Influence of steel fibers on the shear and flexural performance of high-strength concrete beams tested under blast loads

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Abstract. This paper presents the results of a study examining the effect of steel fibres on the blast behaviour of high-strength concrete beams. As part of the study, a series of three large-scale beams built with high-strength concrete and steel fibres are tested under simulated blast loading using the shock-tube testing facility at the University of Ottawa. The specimens include two beams built with conventional high-strength concrete (HSC) and one beam built with high-strength concrete and steel fibres (HSFRC). The effect of steel fibres on the blast behaviour is examined by comparing the failure mode, mid-span displacements and, overall blast resistance of the specimens. The results show that the addition of steel fibres in high-strength concrete beams can prevent shear failure and substitute for shear reinforcement if added in sufficient quantity. Moreover, the use of steel fibres improves flexural response under blast loading by reducing displacements and increasing blast capacity. Finally, the provision of steel fibres is found to improve the fragmentation resistance of high-strength concrete under blast loads.

1. Introduction
High-strength concrete (HSC) may be defined as concrete having a compressive strength which exceeds 60 MPa. The high-strength properties of HSC are achieved by reducing the porosity in the concrete matrix through careful selection and proportioning of mix constituents (cement, sand, aggregate), use of low water-cement ratio and use of chemical and mineral admixtures (e.g. superplasticizers and silica fume). The high-strength of HSC makes it ideal for heavily-loaded structures (e.g. columns in high-rise buildings) while its high stiffness and reduced porosity make it well-adapted for use in long-span structural components, and structures where durability has increased importance (e.g. bridges). On the other hand, the high strength of HSC results in reduced ductility, with brittle failure in compression and poor tensile resistance.

The provision of steel fibres is a practical solution for the brittle response of HSC. The ability of fibres to arrest and redistribute cracking allows high-strength fibre-reinforced concrete (HSFRC) to show more ductile failure in compression, while also allowing the material to have increased tensile resistance and post-cracking capacity. The provision of fibres also results in increased toughness and fragmentation resistance. The high-performance properties of HSFRC make it ideally-suited for use in extreme loading applications, such as impact and blast.

Over the years, several researchers have investigated the effect of steel fibres on the behavior of concrete under high stress-rates. Most of the previous studies have focused on material tests,
conducted on smaller-scale specimens, using various impact setups [1-5]. A relatively fewer investigations have focused on the impact and blast performance of larger-scale structural components. Most previous studies in this area have focused on slabs [6-8], with a limited number of investigations examining behavior of beams and columns [9-10]. This paper presents the results from an experimental program examining the effect of steel fibres on the blast behaviour of high-strength concrete beams. As part of the study three beams built with and without steel fibres are tested under simulated blast loads using a high-capacity shock-tube. The effect of HSFRC on blast behaviour is examined by comparing the failure mode, mid-span displacements and overall blast resistance of the beams.

2. Experimental program

2.1. Specimen designs
Three reinforced concrete beams were built and tested in this research program. Table 1 summarizes the design details of the specimens. As shown Figure 1, the beams had cross-section of 125 mm x 250, with a total length of 2440 mm. The beams were simply supported over a span of 2232 mm, with a constant moment region of 750 mm and two equal shear spans of 741 mm. Two of the beams were cast with plain high-strength concrete (HSC), with the remaining beam cast with HSC and 1% of steel fibers by volume of concrete (80 kg/m³). Longitudinal reinforcement consisted of 2-20M Canadian size bars (d_b = 19.5 mm, A_s = 300 mm²). One of the HSC beams and the HSFRC beam were designed without stirrups. The remaining HSC beam was reinforced with U-shaped stirrups, made from 6.3 mm diameter smooth steel wire, spaced at 100 mm in the shear spans. Two 6.3 mm bars were also provided at the top of the beams in the shear spans only. The specimen nomenclature reflects the test variables which include concrete type (where “HSC-F0” refer to plain HSC and “HSC-F1” refers to HSFRC) and shear reinforcement details (“S” for presence of stirrups and “0” for lack of stirrups).

