PERFORMANCE OF STEEL FIBRE REINFORCED CONCRETE COLUMNS UNDER SIMULATED BLAST LOADING

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Keywords: steel fibres, reinforced concrete, shockwave loading, blast resistance, columns.

Summary: Research has shown that steel fibre reinforced concrete (SFRC) can enhance many of the properties of concrete, including improved post-cracking tensile capacity, enhanced shear resistance and increased ductility. The improved toughness, ductility and damage tolerance of SFRC make it an ideal candidate for use in the blast resistant design of structures. There is limited research on the behaviour of SFRC under impact and blast loading and some of this data is conflicting, with some researchers showing that the additional ductility normally evident in SFRC is absent or reduced at high strain loading. On the other hand, other data indicates that SFRC can improve toughness and energy-absorption capacity under extreme loading conditions. This paper presents the results of an ongoing experimental program which is examining the behaviour of SFRC columns under simulated blast loading. In the experimental program half-scale SFRC columns were constructed and exposed to different simulated blast pressure–impulse combinations using state-of-the-art shock-tube testing facilities at the University of Ottawa. The columns were designed according to CSA A23.3 (Canadian) standard as first-story columns and were constructed using a self-consolidating concrete mix and varying quantities of steel fibres (0-1.5%).

1 INTRODUCTION

It is becoming increasingly important to ensure that strategic buildings (government offices, military structures, embassies, etc) are blast resistant. In the wake of increased threats, the ground-storey columns in such buildings need to be properly detailed to provide the ductility and continuity necessary to prevent progressive collapse. To achieve this behaviour, columns must be detailed to have sufficient ductility and energy dissipation. The detailing necessary to ensure adequate performance can lead to heavily congested sections. It is therefore important to develop methods that can simultaneously improve blast resistance and ensure ease of construction.

Extensive research has shown that steel fibre reinforced concrete (SFRC) can enhance many of the properties of traditional concrete. Research on beams has shown that SFRC improves diagonal tension capacity resulting in significant increases in shear resistance. Research on columns has shown that SFRC significantly enhances confinement and delays concrete cover spalling. In structures subjected to reverse cyclic loading SFRC can be used to increase ductility and damage tolerance. Studies also show that SFRC can be used to improve impact resistance and toughness.

The enhanced strain capacity, ductility and toughness of SFRC make it an ideal material for use in the blast resistant design of structures. In columns, SFRC can be used to improve performance and can potentially be used to relax required detailing resulting in improved constructability.

Although SFRC has potential for use in the blast resistant design of columns, research data on the blast behaviour of SFRC structural components in general (and SFRC columns in particular) is scarce in the literature. This paper presents the results from an ongoing experimental program which is examining the behaviour of SFRC columns under simulated blast loading. In this study SFRC columns were exposed to different simulated blast pressure–impulse combinations using state-of-the-art shock-
tube testing facilities at the University of Ottawa. The results indicate that SFRC can be used to enhance the blast behaviour of columns subjected to blast loading.

2 LITERATURE REVIEW

2.1 Previous Investigations of the Behaviour of SFRC under High Strain Rates

Over the past decade there has been great interest in studying the behaviour of SFRC under impact loading. While we have significant knowledge and understanding of the properties and behaviour of SFRC subjected to quasi-static loading, the behaviour and properties of SFRC under high-strain loading is not completely understood. Although no standardized test exists for testing SFRC under impact loading [1], several researchers have studied the behaviour of fibre reinforced concretes under impact loading using Pendulum, Split Hopkinson Pressure Bar (SHPB) and Drop-Weight tests.

Gopalaratnam and Shah [2] used an instrumented Charpy (pendulum) Impact Machine to study the behaviour of SFRC flexural beam specimens reinforced with smooth steel fibres under varying strain-rates. The tests determined that the Dynamic Increase Factor (DIF) for SFRC is dependent on the strain rate, as well as the volume and aspect ratio (l/d) of the fibres. Similar conclusions were found in an experiment by Naaman and Gopalaratnam [3]. Banthia et al. [4] also studied the impact behaviour of SFRC using a modified pendulum test and found that addition of fibres results in improved fracture energy and toughness. The results showed that the behaviour was influenced by fibre type and fibre content.

