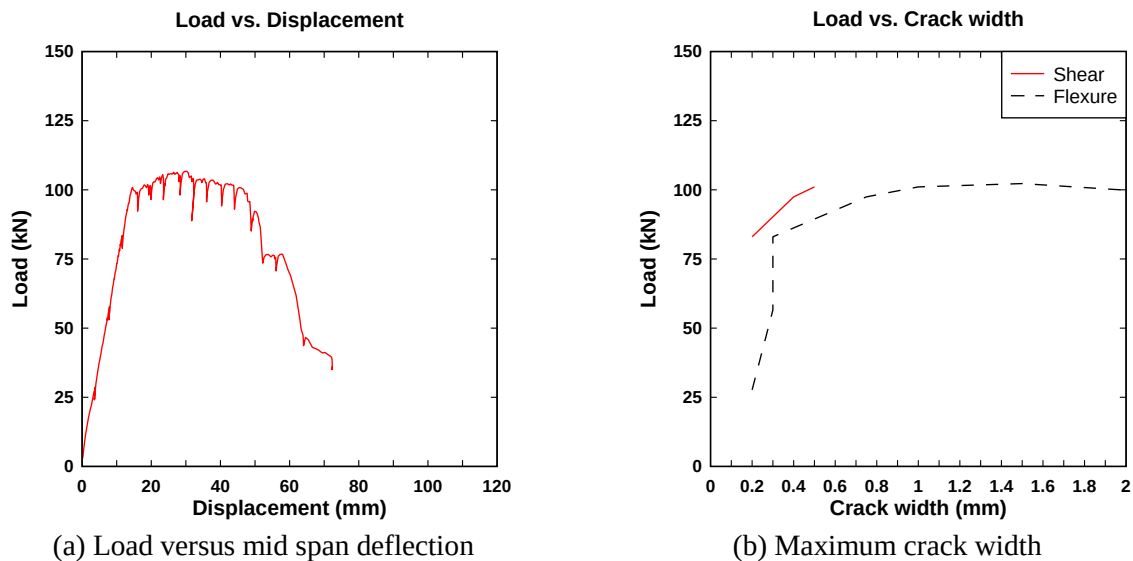


Figure 4.9 Experimental results for Beam SCC 0.5% ZP

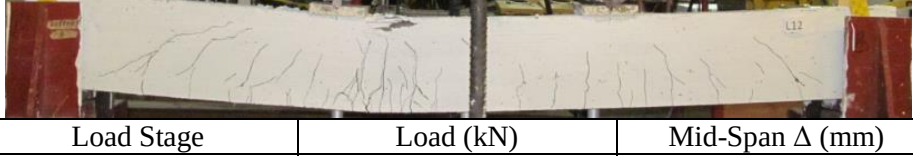
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	28	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	83	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	103	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	101	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L12	95	54
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L15	36	72
		

Figure 4.10 Beam SCC 0.5% ZP during various load stages of static testing

4.1.5 SCC 1% ZP

This beam is the second of the SFRC specimens tested to study the effect of combined use of SCC and steel fibers on beam performance. It has the same properties of the previous specimen with the exception of the fiber content which was increased to 1% (80 kg/m^3).

The first hairline crack in the tension side occurred at an applied load of 39 kN. The first shear cracks appeared on both side of the beams at an applied load of 94 kN. A peak load of 114 kN was recorded at a deflection of 28 mm, right before crushing was first observed near the east point load and located within the constant moment region. After load stage 15 ($\Delta = 72 \text{ mm}$), the test was continued until the mid-span deflection reached 112 mm at which point the test was stopped. The recorded load at the end of the test was 44 kN. Figure 4.11 (a) shows the total load that applied to the specimen versus mid-span deflection. The mid-span deflection recorded before the loss of strength due to the degradation of the crushing zone was 30 mm. Figure 4.11 (b) shows a plot of the crack widths versus load. The maximum shear crack width observed was 0.3 mm and the flexural crack width increased to over 2 mm at an applied load of 111 kN and a mid-span deflection of 28mm. Figure 4.12 includes photographs detailing the state of the beam at various load stage.

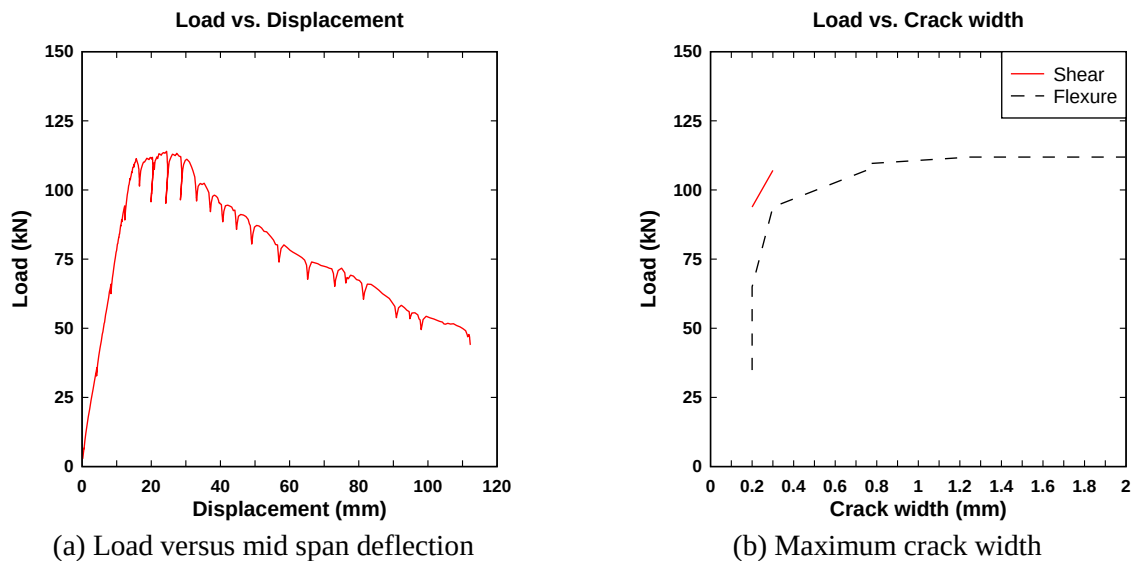


Figure 4.11 Experimental results for Beam SCC 1% ZP

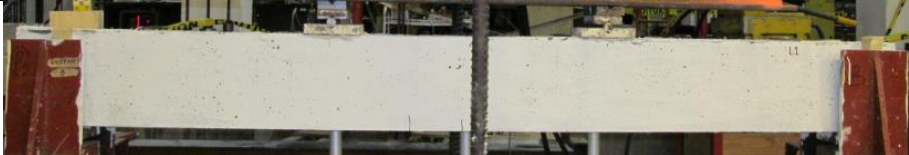
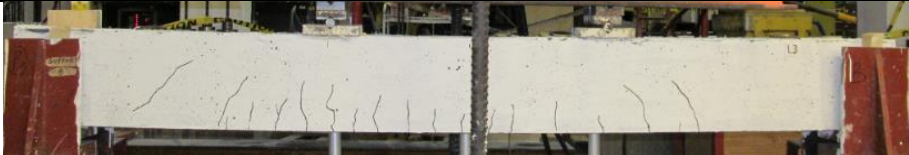
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	35	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	94	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	112	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	100	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L12	87	54
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L15	70	72
		

Figure 4.12 Beam SCC 1% ZP during various load stages of static testing

4.1.6 SCC 1.5% ZP

This beam is the third of the SFRC specimens with ZP fibers tested in this study. It contained 1.5 % (120 kg/m³) of the normal strength ZP fiber. It was constructed to have identical properties as the previous three beams.

The first hairline crack, in the form of flexural crack, occurred on the tension side at an applied load of 31.3 kN near the right point load. The first shear cracks appeared on the right side of the beams at an applied load of 88 kN. Crushing was first observed near the east point load within the constant moment region of the beam at an applied load of 113 kN. After load stage 15 ($\Delta = 72$ mm), the test was continued until the transfer beam began to interfere with the beam specimen, at which point the testing was stopped. The mid-span deflection and peak load recorded at the end of the test was 100 mm and 89 kN respectively. Figure 4.13 (a) shows the total load applied versus mid-span deflection. The maximum applied load measured during testing was 115 kN and the mid-span deflection recorded before the loss of strength due to the degradation of the crushing zone was 51 mm. Figure 4.13 (b) shows a plot of the crack widths versus load. The maximum shear crack width observed was 0.75 mm and the flexural crack width increased over 2 mm at an applied load of 112 kN. Figure 4.14 includes photographs detailing the state of the beam at various load stage.

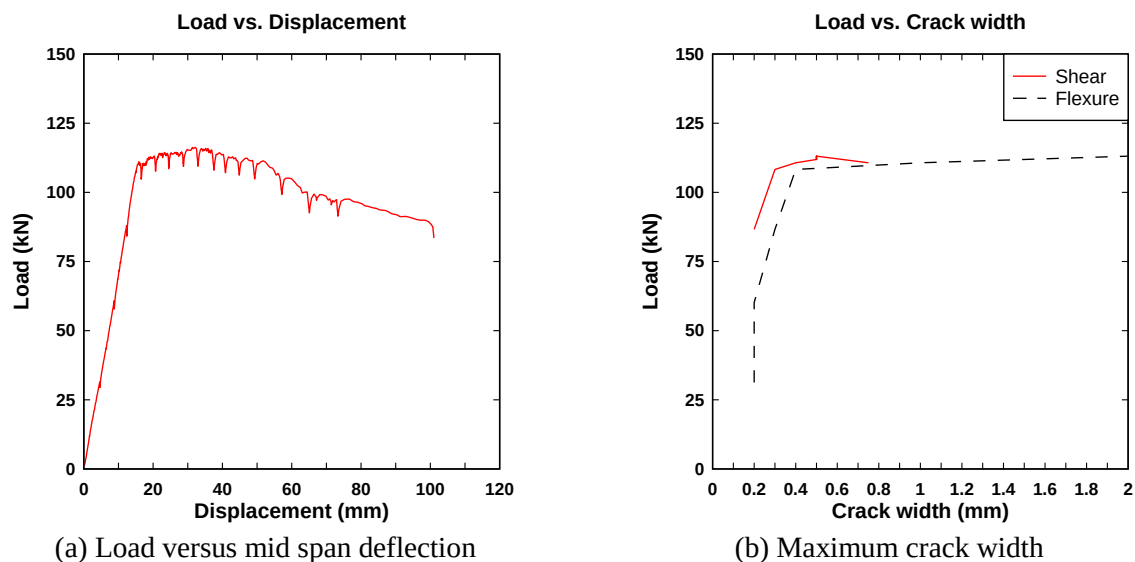


Figure 4.13 Experimental results for Beam SCC 1.5% ZP

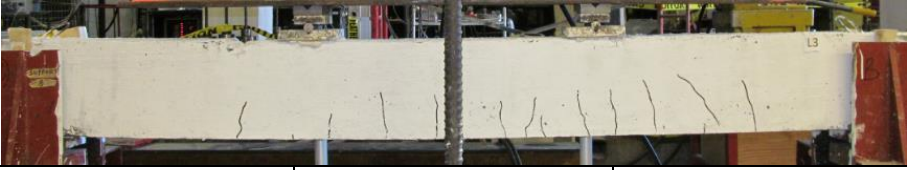
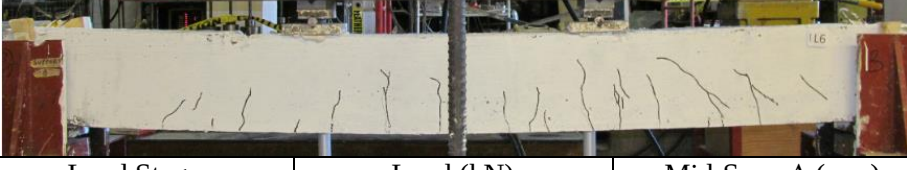
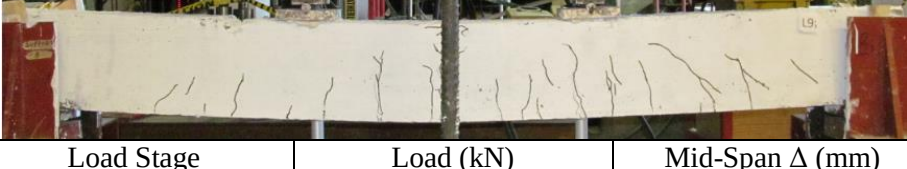
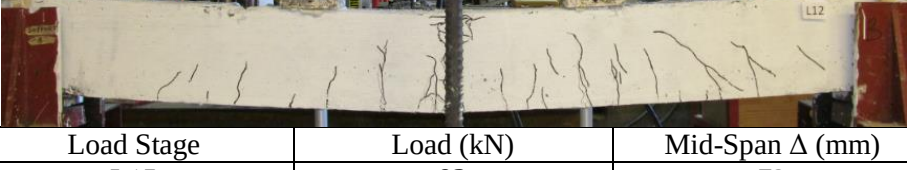
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	31	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	87	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	112	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	113	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L12	108	54
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L15	93	72
		

Figure 4.14 Beam SCC 1.5% ZP during various load stages of static testing

4.1.7 SCC 1.5% 5D

This SFRC beam was built to study the effect of steel fiber type. It contained 1.5 % (120 kg/m³) of the high strength 5D fibers. Other details were identical to the companion beam in the ZP series.

The first hairline occurred at an applied load of 41 kN near the right point load on the tension side. The first shear cracks appeared on the right side of the beams at an applied load of 70 kN. Crushing was first observed at a load of 123KN near the east point load within the constant moment region of the beam. After load stage 15 ($\Delta = 72$ mm), the test was continued until the mid-span deflection reached 103 mm, at which point the test was stopped. The final recorded load was 88KN. Figure 4.15 (a) shows a plot of the total load that was applied to the specimen versus mid-span deflection. The maximum applied load measured was 126.5 KN and a mid-span deflection recorded before the loss of strength due to the initiation of crushing and degradation of the crushing zone was 34 mm. Figure 4.15 Figure 4.16(b) shows a plot of the crack widths versus load. The maximum shear crack width observed was 1.25 mm and the flexural crack width increased over 2 mm at an applied load of 123kN and a mis-span deflection of 24 mm. Figure 4.16 includes photographs detailing the state of the beam at various load stages.

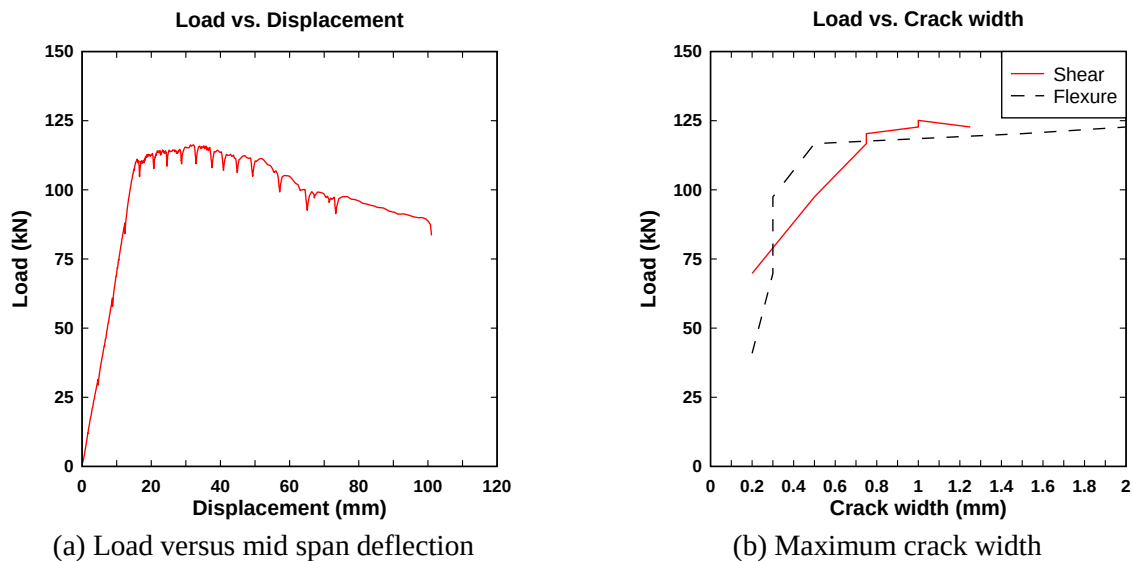


Figure 4.15 Experimental results for Beam SCC 1.5% 5D

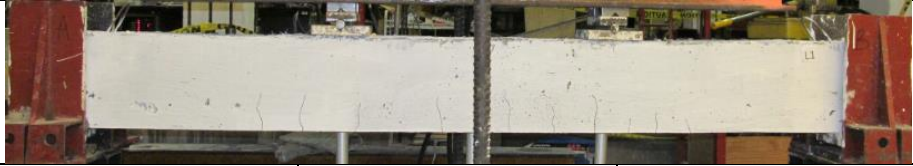
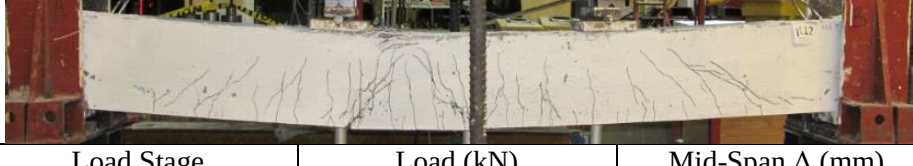
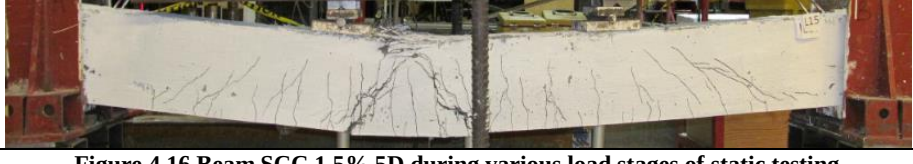
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	41	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	97	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	120	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	114	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L12	105	54
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L15	85	72
		

Figure 4.16 Beam SCC 1.5% 5D during various load stages of static testing

4.1.7.1 SCC 0.75% BP

This beam was the second of the SFRC specimens tested to study the effect of steel fiber type. It has a fiber content of 0.75 % (60 kg/m^3) of the high strength BP80/30 fibers.

Crushing was first observed near the west (right) point load within the constant moment region of the beam. An applied load of 107kN and a mid-span deflection of 33 mm was recorded. After load stage 15 ($\Delta = 72 \text{ mm}$), the test was continued until the mid-span deflection reached 116 mm. When the testing was stopped, the recorded load was 84.5 KN. Figure 4.17 (a) shows a plot of the total load that was applied to the specimen versus mid-span deflection. The maximum applied load measured during testing was 108 KN. After crushing was observed, the applied load gradually dropped, but not in a significant way. Figure 4.17 (b) shows a plot of the crack widths versus load. The first hairline crack in the form of flexural crack occurred at an applied load of 30 KN near the right point load on the tension side. The first shear cracks appeared on both side of the beams at an applied load of 84 kN. The maximum shear crack width observed was 1mm and the flexural crack width increased over 2 mm at an applied load of 102kN and a deflection of 40 mm. Figure 4.18 includes photographs detailing the state of the beam at various load stages.

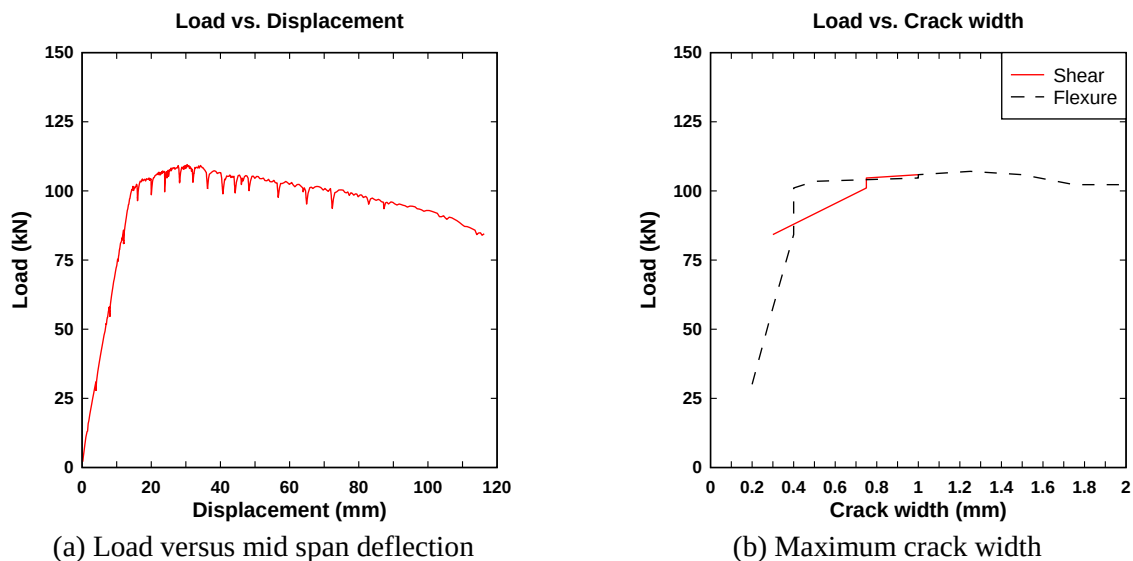


Figure 4.17 Experimental results for Beam SCC 0.75% BP

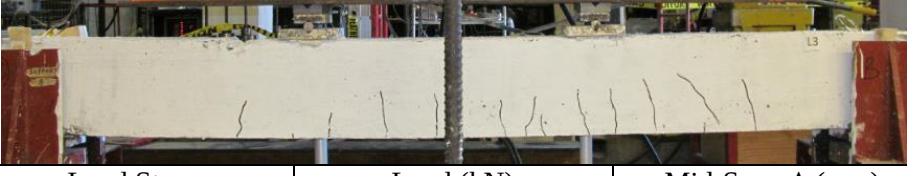
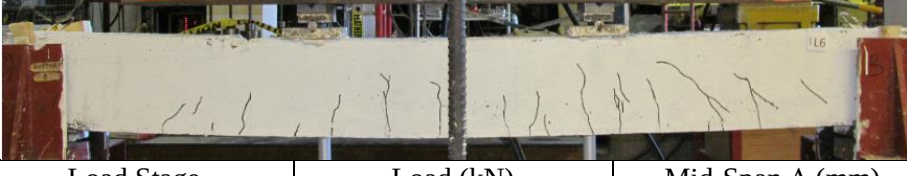
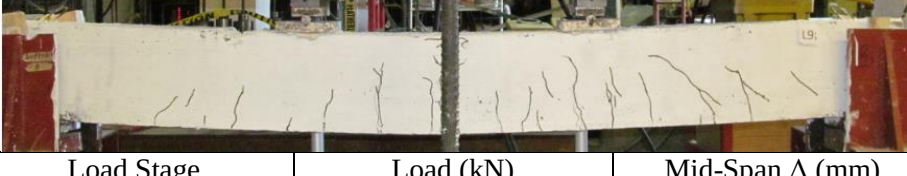
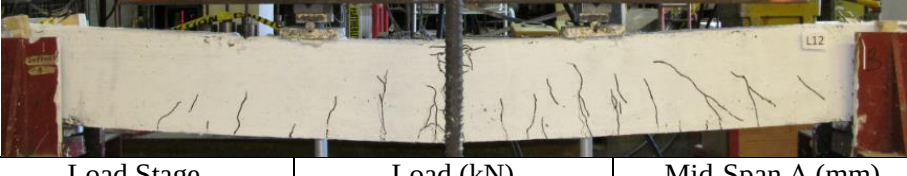
Load Stage	Load (kN)	Mid-Span Δ (mm)
L1	30	4
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L3	84	12
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L6	105	24
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L9	106	40
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L12	102	54
		
Load Stage	Load (kN)	Mid-Span Δ (mm)
L15	96	72
		

Figure 4.18 Beam SCC 0.75% BP during various load stages of static testing

4.2 Dynamic Test Series

This section presents the results from the eleven beams tested under shock tube induced blast loading. The response of these beams in terms of pressure-impulse time history, pressure-displacement history, maximum and residual displacements, strains in the reinforcing steel, crack propagation, damage and failure mode will be presented. Section 4.2 presents an overall summary for all the tests while section 4.3 summarizes the response of individual beams

4.2.1 Summary of results

Overall summaries of the test results for the beams tested under shock tube loading are presented in Table 4.4 and Table 4.5. The table reports the shockwave properties for each test, including the peak reflected pressure (P_r), total reflected impulse over the positive phase n (I_r) and the positive phase duration (t_d), along with the response of each beam including the maximum (D_{max}) and residual (D_{max}) displacement measured at mid-span, as well as the maximum support rotations (Θ_{max}). The maximum and residual mid-span displacements for each blast tests are summarized in Figure 4.19 through Figure 4.22 along with notes on particular failure modes.

Four blasts were typically used to test the beams. Blast 1 was selected to keep the beam within the elastic range and Blast 2 to bring the reinforcement at the yield strain. Finally Blast 3 and Blast 4 were selected to test the beam in the plastic region until failure. Only one beam required a fifth blast to cause failure.

Pressure values listed in Table 4.4 and Table 4.5 were those acting on the load transfer device, as recorded by pressure transducers on the interior of the shock tube expansion section. Impulse values presented in the tables are the integral of the recorded pressure-time histories of the positive pressure phase. These impulse values were obtained by calculating the area under the positive phase of the pressure-time curve using the trapezoidal method using software *D-plot*.

Note, that the displacement and rotation values reported in the tables are not cumulative since the LVDTs were re-zeroed following each blast test. The cumulative values for residual displacement are reported in section 4.3.

The beam strain gauges were also zeroed prior to each test. The total strain (ϵ_{tot}), reported in parentheses) in the following section is the sum of the recorded maximum strains and the residual strain from the previous test.

Table 4.4 Summary of steel fiber dynamic test series (Control and ZP fiber)

Beam	Blast #	Shockwave Properties			Maximum Mid-Span Displacement	Residual Mid-Span Displacement	Calculated Support Rotation
		P_r	t_d	I_r	D_{max}	D_{res}	Θ_{max}
		(kPa)	(msec)	(kPa*msec)	(mm)	(mm)	(°)
SCC 0%	Blast 1	31.3	14.41	235	11.5	1.1	0.59
	Blast 2	50.4	15.4	359	23.9	11.9	--
SCC 0% 100mm	Blast 1	27.3	14.04	224	11.6	0.8	0.60
	Blast 2	61.1	15.46	348	22.8	4.5	1.17
	Blast 3	72.7	16.03	485	41.5	20.3	2.13
	Blast 4	91.8	16.19	570	83.7	54.2	4.29
SCC 0.5% ZP	Blast 1	30.9	14.38	236	11.6	1.1	0.60
	Blast 2	48.3	15.46	369	23.9	2.2	1.23
	Blast 3	58.2	16.6	487	52.4	19.1	2.69
	Blast 4	69.2	16.81	607	116.4	83.3	--
SCC 0.75% ZP	Blast 1	30.8	14.61	228	12.1	1.4	0.62
	Blast 2	49.9	15.69	369	22.4	3.2	1.15
	Blast 3	61.0	16.03	527	40.5	28.8	--
SCC 1% ZP	Blast 1	35.0	13.95	214	9.1	0	0.47
	Blast 2	56.2	15.18	345	16.9	1.6	0.87
	Blast 3	68.2	16.31	517	36.2	12.1	1.38
	Blast 4	75.3	16.88	600	65.5	26.8	3.36
SCC 1.5% ZP	Blast 1	29.5	14.61	242	9.9	0.6	0.51
	Blast 2	41.2	14.61	315	16.3	1.5	0.84
	Blast 3	59.4	16.03	427	36.9	12.1	1.89
	Blast 4	74.2	16.6	552	94.8	57.4	4.86

Table 4.5 Summary of steel fiber dynamic test series (BP and 5D fiber)

Beam	Blast #	Shockwave Properties			Maximum Mid-Span Displacement	Residual Mid-Span Displacement	Calculated Support Rotation
		P_r	t_d	I_r	D_{max}	D_{res}	Θ_{max}
		(kPa)	(msec)	(kPa*msec)	(mm)	(mm)	(°)
SCC 0.75% BP	Blast 1	20.9	14.32	200	9.9	1.0	0.51
	Blast 2	42.3	15.75	325	20.4	2.2	1.05
	Blast 3	54.5	16.47	485	40.5	14.5	2.08
	Blast 4	69.9	16.85	569	68.1	36.2	3.49
SCC 0.5% 5D	Blast 1	36.1	14.13	231	10.4	0.0	0.53
	Blast 2	52.0	15.74	374	22.3	2.2	1.14
	Blast 3	62.5	16.76	491	39.9	16.2	2.05
	Blast 4	71.4	16.75	584	71.2	45.1	--
SCC 0.75% 5D	Blast 1	31.3	14.37	235	10.3	0.0	0.53
	Blast 2	46.4	12.55	294	19.9	2.7	1.02
	Blast 3	48.17	15.71	381	37.9	17.9	1.95
	Blast 4	63.6	15.45	461	77.9	48.9	3.99
SCC 1% 5D	Blast 1	30.1	14.2	253	10.2	0.0	0.52
	Blast 2	52.5	15.18	378	21.2	2.2	1.09
	Blast 3	68.4	15.17	469	33.9	11.5	1.74
	Blast 4	73.2	17.81	570	53.8	23.6	2.76
	Blast 5	74.4	18.32	648	101	48.7	5.17
SCC 1.5% 5D	Blast 1	32.4	14.37	254	10.5	0.8	0.54
	Blast 2	49.0	15.18	399	18.2	1.0	0.93
	Blast 3	71.1	15.70	482	35.6	22.5	--

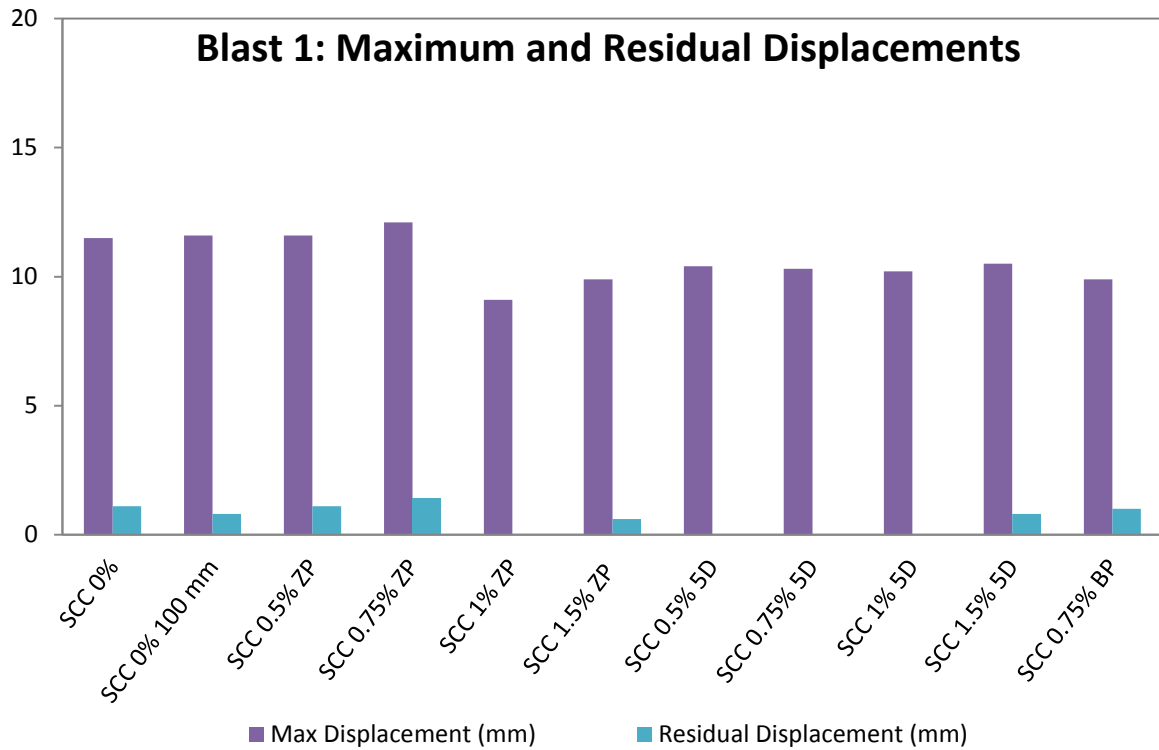


Figure 4.19: Maximum and Residual Displacements for Blast 1

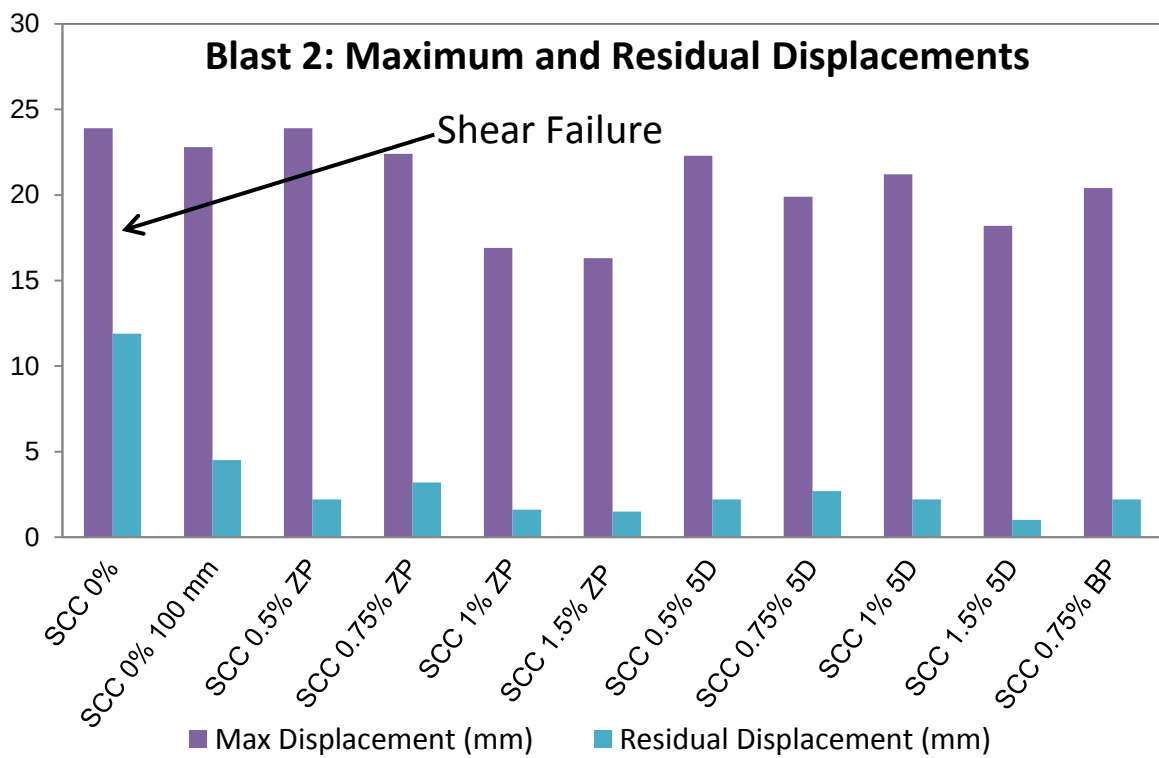


Figure 4.20: Maximum and Residual Displacements for Blast 2

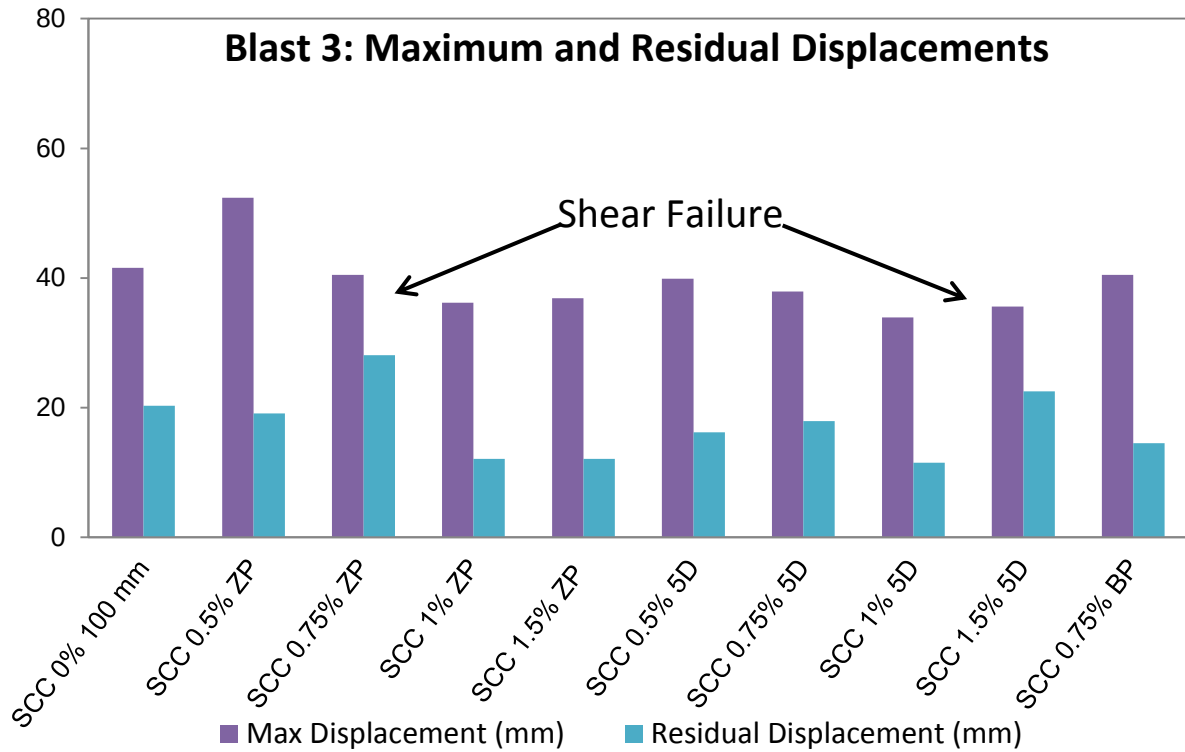


Figure 4.21: Maximum and Residual Displacements for Blast 3

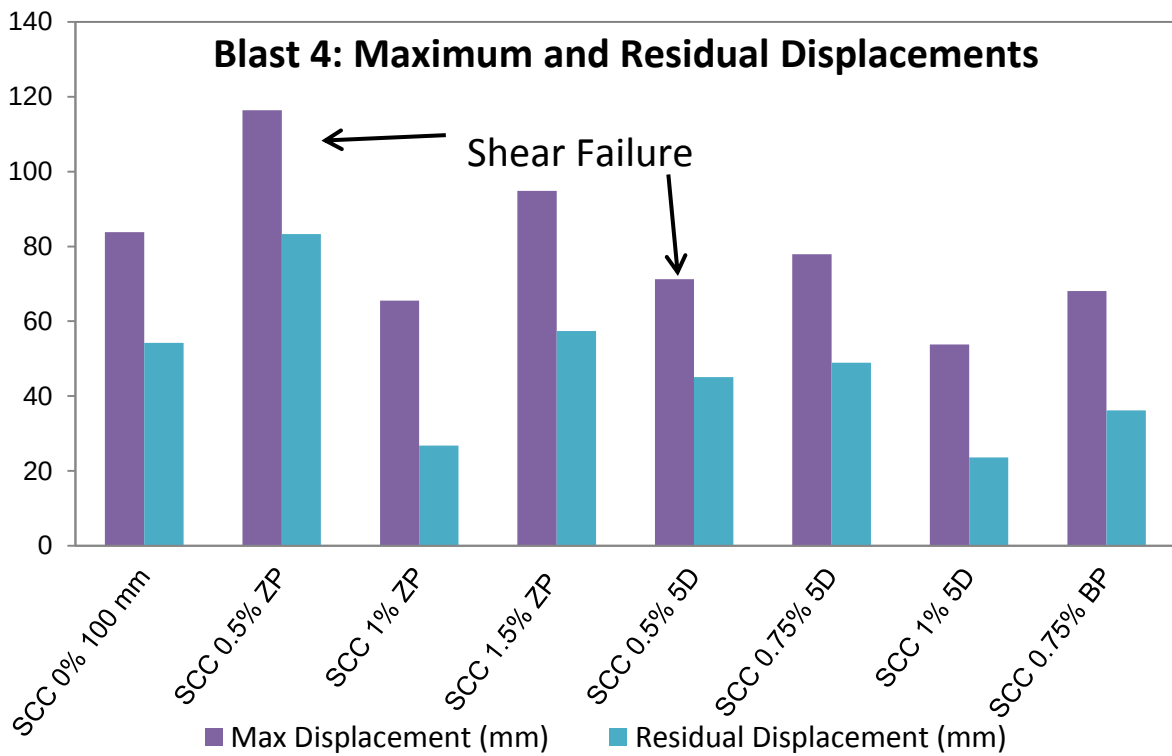


Figure 4.22: Maximum and Residual Displacements for Blast 4

4.2.2 Description of Experimental Results - Dynamic test series

4.2.2.1 SCC 0% 100mm

This beam represents the first "control" specimen built with SCC and without fibers. This particular beam was built with transverse reinforcement spaced at 100 mm in the shear spans. It served as a baseline for comparison with the other beams in this experimental program. The shockwave data, as recorded by the shock tube pressure inducers and LVDTs can be found in Table 4.4. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.23. Figure 4.24 and Figure 4.25 includes photographs detailing the effect of each blast on the beam.