| Beam I.D.   | Concrete Mix | Concrete Strength f'c (MPa) | Steel fibre properties Lf/Dr (mm/mm) | Vf (%) | Steel reinf. properties | Transverse Steel | Flexural Steel |
|------------|--------------|----------------------------|------------------------------------|--------|--------------------------|-----------------|---------------|
| HSC-F0-20M-0 | HSC          | 110                        | -                                  | -      |                          |                 |               |
| HSC-F1-20M-0 | HSFRC        | 104                        | 30/0.55                            | 1.0    | 6.3 mm stirrups @ s = 100 mm |                 | 2-20M         |

2.2. Materials
The high-strength concrete in this study had a target strength of 100 MPa. The mix constituents included Portland cement, slag, silica fume, coarse aggregate (13 mm and 20 mm), sand and liquid admixtures (super-plasticizer and set retarder). The HSFRC used the same mix, with the addition of 30 mm hooked-end steel fibres at a dosage (Vf) of 1% by volume of concrete (80 kg/m³). The properties of the HSC and HSFRC concrete in terms of compressive strength, obtained by testing 100 mm x 200 mm cylinders, are summarized in Table 1. Sample stress-strain curves are shown in Figure 2, along with sample flexural test results obtained from testing 100 mm x 100 mm x 400 mm prisms in accordance with the ASTM C1609 Standard. The normal-strength 20M longitudinal steel reinforcement had an average yield strength of 460 MPa, while the 6.3 mm steel wire used for the transverse reinforcement had an average yield strength of 540 MPa (sample stress-curves curves are also shown in Figure 2).
2.3. Test setup

The University of Ottawa Blast Research Laboratory is equipped with a high-capacity shock-tube that can simulate the shockwaves generated by blasts without the need for live explosives. As shown in Figure 3a, the shock-tube consists of four main components: (1) a variable length driver section, (2) a spool section, (3) an expansion section and (4) a rigid end test frame. The driver section generates the blast energy, while the firing of the shockwave is controlled using the spool section. The rigid end test frame has a 2m x 2m square opening where test specimens can be attached. For non-planar elements, such as beams, a load transfer device (LTD) is used to collect the shockwave pressure at the shock-tube opening and redirect it onto the test specimens. In the current study the LTD resulted in the application of blast loading under four-point bending. Figure 3b shows a typical beam prior to testing. Complete displacement-time histories were recorded using two linear variable differential transducers (LVDT) placed at 1/2 (mid-height) and 1/3rd span of the beam (see Figure 3b). A high-speed camera was placed at the side of the beams during testing, and recorded response at a frame rate of 500 frames per second.

Testing of the beams was conducted under gradually increasing blast pressures until failure. Blast 1 was meant to test the specimens under elastic conditions, while Blast 2 was meant to bring the steel reinforcement in the beams to yielding. Blasts 3, 4 and 5 were applied to cause damage and failure in those specimens which reached flexural capacity. Examples of the shockwaves for Blasts 1 to Blast 5 are shown in Figure 3c. Shockwave properties are also summarized in Table 2.

Figure 1. Dimensions and reinforcement for beams with & without shear reinforcement.
3. Results

Table 2 summarizes the experimental results for the three beam specimens, including the shockwaves properties for each test (reflected pressure $P_r$, reflected impulse $I_r$, positive phase duration $t_p$) as well as beam response in terms of maximum ($d_{max}$) and residual ($d_{res}$) mid-span displacements. Table 3 to 5 show the progression of damage in the beams during testing, while Figure 4 compares the displacement response of the beams at selected blasts.
Table 2. Blast test results.