Lok and Zhao [5] tested SFRC specimens at strain rates varying from ≈20s\(^{-1}\) up to ≈100s\(^{-1}\) using a SHPB test setup. The test specimens were constructed with SFRC using hooked-end steel fibres, and a fibre content of 0.6% by volume. The authors remarked that while SFRC exhibits good post-peak ductility if tested under quasi-static or low strain-rates, post-peak ductility was absent at higher strain-rates. For the specimens tested at a strain rate of 20s\(^{-1}\), there was distinct mobilization of the steel fibres in providing ductility; however specimens tested at a strain rate above 50s\(^{-1}\) showed reduced ductility enhancement. This finding coincides with the previous experimental program reported by Zhao et al. [6], where SFRC was tested at a strain rate of 50s\(^{-1}\). This finding is of importance for structures subject to blast loading where strain rates can range from approximately 100s\(^{-1}\) to 10,000s\(^{-1}\). It should be noted that the fibre content in the samples of this study was relatively low. As reported by other authors, the behaviour of SFRC under dynamic loading is dependent on the fibre content. A further SHPB test on SFRC was conducted by Wang et al. [7]. In this study, the samples were constructed with straight fibres at volume contents of 0, 3.0%, and 6.0% fibres, and were tested under strain rates from 42s\(^{-1}\) to 99s\(^{-1}\). The authors noted that the behaviour of SFRC is significantly sensitive to strain rate with results demonstrating that the peak stress, peak strain, and slope of the descending portion of the stress-strain curve all increase with increases in strain rate. The findings also demonstrated that the increase in peak strain with increasing strain-rate is more significant for specimens with higher fibre contents. The authors noted that the addition of fibres resulted in improvements in overall toughness and behaviour. However, when comparing the descending branch of the stress-strain curves, it is noted that the slopes are greater for the SFRC samples when compared to the companion plain concrete samples (see Figure 1).

Bindiganaville et al. [8] studied the performance of normal steel fibre reinforced concrete (SFRC), polypropylene fibre reinforced concrete (PFRC) and ultra high-performance fibre reinforced concrete (UHPFRC) under impact loading using a drop-weight testing device. While the authors found UHPFRC to perform very well at high-strain rates, they observed a significant drop in the toughness of the SFRC samples as the loading rate increased (see Figure 2). In accordance with previous findings, the authors of this study reported that SFRC composites can fracture across cracks at higher strain rates, consequently producing brittle failures.
2.2 Previous Investigations of the Behaviour of SFRC under Blast Loads

Experimental data on the behaviour of SFRC under blast loading is very scarce. However some limited research has been conducted on the behaviour of SFRC slab panels and beams. Lok and Xiao [9] completed a series of tests of SFRC panels to varying blast overpressures. The panels were made with hooked-end steel fibres with fibre contents varying from 0.5%–1.5%, and varying aspect ratios (33.4, 60, and 75). The panels were exposed to hemispherical blast waves from different charge weights of TNT (8kg, 20kg, and 40kg). The blast wave overpressures were measured by pressure transducers mounted in front of two of the supports, and a damped plunger was positioned to measure the maximum displacement of the panels. The maximum deflections of the panels were then compared. Although the authors did not report a comparison between the experimental data for the SFRC and concrete specimens, they noted that the SFRC panels demonstrated improved damage tolerance.

Magnusson and Hallgren [10] tested a large series of SFRC beams under quasi-static and air-blast loading. Both regular and high-strength concrete mixes were reinforced with hooked-end fibres having lengths of 30mm and 60mm, and an aspect ratio of 80. It should be noted that there was no mention of traditional longitudinal and transverse rebar reinforcement in the beams. The dynamic testing was conducted using a shock tube with a rectangular inner cross section, and airblast loading was achieved by the detonation of a spherical plastic explosive placed 10m from the beam within the
centre of the shock tube. The tests determined that the positive influence of fibre reinforcement is reduced under air-blast loading when compared to static loading. It was also noted that longer fibres were less effective under dynamic loading; the authors thus postulated that it may be beneficial to use shorter fibres with smaller aspect ratios.