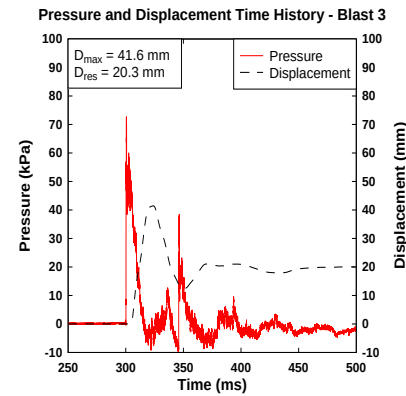
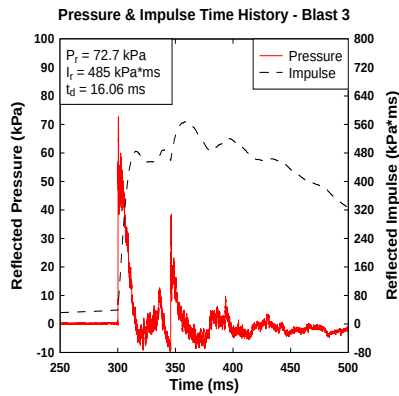
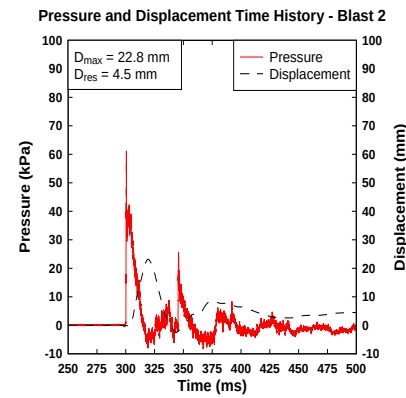
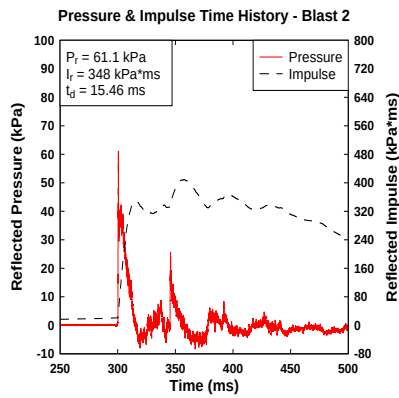
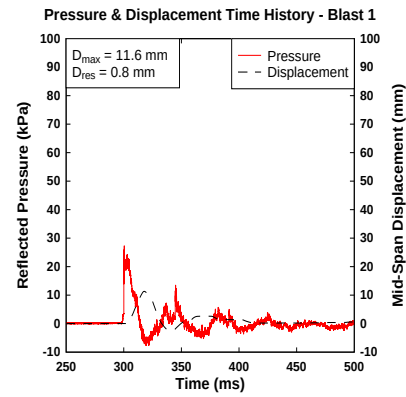
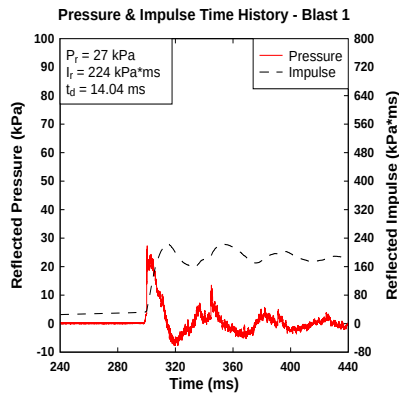
Blast 1 was intended to keep the beam within its elastic range. The maximum and residual displacement observed were 11.6 mm and 0.8 mm respectively. Strain gauge data shows a maximum stain of 0.002 which indicates that the longitudinal bars were just at the limit of elasticity. Only a few flexural cracks were observed on the tension face as well as shear cracks which can be seen in Figure 4.24 and Figure 4.25. The maximum flexural and shear cracks width were both measured to be 0.2 mm.

Blast 2 was intended to bring the beam in the plastic range. The maximum and residual displacement observed was 22.8 mm and 4.8 mm (5.6 mm cumulative) respectively. The strain gauge data was unavailable for this test, however the displacements showed that there was some plasticity as there is residual displacement. More shear and flexural cracks appeared. The shear cracks slightly opened up to 0.3 mm and the flexural cracks to 2 mm.

Blast 3 was intended to bring the beam further in the plastic range and induce plastic deformation to the specimen. The maximum and residual displacement observed was 41.6 mm and 20.3 mm (25.9 mm cumulative) respectively. Crushing was observed on the compression face. Further cracking was also observed. The shear cracks stayed the same size while the flexural cracks were beyond 2 mm. No spalling or fragmentation was observed when analysing the high-speed video.

Blast 4 was intended to bring the beam to failure. The maximum and residual displacement observed was 83.7 mm and 54.2 mm (81.3 mm cumulative) respectively. Figure 4.24 d) and Figure 4.25 b) shows extensive damage to the compressive zone due to crushing. It also shows damage to the cover of the tension zone. Analysing the high-speed camera footage revealed that fragments

of the tension cover was thrown across the room and that fragments were thrown from the crushing zone.



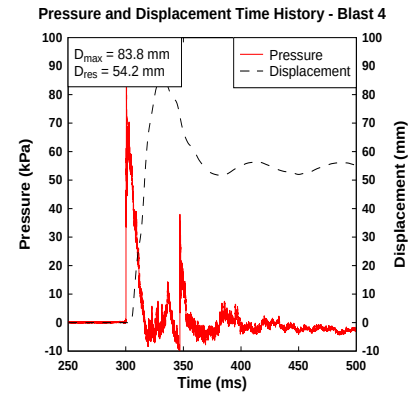
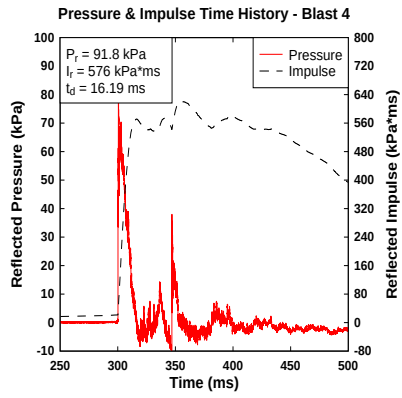


Figure 4.23 Beam SCC 0% 100mm: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(c) Blast 2



(c) Blast 3



(d) Blast 4

Figure 4.24 Beam SCC 0% 100mm at the end of Blast 1-4



(a) Mid-Span Result of Blast 3



(b) Mid-Span Result of Blast 4

Figure 4.25 Mid-Span damage for Beam SCC 0% 100mm

4.2.2.2 SCC 0%

This Beam was the second "control" beam built with plain SCC, but unlike the previous specimen this beam was built without any transverse reinforcement. The specimen was expected to have a shear failure and serve as a baseline to examine the benefits of transverse reinforcement and fibers when compared to the other beams in the experimental series. The shockwave data for this beam can be found in Table 4.4. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.26. Figure 4.27 and Figure 4.28 include photographs detailing the effect of each blast on the beam.

Blast 1 was intended to bring the beam close to the yield point. The maximum strain observed was of 0.0023 mm/mm which indicates the beam reinforcement was right the yield strain. A maximum mid-span and residual displacement of 11.5 mm and 1.1 mm was observed. Figure 4.27 (a) and Figure 4.28 (a) include photographs of the damage after blast 1. No visible shear cracks were found and a few flexural cracks were observed. The flexural crack width measured at mid-span was 0.2 mm.

Blast 2 caused the beam to fail in shear. This blast was intended to bring the beam past the yield limit. As noted previously this beam was expected to fail in shear since the concrete contribution

to shear resistance was insufficient to fully develop the beam's flexural capacity. Figure 4.27 and Figure 4.28 show photographs of the shear failure which occurred in the top shear span. The maximum and residual mid-span displacement recorded during the test was 23.7 mm and 11.9 mm respectively (13.0 mm cumulative). A maximum strain of 0.0075 mm/mm ($\epsilon_{\text{tot}} = 0.0076 \text{ mm/mm}$) was observed when examining the strain data. The high-speed videos show that a few concrete fragments were projected from the shear crack, but no large pieces were observed.

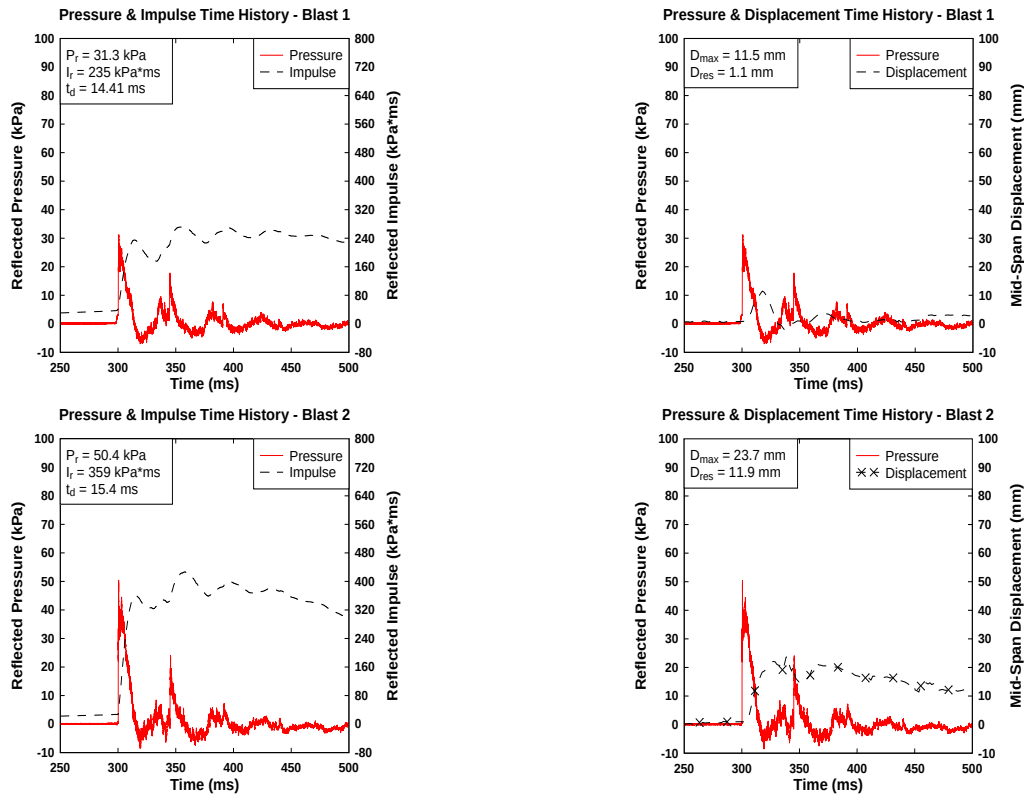


Figure 4.26 Beam SCC 0%: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2

Figure 4.27 Beam SCC 0% at the end of Blast 1-2



(a) Mid-Span Result of Blast 1



(b) Shear Failure of Blast 2

Figure 4.28 Damage for Beam SCC 0%

4.2.2.3 SCC 0.5% ZP

This beam was the first of the SFRC specimens tested to study the effect of combined use of SCC and steel fibers on beam performance. It contained 0.5% of the normal strength ZP fiber. It was constructed to have identical properties as the control SCC 0% beam. The shockwave data for this beam can be found in Table 4.4. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.29. Figure 4.30 and Figure 4.31 includes photographs detailing the effect of each blast on the beam.

Blast 1 was intended to keep the beam near the yield point of the beam. The maximum strain observed was 0.0019 mm/mm which indicates that the steel did not yield. The maximum and residual mid-span displacement observed was 11.6mm and 1.1 mm. Flexural cracks were observed at mid-span on the tension face as seen in Figure 4.30 (a). A maximum flexural crack width of 0.2 mm was measured. No shear cracking was observed.

Blast 2 was intended to bring the beam in the plastic range. The maximum and residual displacement observed was 23.9 mm and 2.2 mm (3.3 mm cumulative) respectively. Strain gauge data shows a maximum strain of 0.0039 mm/mm ($\epsilon_{tot} = 0.0042\text{mm/mm}$) which indicates that the steel is beyond the yield point. The size and number of flexural cracks observed increased, as seen in Figure 4.30 (b), with the maximum crack size observed of 0.5 mm. Shear cracks were observed in both shear spans with a maximum crack width of 0.3 mm.

Blast 3 resulted in a maximum and residual displacement of 52.4 mm and 19.1mm (22.4 mm cumulative) respectively. Strain gauge data was lost during this test. Crushing was observed at mid-span on the compression side as seen in Figure 4.31 (a). Increased cracking was observed and the maximum shear crack width increased to 2 mm, indicating fiber pullout had initiated. This was also confirmed from the high-speed video.

Blast 4 caused the beam to fail in shear, with diagonal shear cracks occurring at both the top and bottom shear spans as seen in Figure 4.30 d) and Figure 4.31 b). Despite the shear failure, the steel fibers were able to delay the failure for a further 2 shots over the companion control beam built with plain SCC. Maximum and residual displacements of 116.4mm and 83.3mm (105.7 mm cumulative) were recorded during the failure test. The high-speed camera showed that some spalling occurred in the vicinity of the shear crack and at mid-span.

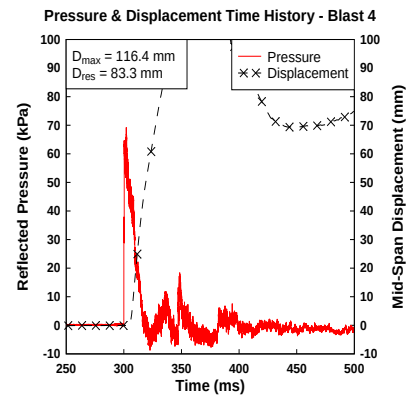
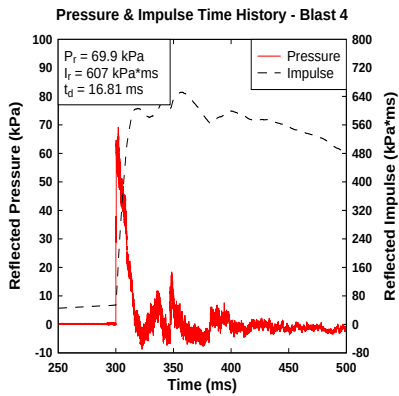
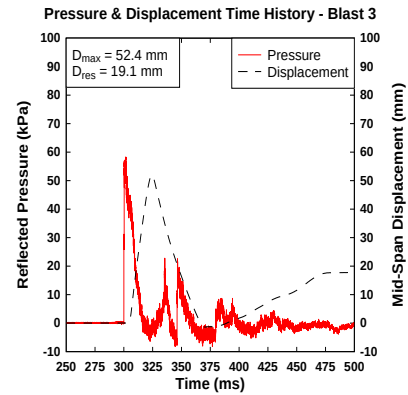
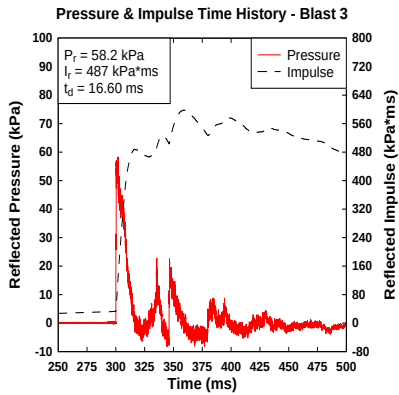
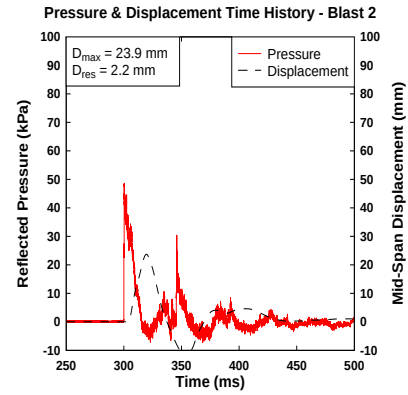
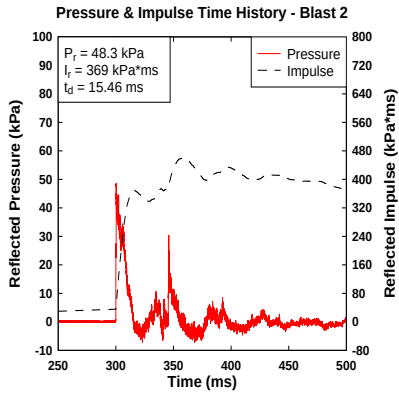
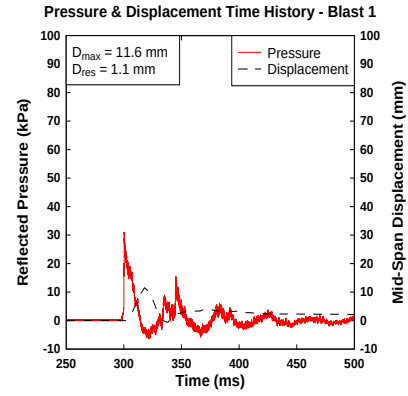
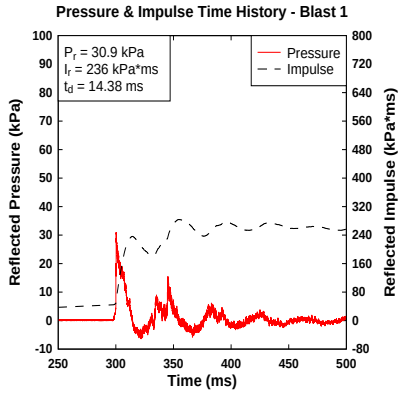


Figure 4.29 Beam SCC 0.5% ZP: recorded reflected pressure, impulse, and displacement



(a) Blast1



(b) Blast 2



(c) Blast 3

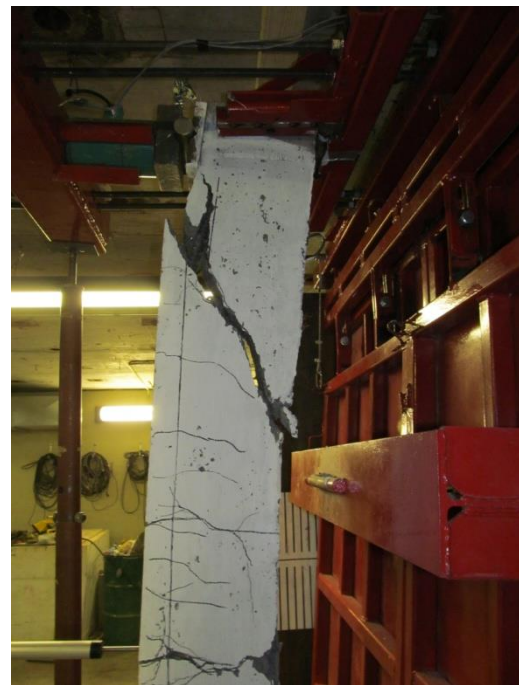


(d) Blast 4

Figure 4.30 Beam SCC 0.5% ZP at the end of Blast 1-4



(a) Mid-Span Result of Blast 3



(b) Shear Failure of Blast 4

Figure 4.31 Damage for Beam SCC 0.5% ZP

4.2.2.4 SCC 0.75% ZP

This beam was the second of the SFRC specimens tested to study the effect of combined use of SCC and steel fibers on beam performance. It was constructed to have identical properties as the control beam SCC 0% (no transverse reinforcement) except it has a 0.75% of the normal strength ZP fiber. The shockwave data for this beam can be found in Table 4.4. Pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.32. Figure 4.33 and Figure 4.34 includes photographs detailing the effect of each blast on the beam.

Constant with the previous tests, the beam was brought near its elastic point at blast 1. The maximum strain measured by the strain gauges was of 0.0017 mm/mm which indicates that the steel had not quite reached the yield point. A maximum and residual displacement at mid-span of 12.1 mm and 1.4 mm was observed. A very small crack was observed at mid-span on the tension side of the beam, as seen in Figure 4.33 (a). No shear crack was observed.

Blast 2 resulted in a maximum and residual displacement of 22.4 mm and 3.2 mm (4.6 mm cumulative) respectively. The maximum strain measured was of 0.0174 ($\epsilon_{\text{tot}} = 0.0042\text{mm/mm}$). The strain and mid-span residual displacement indicates that plasticity was achieved. The crack at mid-span increased to a width of 0.3 mm while no shear crack was observed as seen in Figure 4.33 and Figure 4.34.

Unlike the previous beam, the specimen failed in shear at blast 3. It is noted that reflected impulse was higher at this blast for this beam when compared to the companion specimen with 0.5% fibers (527 KPa*msec vs. 487 KPa*msec), with a slight increase in reflected impulse (61 KPa vs 58 KPa), which can explain the difference in the expected performance trend. A large shear crack was observed at the top of the specimen as seen in Figure 4.33 and Figure 4.34. Strain gauge data was unavailable for this test. A maximum mid-span displacement of 40.5 mm was observed as well as a residual displacement of 28.8 mm (33.4 mm cumulative). The high-speed camera footage was analysed and it can be observed that only small amount of fine concrete particles was projected from the shear crack at failure.

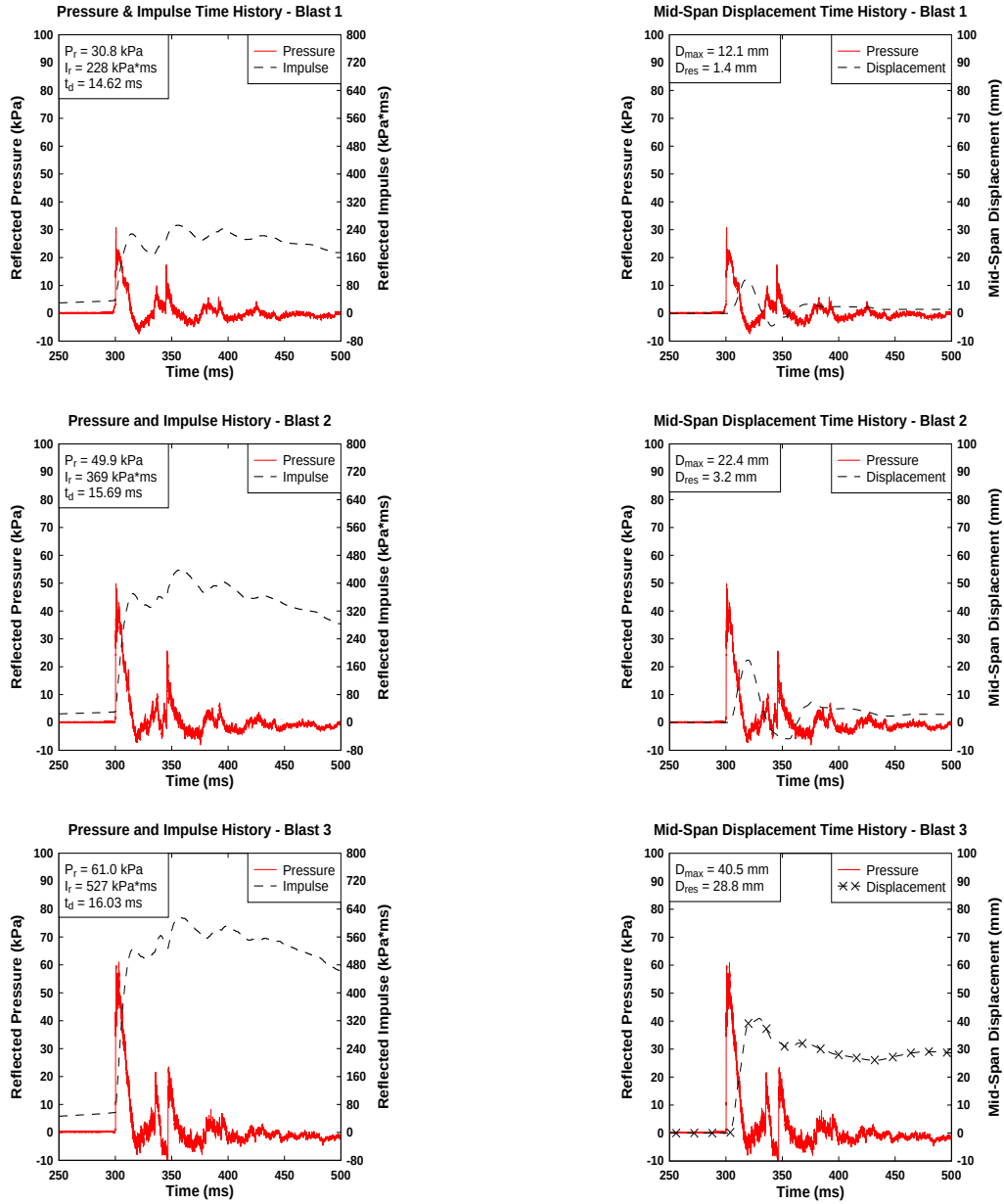


Figure 4.32 Beam SCC 0.75% ZP: recorded reflected pressure, impulse, and displacement



(a) Blast1



(b) Blast 2

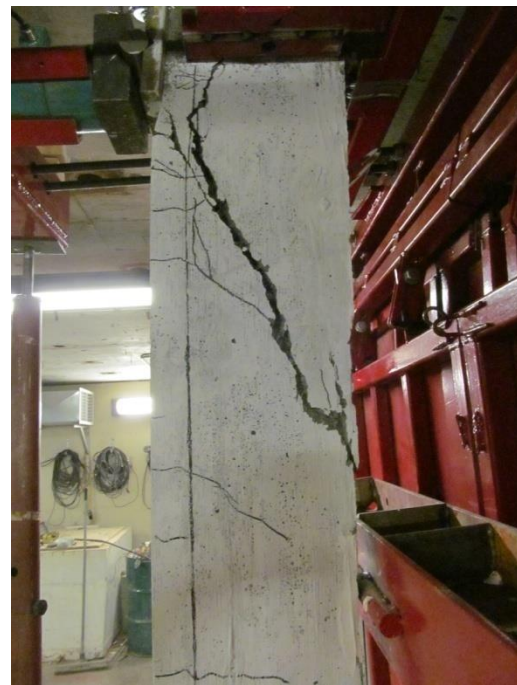


(c) Blast 3

Figure 4.33 Beam SCC 0.75% ZP at the end of Blast 1-3



(a) Mid-Span Damage, Result of Blast 2



(b) Shear Failure of Blast 3

Figure 4.34 Damage for Beam SCC 0.75% ZP

4.2.2.5 SCC 1% ZP

This beam was the third of the SFRC specimens in the ZP fiber series. It contained 1% of the normal strength ZP fiber. It was constructed to have identical properties as the control beam SCC 0%. The shockwave data for this beam can be found in Table 4.4. Pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.35. Figure 4.36 and Figure 4.37 includes photographs detailing the effect of each blast on the beam.

Blast 1 resulted in maximum displacement of 9.1 mm with no permanent residual displacement. The maximum recorded strain was 0.0015 mm/mm. Contrary to the previous test, this beam stayed within the elastic region for the first blast. No cracks were observed after the test.

Blast 2 resulted in a maximum strain of 0.0030 mm/mm which indicated that the beam was slightly past the yield point. A maximum and residual displacement of 19.9 mm and 1.6 mm was observed. Flexural cracks were observed near the mid span of the beam, in between the two point loads. Larger cracks were observed in the upper half of the beam as seen in Figure 4.36. A shear crack was also observed in the top shear span following this test.

Blast 3 pushed the beam further into the plastic region. A maximum and residual mid-span displacement of 36.2 mm and 12.5 mm (10.5 mm cumulative) respectively were recorded. Strain gauge data showed a maximum strain of 0.0136 mm/mm ($\epsilon_{\text{tot}} = 0.0137$ mm/mm). More flexural cracks were observed, especially near the upper point load as seen in Figure 4.36 and Figure 4.37. Slight signs of crushing could be observed underneath the top load point. A shear crack was observed at the bottom and another at the top.

Blast 4 resulted in significant crushing near the upper point load as seen in Figure 4.36 and Figure 4.37. The high-speed camera footage was analysed and it was observed that even with the extensive damage, only a small amount of concrete was thrown from the beam. It was also observed that most of the concrete projectiles were very small and most of it was dust. Maximum and residual mid-span displacements of 65.5 mm and 26.8 mm (37.3 mm cumulative) were measured with the LVDTs. Strain data was unavailable for this test. Although the beam had residual capacity it was decided to stop testing at this stage because of the damage to the beam.

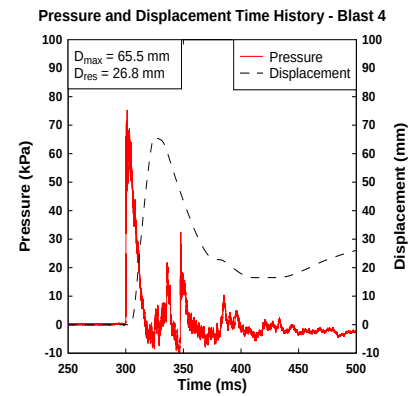
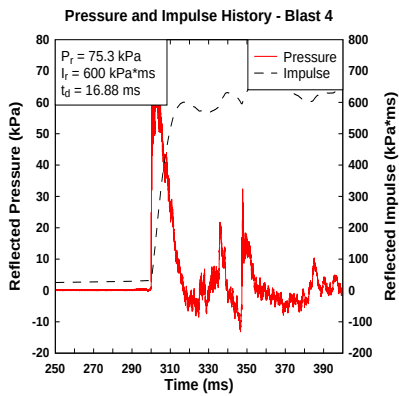
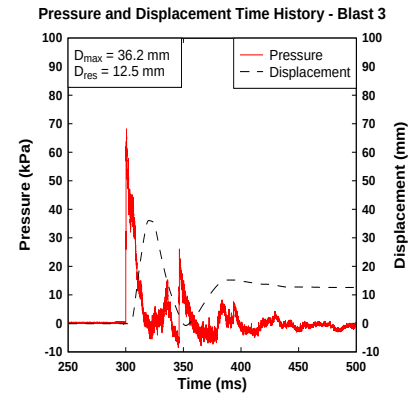
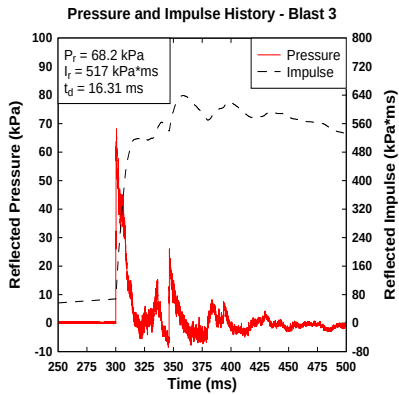
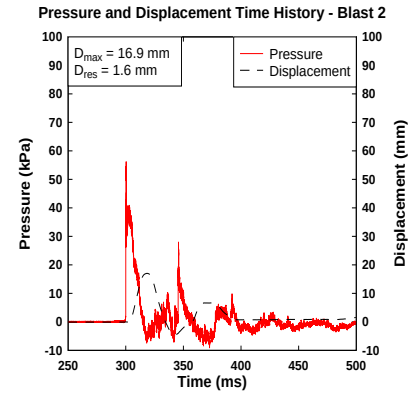
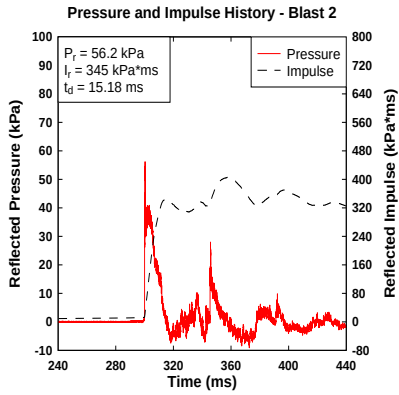
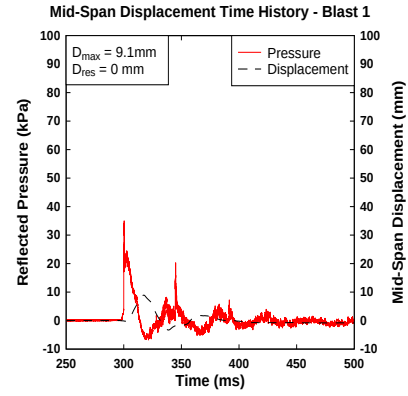
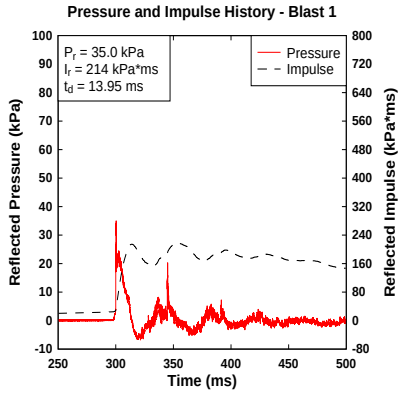


Figure 4.35 Beam SCC 1% ZP: recorded reflected pressure, impulse, and displacement



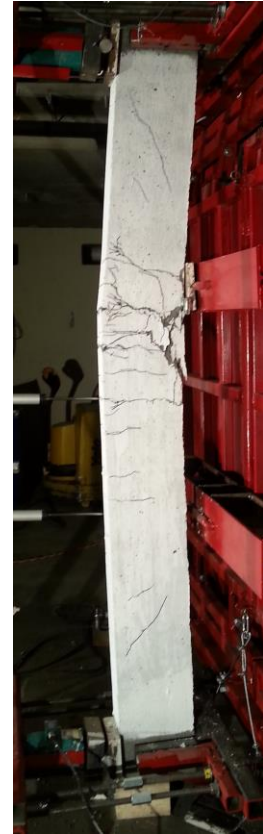
(a) Blast 1



(b) Blast 2



(c) Blast 3

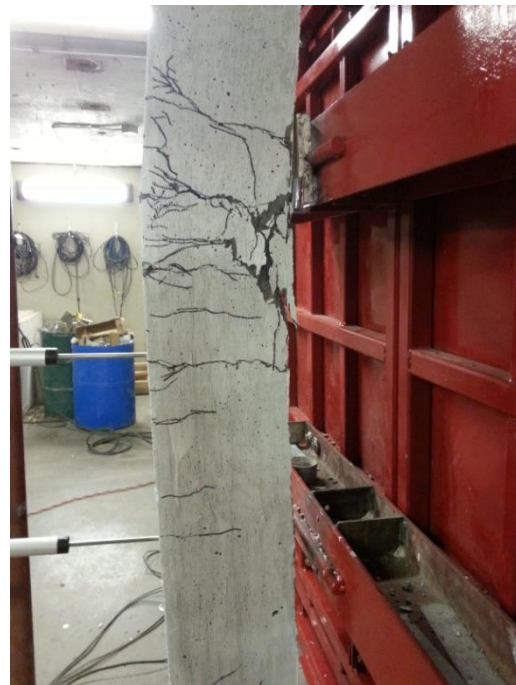


(d) Blast 4

Figure 4.36 Beam SCC 1% ZP at the end of Blast 1-4



(a) Mid-Span Results of Blast 3



(b) Mid-Span Results of Blast 4

Figure 4.37 Mid-Span damage for Beam SCC 1% ZP

4.2.2.6 SCC 1.5% ZP

This beam was the fourth of the SFRC specimens in the ZP fiber series. It contained 1.5% of the normal strength ZP fiber, and as with the other SFRC specimens, did not contain stirrups. The shockwave data for this beam can be found in Table 4.4. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.38. Figure 4.39 & Figure 4.40 includes photographs detailing the effect of each blast on the beam.

Blast 1 resulted in a maximum and residual mid span displacement of 9.9 mm and 0.6 mm respectively. The maximum recorded strain was 0.0014 mm/mm and this indicated that the beam stayed in the elastic range. One small flexural crack ($w_{\max, \text{flex}} = 0.2 \text{ mm}$) was observed on the tension face of the beam as seen in Figure 4.39.

Blast 2 placed the beam slightly past the yield point. A maximum and residual mid-span displacement of 16.9 mm and 1.5 mm (2.1 mm cumulative) was recorded with the LVDTs. The maximum strain recorded was 0.0018 mm/mm ($\epsilon_{\text{tot}} = 0.0019 \text{ mm/mm}$). More flexural cracks ($w_{\max, \text{flex}} = 0.5 \text{ mm}$) appeared on the tension face within the constant moment region but no shear cracks were observed.

Blast 3 resulted in a maximum mid-span displacement of 36.9 mm and a residual displacement of 12.1 mm. A maximum strain of 0.0045 mm/mm ($\epsilon_{\text{tot}} = 0.00048 \text{ mm/mm}$) was recorded which indicate that the beam is well within the plastic region. The size and number of flexural cracks ($w_{\max, \text{flex}} > 2 \text{ mm}$) are more significant than the previous blast and shear cracks ($w_{\max, \text{shear}} = 0.2 \text{ mm}$) were observed at the top shear span of the beam. Crushing was observed on the compression face at mid-span.

Blast 4 resulted in the failure of the beam. Significant damage was observed at mid-span as seen in Figure 4.40. Extensive crushing was observed as well as significant cracking going from the crushing zone to the tension face of the beam. Around mid-span another large crack was observed running along the longitudinal rebar. It can be observed the majority of the cracking happened in the upper half of the beam. Analysis of the high-speed camera shows concrete fragments being projected from the crushing zone. Maximum and residual mid span displacement of 94.8 mm and 57.4 mm (73.6 mm cumulative) were recorded with the LVDTs.