| Beam I.D. | Blast # | Shockwave Properties | Displacement |
|-----------|---------|----------------------|-------------|
|           |         | Pressure $P_r$ (kPa) | Impulse $I_r$ (kPa*ms) | Duration $t_p$ (ms) | $d_{max}$ (mm) | $d_{res}$ (mm) |
| HSC-F0-20M-0 | 1 | 23.9 | 239.5 | 20.0 | 12.6 | 3.4 |
| HSC-F0-20M-0 | 2 | 39.2 | 370.8 | 19.3 | 9.2 |
| HSC-F0-20M-S | 1 | 39.2 | 360.0 | 18.4 | 15.1 | 0.2 |
| HSC-F0-20M-S | 2 | 57.4 | 538.2 | 18.8 | 32.9 | 12.4 |
| HSC-F0-20M-S | 3 | 68.8 | 702.6 | 20.4 | 118.1 | 71.7 |
| HSC-F1-20M-0 | 1 | 23.4 | 244.0 | 20.9 | 8.4 | 1.4 |
| HSC-F1-20M-0 | 2 | 41.8 | 387.0 | 18.5 | 14.7 | 3.4 |
| HSC-F1-20M-0 | 3 | 57.1 | 571.2 | 20.0 | 20.8 | 4.1 |
| HSC-F1-20M-0 | 4 | 69.6 | 734.5 | 21.1 | 42.1 | 19.3 |
| HSC-F1-20M-0 | 5 | 75.3 | 738.0 | 19.6 | 62.4 | 37.4 |

3.1. Beam HSC-F0-20M-0
Beam HSC-F0-20M-0 was constructed with plain high-strength concrete and 20M normal-strength steel. The specimen was built without shear reinforcement. Blast 1 was meant to test the beam within the elastic range, and resulted in cracking of concrete and small residual displacements. Under Blast 2, the beam suffered a brittle shear failure with a diagonal crack forming in the top shear span as shown in Table 3 and resulted in maximum & residual displacements of 19.3 and 9.2 mm.

Table 3. Progression of blast damage in beam HSC-F0-20M-0

| Blast | Close-up of damage at failure |
|-------|-------------------------------|
| Blast 1 | ![Close-up of damage at failure](image) |
| Blast 2 | ![Close-up of damage at failure](image) |

3.2. Beam HSC-F0-20M-S
Beam HSC-F0-20M-S was constructed with plain high-strength concrete and 20M normal-strength steel, however unlike the previous specimen the beam was reinforced with transverse reinforcement spaced at 100 mm in the shear spans. Blast 1 was meant to test the beam within the elastic range, and resulted in cracking of concrete and small residual displacements. Blast 2 brought the 20M steel close to yield levels and resulted in maximum displacement of 15.1 mm with minimal residual deformations. The provision of shear reinforcement in this beam prevented shear failure. The 20M reinforcement in the beam went into the plastic range after Blast 3, resulting in a maximum displacement of 32.9 mm and larger residual displacement of 12.4 mm. Cracking became more prominent after this test with a flexural crack propagating the full depth of the beam. Blast 4 (70 psi) was the last shot for this specimen and resulted in maximum and residual displacements of 118 mm and 72 mm. As shown in Table 4, failure occurred in the compression zone due to severe concrete
crushing at mid-span. High-speed video shows the generation of important secondary fragments at failure.

| Table 4. Progression of blast damage in beam HSC-F0-20M-S |
|---------------------------------|-----------------|-----------------|-----------------|-------------------|
| Blast 1                         | Blast 2         | Blast 3         | Blast 4         | Close-up of damage at failure |
| ![Image](image1.png)            | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) |

