Influence of steel fibres on the blast response of normal-strength and high-strength reinforced concrete columns

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Abstract. This paper examines the influence of steel fibres on the blast performance of normal-strength concrete and high-strength concrete columns. As part of the study, four normal-strength and high-strength concrete columns built with and without steel fibres are tested under simulated blast loads using the shock-tube facility at the University of Ottawa. The specimens include two columns built with plain concrete and two columns built with steel fibre-reinforced concrete. The results show that the addition of steel fibres in reinforced concrete columns leads to important enhancements in blast performance, with improved control of mid-span displacements at equivalent blasts and increased damage tolerance.

1. Introduction
Availability of constituent ingredients, ease of construction, and design flexibility are among the many qualities that make concrete the material of choice for the design and construction of modern infrastructure. Despite its many advantages, concrete’s deficiency is in its poor tensile resistance. The addition of steel fibres is a practical solution to this problem, and allows concrete to have increased tensile resistance, post-cracking capacity and toughness [1]. In reinforced concrete structures such as beams, the provision of fibres leads to enhanced shear resistance and flexural ductility [2-5]. In structures subjected to seismic load-reversals, the use of fibres can be used to relax transverse reinforcement requirements and increase energy-dissipation capacity [6]. The toughness and fragmentation resistance of steel fibre-reinforced concrete (SFRC) also make it well-suited for use in impact and blast applications [7-10].

This paper presents the results from an ongoing experimental program examining the effect of steel fibres on the blast behavior of reinforced concrete columns. The paper presents the results from four normal-strength and high-strength concrete columns, built with and without steel fibres, which are tested under simulated blast loads using a high capacity shock-tube at the University of Ottawa. The effect of steel fibres on blast behaviour is examined by comparing mid-span displacements and damage tolerance of companion columns at equivalent blasts.

2. Experimental program
2.1. Specimen designs
A total of four reinforced concrete columns are included in this study. Table 1 summarizes the design details of the specimens and includes information on concrete type, fibre properties and reinforcement.
details. As shown Figure 1, the columns had cross-sectional dimensions of 152 mm x 152 mm, with a total length of 2440 mm. Longitudinal reinforcement in the columns consisted of 4 - 10M Canadian size bars (d_b = 11.3 mm, A_s=100 mm²), while transverse reinforcement was provided using square ties made from 6.3 mm steel wire (A_t=31 mm²), spaced at s = 75 mm over the column height. In all cases the clear concrete cover was kept constant at 5 mm. Two concrete types were considered in the test program. The first mix which is described as “NSC” in the specimen nomenclature, had a target strength of 50 MPa, while the second consisted of a high-strength concrete (HSC) mix with a target strength of 100 MPa. For each concrete type, one column was built with plain concrete and one column was cast with fibre-reinforced concrete having a volumetric ratio of 1% of steel fibres (80 kg/m³) (the use of “F0” and “F1” in the specimen names refers to the use of 0% and 1% fibres, respectively). The hooked-end fibres had a length (L_f) of 30 mm, a diameter (D_f) of 0.55 mm, with tensile strength of 1350 MPa. The concrete strengths for each column were obtained by testing 100 mm x 200 mm cylinders in compression and are summarized in Table 1. Sample stress-strain curves for the plain and fibre-reinforced HSC are shown in Figure 2 as examples. The 10M bars used in the NSC columns had an average yield strength of 483 MPa, while those in the HSC columns had yield strength of 474 MPa. The steel wire used for the transverse reinforcement had average yield strength of 604 MPa and 542 MPa in the NSC and HSC columns, respectively. Sample stress-strain curves for the steel reinforcement are shown in Figure 2.

Table 1. Column test matrix.

| Beam I.D.       | Concrete Mix type | Concrete Strength f_c (MPa) | Steel fibre properties | Steel reinf. properties |
|-----------------|-------------------|-----------------------------|------------------------|------------------------|
| NSC-F0-10M-75   | NSC               | 51.6                        | -                      | 6.3 mm square ties @ s = 75 mm |
| NSC-F1-10M-75   | NC                | 46.1                        | 30/0.55 1.0            | 4 - 10M                |
| HSC-F0-10M-75   | HSC               | 93.9                        | -                      |                        |
| HSC-F1-10M-75   | HSC               | 93.3                        | 30/0.55 1.0            |                        |

Figure 1. Dimensions and reinforcement properties for reinforced concrete columns.