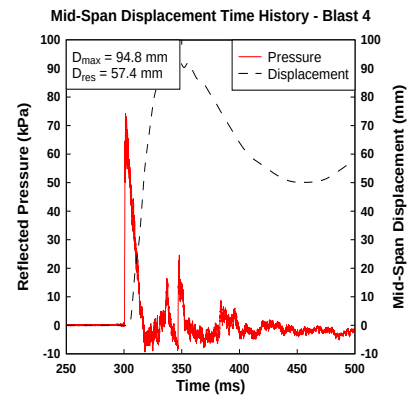
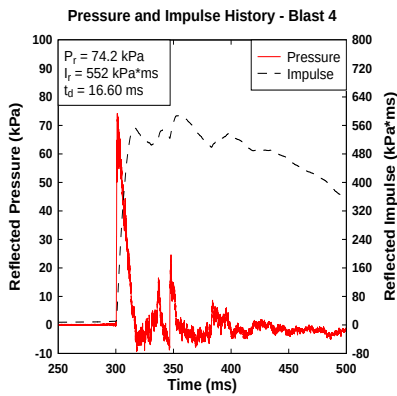
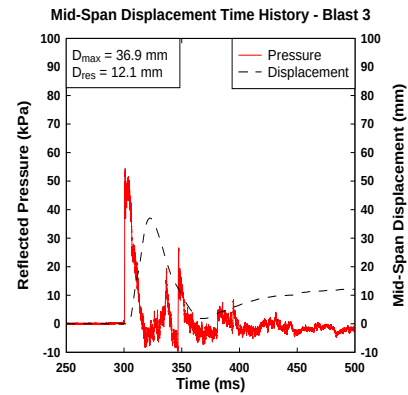
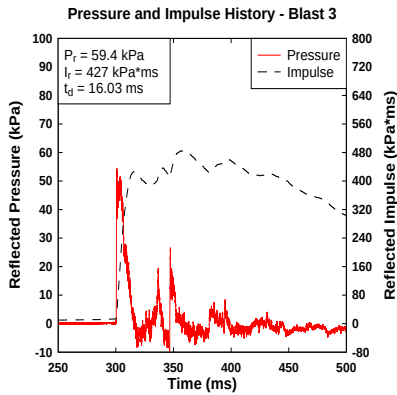
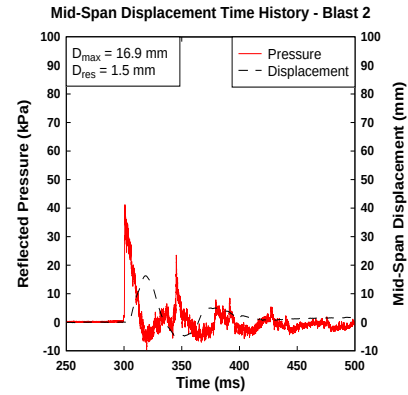
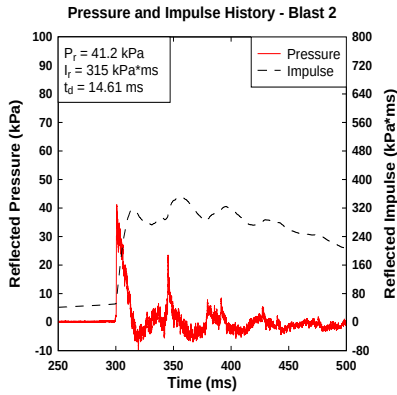
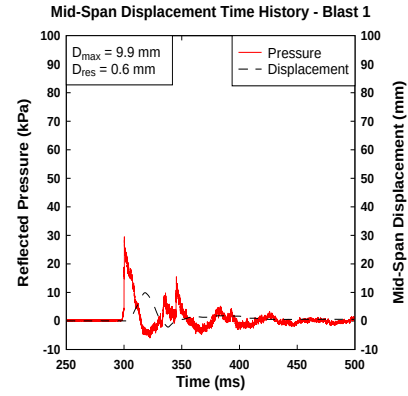
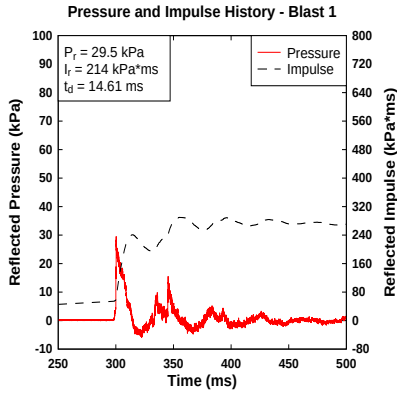


Figure 4.38 Beam SCC 1.5% ZP: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2



(c) Blast 3

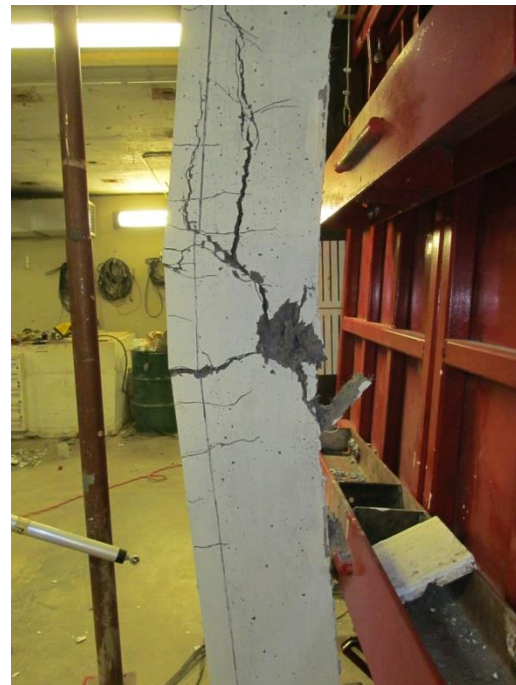


(d) Blast 4

Figure 4.39 Beam SCC 1.5% ZP at the end of Blast 1-4



(a) Mid-Span Results of Blast 3



(b) Mid-Span Results of Blast 4

Figure 4.40 Mid-Span damage for Beam SCC 1.5% ZP

4.2.2.7 SCC 0.5% 5D

This beam was the first SFRC specimens tested to study the effect of varying fiber properties such as strength and length. It contained 0.5% of the high strength, 60 mm long, doubly hooked 5D fiber. It was constructed to have identical properties as the control SCC 0% and SCC 0.5% ZP beams. The shockwave data for this beam can be found in Table 4.5. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.41. Figure 4.42 and Figure 4.43 include photographs detailing the effect of each blast on the beam.

Blast 1 resulted in a maximum displacement of 10.4 mm with no permanent residual displacement. The maximum recorded strain was 0.0018 mm/mm. The data indicated that the beam stayed in the elastic region for the first blast. Only a few small cracks ($w_{\max, \text{flex}} = 0.2 \text{ mm}$) were observed on the tension face and no shear cracks were seen.

Blast 2 resulted in a maximum strain of 0.0030 mm/mm ($\epsilon_{\text{tot}} = 0.0033 \text{ mm/mm}$). A maximum and residual displacement of 22.3 mm and 2.2 mm were recorded with the LVDTs. More flexural cracks were observed in between the two point loads but the maximum width of the cracks did not noticeably increased. It can be observed in Figure 4.42 that a large shear crack ($w_{\max, \text{shear}} = 1 \text{ mm}$) has formed in the upper shear span of the beam.

Blast 3 pushed the reinforcement in the beam further into the plastic region. Maximum and residual mid-span displacements of 39.9 mm and 16.6 mm (18.8 mm cumulative) were recorded. Strain gauge data showed a maximum strain of 0.0136 mm/mm ($\epsilon_{\text{tot}} = 0.0137 \text{ mm/mm}$). It can be observed that the number and size of flexural cracks ($w_{\max, \text{flex}} = 2 \text{ mm}$) continued to grow. It was observed that the width of the shear crack ($w_{\max, \text{shear}} = 2 \text{ mm}$) increased but the crack did not expand. No shear cracks were visible at the bottom part of the beam.

Blast 4 resulted in the shear failure of the beam. Figure 4.43 (b) illustrates the critical shear crack which formed at the top of the beam. A small shear crack also appeared at the bottom of the beam. A maximum and residual mid-span displacement of 71.2 mm and 45.1 mm (63.9 mm cumulative) respectively were recorded. Strain data was unavailable.

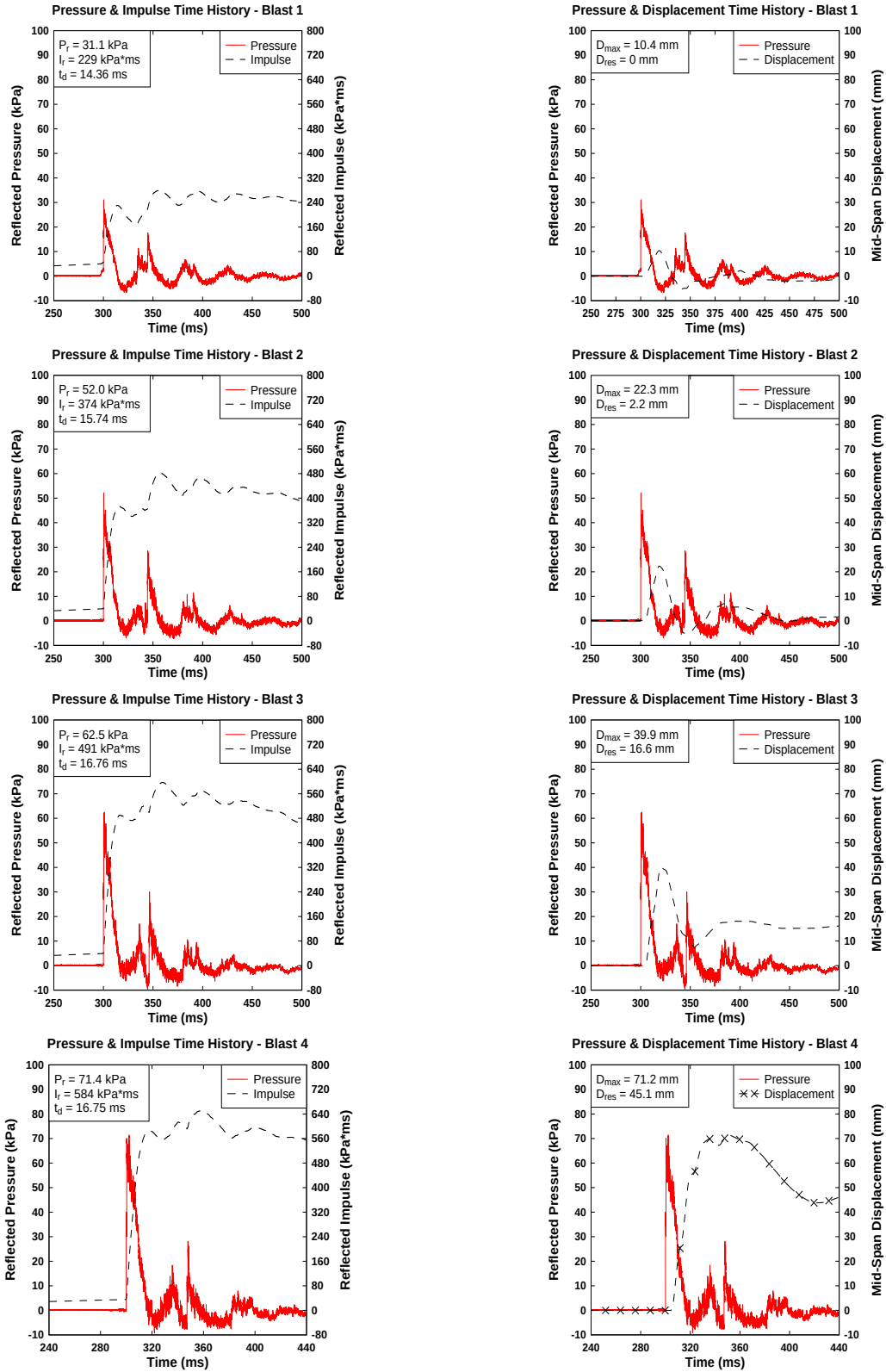


Figure 4.41 Beam SCC 0.5% 5D: recorded reflected pressure, impulse, and displacement



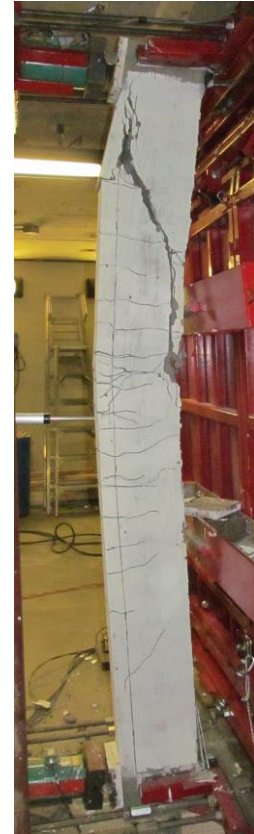
(a) Blast 1



(b) Blast 2



(c) Blast 3



(d) Blast 4

Figure 4.42 Beam SCC 0.5% 5D at the end of Blast 1-4



(a) Mid-Span Result of Blast 3



(b) Shear Failure of Blast 4

Figure 4.43 Damage for Beam SCC 0.5% 5D

4.2.2.8 SCC 0.75% 5D

This beam was the second SFRC specimen tested in the 5D fiber series and contained a 0.75% of the high strength 5D fiber. In addition to investigating into the effect of fiber content, the beam was a companion to specimen SCC 0.75%ZP and can therefore be used to examine the effect of fiber type. The shockwave data for this beam can be found in Table 4.5. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.44. Figure 4.45 and Figure 4.46 include photographs detailing the effect of each blast on the beam.

Blast 1 resulted in a maximum mid span displacement of 10.3 mm and no residual displacement. The maximum recorded strain was 0.0018 mm/mm. The data indicated that the beam stayed in the elastic region for the first blast. Only three small cracks ($w_{\max, \text{flex}} = 0.2 \text{ mm}$) were observed on the tension face and no shear cracks were observed.

Blast 2 placed the beam slightly past the yield point. A maximum and residual mid span displacement of 19.9 mm and 2.7 mm were recorded. The maximum strain recorded was 0.0066 mm/mm ($\epsilon_{\text{tot}} = 0.0069 \text{ mm/mm}$). More flexural cracks ($w_{\max, \text{flex}} = 0.3 \text{ mm}$) appeared on the tension face within the constant moment region and a shear crack ($w_{\max \text{ shear}} = 0.5 \text{ mm}$) was observed in the top of the beam as observed in Figure 4.45 (b).

Blast 3 resulted in a maximum mid-span displacement of 37.9 mm and a residual displacement of 17.9 mm (20.6 mm cumulative). No strain data was recorded in this test. The size and number of flexural cracks ($w_{\max, \text{flex}} = 2 \text{ mm}$) are more significant than the previous blast. Another shear crack appeared in the bottom shear span of the beam and the width of the top one increased. ($w_{\max \text{ shear}} = 1.25 \text{ mm}$). Crushing was observed on the compression face at mid-span.

Blast 4 resulted in the flexural failure of the specimen. Significant crushing was observed at mid span as seen in Figure 4.46 (b). Significant cracking can be observed in the tension face at mid span while shear cracks stayed the same. A maximum and residual mid-span displacement of 77.9 mm and 48.9 mm (69.5 mm cumulative) respectively was recorded. Analysis of the high-speed camera footage reveals small debris being thrown backwards and some medium sized pieces of concrete falling on the floor in front of the beam.

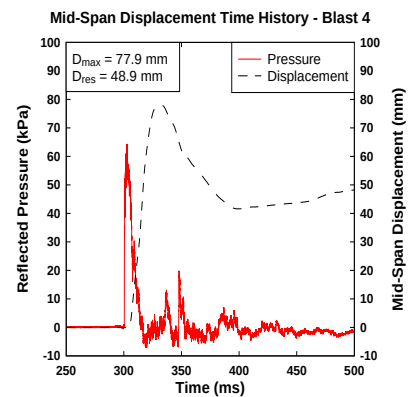
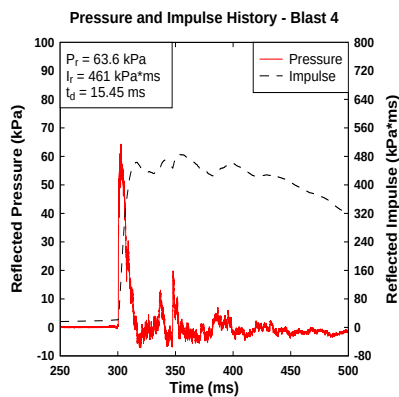
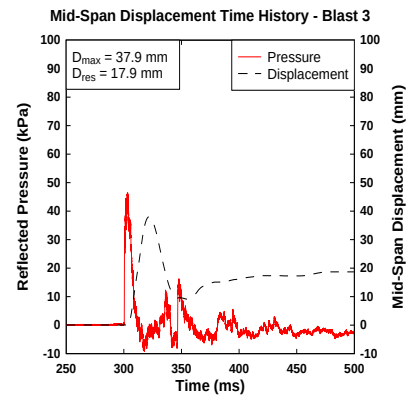
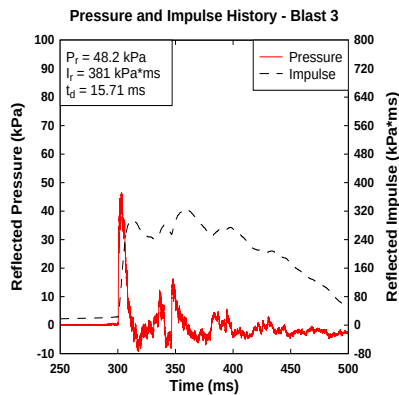
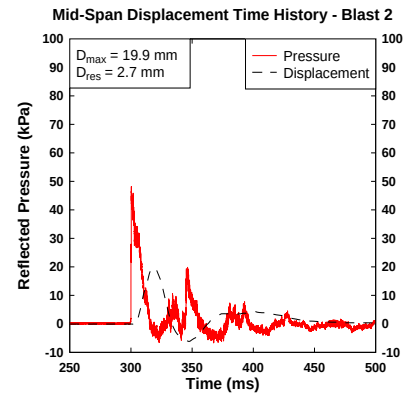
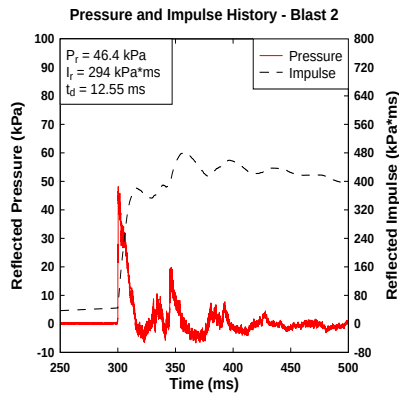
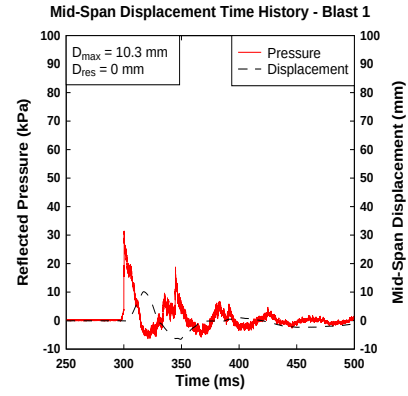
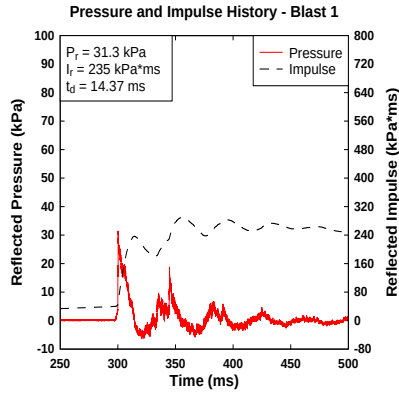


Figure 4.44 Beam SCC 0.75% 5D: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2



(c) Blast 3



(d) Blast 4

Figure 4.45 Beam SCC 0.75% 5D at the end of Blast 1-4



(a) Mid-Span Results of Blast 3



(b) Mid-Span Results of Blast 4

Figure 4.46 Damage for Beam SCC 0.75% 5D

4.2.2.9 SCC 1% 5D

This beam was the third SFRC specimens tested in the 5D fiber series. It contained 1% of the high strength, doubly hooked 5D fiber. As with the previous specimen, this beam was used to examine the effect of fiber content and fiber type. The shockwave data for this beam can be found in Table 4.5. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.47. Figure 4.48 and Figure 4.49 include photographs detailing the effect of each blast on the beam.

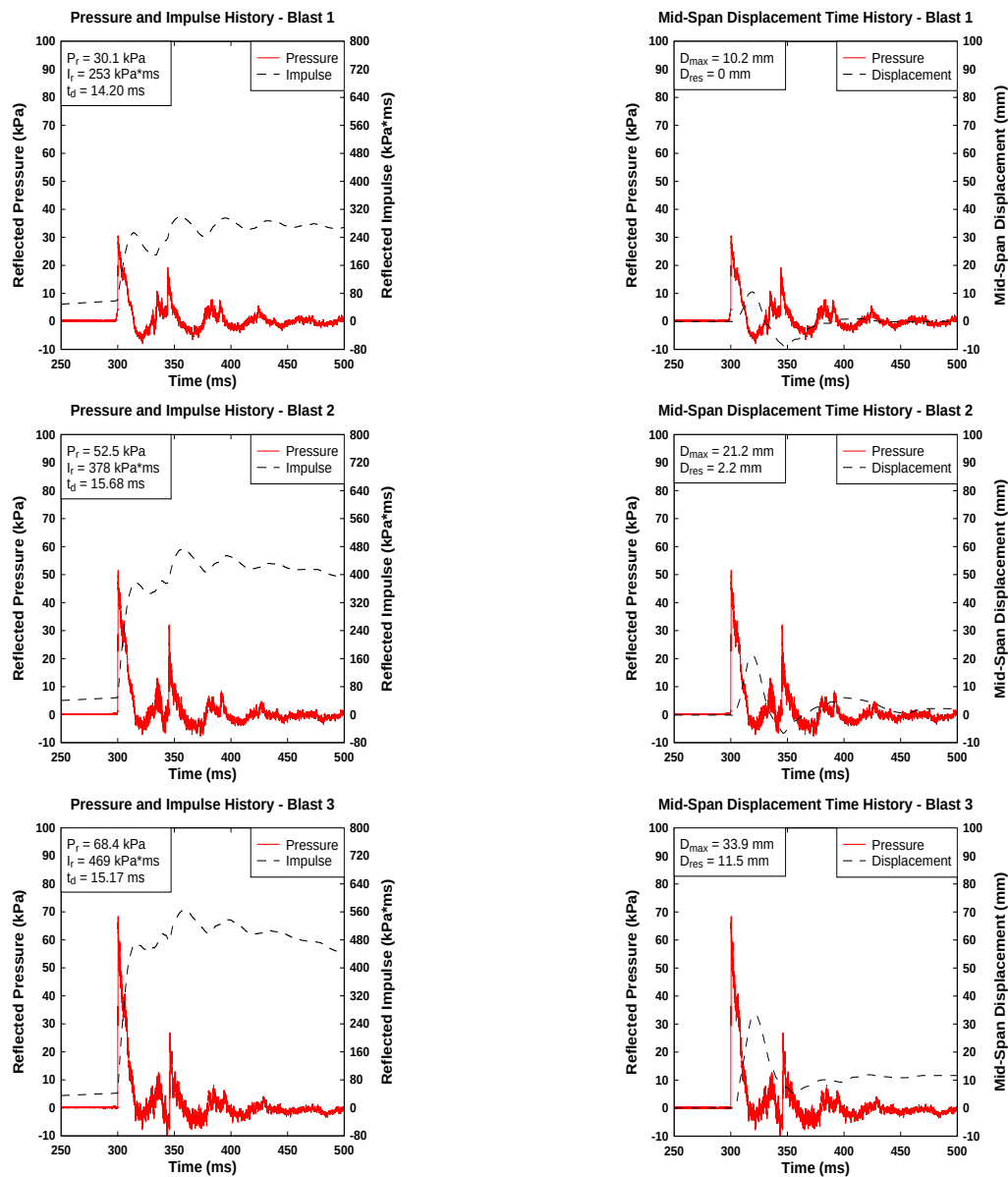
Blast 1 resulted in a maximum displacement of 10.2 mm and no residual displacement. The maximum recorded strain was 0.0018 mm/mm and this indicates that the beams stayed in the elastic range. A few cracks ($w_{\max, \text{flex}} = 0.2 \text{ mm}$) were observed within the constant moment region of the beam as seen in Figure 4.48 (a). No shear cracks were observed.

Blast 2 resulted in a maximum strain of 0.0032 mm/mm ($\epsilon_{\text{tot}} = 0.0032 \text{ mm/mm}$). A maximum and residual displacement of 21.3 mm and 2.2 mm (2.2 mm cumulative) was recorded with the LVDTs. In Figure 4.48 (b), it can be observed that the flexural cracks ($w_{\max, \text{flex}} = 1 \text{ mm}$) are more numerous and longer than in the previous test. A shear crack ($w_{\max, \text{shear}} = 0.5 \text{ mm}$) was observed at the top shear span of the beam.

Blast 3 resulted in a maximum and residual mid-span displacement of 33.9 mm and 11.5 mm (13.7 mm cumulative) respectively. No strain data was available for this test. It can be observed in Figure 4.48 (c) that the number and size of flexural cracks ($w_{\max, \text{flex}} = 2 \text{ mm}$) continued to grow. It was observed that the width of the top shear crack ($w_{\max, \text{shear}} = 0.4 \text{ mm}$) increased and that more shear cracks appeared. A small shear cracks were also visible in the bottom part of the beam. Initial signs of crushing were also observed at mid-span.

Unlike the previous specimen, Blast 4 did not result in failure of the beam. Figure 4.48 and Figure 4.49 illustrated that the beam had suffered some damage but no significant crushing can be observed. Further flexural cracks ($w_{\max, \text{flex}} > 2 \text{ mm}$) were observed in the middle of the beam whereas the growth of the shear cracks stayed mostly the same, although the governing shear crack increased in width ($w_{\max, \text{shear}} = 2 \text{ mm}$). Analysis of the high-speed video shows the formation of a small amount of fine concrete during this blast. Maximum and residual displacements of 53.8 mm and 23.6 mm (37.2 mm cumulative) were recorded during this test.

Since damage was limited it was decided to test the beam under Blast 5 loading. Blast 5 resulted in flexural failure of the beam, with maximum and residual displacements of 101 mm and 48.7 mm (86.0 mm cumulative). Extensive crushing and large cracking can be seen in Figure 4.48 (e) and Figure 4.49(b). Analysis of the high-speed camera footage reveals small debris being thrown backwards and two big pieces falling from the crushing zone.



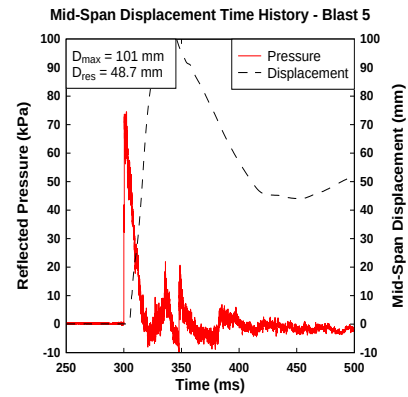
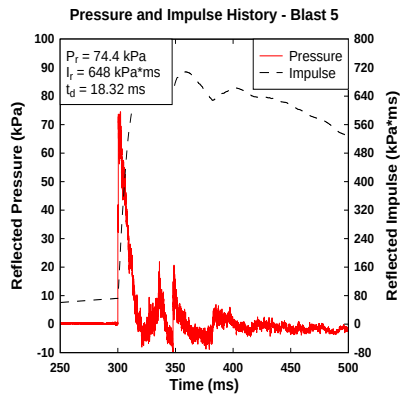
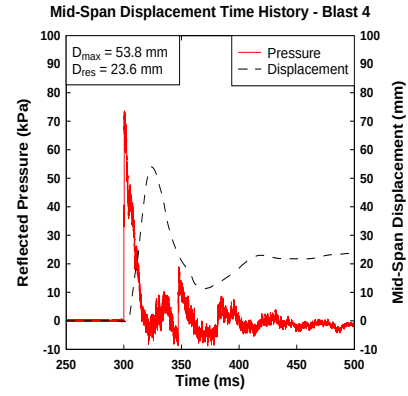
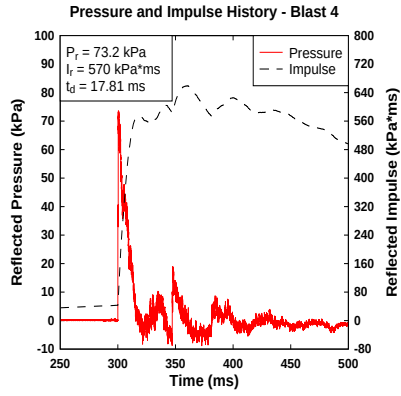


Figure 4.47 Beam SCC 1% 5D: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2



(c) Blast 3

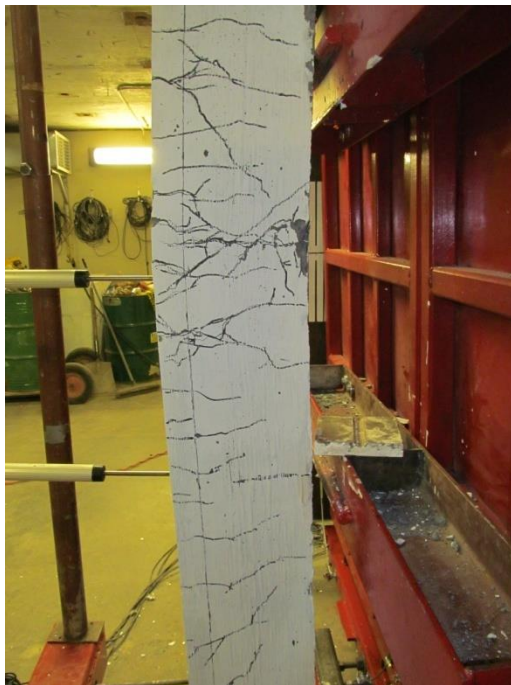


(d) Blast 4



(e) Blast 5

Figure 4.48 Beam SCC 1% 5D at the end of Blast 1-5



(a) Mid-Span Results of Blast 4



(b) Mid-Span Results of Blast 5

Figure 4.49 Damage for Beam SCC 1% 5D

4.2.2.10 SCC 1.5% 5D

This beam was the fourth SFRC specimen in the 5D fiber series and had a fiber content of 1.5%. The shockwave data for this beam can be found in Table 4.5. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.50. Figure 4.51 and Figure 4.52 includes photographs detailing the effect of each blast on the beam.

Blast 1 resulted in a maximum displacement of 10.5 mm and a small residual value of 0.8 mm. Strain gauge data was unavailable for this test, however the low permanent deformation indicated that the beam stayed in the elastic range. Two cracks were observed in the tension face of the beam; one at mid span and the other at the top load point as seen in Figure 4.51(a). No shear cracks were observed.

Blast 2 resulted in a maximum and residual displacement of 18.3 mm and 1.0 mm (1.8 mm cumulative) respectively. In Figure 4.51 (b), it can be observed that the flexural cracks became more numerous and longer than in the previous test. It can also be observed that several diagonal shear cracks appeared in both the top and bottom shear spans with the most significant crack being in the top region. The maximum crack widths measured for both flexural and shear cracks were 0.5mm.

Blast 3 resulted in shear failure of the beam. Figure 4.51 (c) and Figure 4.52 (b) illustrate the shear failure which formed at the top shear span of the beam. Upon closer inspection, it was noted that certain areas of the crack had many fibers and some others have none, indicating poor fiber distribution. This, and the earlier than expected failure, point to probable placement issues during the construction of this beam which used a high dosage (1.5%) of the longer 5D fibers. In addition to the critical shear crack it can be observed that this blast caused the formation of additional flexural and shear cracks when compared to the previous blast. A maximum and residual mid-span displacement of 35.6 mm and 22.5 mm (24.3 mm cumulative) was recorded during this test. No strain data is available for this test. Analysis of the high-speed video reveals small fragments of concrete being projected from the shear crack.

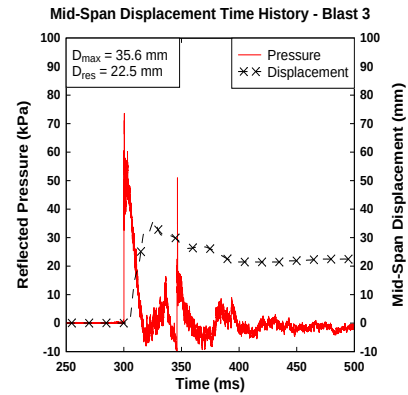
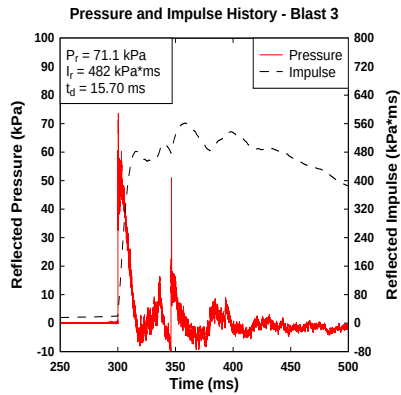
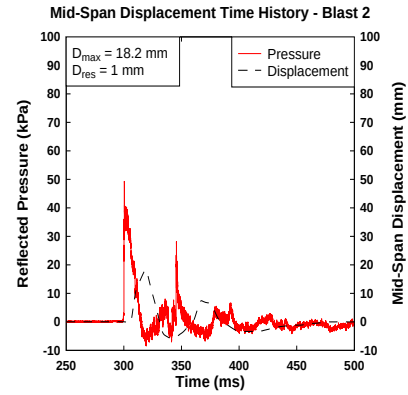
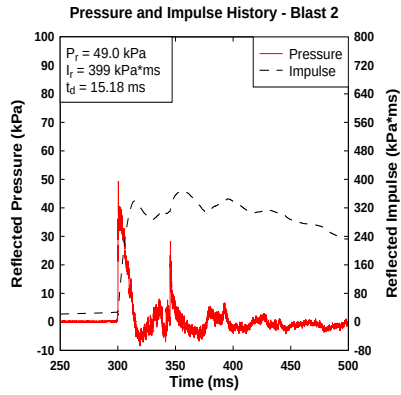
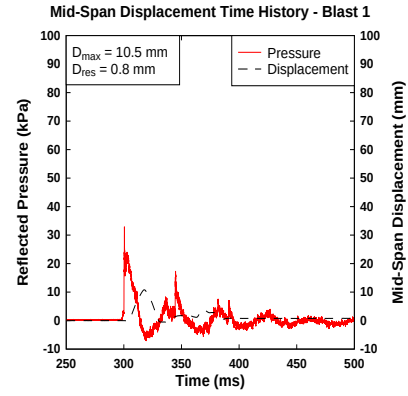
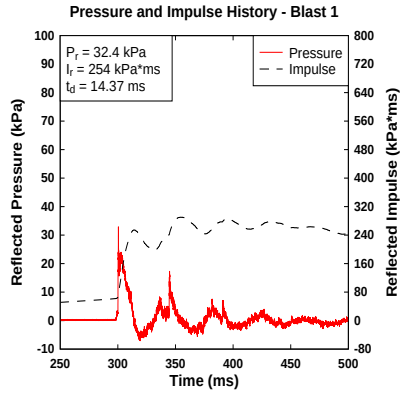


Figure 4.50 Beam SCC 1.5% 5D: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2



(c) Blast 3

Figure 4.51 Beam SCC 1.5% 5D at the end of Blast 1-3



(a) Mid-Span Result of Blast 2



(b) Shear Failure of Blast 3

Figure 4.52 Damage for Beam SCC 1.5% 5D

4.2.2.11 SCC 0.75% BP

This beam was the final SFRC specimen tested in the research program. It contained 0.75% fiber of the 30 mm long, high strength, BP 80/30 fiber. The beam is a companion to beam SCC075% ZP and can be used to examine the effect of fiber properties on blast performance. The shockwave data for this beam can be found in Table 4.5. Complete pressure and impulse time histories as well as pressure and mid-span displacement histories are shown in Figure 4.53. Figure 4.54 and Figure 4.55 includes photographs detailing the effect of each blast on the beam.

Blast 1 resulted in a maximum and residual displacements of 9.9 mm and 1 mm. Strain data was unavailable for this test. Three small flexure cracks on the tension face and no shear cracks were observed after this test. The cracks were located at mid-span and at each point load as seen in Figure 4.54 (a). The maximum flexural crack width measured was 0.2 mm.

Blast 2 resulted in a maximum strain of 0.0034 mm/mm. A maximum and residual displacement of 20.3 mm and 2.2 mm (3.2 mm cumulative) was recorded with the LVDTs. In Figure 4.48 (b), it can be observed that the number of flexural cracks increased and that the one at mid span is longer than in the previous test. Shear cracks were observed in both shear spans. The maximum flexural and shear cracks width were measured to be 0.75 mm and 0.5 mm, respectively.

Blast 3 resulted in a maximum and residual mid-span displacement of 40.5 mm and 14.5 mm (16.7 mm cumulative), respectively. Crushing at mid-span was observed after this blast. Photos for this test were lost during testing. The maximum flexural crack width was greater than 2 mm and the maximum shear crack was 0.75 mm in width.

Blast 4 resulted in flexural failure of the beam. Maximum and residual mid-span displacements of 66.6 mm and 36.2 mm (52.9mm cumulative) were recorded. Figure 4.54 (c) and Figure 4.55 (b) show crushing occurred at mid-span during this test. A tight group of flexural cracks can also be observed within the constant moment region, with shear cracks observed in the top and bottom shear spans. The maximum flexural crack width measured was over 2 mm and maximum shear cracks width remained at 0.75 mm. Analysis of the high-speed video reveals a small amount of fine debris being thrown from the compression zones after crushing.

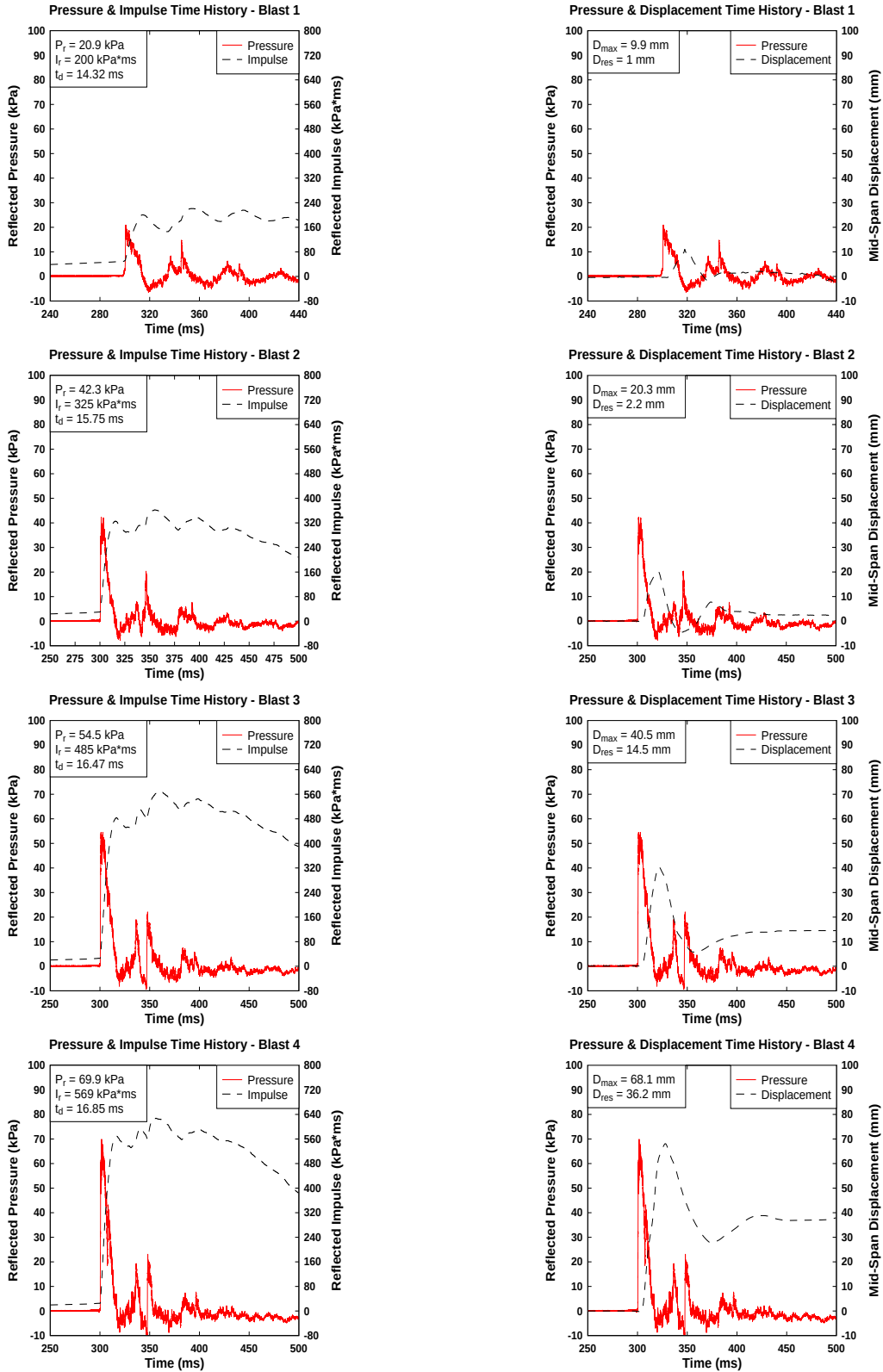


Figure 4.53 Beam SCC 0.75% BP: recorded reflected pressure, impulse, and displacement



(a) Blast 1



(b) Blast 2



(d) Blast 4

Figure 4.54 Beam SCC 0.75% 5D at the end of Blast 1-4



(a) Mid-Span Results of Blast 2



(b) Mid-Span Results of Blast 4

Figure 4.55 Damage for Beam SCC 0.75% BP

5 Discussion

5.1 Section Overview

The purpose of this chapter is to compare and discuss the responses of all eighteen reinforced concrete beams tested in the experimental research program. For static behaviour, the performance criteria for these comparisons are peak load, softening rate parameters, ductility ratio and toughness index as defined in the previous chapter. The performance criteria for dynamic testing are maximum and residual displacement, failure mode, failure blast load magnitudes, damage tolerance and secondary fragmentation.