2.3 Conclusions from Literature review

While many researchers report that fibre reinforcement can be an effective way of enhancing concrete's resistance to impact and blast loads, significant issues remain unresolved and data in the literature is conflicting. There is no consensus on whether the addition of steel fibres does indeed provide the added ductility required in structures exposed to blast loads. Consequently there is a need for further research in this area.

3 UNIVERSITY OF OTTAWA SHOCK TUBE

The University of Ottawa Blast Research Laboratory is equipped with a high-capacity shock tube that can simulate blast-induced shock waves. During an explosion, a zone of compressed air is created and spherically expands as a shock wave from the centre of detonation [11]. The University of Ottawa Shock Tube can simulate the blast wave generated by the hemispherical free air surface bursts of high explosives using a compression chamber that rapidly releases compressed air into an expansion chamber, where it travels along its length until it interacts with a test specimen. The shock tube facility is complemented by a suite of data acquisition equipment, including high speed oscilloscopes, pressure sensors, displacement transducers, accelerometers, strain gauges, and a high speed video camera [11]. As shown in Figure 3, the shock tube consists of four main components, a variable length driver section, a spool section, an expansion section and a rigid end test frame. Shock wave energy is generated in the variable driver section, while firing is controlled by the spool section. To generate the shockwave the driver and spool sections are simultaneously charged to the desired pressure, followed by the sudden releasing of the air in the spool, causing the diaphragm to rupture. The shock wave parameters (reflected pressure and reflected impulse) are controlled by selecting appropriate driver pressure and driver length combinations; the intensity of the load is controlled by varying the driver section pressure while the duration of the load is controlled by selecting the appropriate driver section length [12]. The impulse of the blast wave is a function of the reflected pressure and positive phase duration, and consequently it can be modified by varying these parameters.
Figure 3: Schematic view of the shock tube showing: Top: (1) variable driver length section, (2) spool section, (3) expansion section and rigid end test frame section.

Values for reflected pressures with associated shock tube driver lengths, and approximate equivalent TNT charges are shown in Table 1. For testing, specimens are attached onto the steel frame at the end of the expansion section, allowing for a 2 m by 2 m test area. In the case of wall and slab specimens, the pressure is applied directly on the specimen. In the case of structural components that do not cover the entire opening of the expansion section (such as with beams or column testing), a load transfer mechanism is used. The transfer mechanism consists of a flexible steel sheet that collects the pressure and rigid steel hollow sections that transfer the load on the element to be tested.

Table 1: Shock tube properties and equivalent TNT charges [11]

<table>
<thead>
<tr>
<th>Driver Length (mm)</th>
<th>Reflected Pressure (kPa)</th>
<th>Reflected Impulse (kPa-ms)</th>
<th>Approximate Equivalent TNT Mass (kg)</th>
<th>Standoff Distance (m)</th>
<th>Scaled Distance (m/kg$^{1/3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>305</td>
<td>78</td>
<td>217</td>
<td>8</td>
<td>12</td>
<td>6.0</td>
</tr>
<tr>
<td>915</td>
<td>92</td>
<td>410</td>
<td>42</td>
<td>18</td>
<td>5.2</td>
</tr>
<tr>
<td>1830</td>
<td>100</td>
<td>840</td>
<td>290</td>
<td>33</td>
<td>5.0</td>
</tr>
<tr>
<td>3355</td>
<td>103</td>
<td>1760</td>
<td>2500</td>
<td>67</td>
<td>4.9</td>
</tr>
<tr>
<td>4880</td>
<td>104</td>
<td>2690</td>
<td>10000</td>
<td>106</td>
<td>4.9</td>
</tr>
</tbody>
</table>
4 EXPERIMENTAL PROGRAM

Reinforced concrete columns are elements that are critical to ensuring the overall strength and stability of buildings. The failure of a ground story column can trigger progressive collapse as the upper story beams and columns lose their supports [12]. This experimental program aims at studying the behaviour of half-scale SFRC columns subjected to simulated blast loading using the University of Ottawa Shock Tube. Traditional reinforced concrete columns subjected to blast loading may be deficient in flexural capacity, concrete confinement or shear capacity. The current research program involves examining the potential of using SFRC to improve the flexural strength and inelastic deformability of columns through concrete confinement.