Figure 2. Sample stress-strain curves (HSC series): (a) concrete in compression and (b) steel reinforcement in tension.
2.2. Test setup
The columns in this study were tested under simulated blast loads using the University of Ottawa shock-tube. As shown in Figure 3a, the shock-tube consists of four main parts: (1) a variable length driver section, (2) a spool section, (3) an expansion section and (4) a rigid end test frame with a 2 m x 2m square opening. The shockwave is produced by rapidly releasing compressed air from the driver section into the expansion section using a double-diaphragm firing system in the spool section. For non-planar elements, such as beams and columns, 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 this study, the LTD consists of a light gauge steel metal sheet connected to a series of steel beams which resulted in the application of blast loading as an approximately uniformly distributed load. Figure 3b shows a typical column prior to testing. The columns, which had a clear span of 1980 mm, were fixed to the shock-tube frame using partially-fixed supports. All columns were tested under combined axial loading and transverse blast loads, with axial load (P = 300 kN) applied using a hydraulic jack placed at the bottom of the specimens.

The columns were subjected to different simulated blast pressure–impulse combinations using the shock-tube which tested them under elastic (Blast 1), yield (Blast 2), and ultimate conditions (Blast 3). Sample shockwaves for Blasts 1 to 3 are shown in Figure 3c. The average reflected impulses under Blasts 1-2-3 were approximately 175, 420 and 765 kPa*msec, respectively.

Figure 3. (a) Shock-tube, (b) column setup and (c) sample shockwaves for Blasts 1-3.
3. Results

Table 2 summarizes the experimental results for the four column specimens tested in this study, including the positive phase shockwave impulse ($I_r$) imparted on each column at each blast, and column response in terms of maximum & residual mid-span displacements ($d_{\text{max}}$ & $d_{\text{res}}$), and maximum support rotations. Table 3 shows the damage in the columns at the end of testing, while Figure 4 compares the displacement response of the columns at selected blasts.

Table 2. Blast test results.

| Column I.D.          | Blast # | Shockwave Impulse $I_r$ (kPa*ms) | Displacement | Support rotation $\Theta$ (°) |
|----------------------|---------|---------------------------------|--------------|--------------------------------|
|                      |         | $d_{\text{max}}$ (mm) | $d_{\text{res}}$ (mm) |                               |
| NSC-F0-10M-75        | 1       | 130                            | 6.4          | 1.8                            | 0.37                           |
|                      | 2       | 381                            | 29.9         | 9.7                            | 1.73                           |
|                      | 3       | 781                            | 126.2        | 108.6                          | 7.26                           |
| NSC-F1-10M-75        | 1       | 127                            | 5.1          | 0.6                            | 0.30                           |
|                      | 2       | 411                            | 23.3         | 5.4                            | 1.35                           |
|                      | 3       | 767                            | 87.7         | 47.6                           | 5.06                           |
| HSC-F0-10M-75        | 1       | 233                            | 8.4          | 1.3                            | 0.49                           |
|                      | 2       | 429                            | 33.6         | 14.7                           | 1.94                           |
|                      | 3       | 779                            | 132.6        | 118.7                          | 7.63                           |
| HSC-F1-10M-75        | 1       | 216                            | 7.1          | 0.5                            | 0.41                           |
|                      | 2       | 453                            | 19.4         | 6.7                            | 1.12                           |
|                      | 3       | 734                            | 83.8         | 52.9                           | 4.84                           |

3.1. Column NSC-F0-10M-75

Column NSC-F0-10M-75 was the first specimen tested in the research program. It was constructed with plain normal-strength concrete, 4-10M bars and 6.3 mm ties spaced at 75 mm. The column was undamaged after Blast 1, while Blast 2 resulted in some transverse cracking at the levels of the ties along the column height. Failure of this column occurred under Blast 3 loads, with the column recording maximum & residual displacements of 126 mm and 109 mm, with a maximum support rotation of 7.3°. As shown in Table 3 failure of the column was associated with important damage, with crushing of concrete, spalling of the cover and buckling of the compression steel reinforcement at midspan.

3.2. Column NSC-F1-10M-75

The design of column NSC-F1-10M-75 is identical to that of the previous specimen, with the exception being the addition of steel fibres at a volumetric ratio 1.0% in NSC-F1-10M-75. As with its companion Blast 1 and Blast 2 resulted in limited damage and deformations. Failure of the column would occur under Blast 3 loading. Some improvements are noted both in terms of control of displacements and control of damage when compared to the previous specimen. Maximum and residual displacements after Blast 3 were 88 mm and 48 mm, with a maximum support rotation of 5.1°. As shown in Table 3 the addition of fibres led to minimal spalling and crushing, with prevention of bar buckling.

3.3. Column HSC-F0-10M-75

Column HSC-F0-10M-75 was the first of two specimens built with high-strength concrete. This control column was built without fibres. As in the previous series the relatively moderate blasts at the first two shots resulted in only minor cracking of concrete. Under Blast 3, the column suffered failure
with concrete crushing and spalling at midspan as shown in Table 3. The maximum & residual displacements were recorded to be 133 mm and 119 mm at this blast, with a support rotation of 7.6°.