This chapter is divided into several sections, each presenting a different aspect as listed below:

The effects of transverse reinforcement:

- In static plain SCC beam specimens:
 - SCC 0% vs. SCC 0% 100mm
- In dynamic plain SCC beam specimens:
 - SCC 0% vs. SCC 0% 100mm

The effects of steel fiber and steel fiber content on shear and flexural behavior:

- In static SRFC beam specimens:
 - Controls vs. SCC 0.5% ZP vs. SCC 1% ZP vs. SCC 1.5% ZP
- In dynamic SRFC beam specimens:
 - Controls vs. SCC 0.5% ZP vs. SCC 0.75% ZP vs. SCC 1% ZP vs. SCC 1.5% ZP
 - Controls vs. SCC 0.5% 5D vs. SCC 0.75% 5D vs. SCC 1% 5D vs. SCC 1.5% 5D
 - Controls vs. SCC 0.75% BP

The effects of steel fiber type on shear and flexural behavior:

- In static SRFC beam specimens:
 - Controls vs. SCC 0.75% BP vs. SCC 1.5% ZP vs. SCC1.5% 5D
- In dynamic SRFC beam specimens
 - Controls vs. SCC 0.5% ZP vs. SCC 0.5% 5D
 - Controls vs. SCC 0.75% ZP vs. SCC 0.75% 5D vs. SCC 0.75% BP

- Controls vs. SCC 1% ZP vs. SCC 1% 5D
- Controls vs. SCC 1.5% ZP vs. SCC 1.5% 5D

Damage tolerance and secondary fragmentation:

- Comparing the general behaviour of SFRC against plain SCC

Dynamic vs. Static Resistance curves:

- Comparing the general behaviour of SFRC against plain SCC

5.2 Effect of transverse reinforcement

As expected, the use of traverse reinforcement in the control reinforced concrete beams had a significant influence on shear capacity, changing the failure mode from shear to flexural failure. The following comparison provide further details on the effect of this test parameter.

5.2.1 Static Loading - Effects of transverse reinforcement

The control specimens SCC 0% and SCC 0% 100mm were both designed with plain normal strength concrete (SCC without steel fibers). Control specimen SCC 0% 100 mm had transverse reinforcement spaced at 100 mm in the shear region of the beam while the control beam SCC 0% did not have any transverse reinforcement. Relevant photographs of the beams after testing are included in Figure 5.1. Load displacement curves are presented in Figure 5.2. Comparative charts for peak load, stiffness and softening parameters are provided in Figure 5.3 and Figure 5.4.

By observing the results, the transverse reinforcement had an important effect on failure mode, preventing brittle shear failure. SCC 0% failed in shear at load stage 3 (12 mm) immediately after a shear crack was observed in the left shear span, while SCC 0% 100mm had minimal cracking at the same load stage. SCC 0% 100 mm failed in flexure after load stage 9 (40 mm), with the development of yielding in the longitudinal steel, followed by eventual crushing of concrete in the compression zone, allowing this beam to develop its full flexural capacity. As a result, the peak load increase by 12.9% when compared to specimen SCC 0%, with clear improvements in terms of ductility, overall toughness and structural performance.

Beam	Comments	
SCC 0%	Failure mode	Mid-span Δ (mm)
	Shear	15.1
		
SCC 0% 100mm	Failure mode	Mid-span Δ (mm)
	Steel yielding followed by Concrete crushing	43.3
		

Figure 5.1 Photographs; Effects of transverse reinforcement in SCC beams under static loading

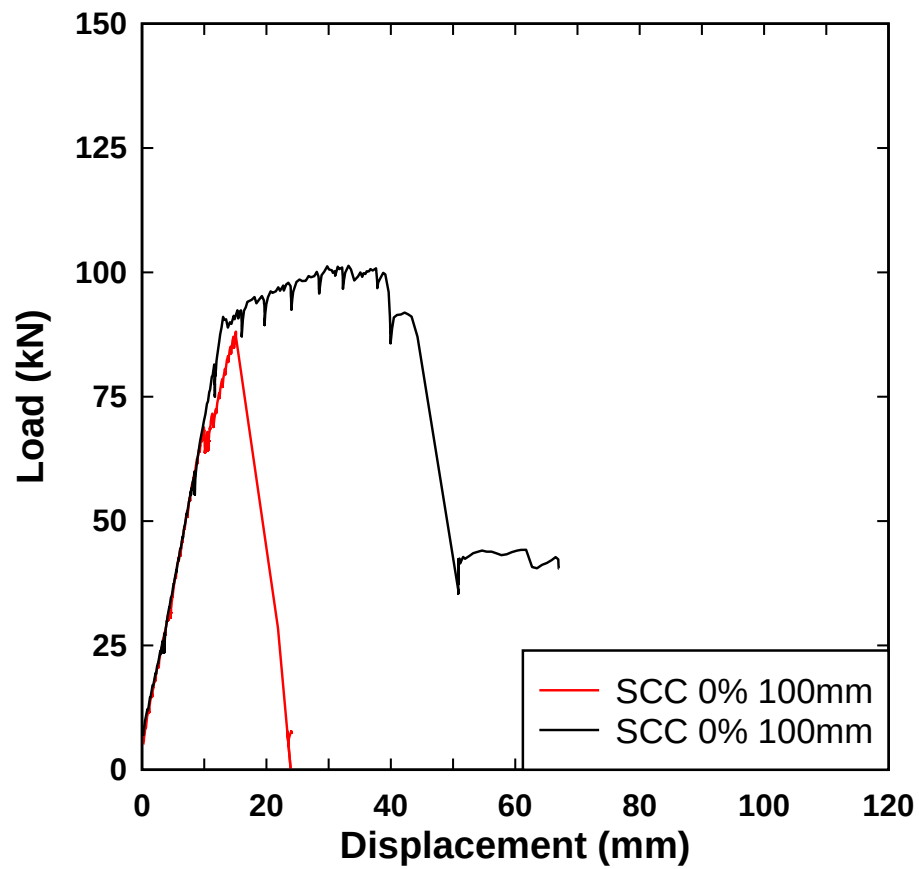


Figure 5.2: Load-displacement curve; Effects of transverse reinforcement in SCC beams under static loading

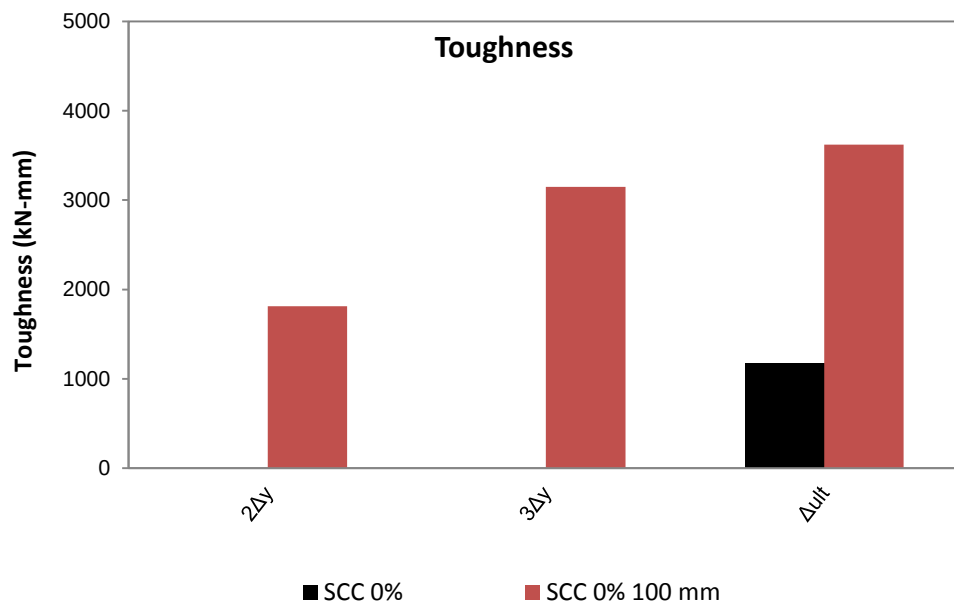


Figure 5.3: Toughness at $2\Delta_y$, $3\Delta_y$, $4\Delta_y$ and Δ_{ult} ; Effects of transverse reinforcement in SCC beams under static loading

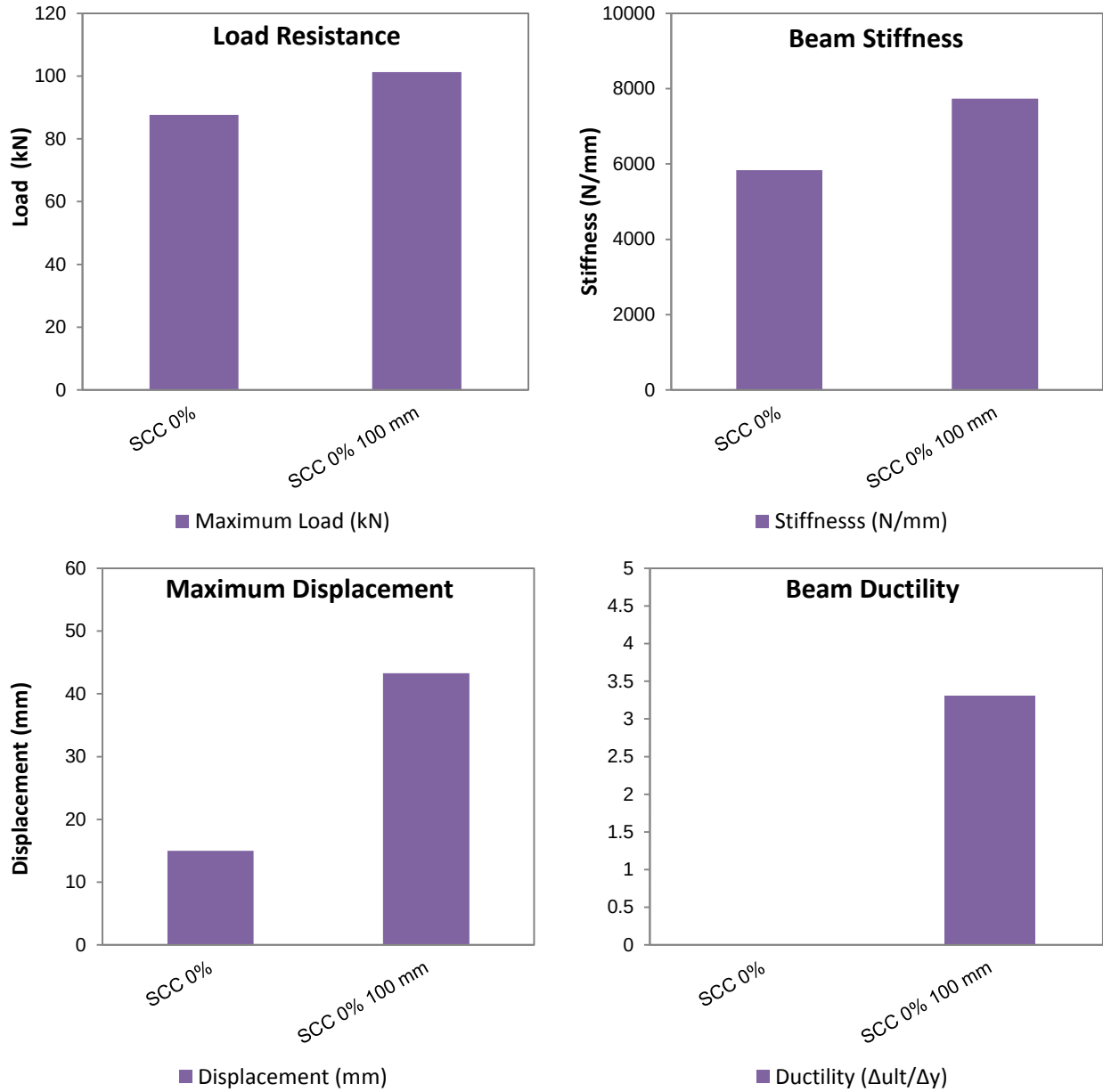


Figure 5.4: Load resistance, Beam stiffness, Maximum displacement and Beam Ductility; Effects of transverse reinforcement in SCC beams under static loading

5.2.2 Dynamic Loading- Effects of transverse reinforcement

The control specimens SCC 0% and SCC 0% 100mm were both designed with normal strength concrete without steel fibers. Relevant photographs of the beams after testing are included in Figure 5.5. Comparative displacement bar charts and time histories for blast 2 are provided in Figure 5.6 and Figure 5.7.

The transverse reinforcement increased the beam shear capacity, and changed the failure mode under blast loading from a brittle shear failure to a ductile flexural failure. As a result, the specimen

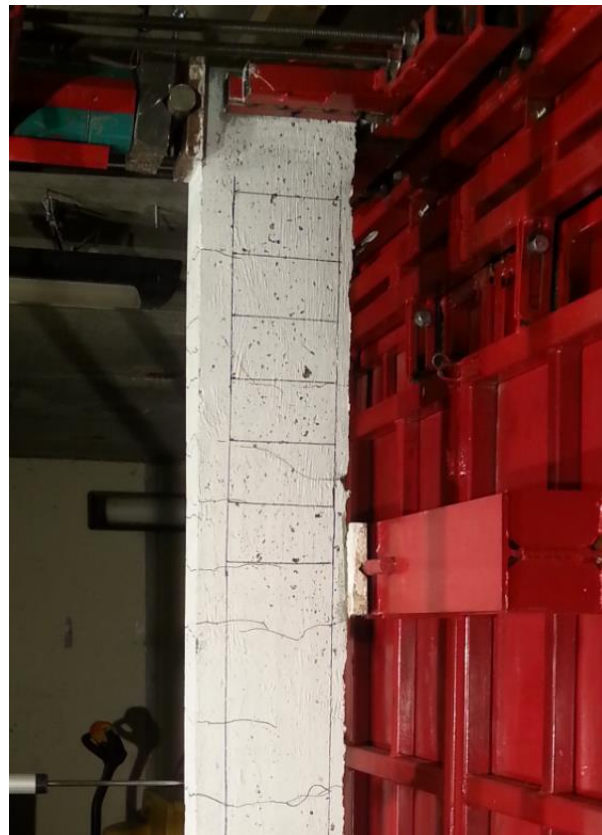
with transverse reinforcement was capable of resisting a greater blast pressures prior to failure when compared to the control without stirrups; while shear failure occurred during blast 2 for the SCC 0% specimen, the companion SCC 0% 100mm beam failed in flexure during blast 4.

The transverse reinforcement provided in specimen SCC 0% 100 mm had a negligible effect on displacements at blast 1 since the longitudinal steel both beams were still in their elastic range, and the concrete strength in both beams being roughly the same. At blast 2, maximum and residual displacement for beam SCC 0% 100 mm were reduced by a magnitude of 4.6% and 62.1% when compared to beam SCC 0%. The decrease in residual mid-span displacement can be attributed to the fact that the specimen without stirrups had failed and had lost all strength.

In summary, the results confirm the importance of providing sufficient transverse reinforcement in conventional RC beams in order to prevent brittle shear failure under blast loading.

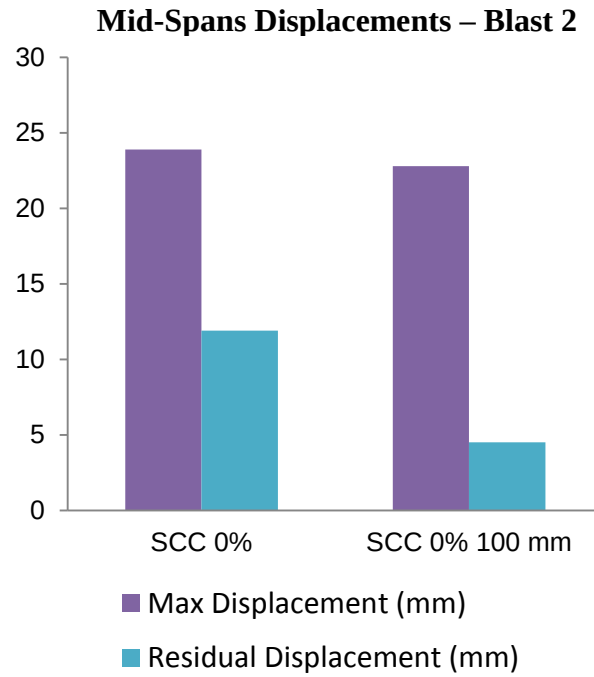


(a) SCC 0% Shear failure at Blast 2



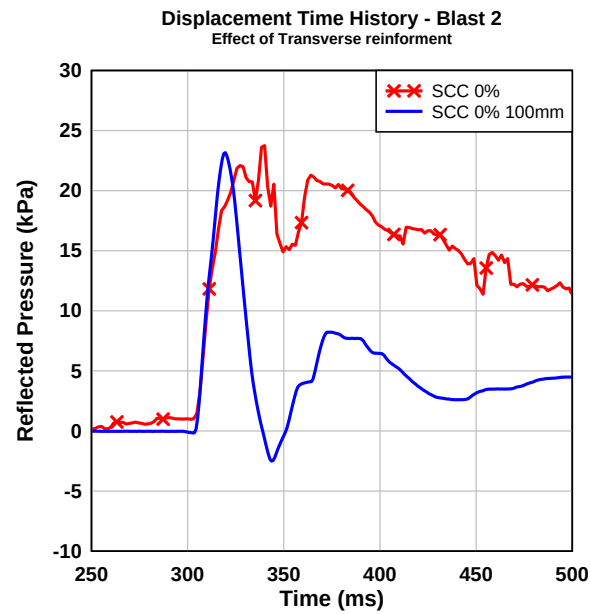
(b) SCC 0% 100mm at Blast 2

Figure 5.5: Photographs; effects transverse reinforcement under blast loading



(a) Blast 2

Figure 5.6: Maximum and residual displacements; effect of transverse reinforcing



(a) Blast 2

Figure 5.7: Displacement time histories; effects of transverse reinforcement

5.3 Effect of steel fiber ratio on shear and flexural behaviour

The beams that were tested in this research showed significant improvement in performance under static and blast loading when steel fibers were added to the concrete mix. The following comparison provide details on the benefits that were observed during the experimental program.

5.3.1 Static Loading -Effects of steel fiber ratio (ZP Fibers)

The control specimens SCC 0% and SCC 0% 100mm were both designed with normal strength concrete without steel fibers. The control SCC 0% 100 mm specimen had transverse reinforcement spaced at 100 mm in the shear span regions, while the second control beam (SCC 0%), and the companion SFRC specimens SCC 0.5% ZP, SCC 1% ZP did not have any transverse reinforcement. Relevant photographs of the beams after testing are included in Figure 5.8. Load-displacement curves are presented in Figure 5.9. Comparative peak load, stiffness and softening parameters bar charts are provided in Figure 5.10 and Figure 5.11.

The addition of fibers to the SCC mix increased the shear capacity of the beams under static loading. Unlike the control beam without stirrups (SCC 0%), all SFRC specimens in this series failed in flexure despite the lack of shear reinforcement, indicating that the fibers were effectively able to replace transverse reinforcement and promote ductile flexural failure.

As well as changing the failure mode from shear to flexure, the use of fibers also increased the flexural ductility of the beams when compared to the control beam with stirrups (SCC 0% 100mm). It can also be observed that the ductility increases with higher fiber ratios. Specimens SCC 0.5% ZP, SCC 1% and SCC 1.5% ZP showed increases in ductility ratio of 4.8%, 115.7% and 91.8 %, respectively, when compared to the control SCC 0% 100 mm beam. While specimen 1.5% ZP did provide increased ductility when compared to the control specimen with stirrups, the SFRC beams with 1.5% and 1% had similar ductility (testing was ended early for specimen with 1.5% fibers).

It can also be observed that the use of fiber increased performance in terms of toughness, with the improvements gradually increasing as fiber content went from 0.5% to 1.5%. When compared to the control beam, specimen SCC 0.5% ZP, SCC 1% ZP and SCC 1.5% ZP had an increased toughness at maximum displacement by 21.7%, 136.0% and 168.0%, respectively. It can be observed that there is a significant increase in toughness between the specimens with 0.5% and 1% fibers, while those with 1% and 1.5% fibers show relatively similar toughness. It is also noted

that increasing fibers beyond 1% had a significant effect on concrete workability (i.e. ease of concrete placement). Thus, the results indicate that 1% fibers maybe the optimal fiber ratio which compromises between structural performance, concrete workability and cost.

In summary, the results showed that steel fiber reinforcement can be used to replace conventional shear reinforcement, changing the failure mode from brittle shear ductile flexural failure. Increasing the fiber content generally resulted in higher peak load, ductility and toughness.

Beam	Comments	
	Failure mode	Mid-span Δ (mm)
SCC 0%	Shear	15.1
		
SCC 0% 100mm	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	43.3
		
SCC 0.5% ZP	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	50.3
		
SCC 1% ZP	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	112.1
		
SCC 1.5% ZP	Failure mode	Mid-span Δ (mm)
	Concrete crushing	101
		

Figure 5.8: Photographs; Effect of steel fiber ratio under static loading (ZP fiber)

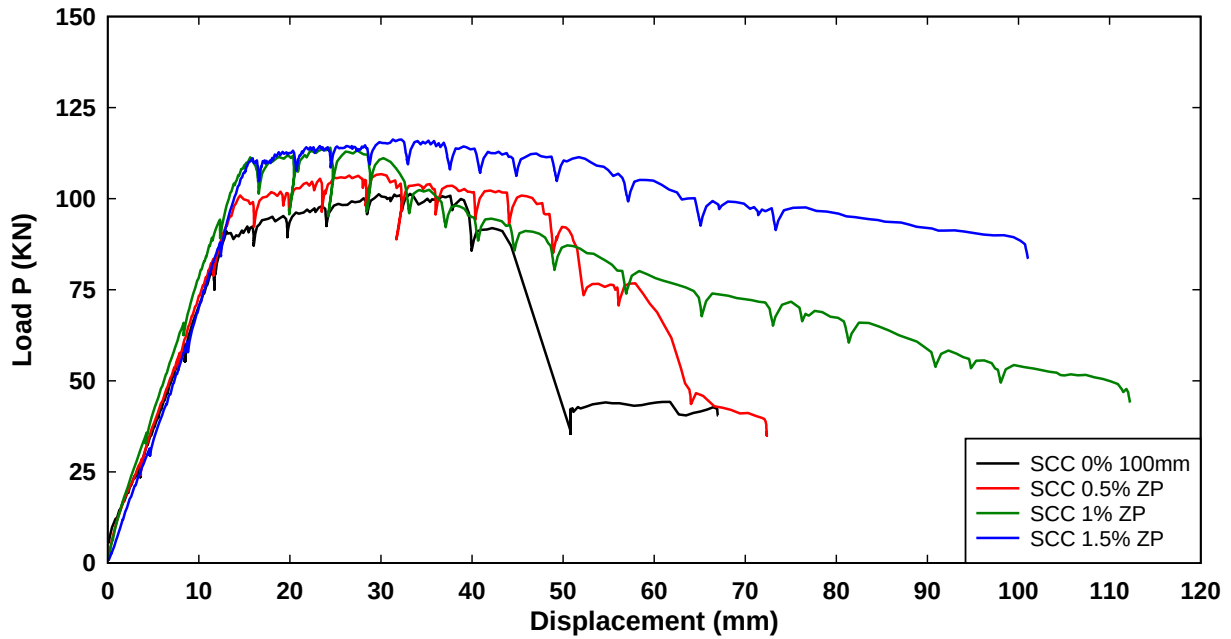


Figure 5.9: Load-displacement curve: Effects of fiber ration in SFRC beams under static loading (ZP fiber)

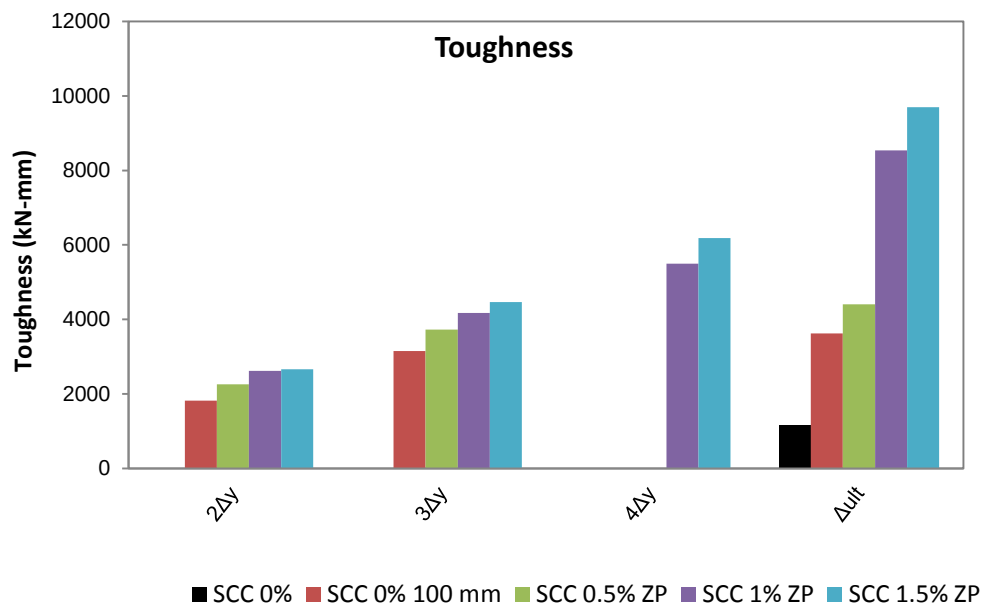


Figure 5.10: Toughness at $2\Delta_y$, $3\Delta_y$, $4\Delta_y$ and Δ_{ult} ; Effects of steel fiber ratio under static loading (ZP fiber)

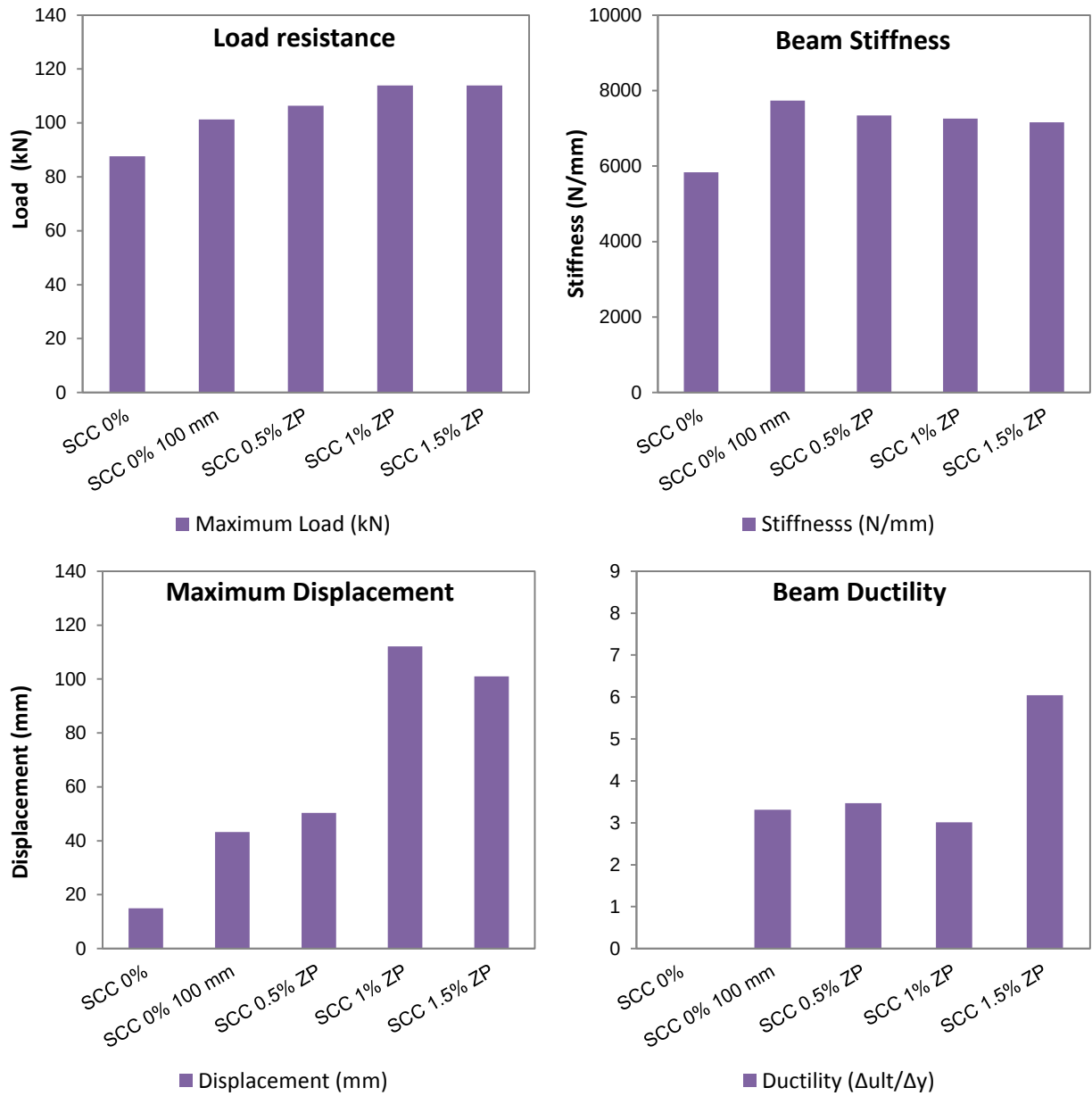


Figure 5.11: Load resistance, Beam stiffness, Maximum displacement and Beam Ductility; Effects of fiber ratio in SCC beams under static loading (ZP fiber)

5.3.2 Dynamic Loading - Effects of steel fiber ratio (ZP Fiber)

The effect of the ZP fibers and fiber ratio on blast performance is examined by comparing the responses of control specimens SCC 0% 100mm & SCC 0%, with specimens SCC 0.5% ZP, SCC 0.75% ZP, SCC 1% ZP and SCC 1.5% ZP. As noted previously, all SFRC specimens in this series did not have any transverse reinforcement. Relevant photographs are included in Figure 5.12. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.13 and Figure 5.14.

The use of ZP fibers increased the shear capacity of all SFRC specimens when compared to the control specimen built without stirrups (SCC 0%). Specimens SCC 0.5% ZP and SCC 0.75% both failed in shear but at blasts 4 and 3, respectively, compared to blast 2 for the control specimen. Specimen SCC 1% ZP and SCC 1.5% showed further enhancements in shear capacity, with both specimens failing in flexure, with the higher fiber ratios effectively substituting for the stirrups and preventing shear failure.

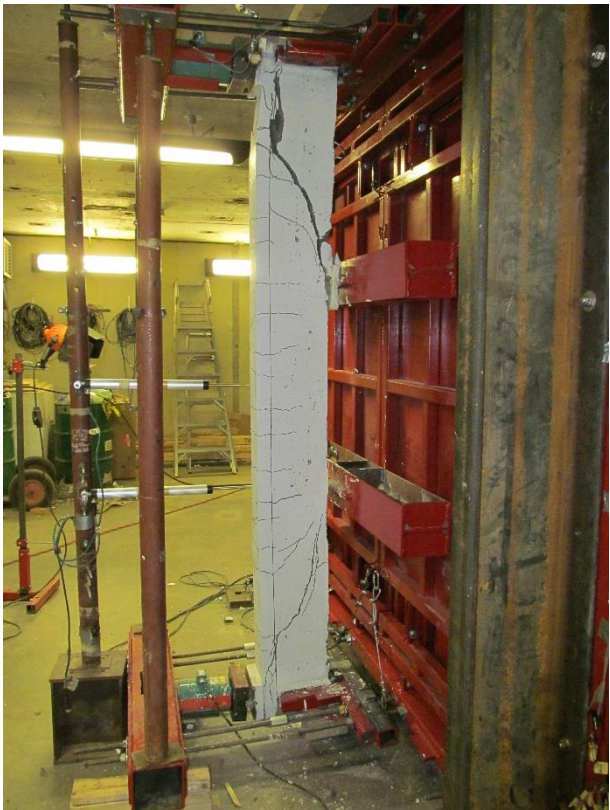
It can be observed that specimen SCC 0.5% ZP failed at blast 4 while specimen SCC 0.75% ZP, which had a higher fiber ratio (0.75% vs. 0.5%) failed in blast 3. This result can be attributed to the higher blast pressure and impulse applied on Specimen SCC 0.75% ZP during blast 3; when compared to Specimen SCC 0.5% ZP, it was subjected to an increase of 4.8% in peak reflected pressure (61.0 vs. 58.2 kPa) and 7.6% in impulse (527 vs. 487 kPa*msec). Another possible factor may have been the lower compression strength of the concrete in the specimen with 0.75% fibers when compared to the companion with 0.5% fibers (44.3 MPa vs. 41.5 MPa, which represents a difference of 6.3% in f'_c).

The use of sufficient amount of fibers (1% and above) effectively prevented shear collapse, and further improved the flexural performance of the SFRC beams when compared to the control beam with stirrups (SCC 0% 100 mm). The use of 1% fibers in specimen SCC 1% ZP allowed for a reduction of 12.9% for maximum displacement and 40.4 % for residual displacement at blast 3. Similarly, at blast 4, the maximum and residual mid-span displacements decreased by 21.8% and 50.57%, respectively for the SFRC specimen.

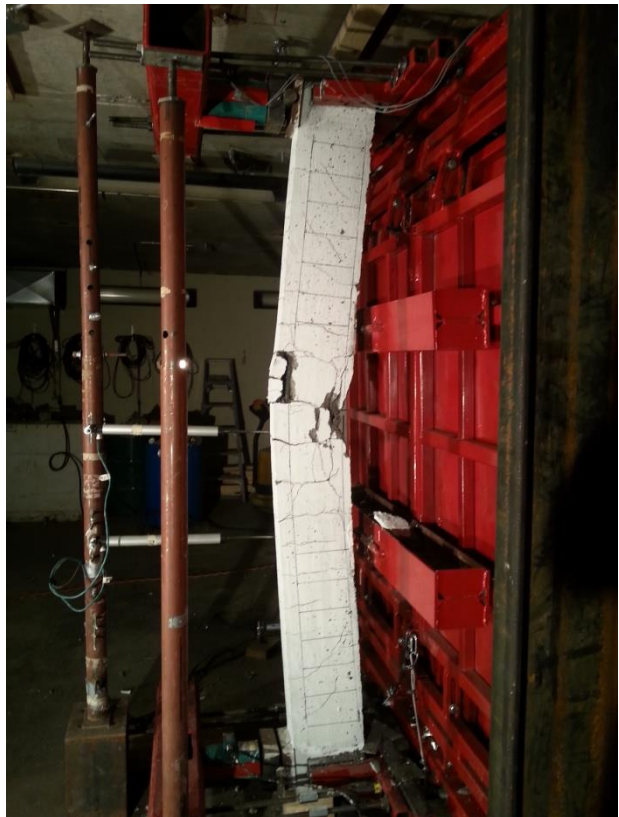
The same effect was observed in specimen SCC 1.5% ZP, which reduced the magnitude of the mid-span displacements when compared to the control beam built with stirrups, however the

improvements were not greater than those of specimen SCC 1% ZP. The use of the higher fiber ratio had a noticeable reduction in workability in term of slump flow which resulted in more difficult placement during construction (Specimen SCC 1.5% ZP had a 31% lower slump when compared to specimen SCC 1% ZP). This may have affected fiber distribution, thereby leading to reduced fiber efficiency on structural response.

In summary, the results indicate that the optimal content for the ZP fibers for this concrete mix corresponds to 1% of ZP fibers by volume of concrete. At the optimal fiber content, the use of fibers was able to effectively replace conventional transverse reinforcement and prevent shear failure, while also resulting in improved control of blast-induced maximum and residual displacements.



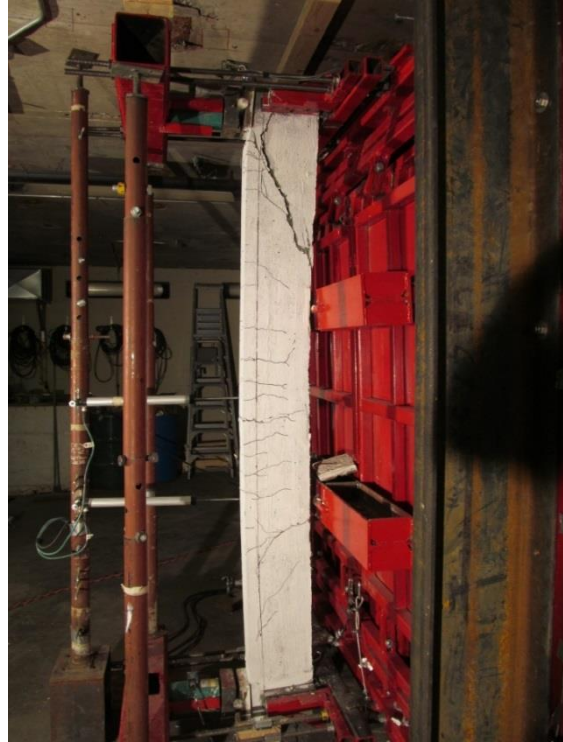
(a) SCC 0% shear failure at Blast 2



(b) SCC 0% 100mm flexural failure at Blast 4



(c) SCC 0.5% ZP shear failure at Blast 4



(d) SCC 0.75% ZP Shear failure at Blast 3



(e) SCC 1% ZP flexural failure at Blast 4



(f) SCC 1.5% ZP flexural failure at Blast 4

Figure 5.12: Photographs; effects of fiber ratio under blast loading (ZP steel fibers)

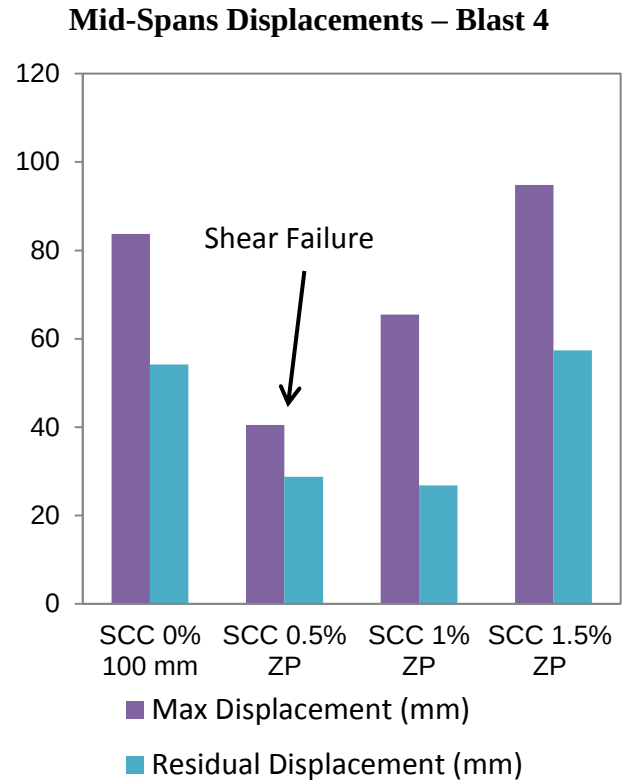
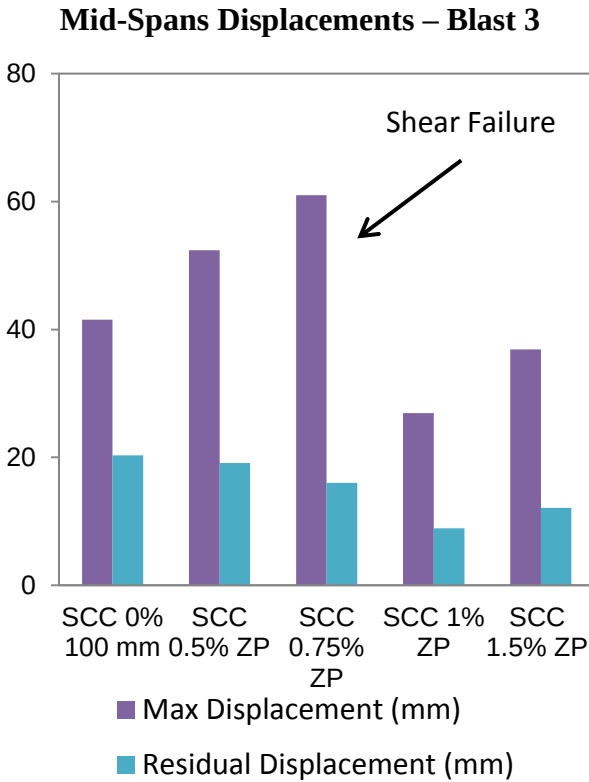


Figure 5.13: Maximum and residual displacements; effect of fiber ratio (ZP fiber)

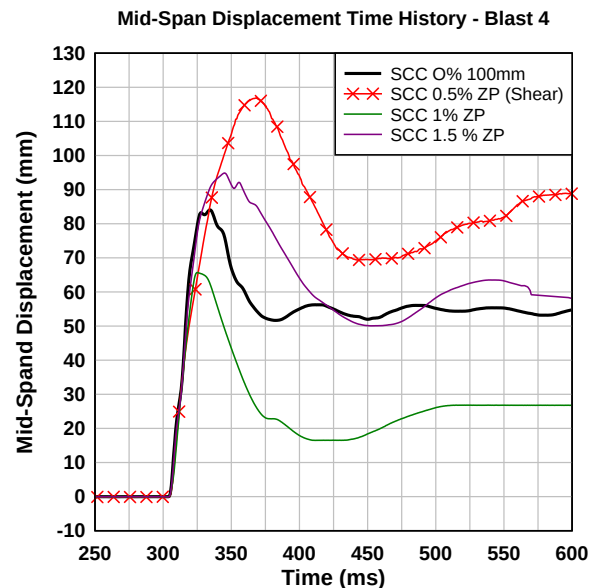
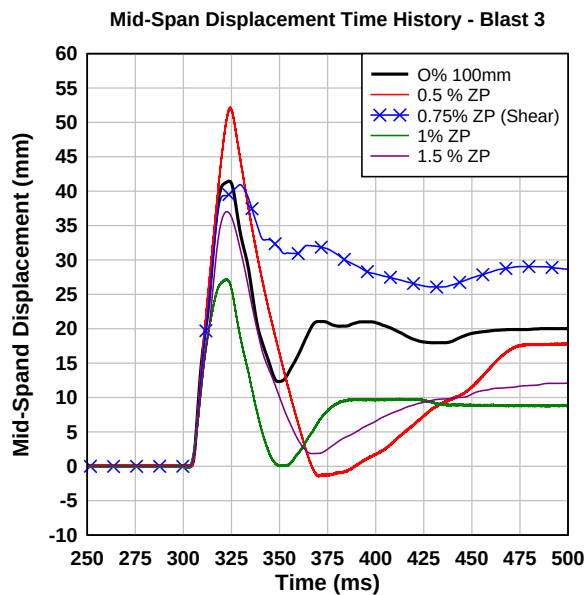


Figure 5.14: Displacement time histories; effects of fiber ratio (ZP fiber)

5.3.3 Dynamic Loading - Effects of steel fiber ratio (5D Fiber)

The next section examined the effect of using 5D fibers and fiber ratio on blast performance when compared to the control specimens (SCC 0%, SCC 0% 100mm). Included in the comparison are the following SFRC specimens: SCC 0.5% 5D, SCC 0.75% 5D, SCC 1% 5D and SCC 1.5% 5D which did not have transverse reinforcement, and were reinforced with 0.5%, 0.75%, 1% and 1.5% 5D fibers. Relevant photographs are included in Figure 5.15. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.16 and Figure 5.17.