4.1 Materials

Although SFRC has potential to enhance the behaviour of structures subjected to extreme loads (earthquake and blast), its use has been hampered by its poor workability at higher fibre contents (1.5% and above). The use of self-consolidating concrete (SCC) can be used to reduce these problems and facilitate placement. Recently, several researchers have shown that the use SCC can allow for the addition of high volume of fibres without compromising workability. The concrete used in this study consisted of a pre-packaged, self-consolidating concrete mix with a specified strength of 50 MPa. The mix contained a maximum aggregate size of 10 mm with a sand-to-aggregate ratio of approximately 0.55 and a water-cement ratio of approximately 0.42. Furthermore, the SCC product contained an air-entraining admixture, a superplasticizer and a viscosity modifying admixture (VMA). The admixtures are incorporated into the blend in the form of dry powder. The Dramix ZP-305 fibres used in the all the mixes were hooked end steel fibres that were 30 mm in length, and had a diameter of 0.55 mm, and a tensile strength of 1100 N/mm². The control mix (without fibres) had a slump flow of 630 mm, while the addition of 0.5%, 0.75% and 1.5% reduced the slump flow values to 580 mm, 520 mm and 430 mm respectively. It is noted that while the mixes were not fully self-consolidating at higher fibre contents, all mixtures were very workable and the 1.5% mix only required very minor internal vibration during placement.

4.2 Details of the test specimens

A total of four column specimens made of self-consolidating concrete and reinforced with steel fibre contents ranging from 0% to 1.5% by volume of concrete were tested in this experimental program. Table 2 summarizes the properties of the various columns. The columns were designed and detailed according to the requirements for moderately ductile columns in the CSA-A23.3-04 Standard and represent half-scale first storey exterior columns in a building. As shown in Figure 4, the columns had a square cross-section of 152.4mm X 152.4mm (6in. X 6in.) and a total height of 2468 mm (8 ft.). The longitudinal reinforcement consisted of 4-10M bars (fy = 480 MPa) and had 90° hooks extending 75mm at each extremity to ensure full development of the reinforcement into the support region. The transverse reinforcement consisted of 6.3mm diameter ties (fy = 600 MPa) with 135° hook extensions and had a centre-to-centre spacing of 75 mm. The clear concrete cover was 5 mm. It is noted that the size of the columns was dictated by the capacity of the shock-tube.
Table 2: Properties of columns tested in the experimental program

<table>
<thead>
<tr>
<th>Column Designation</th>
<th>Cross-section</th>
<th>Reinforcement</th>
<th>Average compressive Strength (MPa)</th>
<th>Fibre Content (% by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC0%-75</td>
<td>152.4 mm x 152.4 mm</td>
<td>4-10 M long. bars (fy = 480 MPa)</td>
<td>56.5</td>
<td>0.0</td>
</tr>
<tr>
<td>SCC0.5%-75</td>
<td></td>
<td>6.3 mm dia. ties s= 75 mm (fy = 600 MPa)</td>
<td>56.6</td>
<td>0.5</td>
</tr>
<tr>
<td>SCC0.75%-75</td>
<td></td>
<td></td>
<td>57.2</td>
<td>0.75</td>
</tr>
<tr>
<td>SCC1.5%-75</td>
<td>5 mm cover</td>
<td></td>
<td>61.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 4: Column cross-section and reinforcement properties.