3.4. Column HSC-F1-10M-75
Column HSC-F1-10M-75 was the last column tested in this research study. It is a companion to specimen HSC-F0-10M-75, and was built with high-strength concrete and 1% steel fibres. Blasts 1 and 2 resulted in small deformations and limited damage in this specimen. Failure of the column would once again occur under Blast 3 loading, however the use of fibres results in improved deformation control, with maximum and residual displacements of 84 mm and 53 mm, and maximum support rotation of 4.8°. As shown in Table 3, damage in the column was more controlled when compared to its plain HSC companion, with limited crushing and spalling. Failure in this column occurred due to pullout of the fibres at a critical crack at midspan.

Table 3. Comparison of damage in columns after Blast 3 loading

| Column ID | NSC-F0-10M-75 | NSC-F1-10M-75 | HSC-F0-10M-75 | HSC-F1-10M-75 |
|-----------|---------------|---------------|---------------|---------------|
|           |               |               |               |               |

![Image of Table 3]
4. Discussion of results

Comparison between the behaviour of companion columns in the NSC and HSC series allows for a study of the effect of fibres on the blast performance of normal-strength and high-strength concrete columns. All four columns in the study failed at Blast 3, however some enhancements in performance are observed in terms of the ability of fibres to improve displacement control under equivalent loading.

The specimens in the NSC series showed similar deformations after Blast 1. However, as shown in Figure 4, the maximum and residual displacements were reduced by 20% and 44% for column NSC-F1-10M-75 (with fibres) when comparing to NSC-F0-10M-75 (plain concrete), after Blast 2. The effect of fibres on controlling displacements is even more clear at Blast 3, with the provision of fibres allowing for reductions of 31% and 56% in maximum and residual displacements.

Similar trends are observed in the high-strength concrete series. As with the previous set, both HSC columns showed similar response under Blast 1. However, as shown in Figure 5 control of maximum deformations was improved for the HSFRC column (HSC-F1-10M-75) at Blast 2 and 3, with reductions of 42% and 37% when compared to the plain HSC column (HSC-F0-10M-75). Residual displacements were also better controlled for column HSC-F1-10M-75 at these blasts, with reductions of 54% and 55% when compared to the plain HSC companion.

The steel fibres also had a significant influence on the damage in the columns. While all four specimens failed at Blast 3, damage was clearly better controlled when fibres were provided (see the close-up photos of damage in Table 3). While the plain NSC and HSC columns show prominent damage with significant crushing and spalling of concrete at mid-span, crushing is more limited and spalling is well controlled in the fibre-reinforced companions. High-speed video shows this translated into a significant reduction in the amount of secondary blast fragments, with the high fragmentation in the plain concrete columns minimised when fibres were provided (see example in Figure 6).

![Figure 4. Mid-span displacement time-histories for NSC columns: (a) Blast 2 and (b) Blast 3.](image)

![Figure 5. Mid-span displacement time-histories for HSC columns: (a) Blast 2 and (b) Blast 3.](image)
5. Conclusions
This paper presented the results from four reinforced concrete columns, built with and without steel fibres, and tested under blast loading. The following conclusions can be summarized from this study:

- The use of steel fibres resulted in enhanced control of maximum and residual displacements in the NSC and HSC columns, although blast capacity was not increased;
- The use of steel fibres improved damage tolerance in the columns, and resulted in reduced concrete crushing and better control of cover spalling;
- The addition of steel fibres significantly reduced the amount of secondary blast fragments at column failure.

References
[1] Li V S 2002 Large volume, high-performance applications of fibers in civil engineering, J. of Applied Polymer Sc. 83(3) 660-86
[2] Barros J A and Figueiras J A 1999. Flexural behavior of SFRC: testing and modeling. J. of Mat. in Civil Eng. 11(4), 331-39.
[3] Meda A, Minelli F, Plizzari G A and Riva P 2005 Shear behaviour of steel fibre reinforced concrete beams. Mat. and Struct. 38(3) 343-51.
[4] Parra-Montesinos G J 2006 Shear strength of beams with deformed steel fibers. Concr. Int., 28(11), 57
[5] Di Prisco M, Plizzari G and Vandewalle L 2009 Fibre reinforced concrete: new design perspectives. Mat. and Struct. 42(9) 1261-81.
[6] Parra-Montesinos G J and Chompreda P 2007 Deformation capacity and shear strength of fiber-reinforced cement composite flexural members subjected to displacement reversals. J. of Struct. Eng. 133(3) 421-31.
[7] Banthia N, Mindess S and Trorrier J E 1996 Impact resistance of steel fiber reinforced concrete. ACI Mat. J. 93 472-79.
[8] Gopalaratnam V S and Shah S P 1986 Properties of steel fiber reinforced concrete subjected to impact loading ACI J. 83(1) 117-26
[9] Lok, T S and Xiao J R 1999 Steel-fibre-reinforced concrete panels exposed to air blast loading Struct. and Build. 134(4) 319-31
[10] Magnusson J, Hallgren M and Ansell A 2010 Air-blast-loaded, high-strength concrete beams - Part I: experimental investigation. Mag. Concrete Res. 62(2) 127-36