As with the previous series, adding 5D fibers to the mix increased shear capacity, and when added in sufficient quantity, promoted ductile flexural failure. The use of 5D fibers in all SFRC increased the shear capacity when compared to the control specimen without stirrups (SCC 0%). Specimen SCC 0.5% failed in shear but at blast 4, compared to blast 2 for the unreinforced control specimen. Specimens SCC 0.75% 5D, SCC 1% 5D experienced ductile flexural failure modes, with the use of 0.75% and 1% 5D fibers preventing shear failure and effectively substituting for transverse reinforcement.

Specimen SCC 0.75% 5D and SCC 1% 5D also showed improved flexural performance, with reduced mid-span displacements when compared to the control specimen with stirrups (SCC 0% 100mm). At blast 3, beam SCC 0.75% 5D showed a reduction of 8.8% and 11.8% in maximum and residual displacements when compared to the control beam, while Specimen SCC 1% 5D showed greater reductions of 18.4% and 43.3% in maximum and residual deformations due to the use of higher 5D fiber content. At blast 4, the maximum and residual mid-span displacements decreased by 6.9% and 9.8% for specimen SCC 0.75% 5D, while the maximum and residual mid-span displacements decreased by 35.8% and 56.5% for specimen SCC 1% 5D, when compared to the control beam built with plain SCC.

The use of 1.5% fibers content did not follow this lead to further enhancements in performance. While beam SCC 1.5% 5D showed reduced mid-span displacement when compared to the control specimen SCC 0% 100mm at the lower blasts (Blast 1 and 2), failure of this beam occurred in shear at Blast 3, indicating there was a problem in the concrete mix when using this higher fiber ratio. Indeed, the concrete mix with 1.5% 5D fibers was prone to segregation, and reduced workability, with placement issues during construction (specimen SCC 1.5% had a 14.3% reduction in slump flow (397 mm vs 457 mm) when compared to specimen SCC 1% 5D).

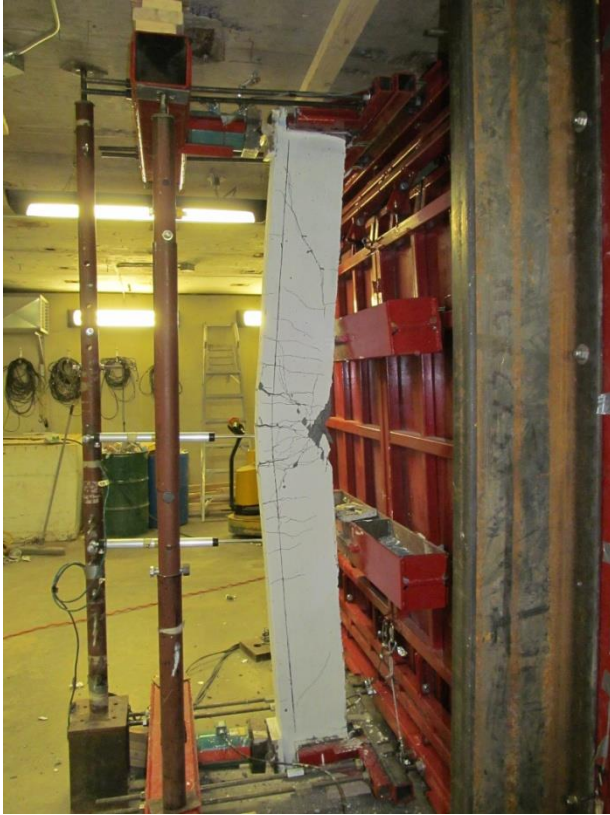
In summary, similar to the previous series, the results showed that the optimal content for the 5D fiber was 1% by volume of concrete. At the optimal fiber content, the use of fibers was able to effectively replace conventional transverse reinforcement and also exhibited the best improvements in terms of control of maximum and residual displacements.



(a) SCC 0% 100mm flexural failure at Blast 4



(b) SCC 0.5% 5D shear failure at Blast 4



(c) SCC 0.75% 5D flexural failure at Blast 4



(d) SCC 1% 5D at Blast 4



(e) SCC 1.5% 5D shear failure at Blast 3

Figure 5.15 Photographs; effect of fiber ratio (5D fiber)

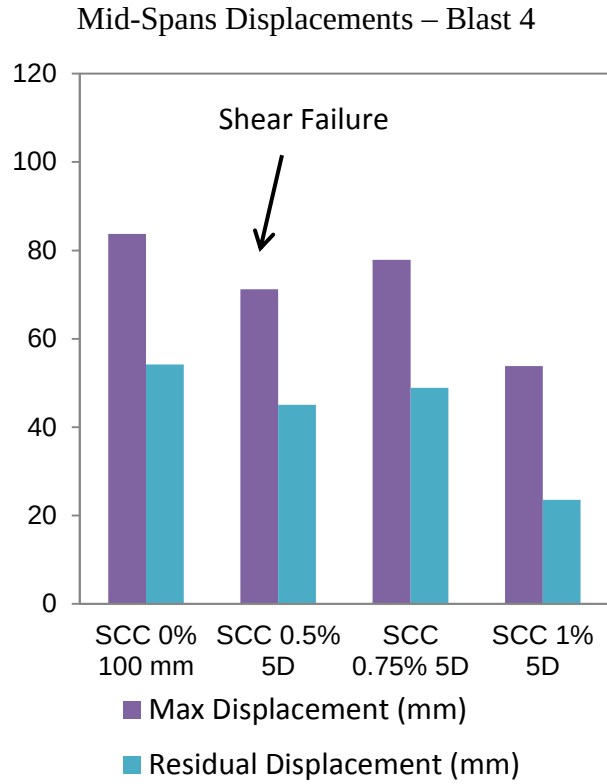
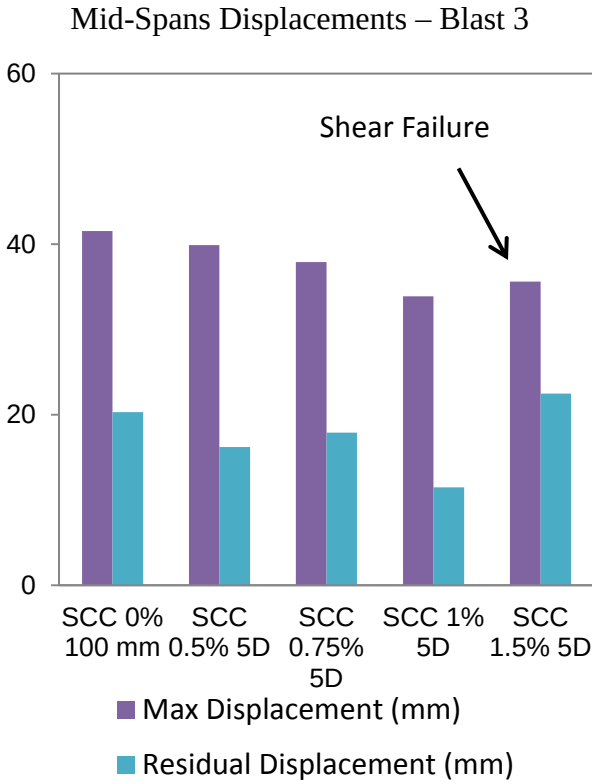


Figure 5.16: Maximum and residual displacements; effect of fiber ratio (5D fiber)

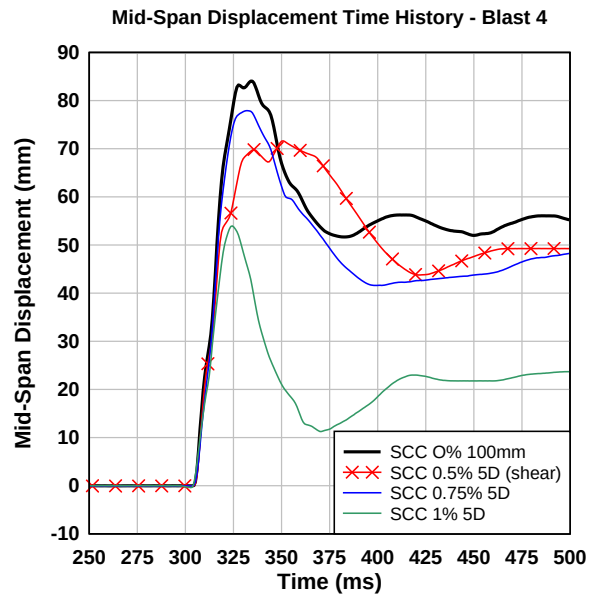
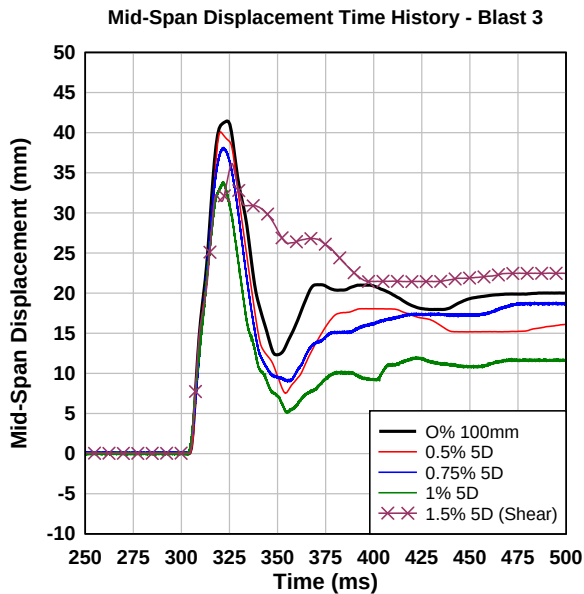
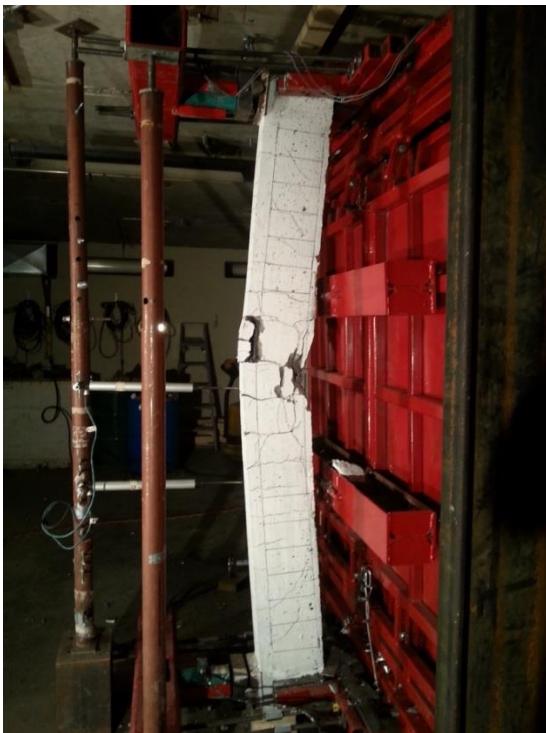


Figure 5.17: Displacement time histories; effects of fiber ratio (5D fiber)

5.3.4 Dynamic Loading - Effects of steel fiber (BP fiber)

This section examines the effect of using the high-strength BP fibers on the blast performance of the beams. Included in the comparison is beam SCC0.75% BP (which had 0.75% BP fibers and no stirrups) and control specimens SCC 0% 100mm and SCC 0%, which were built with plain SCC. Relevant photographs are included in Figure 5.18. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.19 and Figure 5.20.

The use of BP fibers in the SCC mix had a significant effect on both shear and flexural performance. First, the fibers allowed for an increase in shear resistance, with beam SCC 0.75% BP failing in flexure at Blast 4, compared to the shear failure at Blast 2 for the control specimen built without stirrups (SCC 0%). The use of BP fibers in specimen SCC 0.75% BP also greatly reduced the magnitude of the mid-span displacement when compared to the control beam with stirrups. When compared to SCC 0% 100mm, the beam with BP fibers showed reductions of 2.5% for maximum displacement and 28.57 % for residual displacement at blast 3. At blast 4, the maximum and residual mid-span displacements decreased by 18.7% and 33.2%, respectively.



(a) SCC 0% 100mm flexural failure at Blast 4



(b) SCC 0.75% BP flexural failure at Blast 4

Figure 5.18: Photographs; effect of high-strength fibers (BP fiber)

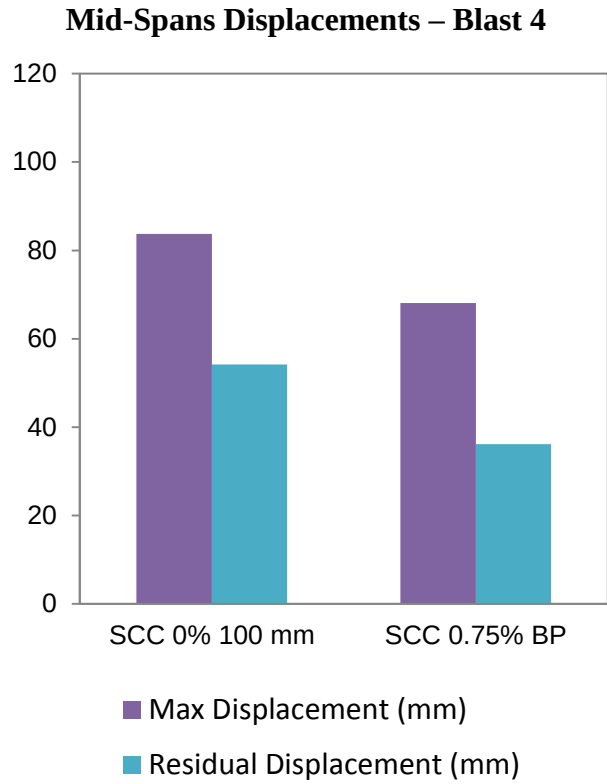
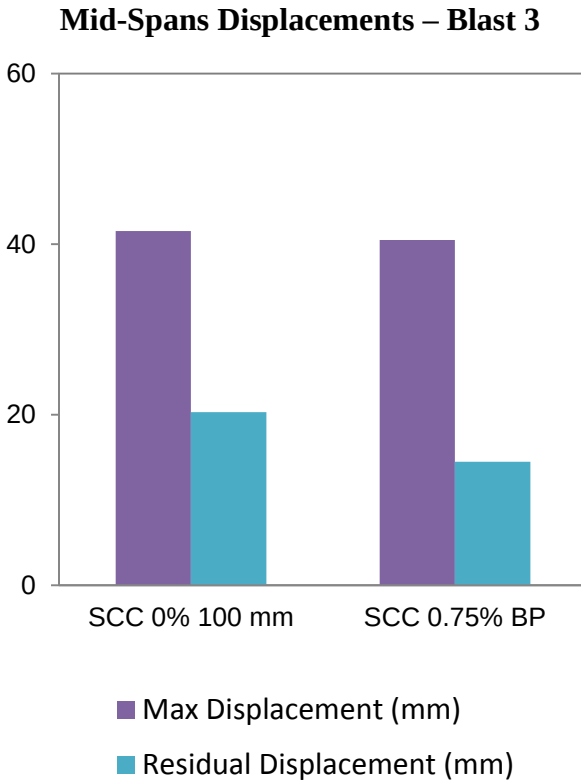


Figure 5.19: Maximum and residual displacements; effect of high-strength fibers (BP fiber)

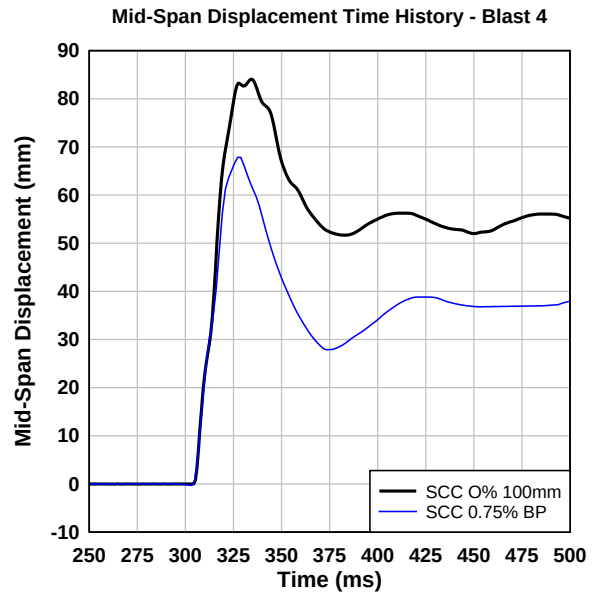
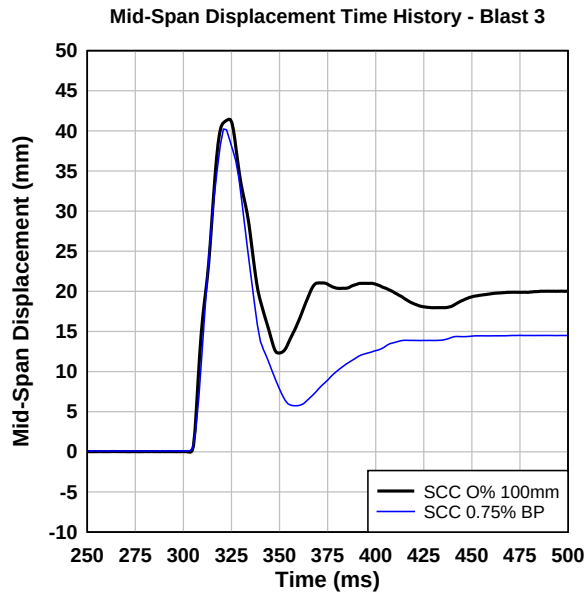


Figure 5.20: Displacement time histories; effects of high-strength fibers (BP fiber)

5.4 Effect of steel fiber type on shear and flexural behavior

The previous sections demonstrated the effects of steel fibers and fiber content on the static and blast performance of the reinforced concrete beams. Three different fibers were investigated in this research, each having different properties in terms of length, strength and aspect-ratio. This section examines the effect of fiber type on beam performance.

5.4.1 Static Loading - Effects of steel fiber type

SFRC specimens SCC 1.5% ZP, SCC 1.5% 5D and SCC 0.75% BP did not have any transverse reinforcement and were designed with 1.5% of ZP, 1.5% of 5D and 0.75% of BP fibers, respectively. It is noted the 5D fiber has longer length (50 mm vs. 30 mm) and improved anchorage properties when compared to ZP and BP fiber. Moreover, the 5D and BP fiber had higher aspect-ratios (65 and 79 vs. 55 respectively) and higher tensile strength (2300 MPa vs. 1100 MPa) when compared to the normal-strength ZP fiber. Relevant photographs of the beams after testing are included in Figure 5.21 and load-displacement curves are presented in Figure 5.22. Comparisons to the control plain SCC specimens are also included in the figures. Comparative peak load, stiffness and softening parameters bar charts are provided in Figure 5.23 and Figure 5.24.

As noted previously, the addition of fibers to the SCC mix increased the shear capacity of the beams when compared to the control specimen without stirrups and without fibers (SCC 0%). Unlike the control beam, all SFRC specimens in this comparison set failed in flexure instead of shear, indicating that the addition of 1.5% ZP/5D and 0.75% BP fibers was sufficient to effectively replace the transverse reinforcement required to develop flexural capacity.

All three SFRC specimens show a plateau due to the development of yielding the longitudinal steel reinforcement, and it can be observed that all three beams show increased peak load when compared to the control SCC 0% 100 mm which had transverse reinforcement and failed in flexure. The greatest improvement was observed in specimen 5D, while the ZP and BP specimens show similar peak capacities. Comparing specimens SCC 1.5% 5D and SCC 1.5% ZP which had the same fiber content of 1.5%, it can be seen that the specimen with 5D fibers showed a relative increase in peak strength of 15.8 %, vs. 24.7 % for the ZP specimen. When comparing the resistance curves, specimen SCC 1.5% 5D also had an increased stiffness. Despite the increased peak resistance, the load-deflection curve dropped to a similar load at around 40mm of mid span deflection.

As well as changing the failure mode from a brittle shear to a ductile flexural failure, the use of fibers greatly increased the ductility of the beams when compared to the control beam with stirrups (SCC 0% 100mm). It can be observed that ductility increases for all SFRC beams although the degree of improvement is influenced by fiber type. Specimen SCC 1.5 % ZP, SCC 1.5% 5D and SCC 0.75% BP recorded improvements in ductility ratio of 91.8%, 55.3% and 138.9 %, respectively. While specimen 1.5% 5D did provide increased ductility when compared to the control specimen with stirrups, the relative enhancement is not greater when compared to specimen SCC 1.5% ZP, indicating that the longer 5D fiber did not lead to increased ductility. It can also be observed that Specimen SCC 0.75% BP which had the fiber with the greatest aspect-ratio had the best response in terms of ductility (despite reduced fiber content from 1.5% to 0.75%) indicating that aspect ratio has a greater effect on ductility when compared to fiber volume fraction.

The same trends regarding 5D and BP fibers can be observed when comparing the toughness of the beams in this set. When compared to the control specimen without fibers, Specimen SCC 1.5 % ZP, SCC 1.5% 5D and SCC 0.75% BP recorded improvements in toughness at maximum displacement of 168%, 101.9% and 201.4%, respectively.

In summary, the results showed the greatest benefits were observed when increasing aspect ratio. Specimen SCC 0.75% BP showed the greatest increase in ductility, toughness even though it only had half the amount of fibers of the other specimens.

Beam	Comments	
SCC 0% 100mm	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	43.3
		
SCC 1.5% ZP	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	101
		
SCC 15% 5D	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	83.3
		

SCC 0.75% BP	Failure mode	Mid-span Δ (mm)
	Steel yielding + Concrete crushing	116.3
		

Figure 5.21: Photographs; Effects of steel fiber type under static loading

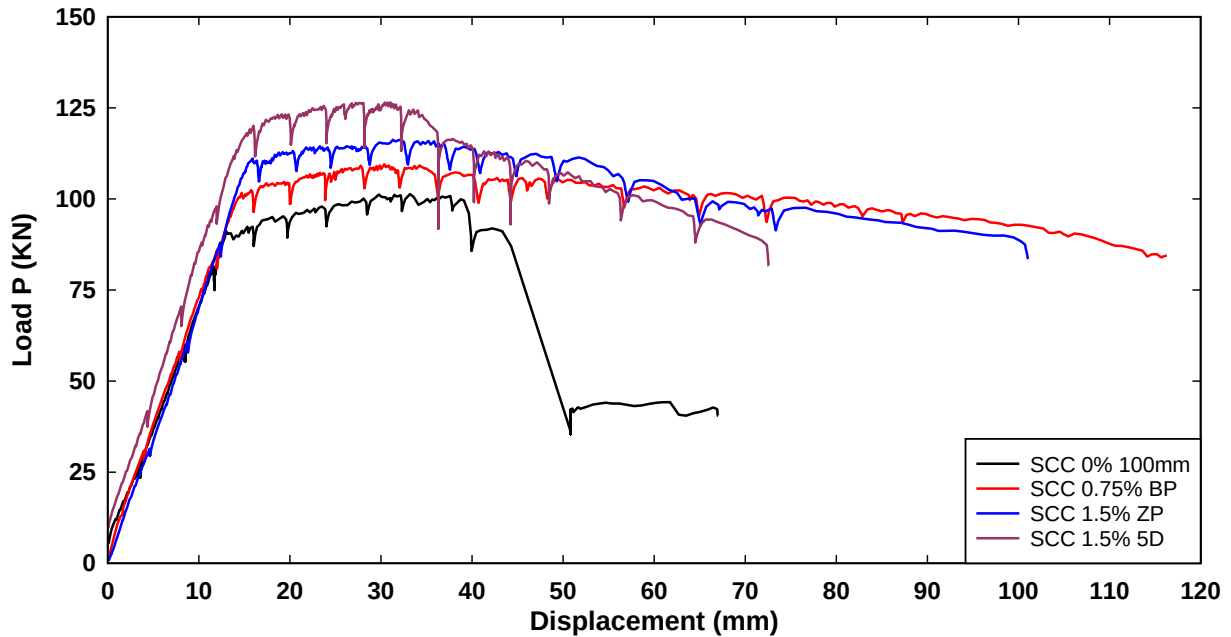


Figure 5.22: Load- displacement curves; Effect of steel fiber type under static loading

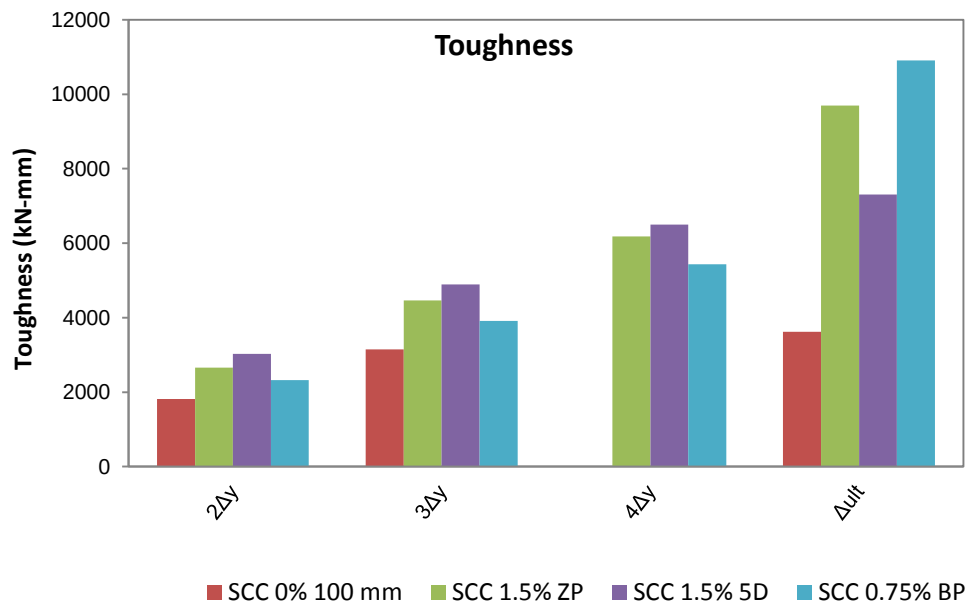


Figure 5.23: Toughness at $2\Delta_y$, $3\Delta_y$, $4\Delta_y$ and Δ_{ult} ; Effects of steel fiber type under static loading

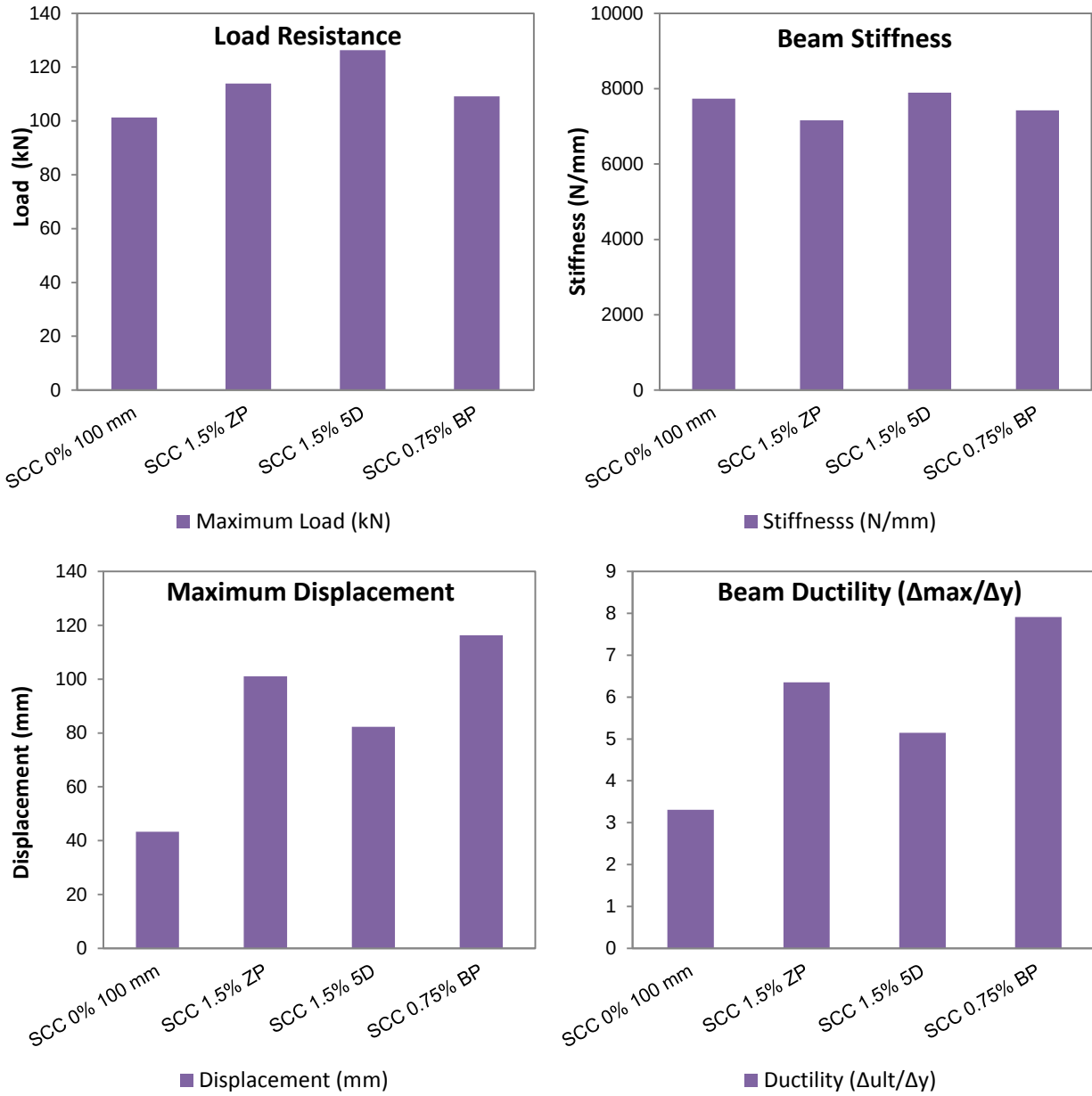


Figure 5.24: Load resistance, Beam stiffness, Maximum displacement and Beam Ductility; Effects of fiber type

5.4.2 Dynamic Loading - Effects of steel fiber type (1 of 3: $V_f = 0.5\%$)

The effect of fiber type on blast response was investigated by comparing the performance of companion SFRC beams having the same fiber content but built with different fiber types. In this section, the response of companion beams built with 0.5% fibers is compared. Included are SFRC specimens SCC 0.5% ZP, SCC 0.5% 5D which were built with ZP and 5D fibers, respectively. Both specimens did not have transverse reinforcement. It is noted the 5D fiber has longer length (50 mm vs. 30 mm), higher aspect-ratio (65 vs. 55), higher tensile strength (2300 mPa vs. 1100 mPa) and also improved anchorage properties when compared to the ZP fiber. Relevant photographs are included in Figure 5.25. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.26 and Figure 5.27.

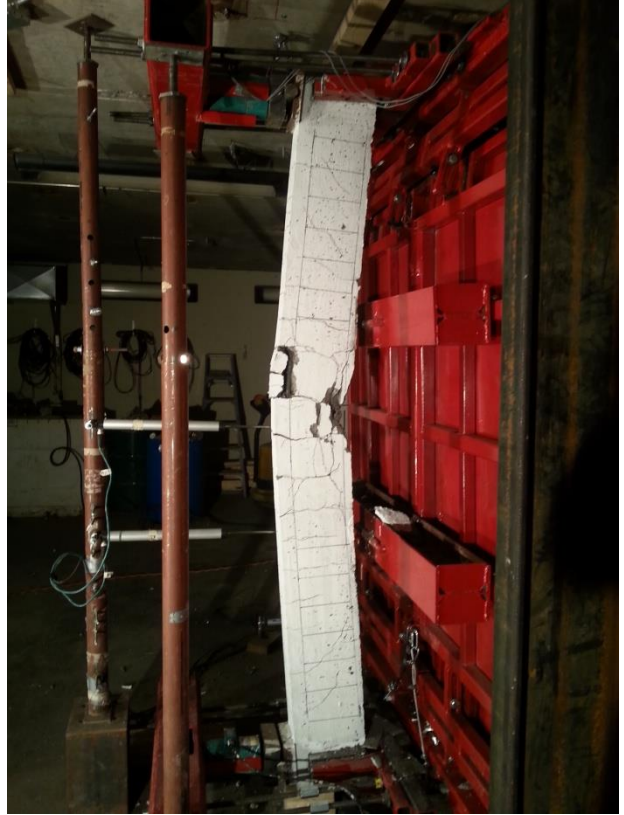
The addition of 0.5% fibers increased the shear capacity of both SFRC beams when compared to the control specimen which had no stirrups (SCC 0%). Nonetheless the relatively low fiber content was not sufficient to prevent shear collapse, with Specimen SCC 0.5% ZP and SCC 0.5% 5D failing at blast 4, which is nonetheless an improvement in blast shear capacity when compared to the control beam which failed at blast 2. While both fiber-reinforced specimens failed at the same blast intensity, the severity of the shear failure is noticeably greater in the beam with ZP fibers.

Because both SFRC beams failed in shear in blast 4, they did not provide an improvement in terms of mid-span displacement control when compared to the SCC specimen with stirrups (SCC 0% 100mm). Specimen SCC 0.5% had an increased maximum displacement by 26.1%, but a reduced residual displacement by 5.9% for blast 3 when compared to the control beam which had stirrups. Specimen SCC 0.5% 5D had reduction of maximum and residual mid span displacements of 4.0% and 20%, respectively when compared to the same control beam at this blast level.

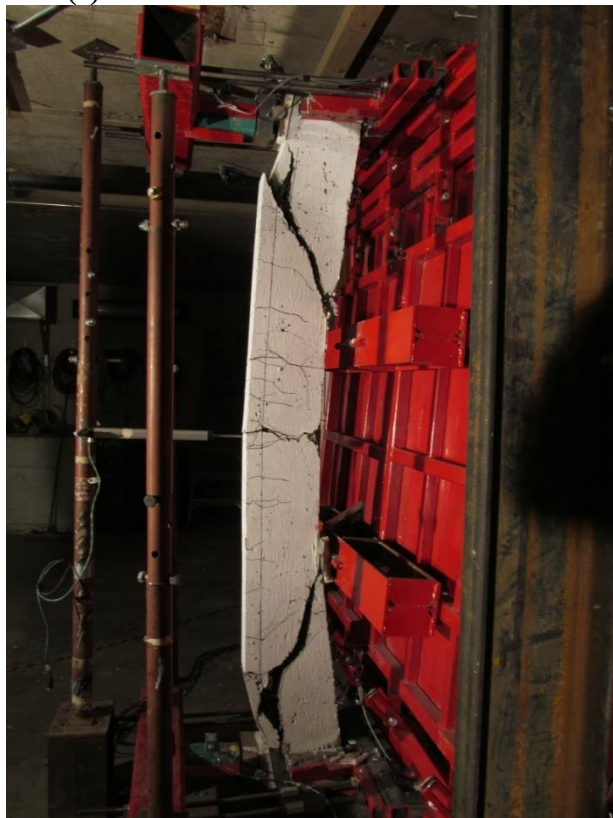
In summary, the results show that while the use of 0.5% fibers improves blast performance it is not sufficient to prevent shear failure. Since companion beams with 0.5% fibers failed in flexure under static loads, the results point to possible reduced fiber performance under blast loads. However, the fact the beams were tested under repeated blasts, where fibers can pullout prior to the final blast application may have been a factor which led to shear failure in the dynamic specimens. Based on the limited tests conducted there are no clear differences between the ZP and 5D fiber type at this lower fiber content, although failure was more severe for the beam with ZP fibers.