4.3 Test procedure and instrumentation

A total of three shock tube induced shockwaves were imparted onto each column. The shock wave pressures were selected based on a previous study by the University of Ottawa research group on traditional reinforced concrete columns having similar properties [13]. For the three loadings the driver length was kept constant at 9 ft (2743 mm) while the selected driver pressures were 10 psi (69 kPa), 30 psi (207 kPa) and 80 psi (552 kPa). The chosen pressure parameters aimed at testing the columns under elastic, yield, and ultimate loading conditions. In addition to the lateral shockwave loading, the columns were loaded axially with a static load to a level that is similar to what can be expected in actual structures (40% of pure axial load capacity). The axial load was applied with a hydraulic jack located below the column and a steel block between the column and the strong floor above. As discussed previously, because the columns are non-planar, a load transfer device which
consists of a light-gauge sheet metal and a series of steel beams is used that transfer the shock-wave load as a series of point loads onto the columns. The setup used in this experimental program is shown in Figure 5. Maximum and residual displacements at the mid-span between the near fixed-end supports were measured using linear variable displacement transducers (LVDT). In addition, a high speed digital video camera was used to record the testing at a frame rate of 500 frames per second, and synchronized to the recorded data histories. Figure 6 shows the instrumentation for a typical column before testing.

![Figure 5: Load transfer mechanism](image)

![Figure 6: Column ready for testing](image)

5 EXPERIMENTAL RESULTS

Table 3 summarizes the results from the experimental program in terms of maximum and residual displacements of the columns. Figures 7 to 10 show the damaged state of the columns at the end of the various tests.

Table 3: Summary of experimental results

<table>
<thead>
<tr>
<th></th>
<th>Driver Pressure (psi)</th>
<th>Driver Length (ft)</th>
<th>Avg. Reflected Pressure (kPa)</th>
<th>Avg. Reflected Impulse(kPa·ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver Pressure</td>
<td>10</td>
<td>35</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Driver Length</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Avg. Reflected Pressure</td>
<td>15</td>
<td>40</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Avg. Reflected Impulse</td>
<td>100</td>
<td>400</td>
<td>800</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column Strength</th>
<th>Driver Pressure (psi)</th>
<th>Max. Displ. (mm)</th>
<th>Resid. Displ. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC0%-75</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>SCC0.5%-75</td>
<td>9</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>SCC0.75%-75</td>
<td>9</td>
<td>9**</td>
<td>2**</td>
</tr>
<tr>
<td>SCC1.5%-75</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

* Adjusted Value due to max displacement not occurring at the mid-span LVDT. ** Driver pressure for shot was 14.5psi
Figure 7: Column SCC0%-75 at various stages of testing

Figure 8: Column SCC0.5%-75 at various stages of testing

Figure 9: Column SCC0.75%-75 at various stages of testing
DISCUSSION

All columns in the experimental program behaved similarly for “shot 1” and “shot 2.” “Shot 1” was meant to keep all columns within their elastic range, and this was indeed the case as all columns had a residual displacement of 0. Unfortunately due to an error, column SCC0.75%-75 was initially tested at a greater pressure, which lead to permanent deformations after the first shot. The results for “shot 2” indicate that all columns behave similarly at this pressure-impulse regime regardless of steel fibre content. The permanent deformations that result from the maximum displacements indicate the formation of cracks in the tension face of the columns, as well as some yielding of the reinforcing steel that will be verified with future analysis. It was noted that the addition of steel fibres did improve crack control at this loading regiment.

The increased blast resistance of the SFRC specimens was highlighted with “shot 3,” when the columns were tested at ultimate. Referring to the noticeable trend of the different specimens for “shot 3” in Table 4, it is demonstrated that the addition of steel fibres gives the columns an increase in blast resistance that results in a significant reduction in maximum displacements as the fibre content is increased. While the control column showed a maximum mid-span displacement of 137 mm, the addition of 0.5% fibres reduced this displacement to 96 mm. A further increase in fibre content to 0.75% and 1.5% further reduced displacements to 82 mm and 73 mm respectively. A structural member’s resistance to blast load can also be described in terms of its *restoring force*, the ability of the member to return to its original position after loading. In dynamic analysis of structures, this is analogous to the *spring constant* for a lumped-mass single degree of freedom model. The preliminary results from this experimental program indicate that members reinforced with steel fibres have a greater ability to control residual displacements, and consequently show improved blast performance. When compared to the specimen without fibre reinforcement, the residual displacements for the SFRC columns are decreased by a factor of approximately 2 for the SCC0.5%-75 and SCC0.75%-75 specimens, and a factor of 3 for the SCC1.5%-75 specimen. Work has begun on developing an analytical model using single degree of freedom analysis to predict deflections of SFRC columns exposed to blast loads.