3.3. Beam HSC-F1-20M-0
The design of beam HSC-F1(ZP)-20M-0 matched that of HSC-F0-20M-0 (20M bars, no shear reinforcement), except for the addition of steel fibres at a ratio 1.0% by volume of concrete. Blast 1 and Blast 2 resulted in limited deformations and very limited damage in the beam. Blast 3 resulted in the formation of a prominent crack at mid-span, however the beam prevented shear failure, with the 20M steel reinforcement reaching post-yield levels. The maximum and residual displacements after this blast were 20.8 mm and 4.1 mm which are reduced when compared to the previous beam. Blast 4 resulted in maximum and residual displacements of 42 mm and 19 mm, and resulted in an increase in crack widths, however, the beam survived this blast. Blast 5 resulted in major opening of the critical crack at mid-span, with the steel fibres showing signs of pull-out, and therefore the beam was deemed to have failed after this shot (see Table 6). Nonetheless, concrete crushing and fragmentation at failure was limited. The maximum and residual displacements were 62 mm and 37 mm, after this blast.

| Table 5. Progression of blast damage in beam HSC-F1-20M-0 |
|---------------------------------|-----------------|-----------------|-----------------|-------------------|
| Blast 1                         | Blast 2         | Blast 3         | Blast 4         | Blast 5           | Close-up of damage at failure |
| ![Image](image1.png)            | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) |

4. Discussion of results
Comparison between the behaviour of beams HSC-F0-20M-0 and HSC-F1-20M-0 allows for an investigation into the effect of steel fibres on shear resistance since both beams were built without stirrups. The plain HSC beam failed in shear at Blast 2 due to the lack of transverse shear
reinforcement. In contrast, the use fibres in specimen HSC-F1-20M-0 prevented shear failure, and allowed the HSFRC beam to survive up to Blast 5 pressures, with failure occurring in flexure.

Comparison of the responses of beams HSC-F1-20M-0 and HSC-F0-20M-0, shows that the HSFRC beam was to not only able to match, but out-perform the companion HSC beam which contained stirrups. As shown in Figure 4, beam HSC-F1-20M-0 reduced maximum displacements by margins of 37% and 64% when compared to beam HSC-F0-20M-S after Blast 3 and Blast 4, respectively (d_{\text{max}} = 20.8 \text{ vs. } 32.9 \text{ mm and } 42.1 \text{ vs. } 118.1 \text{ mm, respectively}). Residual displacements were also significantly reduced for the HSFRC beam, with reductions of 67% and 73% when compared to beam HSC-F0-20M-S (d_{\text{res}} = 4.1 \text{ vs. } 12.4 \text{ mm and } 19.3 \text{ vs. } 72 \text{ mm, respectively}). More importantly, the provision of fibres allowed for an increase in blast capacity with failure delayed from Blast 4 in the plain HSC beam to Blast 5 in the HSFRC companion. Damage tolerance was also significantly affected, with failure in the HSC specimen associated with complete disintegration of concrete in the compression zone, while the HSFRC beam showed limited crushing with failure occurring due to fibre pullout in the mid-span tension region. Because of the ability of the fibres to hold the concrete together, secondary blast fragments where also significantly reduced.

In summary, the results demonstrate clear benefits associated with the use of steel fibres in high-strength concrete beams. The provision of steel fibres was able of effectively substitute for transverse shear reinforcement, prevented shear failure and promoted ductile flexural response. Moreover, the use of fibres allowed for a better control of maximum and residual displacements at equivalent blasts, and led to an increase in blast capacity (ability to sustain larger blast loads).

![Figure 4](image_url)

**Figure 4.** Mid-span displacement time-histories at: (a) Blast 3 and (b) Blast 4.

5. Conclusions
This paper presented the results from three high-strength concrete beams, built with and without steel fibres, and tested under blast loading. The following conclusions can be drawn from this study:

- The provision of steel fibers in the high-strength concrete beams increased shear resistance and prevented brittle shear failure under blast loading;
- The addition of steel fibers in the high-strength concrete beams improved flexural performance by reducing maximum and residual displacements and increasing overall blast resistance;
- The addition of steel fibers to high-strength concrete had an resulted in better control of damage and reduced secondary blast fragments.

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