(a) SCC 0% mm shear failure at Blast 2



(b) SCC 0% 100mm flexural failure at Blast 4



(c) SCC 0.5% ZP shear failure at Blast 4



(d) SCC 0.5% 5D shear failure at Blast 4

Figure 5.25: Photographs; effect of fiber type (0.5% fiber ratio)

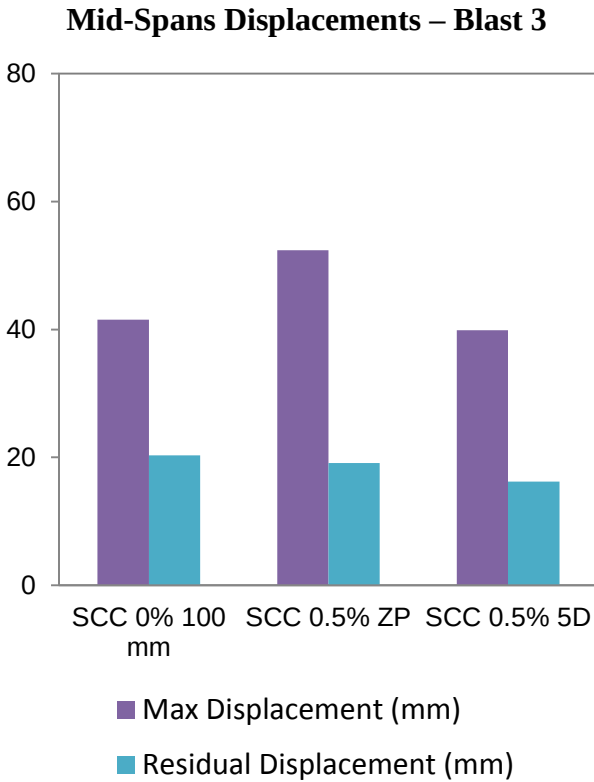


Figure 5.26: Maximum and residual displacements; effect of fiber type (0.5% fiber ratio)

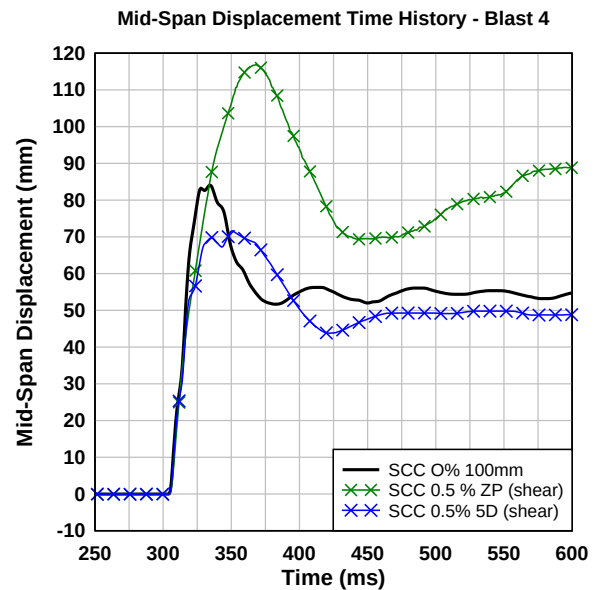
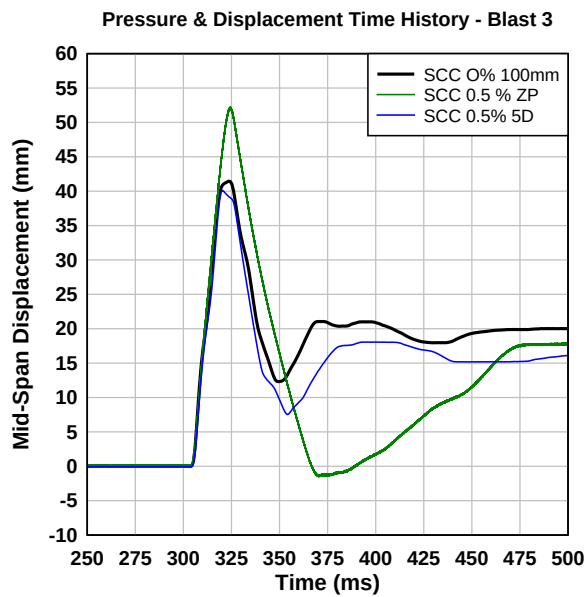


Figure 5.27: Displacement time histories; effects of fiber type (0.5% fiber ratio)

5.4.3 Dynamic Loading - Effects of steel fiber type ($V_f = 0.75\%$)

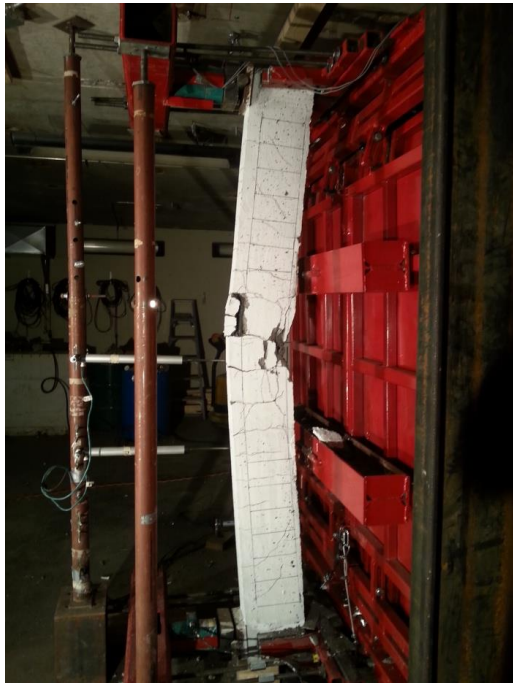
This section examined the effect of fiber type in the SFRC beams built with 0.75% fibers. Included in the comparison are SFRC beams SCC 0.75% ZP, SCC 0.75% 5D and SCC 0.75% BP, which did not have transverse reinforcement but had 0.75% of ZP, 5D and BP fibers, respectively. It is noted the 5D has longer length (50 mm vs. 30 mm) and also improved anchorage properties when compared to both ZP and BP fiber. It is also noted that the 5D and BP fiber had higher aspect-ratios (65 and 79 vs. 55 respectively) and higher tensile strengths (2300 MPa vs. 1100 MPa) when compared to the ZP fiber. Relevant photographs are included in Figure 5.28. Comparative displacement charts and time histories for blast 3 & 4 are provided in Figure 5.29 & Figure 5.30.

The use of 0.75% fibers provided in all SFRC specimens increased shear capacity when compared to the control specimen without stirrups (SCC 0%). Specimen SCC 0.75% ZP with the lowest aspect ratio still failed in shear, but at blast 4 compared to blast 2 for the control specimen. Specimen SCC 0.75% 5D and specimen SCC 0.75% BP, which had improved fiber properties, both failed in flexure instead of shear, thereby demonstrating the enhanced effect of these fiber types on diagonal tension capacity and beam shear resistance.

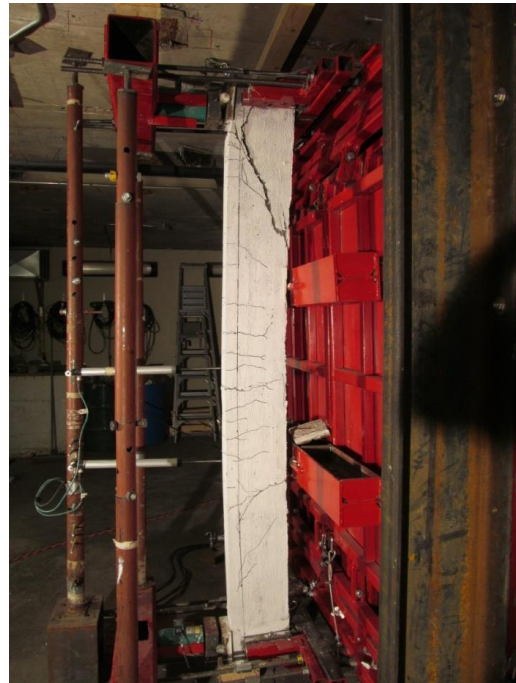
Specimens SCC 0.75% 5D and SCC 0.75% BP also led to improved flexural response in terms of reducing the magnitude of mid-span displacement when compared to the control specimen with stirrups (SCC 0% 100 mm). For blast 3, Specimen SCC 0.75% 5D had reductions of 8.8% and 11.8% for maximum and residual mid span displacement, while specimen SCC 0.75% BP showed reductions of 2.5% and 28.6% for maximum and residual displacement when compared to the control SCC 0% 100mm. At blast 4, Specimens SCC 0.75% 5D and SCC 0.75% BP showed reductions in maximum displacement by margins of 7.0% and 18.7% respectively, and reductions in residual displacements of 18.7% and 33.2%, when compared to the same control. It can be observed that there is a clear trend of improved response in terms of control of residual mid-span displacement with the increase in fiber aspect ratio (BP vs. 5D fibers).

In summary, the results show that using fibers with optimized properties leads to enhanced blast performance. Both the 5D and ZP fibers prevented shear failure at 0.75% fiber content when compared to the companion with 0.75% ZP fiber. Thus it can be concluded that using fibers with higher aspect ratio (as in the case of specimen SCC 0.75% BP) or increased length/enhanced anchorage leads to enhanced blast performance. When comparing the results for the BP and 5D

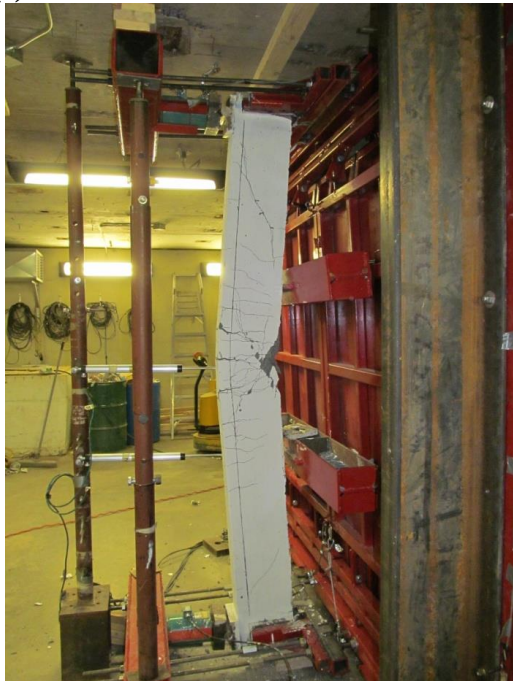
fibers it can be concluded that using fibers with greater aspect ratio has a greater effect when compared to length/anchorage.



(a) SCC 0% 100mm flexural failure at Blast 4



(b) SCC 0.75% ZP Shear failure at Blast 3



(c) SCC 0.75% 5D flexural failure at Blast 4



(d) SCC 0.75% BP flexural failure at Blast 4

Figure 5.28: photographs; effect of fiber type (0.75% fiber ratio)

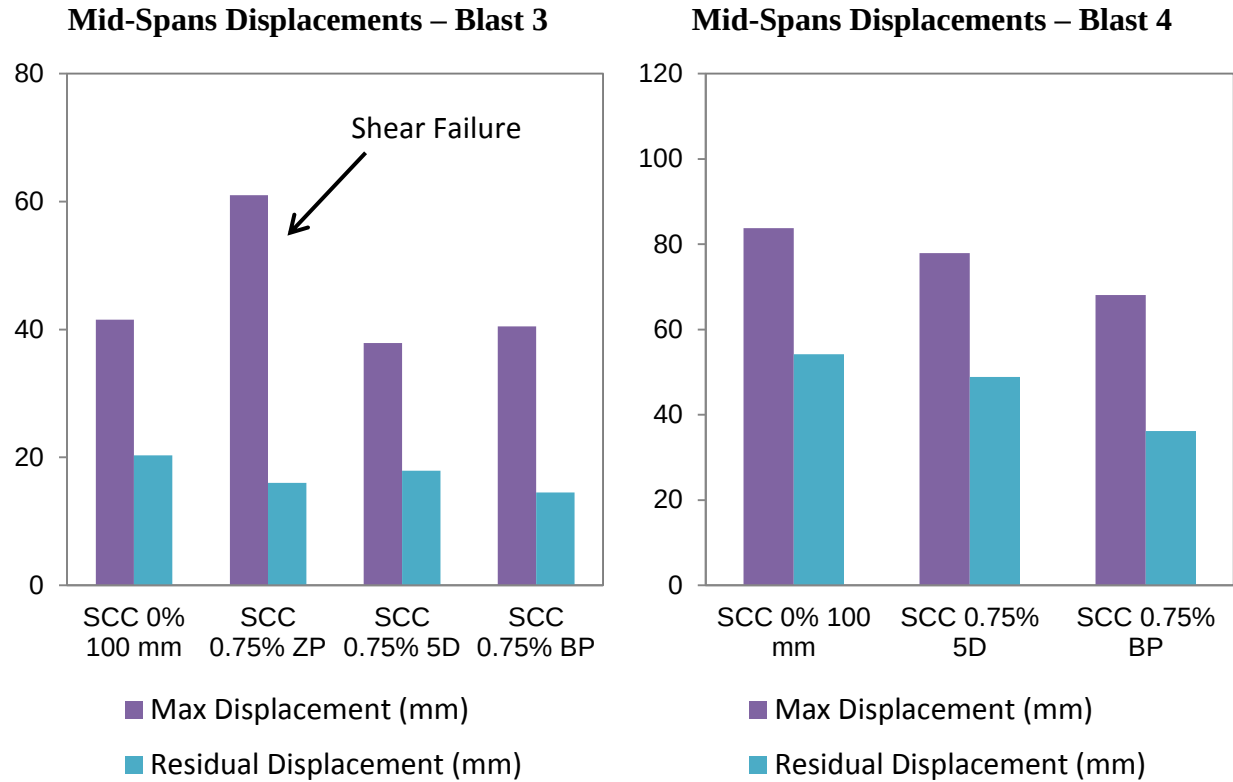


Figure 5.29: Maximum and residual displacements; effect of fiber type (0.75% fiber ratio)

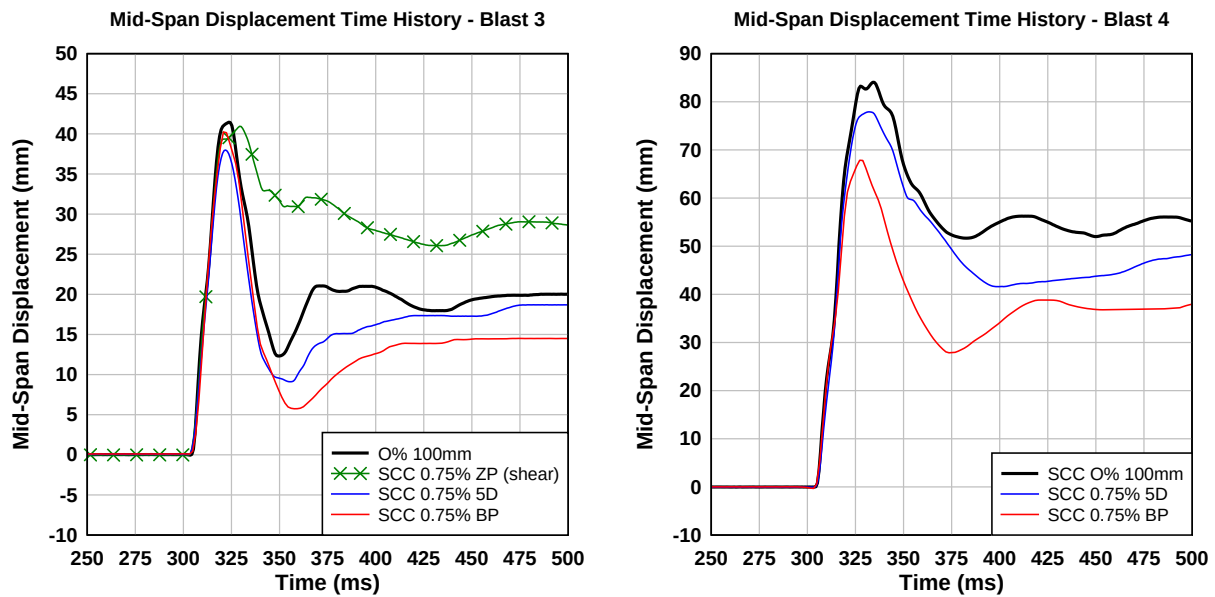


Figure 5.30: Displacement time histories; effects of fiber type (0.75% fiber ratio)

5.4.4 Effects of steel fiber type ($V_f = 1\%$)

This section continues the discussion on the effect of fiber type and examined the response of companion SFRC beams built with 1% fibers. Control specimen SCC 0% 100mm was designed with transverse reinforcement while control specimen SCC 0% did not contain stirrups. Companion SFRC specimens SCC 1% ZP and SCC 1% 5D did not have transverse reinforcement but were built with 1% of ZP and 5D fibers, respectively. Relevant photographs are included in Figure 5.31. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.32 and Figure 5.33.

The use of 1% fibers in both SFRC specimens increased shear capacity when compared to control specimen SCC 0%. Moreover, both specimens failed in flexure instead of shear, demonstrating that 1% fibers was sufficient to substitute for transverse reinforcement in the beams.

The use of 1% fibers in the mix also provided specimens SCC 1% ZP and SCC 1% 5D with enhanced flexural response, with reduced mid-span displacements when compared to the control beam built with stirrups. Beams SCC 1% ZP and SCC 1% 5D had reductions in maximum displacement of 12.9% and 18.4% respectively, and reduction of 40.4% and 43.3% in residual displacement when compared to control SCC 0% 100 mm at blast 3. For blast 4, Specimen SCC 1% ZP had reductions of 21.8% and 50.6% in maximum and residual mid span displacements, while specimen 1% 5D had showed greater reductions in maximum and residual displacement by 35.8% and 56.45% when compared to the same control. It can be observed that there is a trend of improved response in terms of control of mid-span displacements for the fiber with improved length/aspect ratio/ strength (5D fiber vs. ZP fiber). It can also be seen that the specimen with 5D fibers showed more distributed and closely spaced cracking, an indicator of greater fiber effect on concrete tensile resistance and post-cracking capacity.



(a) SCC 0% 100mm flexural failure at Blast 4



(b) SCC 1% ZP flexural failure at Blast 4



(c) SCC 1% 5D at Blast 4

Figure 5.31: Photographs; effect of fiber type (1% fiber ratio)

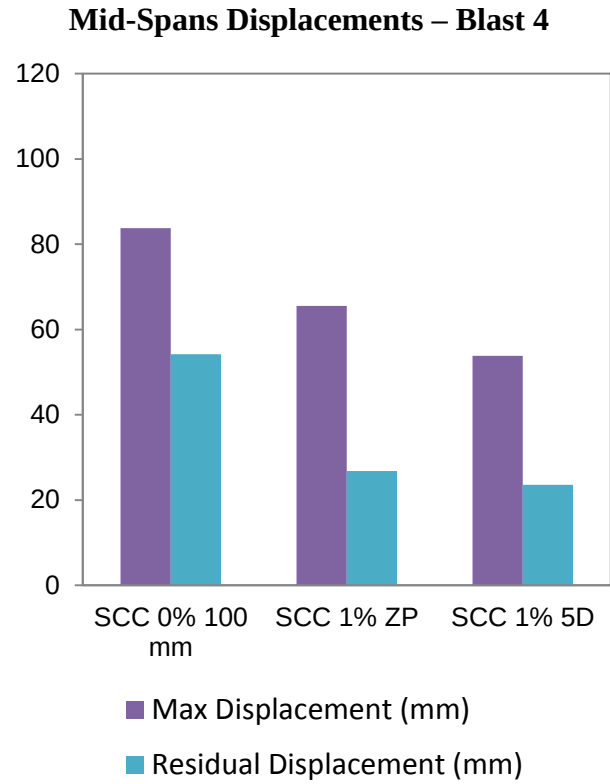
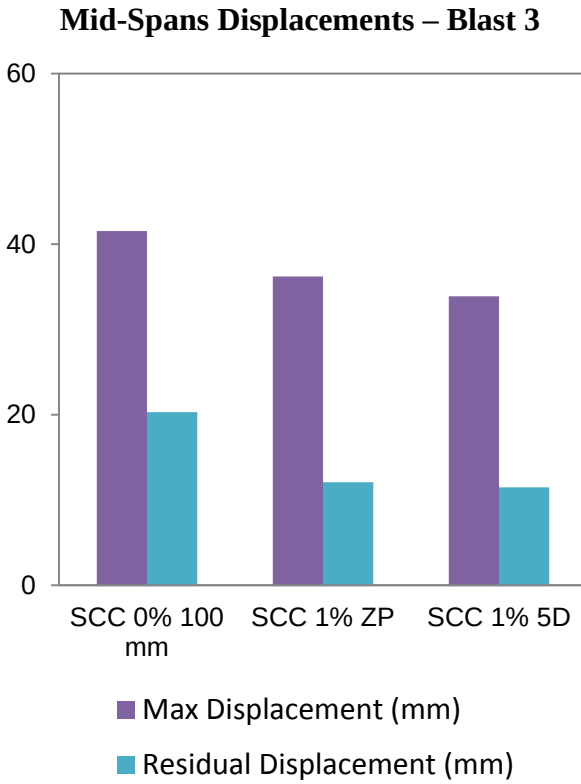


Figure 5.32: Maximum and residual displacements; effect of fiber type (1% fiber ratio)

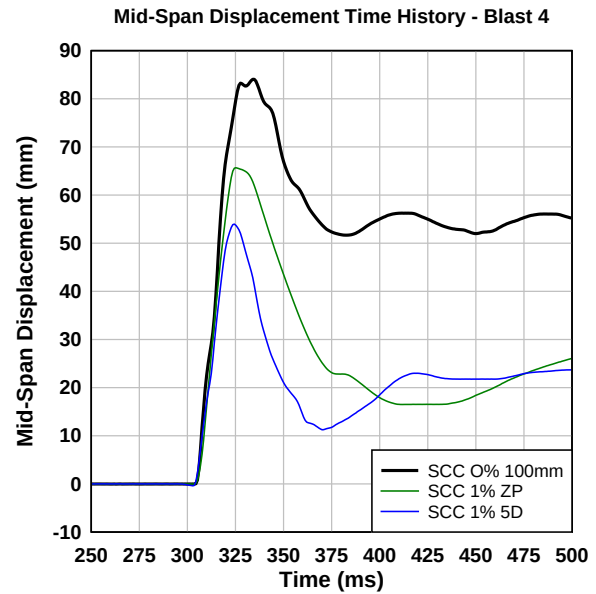
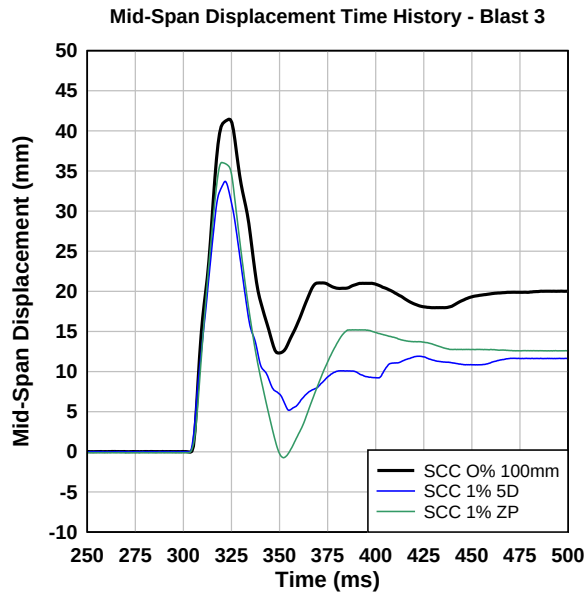


Figure 5.33: Displacement time histories; effects of fiber type (1% fiber ratio)

5.4.5 Effects of steel fiber type ($V_f = 1.5\%$)

This final sub-section examined the effect of fiber type in beams built with 1.5% steel fibers. Included in the comparison are both controls and beams SCC 1.5% ZP and SCC 1.5% 5D which did not have transverse reinforcement but contained 1.5% of the ZP and 5D fibers, respectively. Relevant photographs are included in Figure 5.34. Comparative displacement bar charts and time histories for blast 3 and 4 are provided in Figure 5.35 and Figure 5.36.

In both fiber series, the addition of 1.5% fibers increased shear capacity when compared to the control specimen without stirrups (SCC 0%). However, specimen SCC 1.5% ZP failed in flexure while specimen SCC 1.5% 5D failed in shear at blast 3. Unlike previous series, higher aspect ratio, fiber length and tensile strength did not lead to increase shear resistance. The higher aspect ratio and length, combined with high fiber content had a significant effect on concrete workability which affected fiber distribution when using the longer 5D fibers, thereby leading to reduced fiber efficiency on structural response. Indeed, construction was difficult when using 1.5% of 5D fibers, with important vibration needed during placement (SCC should generally not be vibrated, and clearly this excess vibration and lack of mix uniformity affected this beam's response).

In terms of the effect of fiber type on flexural response, specimen SCC 1.5% 5D failed in shear at blast 3 so mid span displacement cannot be compared to the control specimen SCC 0% 100mm. Specimen SCC 1.5% ZP had some improvement in control of maximum and residual displacement when compared to control specimen SCC 0% 100 mm, with reductions of 11.2 % and 40.4 % respectively for blast 3. The trend reversed at blast 4 where an increased maximum and residual mid-span displacement of 11.6% and 5.6% was observed when comparing to the same control. As previously discussed, results indicate that 1% may be a maximum fiber ratio for this SCC mix.

In summary, the results show that there are limits to the amounts of fibers one can add to concrete before adversely affecting structural performance. For both fiber types use of high fiber content (1.5% by volume) led to problems with concrete workability, which made construction and placement difficult and led to losses in fiber structural efficiency. The high fiber content had a greater influence in the case of the long 5D fibers, which led to greater workability issues and loss of mix uniformity, thereby negating the beneficial effects of steel fibers.



(a) SCC 0% 100mm flexural failure at Blast 4



(b) SCC 1.5% ZP flexural failure at Blast 4



(c) SCC 1.5% 5D shear failure at Blast 3

Figure 5.34: Photographs; effect of fiber type (1.5% fiber type)

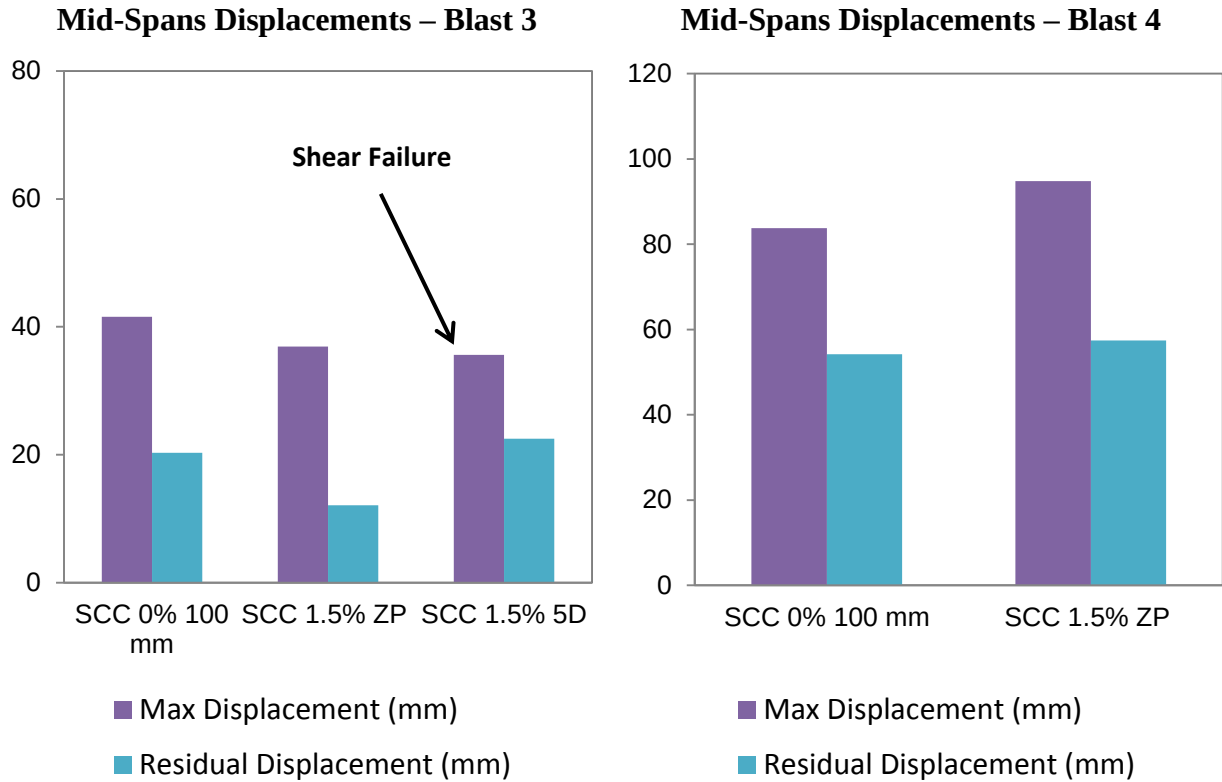


Figure 5.35: Maximum and residual displacements; effect of fiber type (1.5% fiber ratio)

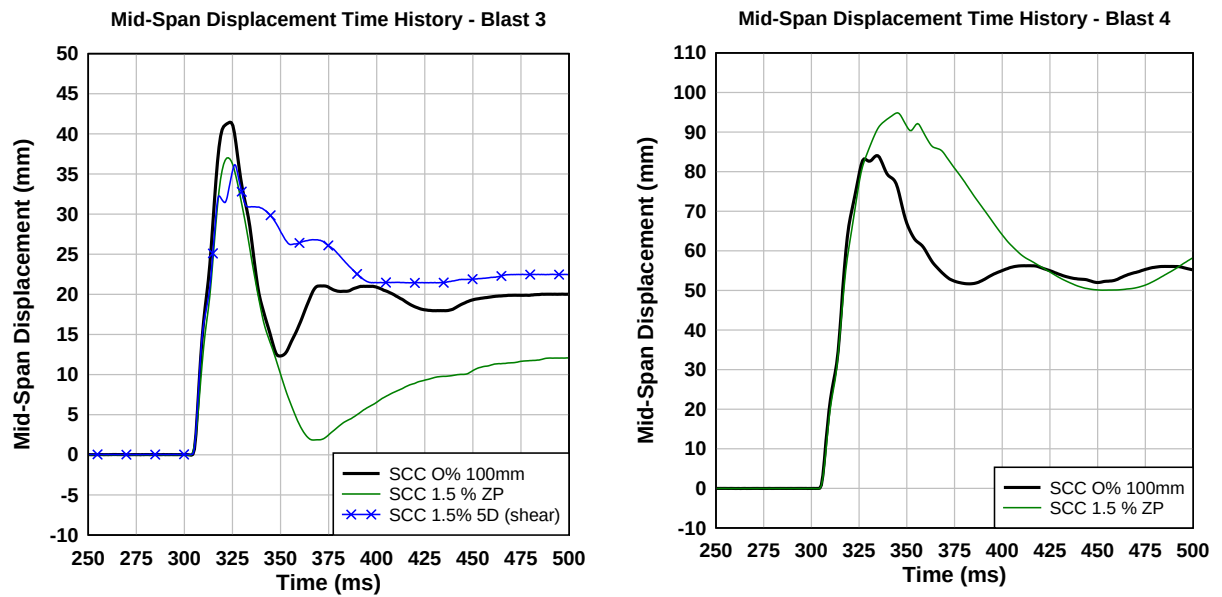


Figure 5.36: effects of fiber type (1.5% fiber ratio)

5.5 Damage Tolerance and Fragmentation

While the increase in shear capacity and control of displacements are the principal criterion in regards to evaluating the blast performance of the beams, another important criterion when examining the benefit of fibers is the effect of SFRC on damage and secondary fragmentation.

When compared to the control specimen with stirrups, the use of SFRC improved the ability to control cracking, spalling and debris. The photographs of the control specimen with stirrups (SCC 0% 100mm) provided in Figure 5.37 (a) shows that the plain SCC beam shows significant damage with excessive crushing on the compression side as well as spalling resulting in the loss of concrete cover and exposure of the reinforcement bars at mid span. On the other hand, specimen SCC 1% ZP which contained 1% fibers showed reduced crushing and generally no spalling on the tension side after the same blast (see Figure 5.37 (b)).

The use of increased fiber content generally led to enhanced damage tolerance in the beams with 5D fibers. The photographs of specimen SCC 0.75% 5D and SCC 1% 5D at blast 4 are included in Figure 5.37(d) and Figure 5.37 (e). It can be observed that the specimen with higher fiber content had reduced crushing and spalling in the compression side. It is however noted that increasing the fiber content beyond 1% to 1.5% led to shear failure in the 5D series. While both specimens with 1% and 1.5% fibers in the ZP series failed in flexure, it can be observed that specimen SCC 1.5% ZP has increased crushing and spalling as well as visually larger cracking when compared to beam SCC 1.% ZP (see Figure 5.37(b) and Figure 5.37 (c)), which further indicated that increasing the fiber content beyond 1% in the ZP series did not lead to enhanced performance.

The effect of fiber properties on damage and cracking can be examined by comparing the photographs of specimens SCC 1% ZP, SCC 1% 5D and sSCC 0.75% BP in Figure 5.37 (b), Figure 5.37 (e) and Figure 5.37(f). When compared to specimen SCC 1% ZP, better damage tolerance can be observed for the companions with 5D and BP fibers in terms of reduced crushing and spalling in the compression zone at failure.

The use of fibers also had an important effect on reducing the amount of secondary fragmentation. As shown in the high-speed video stills in Figure 5.38, the control specimen with stirrups (SCC 0% 100mm) formed significant fragments at failure due to crushing and spalling of concrete. The used of SFRC with enhanced toughness and fragmentation greatly reduced the amount and size a

secondary blast fragmentation due to the ability of the steel fibers to restrain the release of concrete fragments as portrayed in the video stills of specimens SCC 1% ZP, SCC 1% 5D and SCC 0.75% BP at failure (see Figure 5.39, Figure 5.40 and Figure 5.41).

In summary, the results show that using fibers is an effective means of reducing blast-induced fragmentation. In general increasing the fiber content or using fibers with optimized properties leads to further reductions in blast fragments and enhanced damage tolerance.

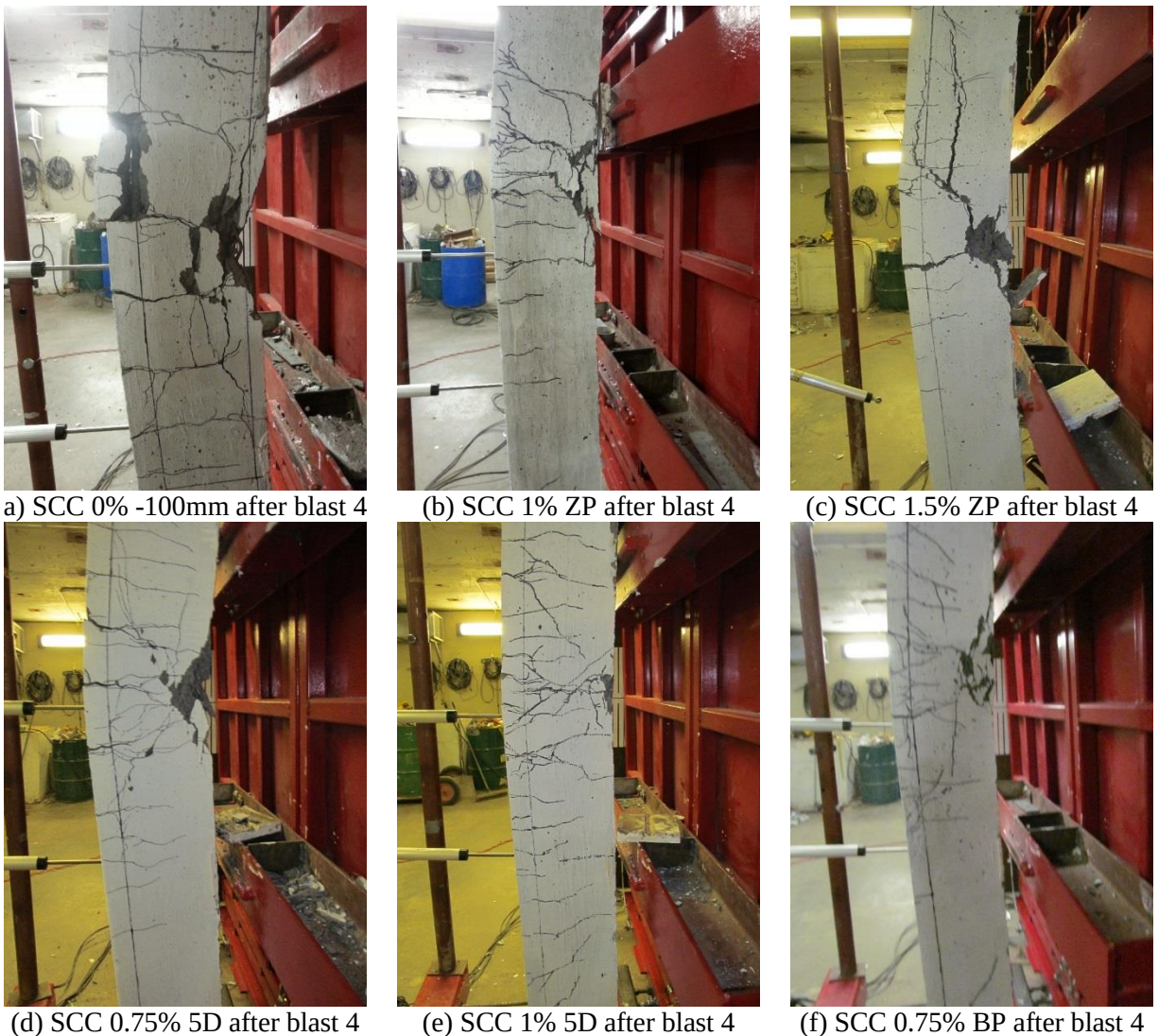


Figure 5.37: Comparison of damage tolerance in SCC and SFRC beams

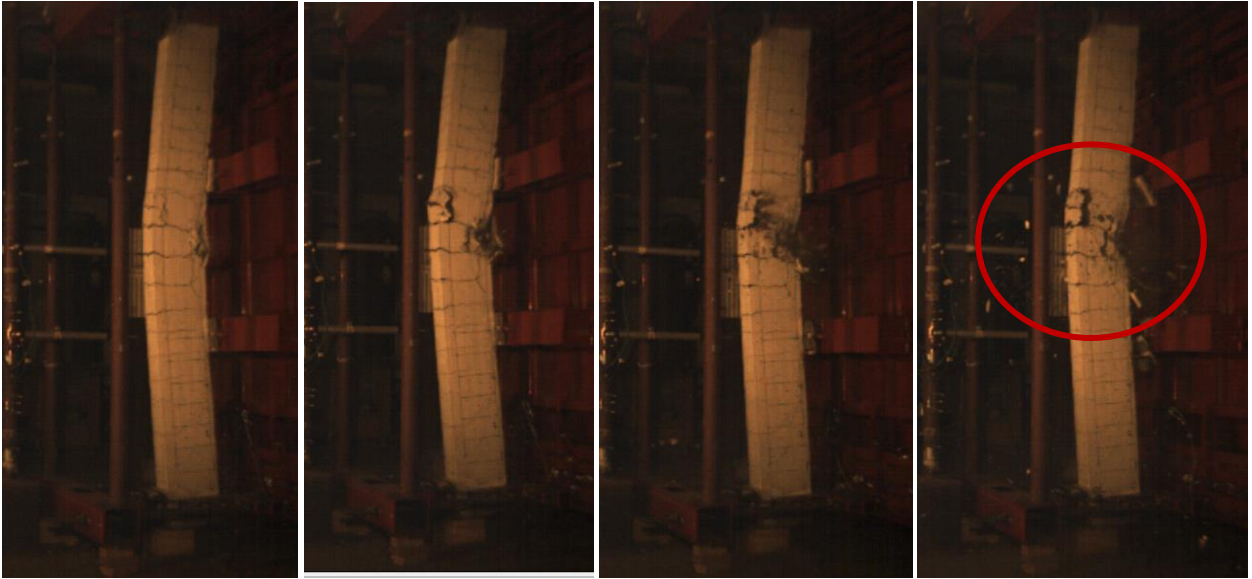


Figure 5.38: SCC 0% 100mm – Secondary fragmentation

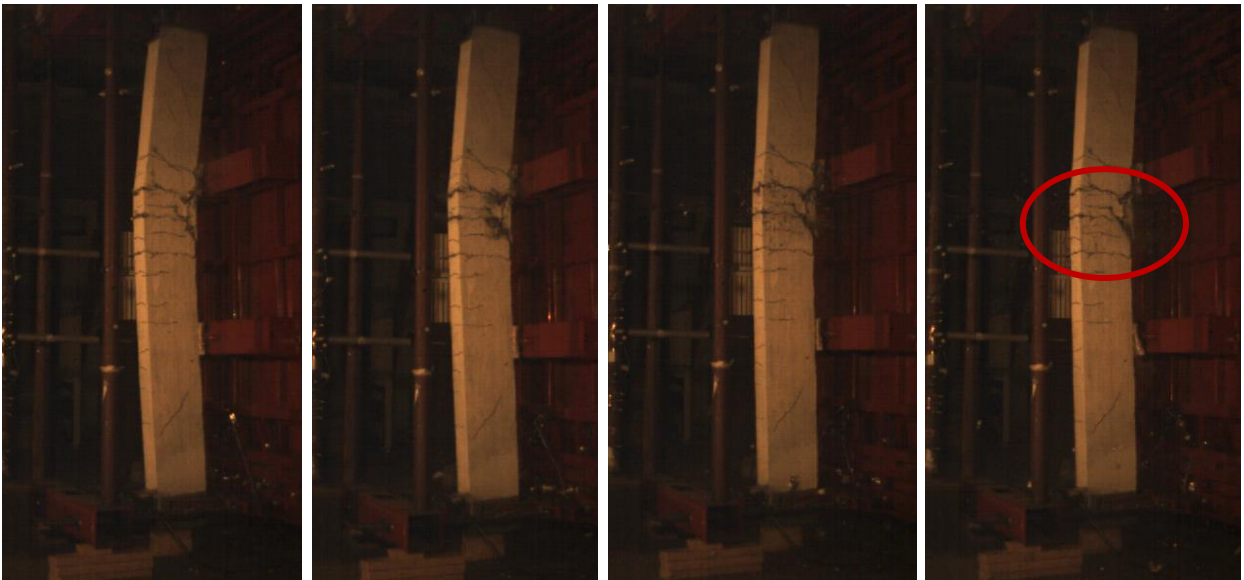


Figure 5.39: SCC 1% ZP – Secondary Fragmentation



Figure 5.40: SCC 1% - Secondary Fragmentation

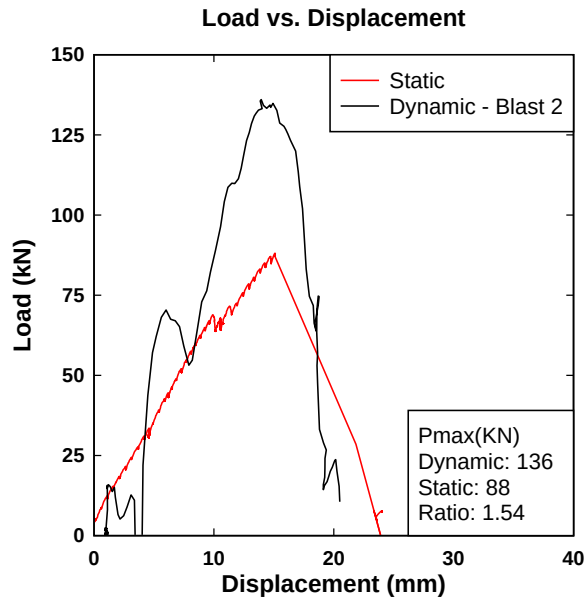


Figure 5.41: SCC 0.75% BP – Secondary Fragmentation

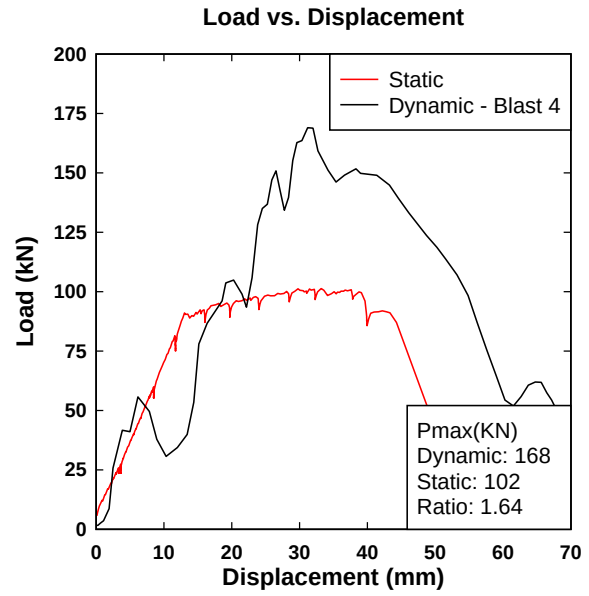
5.5.1 Dynamic vs. Static Resistance

Figure 5.42 shows a comparison of the resistance curves of the SCC and SFRC beams under quasi-static and dynamic blast loading. The dynamic results were obtained by summing the support reactions recorded by the load-cells during testing. The maximum loads under dynamic and static loading, and their ratio (P_{max}^D/P_{max}^S) are also reported in the plots. Higher peak loads were recorded for all beams under blast loading when compared to quasi-static loading. The increase in capacity can be explained by the increase in concrete and reinforcement strengths with the increase in loading-rate (high strain-rate effects). The average dynamic-to-static strength ratio considering all beams is found to be 1.60. The effect of various test parameters (transverse reinforcement and fiber type) on the dynamic resistance curves can be observed in Figure 5.43.