The failure mode for all specimens was compression rebar buckling, and occurred after “shot 3” for each column. However, the degree of damage varied for each specimen in accordance with the fibre amounts: the greater the amount of fibre, the less extensive the damage. For example, while it can be plainly seen in Figure 7 that the compression rebar had buckled for the 0% specimen, significantly closer observation was required to determine that the compression rebar had indeed buckled for the 1.5% specimen due to the significant reduction in maximum displacement. These observations
indicate that structural members reinforced with steel fibres could resist greater blast pressures before failure. A future experimental program is recommended to incrementally increase blast pressures in order to determine maximum blast loading capacity of SFRC columns.

Further to the noted improved response of SFRC columns to blast loading, an examination of Figures 7 through Figure 10, shows that the addition of steel fibres improved damage tolerance and assisted in containing secondary blast hazards, namely flying debris. It was noted for the SCC0%-75 specimen that the failure of the concrete on the tension side of the columns caused cover spalling and flying debris. Comparatively, the SFRC columns showed improved damage tolerance, enhanced control of cracking and spalling, and the ability to eliminate flying debris. Although this may not be critical in the case of columns, flying debris may pose a hazard in other types of reinforced concrete structural elements (e.g. slabs and walls). The use of SFRC with its improved damage tolerance can be used to prevent the effect of flying debris in such elements and could thus eliminate injury to occupants in the event of an incident.

In addition to the experiments described in this paper, research is ongoing and investigating other parameters that could have an influence on the blast behaviour of SFRC columns, including the use of high-strength fibres, and the combined use of fibres and seismic detailing. Furthermore, as part of the same research program tests are currently being conducted on companion specimens with identical properties but with ultra high performance fibre reinforced concrete (UHPFRC) that are reinforced with straight micro fibres, and fibre contents ranging from 2-6%. Figure 11 shows the resulting damage after a UHPFRC column having $V_f=2\%$ that was subjected to a blast shockwave corresponding to “shot 3” of the SFRC test series. The column sustained little damage and did not fail at this shockwave loading with a residual displacement of only 21 mm. Thus the results of the ongoing research program seem to indicate that both SFRCs and more advanced UHPFRCs have potential for use in the blast resistant design of concrete structures.

Figure 11: UHPFRC column with $V_f=2\%$ tested at a driver pressure of 80 psi and driver length of 9ft

7 CONCLUSIONS

- This paper presented a brief literature review on the behaviour of SFRC subjected to impact and blast loading, and preliminary findings of an ongoing experimental study examining the blast performance of SFRC columns performed at the University of Ottawa.
- While some research has shown that SFRC improves performance under impact and blast loading, other research indicates that the ductility normally present in SFRC at quasi-static loading is absent at higher strain rates. There is a need for further research on the blast behaviour of SFRC structural elements, particularly in the case of columns.
- Initial results from this experimental program show that the addition of steel fibres reduces the maximum and residual displacements of columns subjected to the same blast loads, and consequently improves blast behaviour. Theoretical models need to be developed to better understand the behaviour of SFRC columns. The use of SFRC in structures required to resist the
effects of blast loads can reduce the amount of spalling and cracking of concrete, which can render the structure significantly safer in the event of an attack or accidental explosion by reducing the amount secondary blast fragments.

ACKNOWLEDGMENTS

The authors would like to thank Baekert for providing the steel fibres and King Pre-Packaged Materials for providing the SCC materials used in this study. The authors would also like to acknowledge the assistance of University of Ottawa students A. Lloyd, E. Jacques, S. De Carufel, Mustafa Mohammed-Saeed, Nima Aghniaey, as well as M. Spiller during the experimental research program.

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