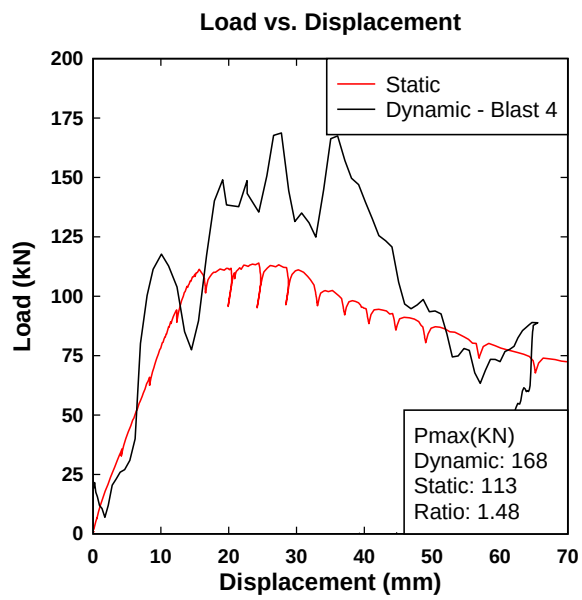
The dynamic resistance curves also show similar trends to those observed in the static series. First, comparing the dynamic results for beams SCC 0% 100 mm and SCC 0% it can be observed that the beam with stirrups showed higher dynamic capacity due to the increase in shear resistance ($P_{max}^D/P_{max}^S = 1.54$ vs 1.64 for SCC 0% and SCC 0% 100mm, respectively). As noted previously, the specimen without stirrup (SCC 0%) failed in shear in blast 2 while the specimen with transverse reinforcement (SCC 0% 100mm) failed in flexure at blast 4. Examining the dynamic resistance curves of beams SCC 0% 100mm, SCC 1% ZP and SCC 0.75% BP it can be observed that all three specimens showed similar dynamic curves with similar strength ratios of $P_{max}^D/P_{max}^S = 1.64$, 1.48 and 1.67, respectively. No clear trend is observable for the effect of fiber type as seen in Figure 5.43 (b). Finally examining Figure 5.44, it can be seen that maximum loads increase with an increase in blast energy; for example, beam SCC 0.75% BP shows strength ratios of $P_{max}^D/P_{max}^S = 1.39$, 1.60 and 1.67 at Blasts 2, 3 and 4, respectively.



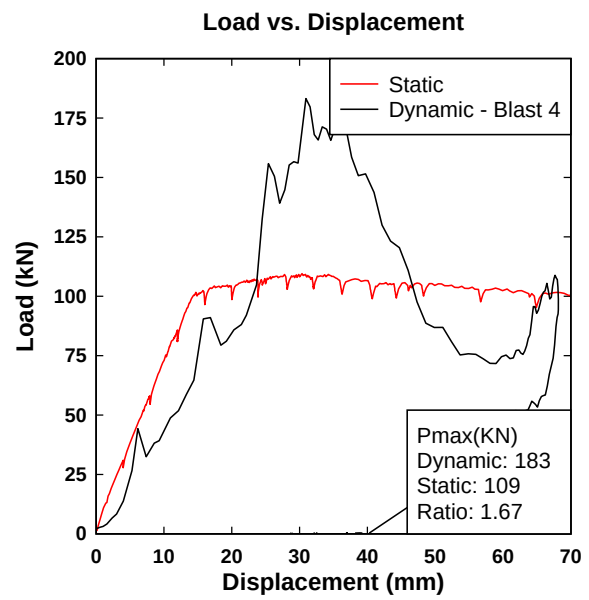
(a) SCC 0%



(b) SCC 0% 100mm

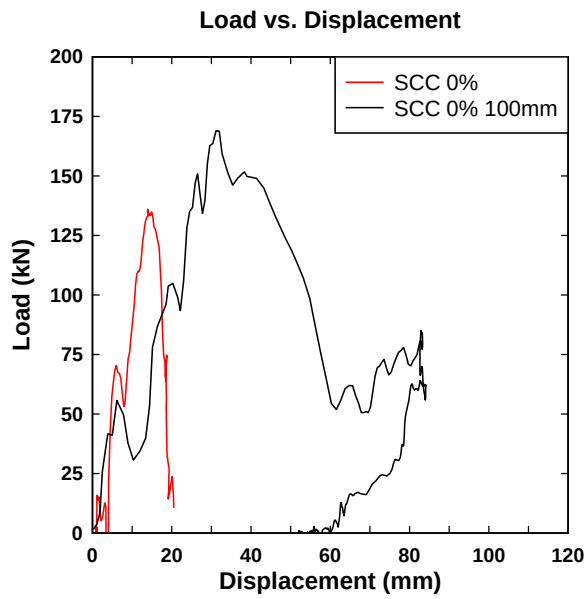


(c) SCC 1% ZP

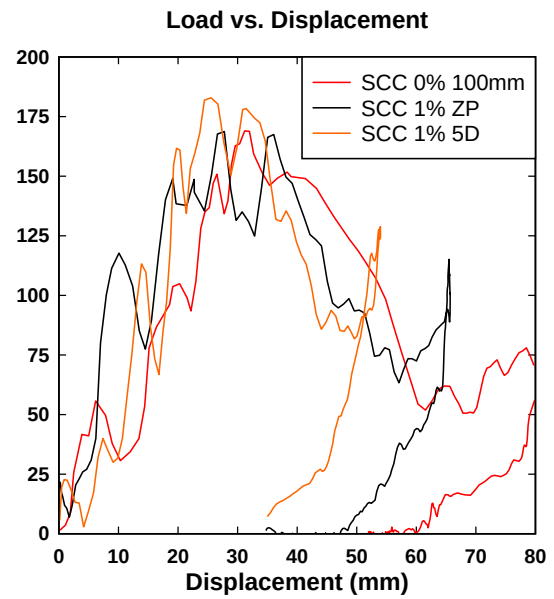


(d) SCC 0.75% BP

Figure 5.42: Comparison of Static vs. Dynamic resistance curves

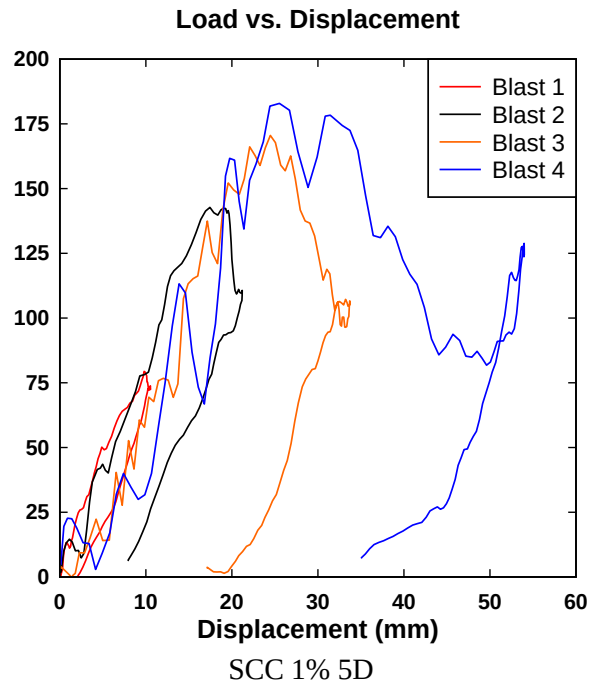
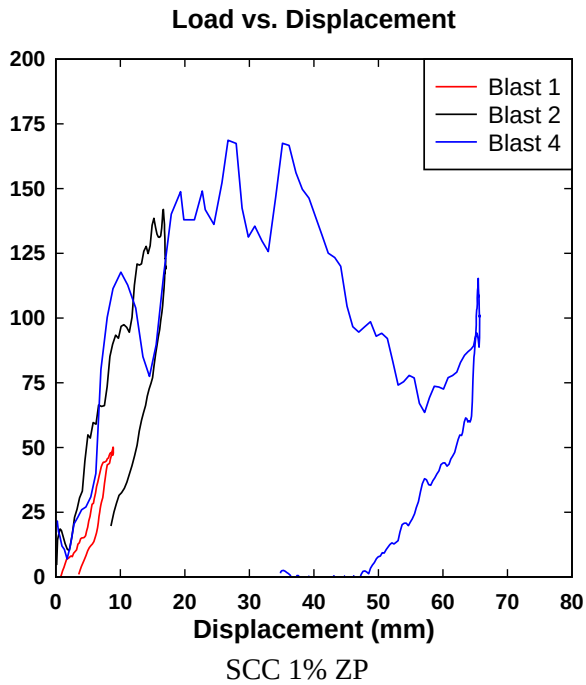


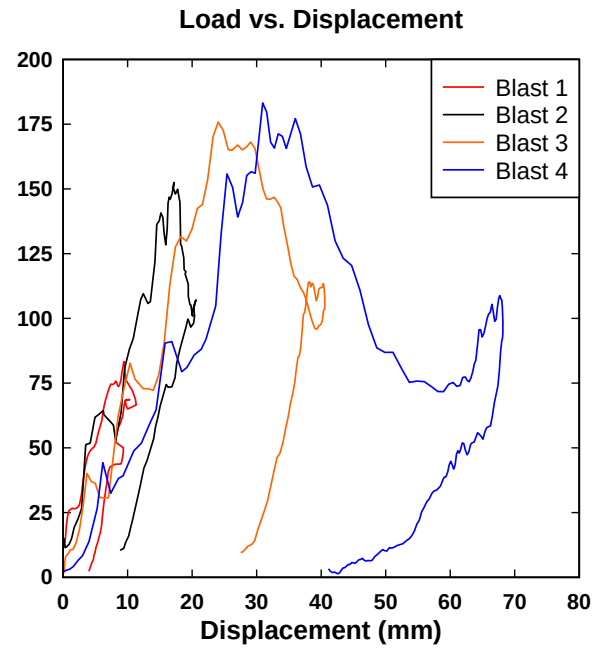
(a) Effect of transverse reinforcement



(b) Effect of fibers

Figure 5.43: Resistance curves - Effect of various test parameters





(c) SCC 0.75% BP

Figure 5.44: Resistance curves - Dynamic intensity of SRFC beams

6 Analysis of Dynamic Tests

6.1 Section Overview

This section presents the analysis of the beams tested in this research program. The dynamic analysis was conducted by using dynamic material properties to develop moment curvature relationships, with moment area method and plastic hinge analysis used to develop dynamic resistance curves. The single-degree-of-freedom (SDOF) analysis procedure implemented in software *RCBlast* was used to predict the dynamic response of the test beams. Section 6.2 presents material models which were used in the sectional analysis section. The dynamic increase factors which were used to obtain dynamic material properties are summarised in section 6.3. Sections 6.4 presents the methodology used to develop the resistance curves and complete the SDOF analysis. Finally, the analysis results are summarised in section 6.5.

6.2 Material Models

This section introduces the stress-strain models for SCC concrete, SFRC and reinforcing steel which were used to develop the beam resistance curves.

6.2.1 Plain Concrete Models

The unconfined concrete compression model proposed by Popovics (1973) was selected to describe the stress-strain behaviour of plain concrete in the SCC control beams. The concrete in tension was assumed to follow a linear-elastic with a slope equal to the modulus of elasticity ($E_c = 3300\sqrt{f'_c}$) for plain concrete and a maximum tensile strength equal to $0.33\sqrt{f'_c}$.

Popovics (1973)

The Popovics (1973) model was the model considered for plain unconfined concrete in compression. The same equation is used for the ascending and descending branches of the stress-strain curve and is presented in equation (6-1). The slope of the descending branch is controlled by the parameter k which can be approximated using equation (6-2) as summarized by Collins and Mitchell (1990). Other parameters such as the curve-fitting factor n , initial tangent modulus E_c and strain at peak stress ε_0 can be calculated using equations (6-3), (6-4) and (6-5). A sample showing the model stress-strain curve is presented in Figure 6.1.

$$f_c(\varepsilon_c) = \frac{n(\varepsilon_c/\varepsilon_0)}{n-1 + (\varepsilon_c/\varepsilon_0)^{nk}} f'_c \quad (6-1)$$

$$k = \begin{cases} 1.0 & \varepsilon_c/\varepsilon_0 \leq 1.0 \\ 0.67 + \frac{f'_c}{62} & \varepsilon_c/\varepsilon_0 > 1.0 \end{cases} \quad (6-2)$$

$$n = 0.8 + \frac{f'_c}{17} \quad (6-3)$$

$$\varepsilon_0 = \frac{f'_c}{E_c} \left(\frac{n}{n-1} \right) \quad (6-4)$$

$$E_c = 3300\sqrt{f'_c} + 6900 \quad (6-5)$$

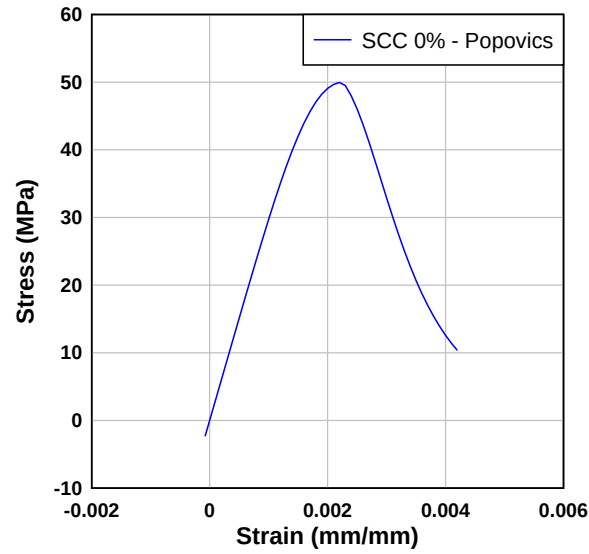


Figure 6.1: Plain concrete stress-strain model sample

6.2.2 Steel Fiber Reinforced Concrete Models

Two models were considered to model the stress-strain behaviour of SFRC; Ou et al. (2012) was selected to model the behaviour in compression and Lok and Pei (1998) was selected to model the tensile behaviour.

Ou et Al. (2012)

The stress strain model proposed by Ou et al. is a modification of a model originally proposed by Carreira and Chu (1985) and can be used to predict the stress-strain response of steel fiber

reinforced concrete in compression. Similar to the model used for plain concrete, the same equation is used to compute the ascending and descending branch of the stress-strain curve and is presented in Equation (6-6). The descending branch is controlled by the coefficient β presented in Equation (6-7) and is affected by the fiber content (v_f), fiber length (l_f) and fiber diameter (d_f). The ultimate compressive strength (f'_{cuf}) and strain at peak stress (ε_{0f}) can be calculated using Equations (6-8) and (6-9), respectively.

$$f_{cf}(\varepsilon_c) = f'_{cuf} \frac{\beta(\varepsilon_c/\varepsilon_{0f})}{\beta - 1 + (\varepsilon_c/\varepsilon_{0f})^\beta} \quad (6-6)$$

$$\beta = 0.71 \left(\frac{v_f l_f}{d_f} \right)^2 - 2.00(c) + 3.05 \quad (6-7)$$

$$\varepsilon_{0f} = \varepsilon'_c + 0.0007 \left(\frac{v_f l_f}{d_f} \right) \quad (6-8)$$

$$f'_{cuf} = f'_{cu} + 2.35 \left(\frac{v_f l_f}{d_f} \right) \quad (6-9)$$

Lok & Pei (1998)

Lok and Pei (1998) was selected to model the stress-strain behaviour of SFRC in tension. It is composed of two stages; pre-cracking and post-cracking. The pre-cracking curve is linear with a slope equal to the modulus elasticity of concrete up to the cracking stress f_{ctf} defined in equation (6-10). The post-cracking stage is modeled using a bilinear relationship which can be either ascending or descending and is related to the pull-out of the steel fibers from the concrete matrix. The first linear portion ends at the stress (ε_2^*) and strain (f_2^*) values defined using equations (6-11) and (6-12) respectively. The matrix bond strength is defined in equation (6-13) and is related to the modulus of elasticity for the fiber (E_{fp}), taken as 200 GPa. Again, the variables defined as v_f , l_f and d_f are the fiber content, fiber length and fiber diameter. The second portion of the post-cracking curve is linearly descending and reached a stress of zero (0) at a strain of 0.02 (Lok and Pei, 1998).

$$f_{ctf} = 0.33\sqrt{f'_c} \quad (6-10)$$

$$f_2^* = \frac{1}{2}v_f\tau_{bond}\frac{l_f}{d_f} \quad (6-11)$$

$$\varepsilon_2^* = \tau_{bond}\frac{l_f}{d_f}\frac{1}{E_{fp}} \quad (6-12)$$

$$\tau_{bond} = 0.6(f'_{cuf})^{2/3} \quad (6-13)$$

Sample SFRC stress-strain Curves

Figure 6.2 (a) presents the stress-strain curve for SFRC with a compressive strength of 50 MPa with various fiber contents of the ZP fiber as predicted by the Ou, et al (2012) model. Figure 6.2 (b) presents the tension stress-strain curve predicted using the Lok and Pei Model. It can be observed that, at 0.5 % and 1% volume of the ZP fiber content, the Lok and Pei model predicts a tension-softening response while at 1.5% it predicts a tension-hardening response.

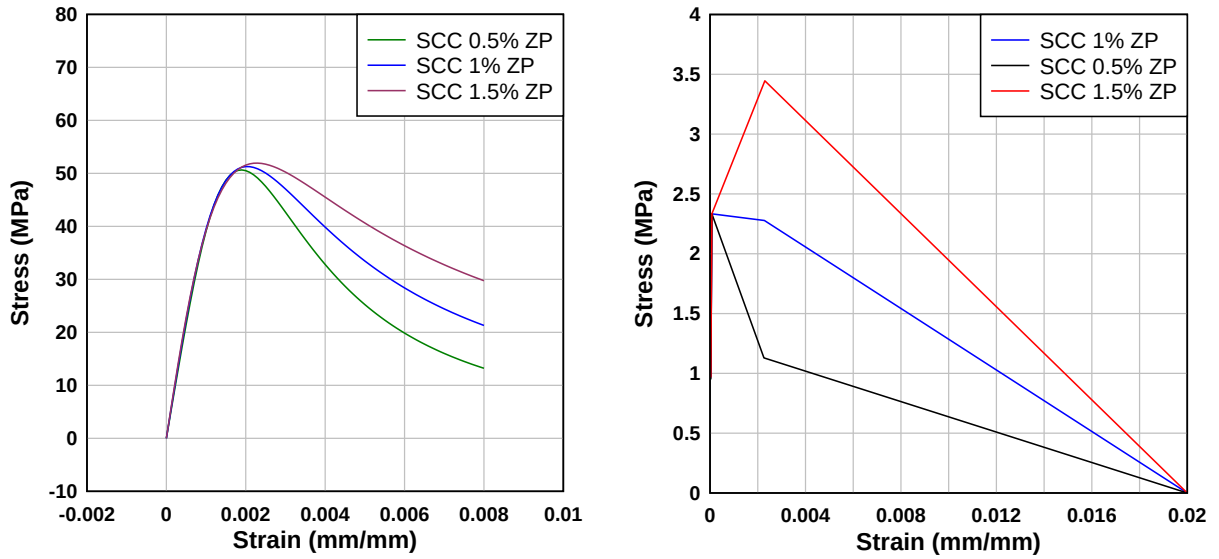


Figure 6.2 Unconfined SFRC stress-strain models sample

6.2.3 Steel reinforcement in Tension

The tensile stress-strain relationship of steel was modelled using the relationships proposed by Jacques et al. (2012). It is noted that this model is found in the software RCBlast (2014) which

was used for the analysis. Equations (6-14) through (6-17) shows the parameters used in the stress strain curves for the elastic, post-yield and strain hardening stages of the curve, where $\varepsilon_{sh} = 0.01$ mm/mm and $\varepsilon_u = 0.1$ mm/mm. Figure 6.3 presents a sample of the model predictions compared to the experimental stress-strain relationship for a 15M bars.

$$f_s = E_s \varepsilon_s \quad \text{for } \varepsilon_s \leq \varepsilon_y \quad (6-14)$$

$$\varepsilon_y = f_y / E_s \quad (6-15)$$

$$f_s = f_y + (\varepsilon_s - \varepsilon_y) \left(\frac{f_{sh} - f_y}{\varepsilon_{sh} - \varepsilon_y} \right) \quad \text{for } \varepsilon_y < \varepsilon_s \leq \varepsilon_{sh} \quad (6-16)$$

$$f_s = f_y + (f_u - f_y) \left[2 \left(\frac{\varepsilon_s - \varepsilon_{sh}}{\varepsilon_u - \varepsilon_{sh}} \right) - \left(\frac{\varepsilon_s - \varepsilon_{sh}}{\varepsilon_u - \varepsilon_{sh}} \right)^2 \right] \quad \text{for } \varepsilon_{sh} < \varepsilon_s \leq \varepsilon_u \quad (6-17)$$

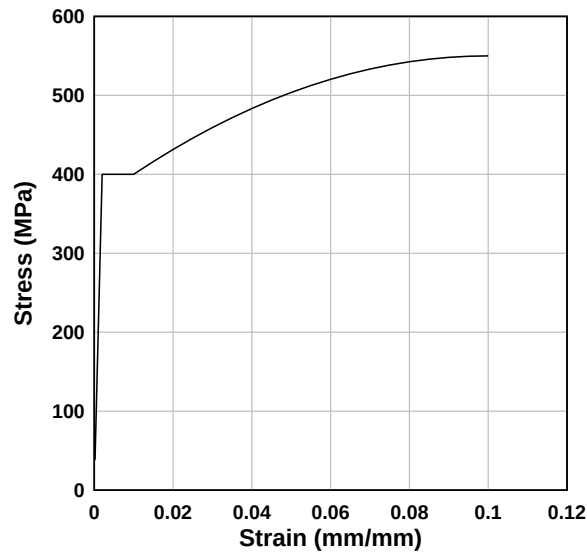


Figure 6.3 Steel Reinforcement stress-strain model sample

6.3 Dynamic Increase Factors

This section presents the models used to account for dynamic effects in concrete, SFRC and steel reinforcement as they are affected by strain rate. For this research, a lower bound strain rate of $\dot{\varepsilon} = 1 \text{ s}^{-1}$ was assumed for the specimens tested using the shock-tube (Saatcioglu et al. 2011).

6.3.1 Dynamic Increase Factors for Concrete Models

Under high-strain rate loading, the compressive and tensile strength of concrete is increased. The apparent increase in strength was taken into account using strain variable dynamic increase factors. In this research program, two (2) models were considered for concrete DIF. In compression, the

Saatcioglu et al. (2011) model was used to account for the DIF of plain concrete and steel fiber-reinforced concrete (SFRC) in compression. No DIF was considered for the dynamic response of plain concrete in tension. The dynamic response of SFRC in tension is taken into account using the equations proposed by Malvar & Ross (1998).

Saatcioglu et al. (2011)

Equation (6-18) proposed by Saatcioglu et al. (2011) was considered for the dynamic increase factor of plain concrete and SFRC in compression. This model is composed of two linear segments with a transition at a strain of 30 s^{-1} . Based on the large scatter of experimental results reported by other researchers, the DIF of concrete in compression is assumed to be independent of concrete strength. At a strain rate of 1 s^{-1} this model predicts a $DIF_c = 1.3$ for both concrete and SFRC.

$$DIF_c = \begin{cases} 0.03 \ln(\dot{\epsilon}) = 1.3 \geq 1.0 & \dot{\epsilon} \leq 30 \text{ s}^{-1} \\ 0.03 \ln(\dot{\epsilon}) - 0.47 & \dot{\epsilon} > 30 \text{ s}^{-1} \end{cases} \quad (6-18)$$

Malvar & Ross (1998)

Typically ignored in the analysis of reinforced concrete elements, the tensile contribution of SFRC is more significant and should not be disregarded. Research has shown that the properties of SFRC in tension are affected by strain rate. For the purpose of this research, the model proposed by Malvar & Ross (1998) was used to account for the dynamic strength of SFRC in tension. Equations (6-19) and (6-20), as proposed in this model, result in a bilinear relationship that can be used to evaluate the dynamic increase factor of concrete in tension. Using this model, a $DIF_t = 1.4$ is predicted at a strain rate of 1 s^{-1} .

$$DIF_t = \begin{cases} (\phi \dot{\epsilon})^\alpha & \text{for } \dot{\epsilon} < \dot{\epsilon}_{BLT} \\ \beta(\dot{\epsilon})^{1/3} & \text{for } \dot{\epsilon} \geq \dot{\epsilon}_{BLT} \end{cases} \quad (6-19)$$

$$\alpha = \frac{\ln(\beta \dot{\epsilon}_{BLT}^{\frac{1}{3}})}{\ln(\phi \dot{\epsilon}_{BLT})}, \beta = \frac{5}{9} \exp\left(\frac{-f'_{cuf}}{230}\right), \phi = 10^5, \dot{\epsilon}_{BLT} = 25 \exp\left(\frac{f'_{cuf}}{130}\right) \quad (6-20)$$

6.3.2 Dynamic Increase Factors for Steel Reinforcement

The material properties of steel reinforcement are sensitive to the rate of loading. In this research program, the equations proposed by Saatcioglu et al. (2011) were selected to evaluate the dynamic stress-strain response of steel reinforcement.

Saatcioglu et al. (2011)

The relationships shown in Equation (6-21), as proposed by Saatcioglu et al. (2011), were considered for the dynamic increase factor of steel reinforcement. The equation results in a bilinear representation of DIF that is independent of steel grade. However, consistent with other research, the model predicts a higher DIF for steel at yield stress (DIF_y) when compared to ultimate (DIF_u). At a strain rate of 1 s^{-1} this model predicts dynamic increase factors of $DIF_y = 1.3$ and $DIF_u = 1.1$.

$$\begin{aligned} DIF_y &= 0.034 \ln(\dot{\epsilon}) + 1.30 \geq 1.0 \\ DIF_u &= 0.010 \ln(\dot{\epsilon}) + 1.10 \geq 1.0 \end{aligned} \tag{6-21}$$

6.3.3 Sample Dynamic Stress-Strain Curves

Figure 6.4 shows sample stress-strain curves for plain concrete in compression, SFRC in compression/tension and steel reinforcement with and without DIF. The curves shown in the figure correspond to the default material stress-strain and DIF model combination considered in the analysis: Concrete in compression – Ou. et al. (2012) & Saatcioglu et al. (2011); Concrete in tension - Lok& Pei (1998) and Malvar& Ross (1998); Steel reinforcement - Jacques et al. (2012) & Saatcioglu et al. (2011).

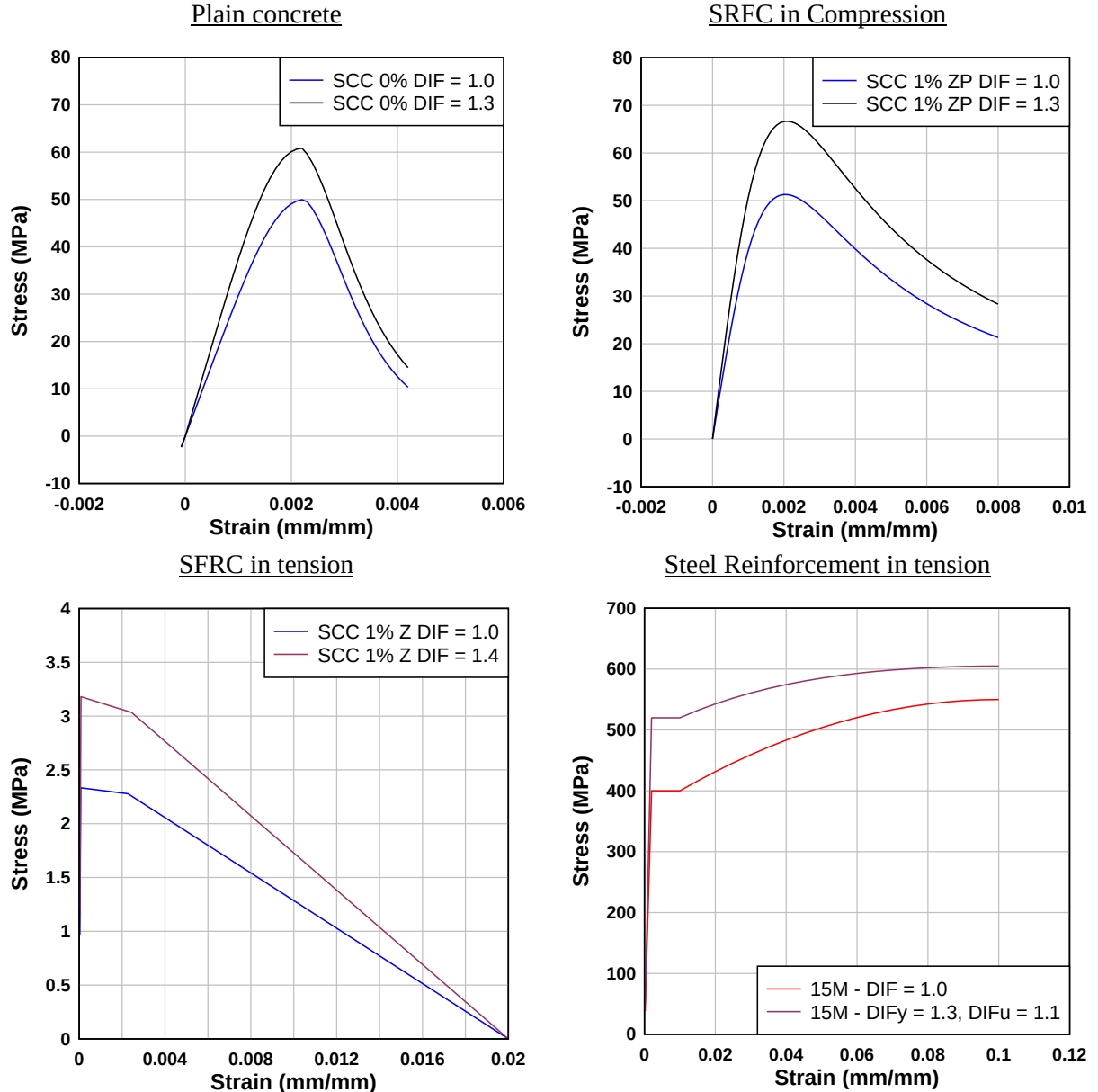


Figure 6.4: Typical stress –strain relationship with DIF

6.4 Development of Resistance Curves and Analysis Methodology

The response of structural members can be simplified and estimated using a single-degree-of-freedom system approach. Figure 6.5 shows an example of an equivalent SDOF mass-spring system for a beam subjected to a dynamic load.



Figure 6.5: SDOF system

The equation of motion presented in equation (6-22) can be used to analytically predict the response of a beam subjected to blast loading, where $u(t)$ is the deflection of the beam at mid-span; $\ddot{u}(t)$ is the acceleration at mid-span; K_{LM} is the load-mass transformation factor; $R(u(t))$ is the resistance of the member as a function of the deflection; m is the total mass of the system; A is the area impacted by the blast pressure, and $P_r(t)$ is the reflected pressure as a function of time. For the purpose of this research, damping was ignored.

The total mass m of the system is a combination of the concrete beam (182kg) and the load transfer system device (267kg) for a total of 450kg. The area A can be taken as the total loaded area of the LTD at the shock-tube frame opening and is estimated to be 3.4m^2 which represents the area of center panel of the load transfer device.

Equation (6-23) can be used to calculate the load and mass transformation factors, K_L and K_m , which were ratios used to determine the force and the mass acting on the equivalent SDOF system to the actual force and mass. K_L is the load factor and is presented in Equation (6-23), where $p(x)$ is the loading function and $\varphi(x)$ is the shape function. K_m is the mass factor and is presented in Equation (6-24). The load mass factor K_{LM} is a ration of the mass factor and the load factor and is presented in Equation (6-25). The K_{LM} factor can also be obtained using the transformation factor table developed by Biggs (1964) and found in UFC 3-340(2002) as presented in Table 6.1. For the load case represented by four-point bending, K_{LM} factors of 0.60 and 0.56 were used for the elastic region and plastic region of the response, respectively.

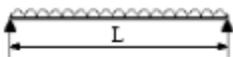
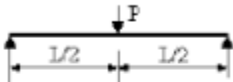
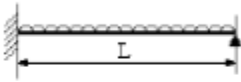
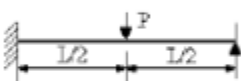
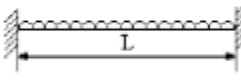
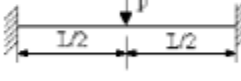
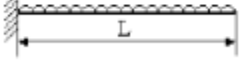
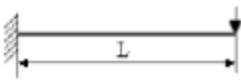
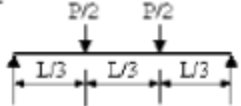
$$K_{LM}m\ddot{u}(t) + R(u(t)) = AP_r(t) \quad (6-22)$$

$$K_m = \frac{M_e}{M} = \frac{\int_0^L m(x)[\varphi(x)]^2}{mL} \quad (6-23)$$

$$K_L = \frac{P_e}{P(x)} = \frac{\int_0^L p(x)\varphi(x) dx}{pL} \quad (6-24)$$

$$K_{LM} = \frac{K_M}{K_L} \quad (6-25)$$

Table 6.1: Transformation factors for beams and on-way slabs with concentrated loads (UFC 3-340-01 2002)

Edge Conditions and Loading Diagrams	Range of Behavior	Load Factor K_L	Mass Factor K_M	Load-Mass Factor K_{LM}
	Elastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.49	0.49
	Plastic	1.0	0.33	0.33
	Elastic	0.58	0.45	0.78
	Elasto-Plastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.43	0.43
	Elasto-Plastic	1.0	0.49	0.49
	Plastic	1.0	0.33	0.33
	Elastic	0.53	0.41	0.77
	Elasto-Plastic	0.64	0.50	0.78
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.37	0.37
	Plastic	1.0	0.33	0.33
	Elastic	0.40	0.26	0.65
	Plastic	0.50	0.33	0.66
	Elastic	1.0	0.24	0.24
	Plastic	1.0	0.33	0.33
	Elastic	0.87	0.52	0.60
	Plastic	1.0	0.56	0.56

The resistance functions used in the dynamic analysis were obtained by first developing moment-curvature relationship using the $M - \phi$ analysis procedure automated in software *RCBlast*, developed by Jacques (2014) at the University of Ottawa.

The first step of the analysis was defining the dynamic material properties of concrete (plain or SFRC) and reinforcing steel (as discussed in the previous section), and to define the cross section of the beam and configuration of the steel reinforcement. Once these parameters were defined, the software was used to generate the moment-curvature relationship for the beam section. As the current version of the software does not include an option to generate the resistance functions for beams subjected to four-point loading, an excel based spreadsheet was developed in this study to convert the moment curvature relationship to the resistance curve. The relationships used to generate the load-deflection resistance curves are outlined in equation (6-26), (6-27) (6-28) and (6-29). For the elastic section of the curve, the displacements were obtained by integrating the beam curvature using the moment-area method as defined in Equation (6-27) and as shown in Figure 6.6 (a). To determine the post-yield displacement the method outlined in Figure 6.6 (b) and equation (6-27) was used, where ϕ_u and ϕ_y are the curvature values at ultimate and yield respectively, and where l'_p is the plastic hinge length. The length was taken as equal to the effective depth of the beam cross-section, $d = 200$ mm. The resistance P was obtained by relating the loading to the moment using equation (6-29).

$$\frac{M}{EI} = \frac{d^2v}{dx^2} \quad (6-26)$$

$$v = \iint_0^{L/2} \frac{M(x)}{EI} dx \quad (6-27)$$

$$\Delta = \begin{cases} A_1 d_1 + A_2 d_2 = 531215\phi & \text{for } \Delta \leq \Delta_y \\ \Delta_y + (\phi_u - \phi_y)l'_p \times \left(l - \frac{l'_p}{2}\right) = 531215\phi_y + 106600(\phi_u - \phi_y) & \text{for } \Delta > \Delta_y \end{cases} \quad (6-28)$$

$$P = \frac{2M}{741} \quad (6-29)$$

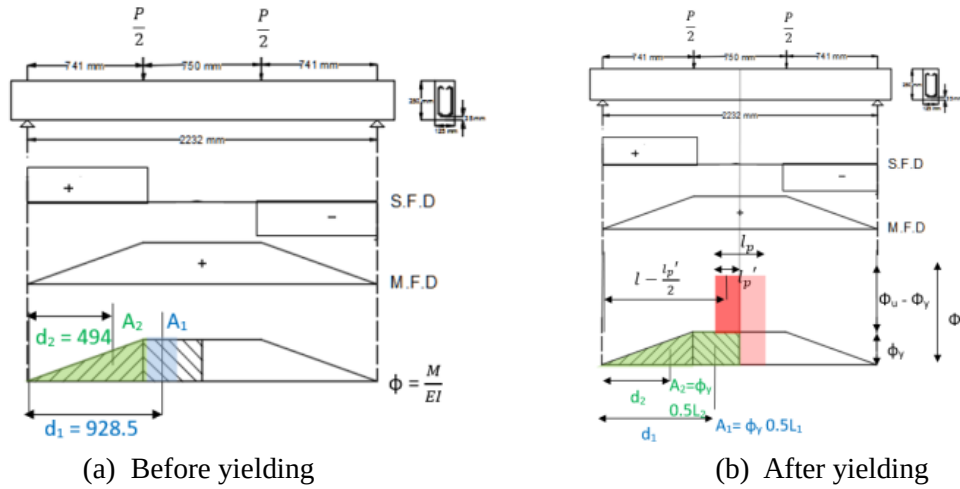


Figure 6.6: Moment-area method to get resistance curve

The final step in the procedure was to use the resulting resistance function and transformation factors, along with an idealized blast load pressure-time history to conduct the dynamic analysis of the beam using software RC Blast. Figure 6.7 shows a comparison of the actual and equivalent triangular blast load used in the analysis. The loads have the same pressure and impulse; the positive phase duration t_d is modified using equation (6-29) to obtain the same impulse I_r while keeping the same peak pressure P_r . The equation of motion was then solved by the software using the average acceleration numerical integration method (Jacques, 2014).

$$t'_p = \frac{2I_r}{P_r} \quad (6-29)$$

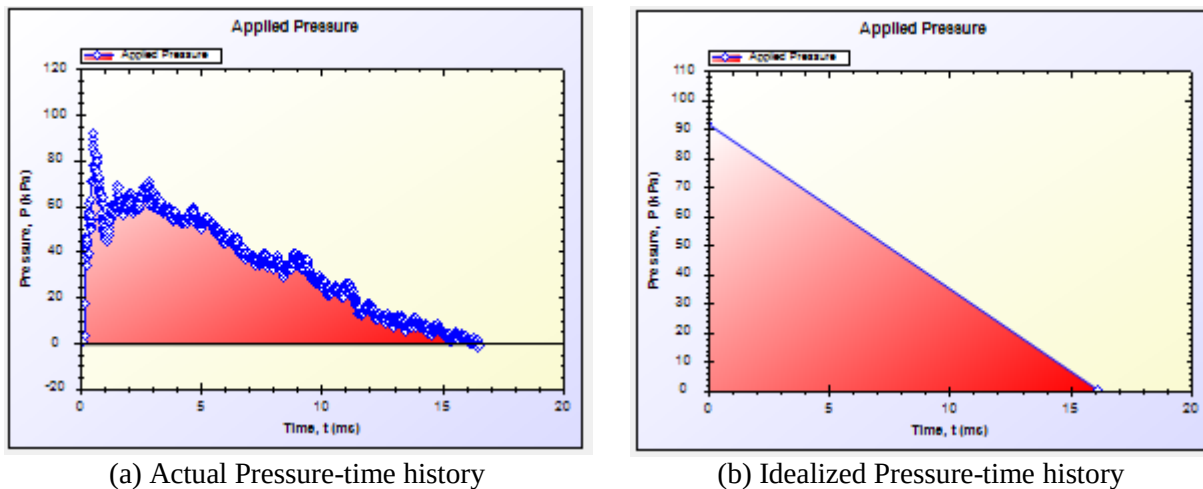
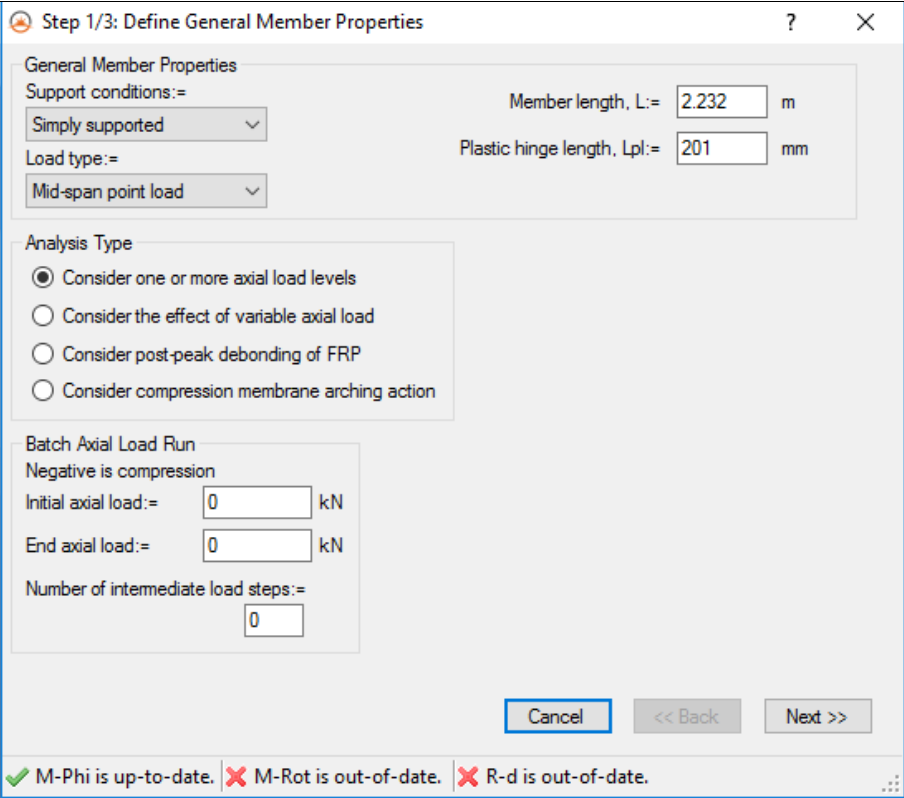
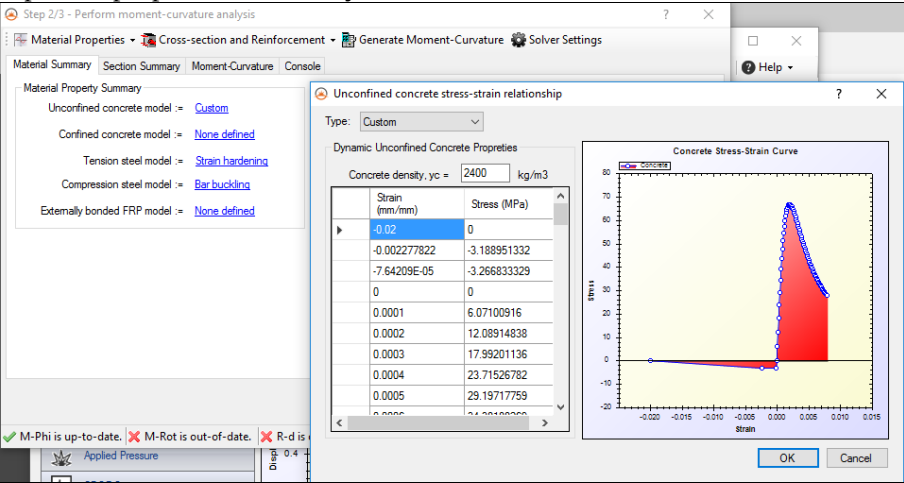
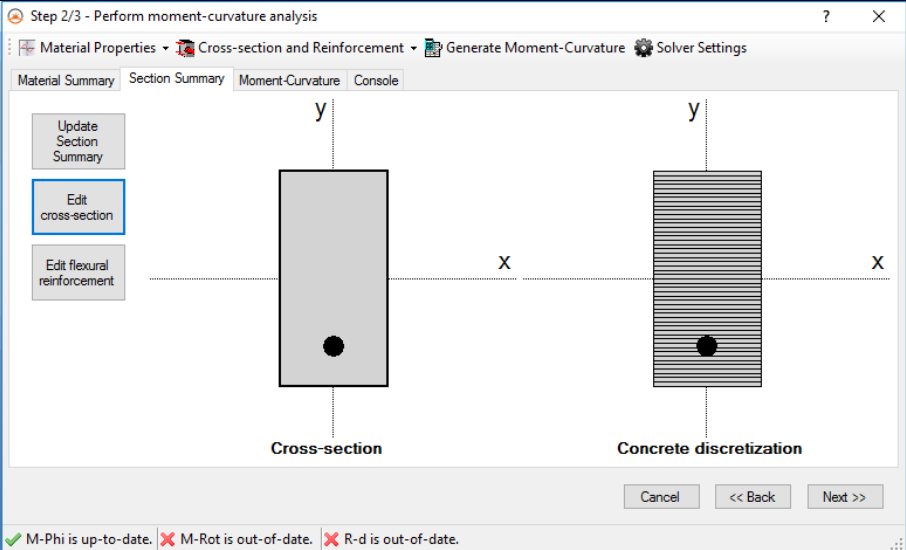
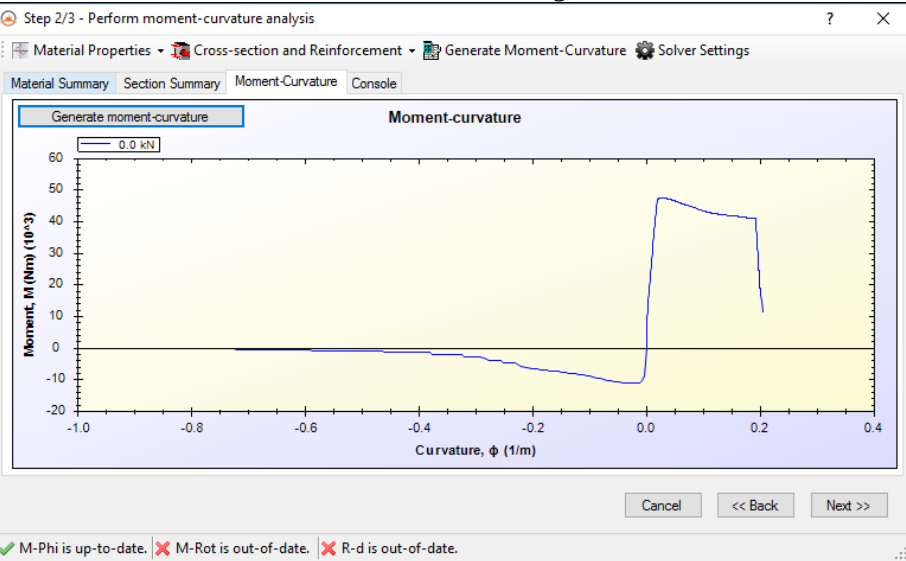


Figure 6.7 Actual and idealized pressure-time history

The table below summarizes the main steps for the analysis in software *RCBlast*. The results of the dynamic analysis are summarized and discussed in the next section,

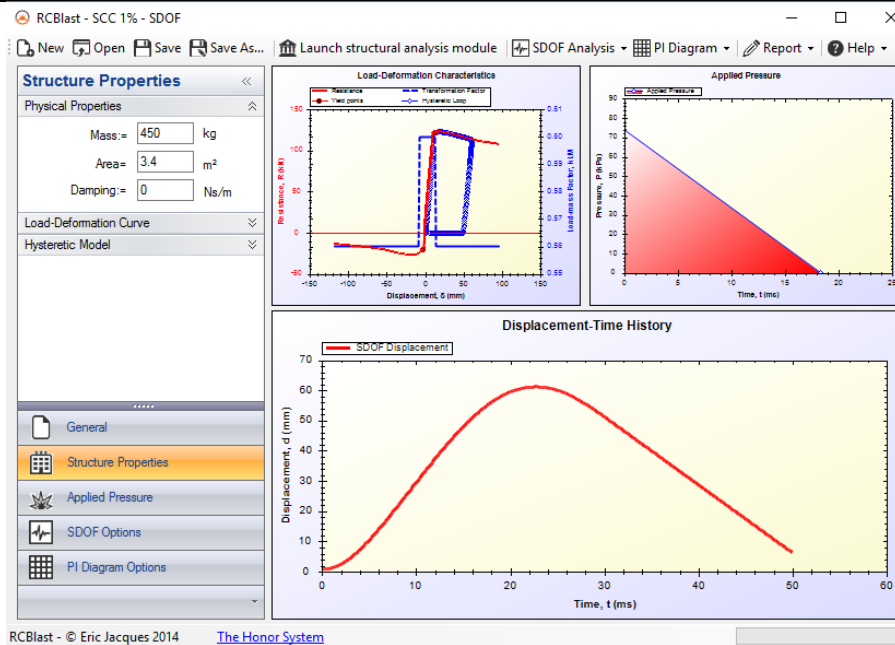
Table 6.2: Steps for conducting an analysis using the RCBlast software

Step 1:	Define the general member properties such as support conditions, load type and member length. 
Step 2:	Input the properties such as dynamic concrete model and tension steel model 
Step 3:	Input the section geometry and reinforcement details.

	
Step 4:	Generate the moment-curvature using <i>RCBlast</i> software 
Step 3:	Paste the data to custom excel spreadsheet to generate load-displacement then input the resistance curve back into <i>RCBlast</i>

ψ (1/m)	M (Nm)	ε_{top}	ε_{btm}	delta (mm)	P (Kn)	klm
-0.034	-11168	-0.00108	0.0073287	-17.8674	-30.14	0.56
-0.026	-11253	-0.0009	0.0056868	-13.99613	-30.37	0.56
-0.019	-11245	-0.00072	0.0040873	-10.21493	-30.35	0.56
-0.013	-11033	-5.40E-04	2.59E-03	-6.656317	-29.78	0.56
-0.007	-10411	-3.60E-04	1.30E-03	-3.524881	-28.1	0.6
-0.002	-8927	-0.00018	0.0003714	-1.171713	-24.09	0.6
0	0	0	0	0	0	0.6
0	0	0	0	0	0	0.6
0.0003	2979.7	-4.00E-05	4.44E-05	0.179418	8.0424	0.6
0.0007	5902.3	-8.00E-05	8.97E-05	0.360628	15.931	0.6
0.0011	8068.5	-1.20E-04	1.51E-04	0.575129	21.777	0.6
0.0016	9759.7	-1.60E-04	2.29E-04	0.825858	26.342	0.6
0.0021	11273	-0.0002	0.0003197	1.104262	30.428	0.6
0.0026	12718	-0.00024	0.0004202	1.402805	34.328	0.6
0.0032	14138	-2.80E-04	5.26E-04	1.716541	38.16	0.6
0.0038	15552	-3.20E-04	6.41E-04	2.041835	41.975	0.6
0.0045	16964	-0.00036	0.0007577	2.37485	45.787	0.6
0.0051	18378	-0.0004	0.0008776	2.714686	49.604	0.6
0.0058	19797	-0.00044	0.0009992	3.058093	53.432	0.6
0.0064	21210	-0.00048	0.0011225	3.405023	57.247	0.6
0.0071	22624	-5.20E-04	0.0012473	3.755289	61.064	0.6
0.0077	24027	-0.00056	0.001372	4.105311	64.849	0.6
0.0084	25437	-0.0006	0.0014971	4.455388	68.657	0.6
0.0091	26834	-0.00064	0.0016232	4.808367	72.425	0.6
0.0097	28217	-0.00068	0.0017485	5.160281	76.16	0.6
0.0104	29600	-0.00072	0.0018731	5.509306	79.831	0.6
0.011	30969	-0.00076	0.0019982	5.860735	83.586	0.6
0.0117	32325	-0.0008	0.0021228	6.210501	87.248	0.6
0.0123	33667	-0.00084	0.0022463	6.558036	90.869	0.6
0.013	34991	-0.00088	0.0023688	6.903175	94.441	0.6
0.0136	36299	-0.00092	0.0024903	7.246473	97.974	0.6

Step 3: Define the physical properties (mass, loaded area) of the system and the blast parameters (pressure-time history), then run the SDOF analysis to obtain the maximum displacement.



6.5 Analysis Results

This section summarises the results from the dynamic analysis using the procedure outlined in the previous section. Table 6.3 presents the models selected for the dynamic analysis. Table 6.4 and Table 6.5 summarizes the analytical (δ_{anls}) and experimental (δ_{exp}) mid-span maximum displacement, the displacement ratios ($\delta_{\text{anls}}/\delta_{\text{exp}}$) and the % of error while Table 6.6 presents a statistical analysis of the results including the mean displacement ratio, standard deviation, coefficient of variance and % of error for each blast. To illustrate the accuracy of the analysis, the analytical results vs. the experimental results have been plotted and are presented in Figure 6.8. Finally, the experimental and analytical displacement-time histories for each specimen are presented in Figure 6.9. It should be noted that an analysis was not completed for those shots where specimens failed in shear (Ex. SCC 0% - blast 2) as the displacement cannot be compared.

By observing the results for the plain concrete specimens, it can be concluded the combinations of Popovics (1973) and Jacques et al. (2012) models with associated DIF resulted in reasonably accurate results. For specimen SCC 0% and SCC 0% 100 mm the average displacement ratios for blast 1-4 were 112.6%, 110.9%, 100.4% and 68.6%. The results appear to be less accurate for blast 4 with the analytical displacement being lower than the experimental (83.77mm vs. 57.47mm). This could be attributed to the repeated nature of the testing (i.e. effects of accumulated damage). The analysis did not take into effect previous damage to the specimens.

The analytical SFRC with the ZP results shows a similar trend as the plain concrete specimens. The average displacement ratios observed are 121.2%, 107.0%, 92.8% and 59.3% for blast 1-4. Once again, the results are reasonably accurate for the first 3 blasts, but not for blast 4. The analytical results are lower than the experimental results and this could be again attributed to the repeated nature of the testing. By the time the beam reaches blast 4, it is possible that the fibers have started pulling out of the concrete matrix and their contribution diminished.

When comparing the analytical results of the high strength fibers (5D & BP) to their experimental counterpart they appear to be generally lower. The displacement ratios for blast 1-4 are 89.5%, 77.7%, 64.1% and 39.7%. It can be observed that the ratios decrease at each blast once again, likely due to the repeated nature of the testing. It might also indicate that Ou et al. with the corresponding DIF may not be accurately modeling the effect of the high strength fibers on SFRC material response.

Table 6.3: Selected model for dynamic analysis

Specimen	Concrete Models		Steel Models
	Compression (DIF)	Tension (DIF)	Tension (DIF)
Plain Concrete	Popovics <i>Saatcioglu et al.</i> (1.3)	Linear slope (1.0)	Jacques et al. <i>Saatcioglu et al.</i> (y: 1.3 & u: 1.1)
Steel fiber-reinforced concrete (SRFC)	Ou. et al. <i>Saatcioglu et al.</i> (1.3)	Lok & Pei <i>Malvar & Ross</i> (1.4)	Jacques et al. <i>Saatcioglu et al.</i> (y: 1.3 & u: 1.1)

Table 6.4 Summary of analysis for plain concrete specimen and SFRC specimen with ZP fiber

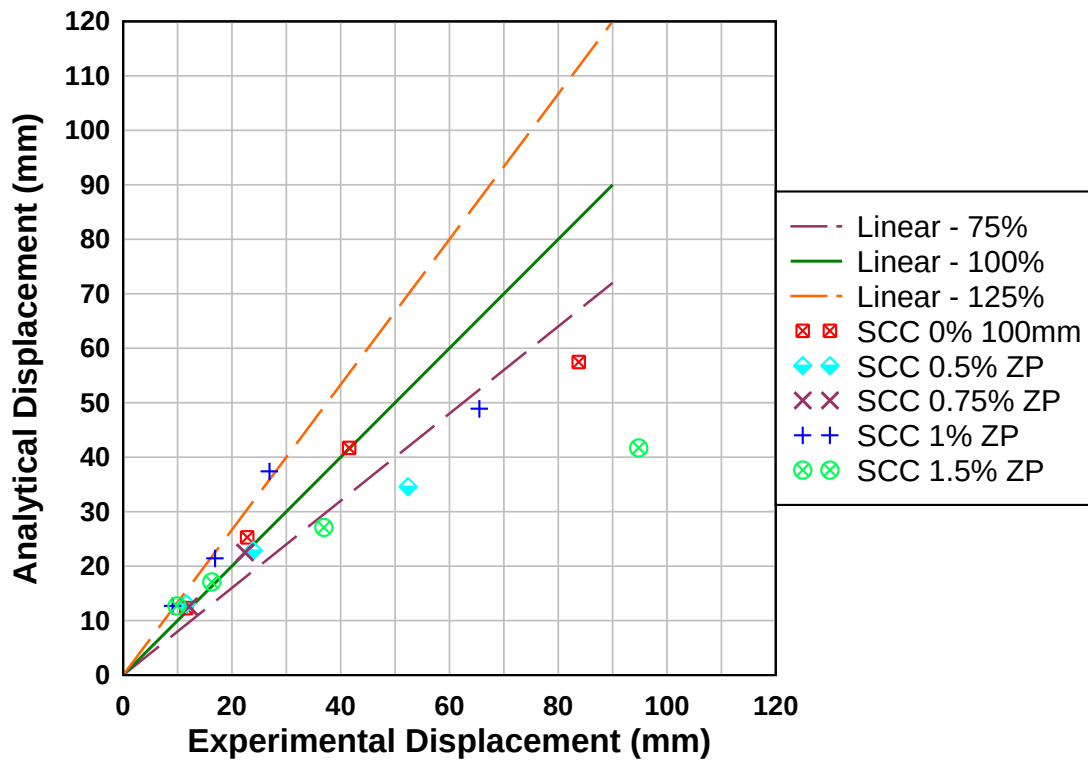
Beam	Blast #	Shockwave Properties			Maximum Mid-Span Displacement			
		P _r (kPa)	t _d (msec)	I _r (kPa*msec)	δ _{exp} (mm)	δ _{anls} (mm)	δ _{anls} / δ _{exp}	% error
SCC 0%	Blast 1	31.3	14.41	235	11.5	13.7	119.1%	19.1%
	Blast 2	50.4	15.4	359	Shear	--	--	--
SCC 0% 100mm	Blast 1	27.3	14.04	224	11.6	12.3	106.0%	6.0%
	Blast 2	61.1	15.46	348	22.8	25.2	110.9%	10.9%
	Blast 3	72.7	16.03	485	41.5	41.7	100.4%	0.4%
	Blast 4	91.8	16.19	570	83.7	57.4	68.6%	-31.4%
SCC 0.5% ZP	Blast 1	30.9	14.38	236	11.6	13.1	112.9%	12.9%
	Blast 2	48.3	15.46	369	23.9	22.9	95.8%	-4.2%
	Blast 3	58.2	16.6	487	52.4	34.6	66.0%	-34.0%
	Blast 4	69.2	16.81	607	Shear	--	--	--
SCC 0.75% ZP	Blast 1	30.8	14.61	228	12.1	12.6	104.1%	4.1%
	Blast 2	49.9	15.69	369	22.4	22.5	100.4%	0.4%
	Blast 3	61	16.03	527	Shear	--	--	--
SCC 1% ZP	Blast 1	35	13.95	214	9.1	12.7	139.6%	39.6%
	Blast 2	56.2	15.18	345	16.9	21.4	126.8%	26.8%
	Blast 3	68.2	16.31	517	36.2	37.4	103.3%	3.3%
	Blast 4	75.3	16.88	600	65.5	48.9	74.7%	-25.3%
SCC 1.5% ZP	Blast 1	29.5	14.61	242	9.9	12.7	128.3%	28.3%
	Blast 2	41.2	14.61	315	16.3	17.1	104.9%	4.9%
	Blast 3	59.4	16.03	427	36.9	27.1	73.4%	-26.6%
	Blast 4	74.2	16.6	552	94.8	41.7	44.0%	-56.0%

Table 6.5 Summary of analysis for SFRC specimen with 5D and BP fiber

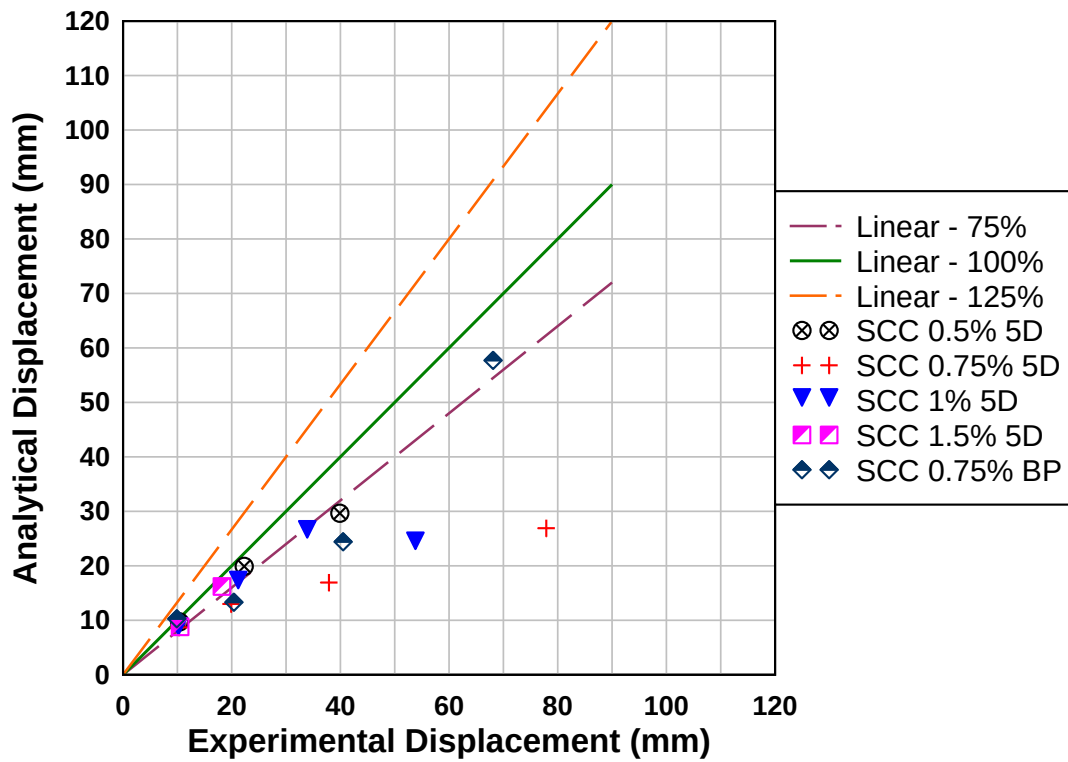
Beam	Blast #	Shockwave Properties			Maximum Mid-Span Displacement			
		P_r (kPa)	t_d (msec)	I_r (kPa*msec)	δ_{exp} (mm)	δ_{anls} (mm)	$\delta_{anls}/\delta_{exp}$	%error
SCC 0.75% BP	Blast 1	20.9	14.32	200	9.9	10.2	103.6%	3.6%
	Blast 2	42.3	15.75	325	20.4	13.3	65.2%	-34.8%
	Blast 3	54.5	16.47	485	40.5	24.4	60.3%	-39.8%
	Blast 4	69.9	16.85	569	68.1	57.7	84.7%	-15.3%
SCC 0.5% 5D	Blast 1	36.1	14.13	231	10.4	9.7	93.3%	-6.7%
	Blast 2	52	15.74	374	22.3	19.9	89.2%	-10.8%
	Blast 3	62.5	16.76	491	39.9	29.6	74.3%	-25.7%
	Blast 4	71.4	16.75	584	Shear	--	--	--
SCC 0.75% 5D	Blast 1	31.3	14.37	235	10.3	8.7	84.5%	-15.5%
	Blast 2	46.4	12.55	294	19.9	13	65.3%	-34.7%
	Blast 3	48.1	15.71	381	37.9	16.9	0.4467	-55.3%
	Blast 4	63.6	15.45	461	77.9	26.9	34.5%	-65.5%
SCC 1% 5D	Blast 1	30.1	14.2	253	10.2	8.4	82.4%	-17.6%
	Blast 2	52.5	15.18	378	21.2	16.9	79.7%	-20.3%
	Blast 3	68.4	15.17	469	33.9	26.2	77.3%	-22.7%
	Blast 4	73.2	17.81	570	53.8	24.1	44.8%	-55.2%
	Blast 5	74.4	18.32	648	101	44.3	43.9%	-56.1%
SCC 1.5% 5D	Blast 1	32.4	14.37	254	10.5	8.8	83.8%	-16.2%
	Blast 2	49	15.18	399	18.2	16.2	89.0%	-11.0%
	Blast 3	71.1	15.7	482	Shear	--	--	--

Table 6.6 Analysis Statistics

	Mean	Standard Deviation	Coefficient of variation	% of error
Blast 1-4	86.5%	27.2%	31.5%	13%
Blast 1	105.2%	18.8%	17.8%	-5%
Blast 2	92.7%	19.5%	21.0%	7%
Blast 3	79.4%	28.4%	35.7%	21%
Blast 4	58.6%	30.0%	51.2%	41%

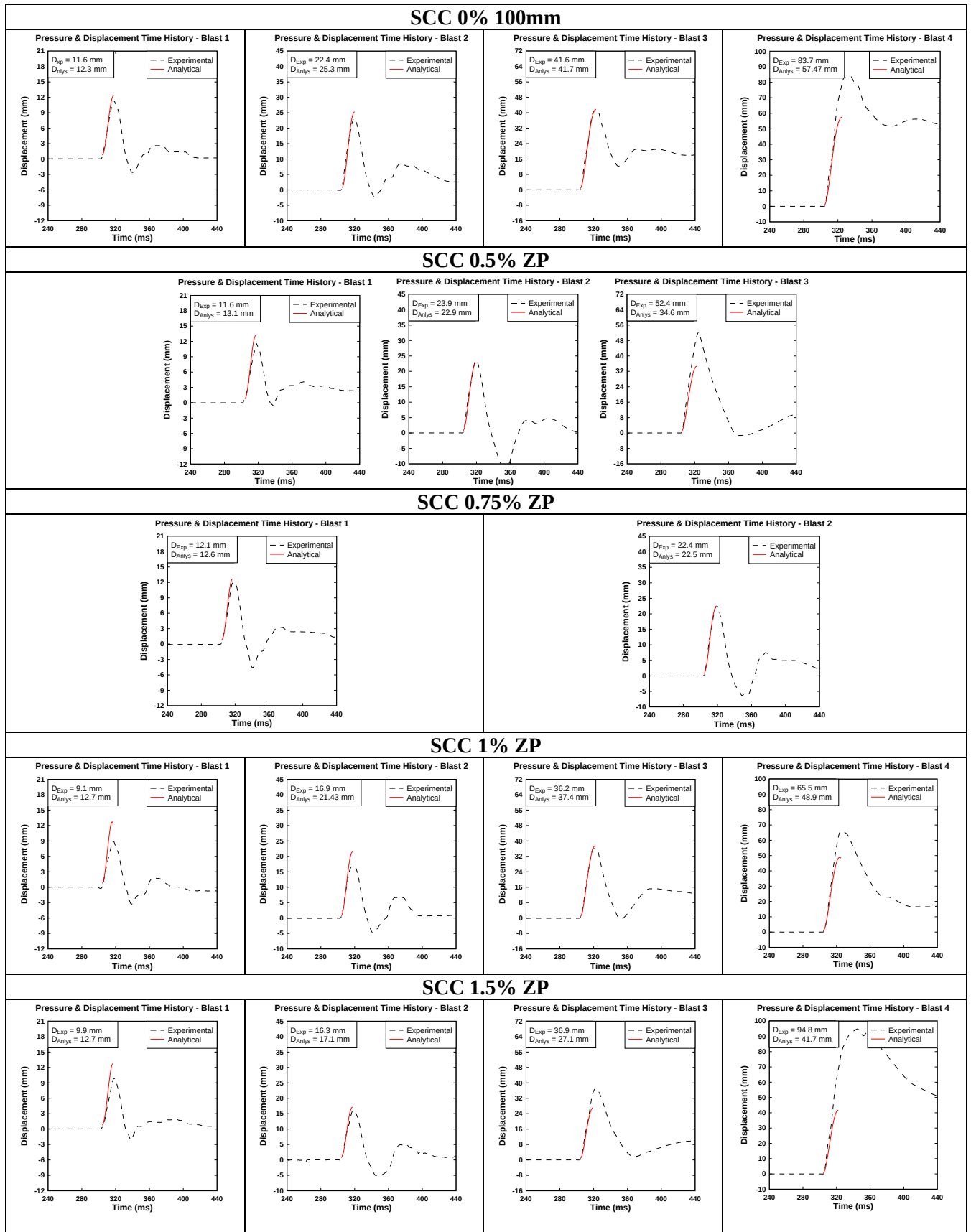


(a) – Plain concrete and SRFC with ZP fiber



(b) – SRFC with 5D and BP fiber

Figure 6.8 Experimental vs. Analytical Displacements



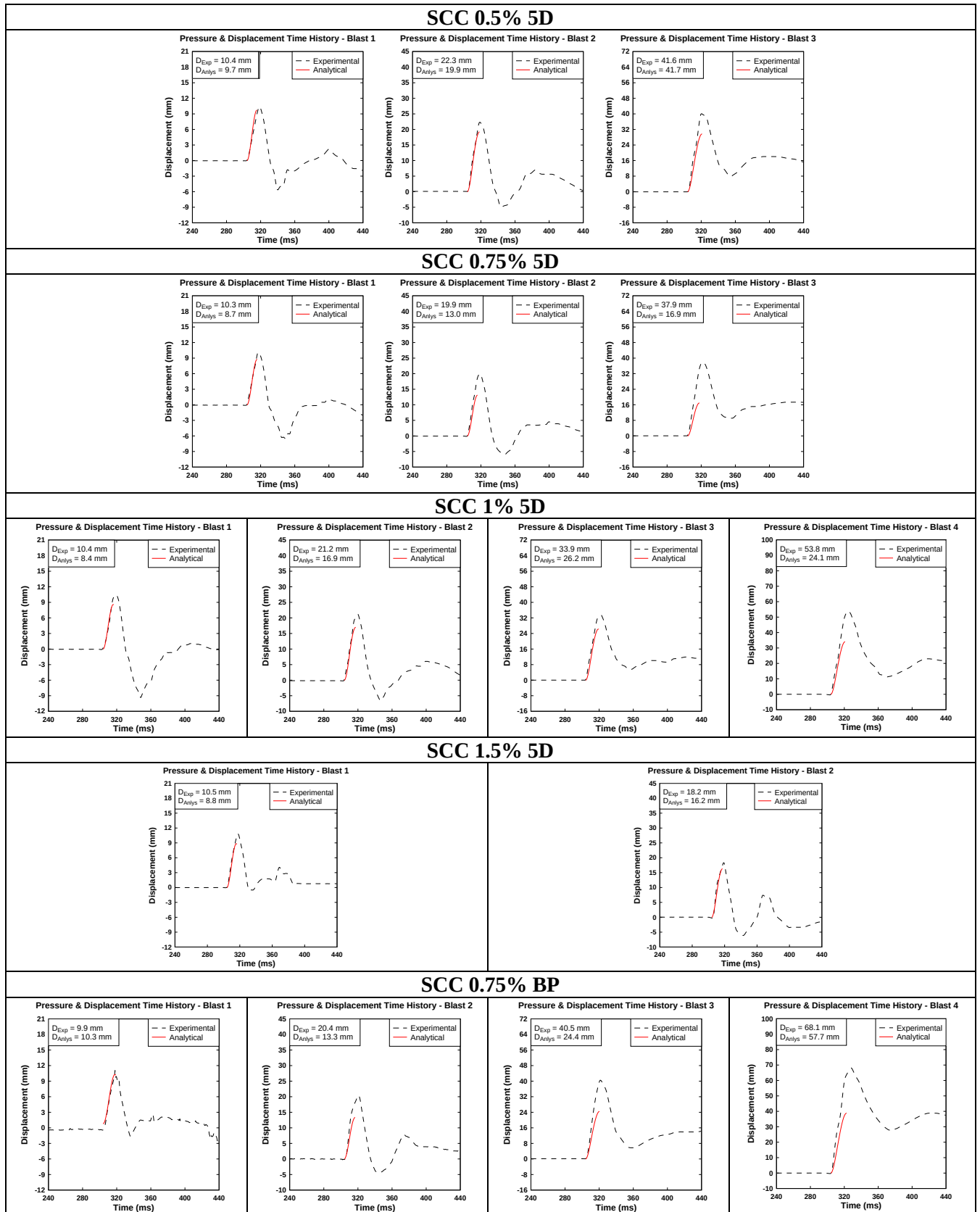


Figure 6.9: Experimental and Analytical Displacement-time histories

6.6 Potential Sources of Error

The maximum displacements were predicted using a dynamic inelastic SDOF analysis. This section explores a list of potential sources of error which may have influenced the accuracy of the predictions

- One factor which affected the accuracy of the analysis is the repeated nature of the loading used in this research program. Blast 1 was in the elastic range and blast 2 was slightly past the yield point of the specimens so they had minimal effect on specimen response. This was reflected in the analytical results at blast 1, 2 and 3 which generally produced accurate results. Blast 3 pushed the reinforcement in the specimens into the plastic region and resulted in some concrete damage. Slight concrete crushing and tension cracking was generally observed after Blast 3. This potentially affected the response of the beams as the existing damage could have lowered the stiffness of the beams due to reduced residual compression capacity and flexural cracking. In the case of SFRC beams the tension cracking may have also led to partial fiber pullout, thus lowering the contribution of steel fibers when compared to the assumptions made in the analysis. This would explain why analytical results for blast 4 were significantly lower when compared to blast 1, 2 and 3
- Another source of potential error is the choice of the plastic hinge length ($l'_p = d = 200mm$). Some previous research has suggested that plastic hinge length in SFRC members is smaller when compared to conventional reinforced concrete members, which would affect the post yield section of the resistance curve. Moreover, in this analysis the hinge length was concentrated at midspan whereas it may be argued plastic hinging should extend over the entire constant moment region.
- One potential source of error is the choice of effective area for the LTD ($A = 3.4m^2$). Previous research by Lacroix (2017) has suggested that the effective area load transfer device is somewhere between the area of the center panel ($A = 3.4m^2$) and the total shock tube opening area ($A = 4.13m^2$).
- In this research program, models for material behaviour and dynamic increase factors (DIF) were selected and they could be a potential source of error. As previously observed, the % of error observed was greater for the specimens with the 5D and BP when compared to the specimens with the ZP fiber. It is possible that the model chosen to predict the concrete

compressive and tensile strength is not accurate for the fibers with increased aspect ratio, length, and improved hook properties.

- Previous research has suggested that the concrete compression strength in the compressive zone of a structural member is lower than the peak compressive strength obtained from cylinder testing (due to size effect) and some researchers have suggested the use of a reduction factor (e.g. 0.85 in the case of columns). This could affect the maximum load and stiffness of the resistance curve and affect the post yield displacements.

7 Conclusion and Recommendation

This thesis presented an experimental and analytical study examining the blast performance of steel fiber-reinforced concrete (SFRC) beams. Parameters such as concrete type, fiber content and fiber type, as well as transverse steel ratio on performance were investigated.

As part of this study a total of 14 SFRC beams and 4 companion beams without fibers, were tested. A total of 7 beams were tested under quasi-static loading and a total of 11 beams were tested under simulated blast. For static tests, the performance of the beams was compared in terms of the test parameters on load resistance, ductility, toughness and failure mode. For the dynamic tests, the influence of the parameters was investigated by studying various performance criteria including the overall blast capacity, maximum and residual mid-span displacement, secondary fragmentation and damage control. The conclusion from the research study can be summarized as follows:

- SFRC specimens were capable of effectively replacing transverse reinforcement in beams subjected to quasi-static loads, preventing brittle shear failure and promoting ductility. Similarly, SFRC specimens with a high enough fiber content (1%) were capable of effectively replacing transverse reinforcement in beams subjected to blast loading. Increasing the fiber content in beams subjected to quasi static loading resulted in improvements in terms of peak load, ductility and toughness.
- The use of fiber greatly improved the damage tolerance and also significantly reduced secondary blast fragments in the beams when compared to the case of plain concrete.
- Improved blast performance was observed by increasing fiber content up until a critical fiber content (1%). After the critical fiber content was reached, a reduction in blast performance was observed, likely as a result of workability/placement issues and loss of mix uniformity at higher fiber contents.
- The results show that using fibers with higher aspect ratio (55 vs. 65 vs. 79) increases performance of the beams subjected to both quasi-static loading and blast loading.

Dynamic inelastic analysis was used to predict the response of the test specimens. Moment-curvature relationships and resistance curves were developed using dynamic material models for plain concrete, SFRC and steel reinforcement. SDOF analysis was then conducted using software *RC blast*. The conclusions from the analytical study are summarized below:

- The SDOF analysis, with appropriate development of dynamic resistance functions, was able to accurately predict the dynamic response of the beams at earlier blasts, although accuracy reduced at later blast intensities. Predictions were also not as accurate for beams built with the BP and 5D fibers which had enhanced fiber properties.
- Some potential sources of error include the effect of accumulated damage (from repeated blasts) which was not considered in the analysis and the choice of plastic hinge length. There is also a need to develop material and dynamic models for SFRC made of different fiber types.

7.1 Recommendation for Future Research

Based on this study, the following research is suggested for future investigations:

- Studying the effects of combining steel fibers with transverse reinforcement in SFRC beams subjected to blast loads.
- Studying the effect of combining steel fiber reinforcement with high strength concrete structural members subjected to blast loads.
- Further blast loads testing on virgin specimens to failure (i.e. tests under single blast) and comparison to specimens tested under repeated blast loads.
- Further experimental studies investigating the effect of close-in blast loading on the performance of SFRC beams.
- Further analytical research of the modeling of the effect of repeated blast loading on beam resistance.
- Further analytical research on the blast modeling of SFRC members using more advanced modelling techniques (e.g. finite element modeling).

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