

Performance of reinforced concrete columns using ultra-high-strength fiber-reinforced self-compacting concrete (UHS-FRSCC)

Abstract

Ultra-high-strength concrete (UHSC) low ductility leads to unfavorable brittle failure. Therefore, the use of steel fibers in UHSC will extend the possible fields of application. Owing to the very low water content of UHSC mixes, the incorporation of fibers seems to be impossible. Hence, modification of the UHSC mix to become a self-compacting mix will enable the inclusion of steel fibers without sacrificing its workability. In this study, the behavior of eight axially loaded medium scale columns cast with ultra-high-strength fiber-reinforced self-compacting concrete (UHS-FR-SCC) is investigated. The parameters included the effect of fiber inclusion, fibers volume fraction and the transverse steel percentage (i.e. stirrups). Two columns were tested as control specimen without fiber inclusion; the remaining six columns were tested in 3 groups, each group consisted of 2 columns. The fiber volume fraction was varied between the three groups. In each group, the transverse steel percentage was varied. The behavior of the tested columns was evaluated with respect to ultimate load, strain in concrete, axial reinforcement and transverse reinforcement, and modes of failure of the tested columns. It was found that the inclusion of steel fibers increased the deformability (i.e. axial deformation) and load carrying capacity of the UHSC especially at high fiber volume fractions. At high fiber volume fraction the high deformability of the concrete activated the confinement exerted by the stirrups.

Keywords: transverse reinforcement, ductility, stirrups, axial deformation

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Abbreviations: FRC, fiber-reinforced concrete; HSC, high-strength concrete; l, fiber length; l/d, fiber aspect ratio; NSC, normal strength concrete; SCC, self-compacting concrete; UHSC, ultra-high strength concrete; Vf, fiber volume fraction; w/b, water to binder ratio

Introduction

Construction of high-rise buildings and mega projects around the world, and the increasing demands of owners and designers led to an increasing demand on high-strength concrete (HSC). It should be noted that the definition of HSC has changed over the years and will no doubt continue to change. Progress in concrete materials science and technology during the last 30 years has far exceeded that made during the previous 150 years.¹ Ultra-high-strength concrete (UHSC) is a result of such development. This new type of concrete is characterized with its very high compressive strength; higher than 100MPa. UHSC shows very brittle failure behavior and therefore a limited post-crack behavior. UHSC fails explosively without any omen.² By the addition of fibers the loaddisplacement behavior and consequently the ductility and fracture toughness can be improved.³⁻⁵

The use of fibers to produce ultra-high-strength fiber-reinforced concrete (UHS-FRC) will enable the structures to have innovative features and open new areas for the application of UHSC. Inclusion of steel fibers with UHSC mixtures is more critical than that of normal-strength concrete (NSC), especially with the very low water-to-binder ratio (w/b) of UHSC which is considered essential. Steel fibers will have a great negative impact on the workability of UHSC. The development and use of self-compacting concrete (SCC) has opened

the avenue for resolving the workability issue. The applicability of steel fibers with self-compacting concrete has been investigated and has proven to be feasible.⁶⁻⁸ UHSC and UHS-FRC seems to be promising materials for special applications and structures. But this would not be achieved without studying its performance before being widely adopted in construction.^{1,9} Also, the behavior of structural elements made with UHSC and UHS-FRC needs better understanding, together with design provisions. The main objective is to develop detailed behavior of columns made with ultra-high-strength fiber-reinforced self-compacted concrete (UHS-FR-SCC), to help in developing basic guidelines for structural design using such material. This study presents the preliminary results of an experimental program to investigate the different parameters affecting the behavior of columns made with UHS-FR-SCC.

Table 1 gives the mix proportions of the ultra-high-strength self-compacting concrete (UHS-SCC) reference mix. Slump flow test was used to judge the flow ability characteristics of the concrete mixes. The 28-days and 90-days compressive strength of the mix were 110 and 135 MPa respectively. The admixture dosage was adjusted for the mixes with different fiber volume fractions in order to have a slump flow higher than the minimum value of 600mm required for self-compacted concrete (SCC).^{10,11} One type of steel fibers is used in the investigation; (HELIX 5-25[®]). The fibers are twisted with a triangular cross sectional shape, with an average dimensions 0.5mm and average length of 25mm, as shown in Figure 1. The aspect ratio of the fibers (l/d) is 50. The steel fibers are zinc galvanized wires with silver color. Three fiber volume fractions (Vf) of 0.08%, 0.12% and 0.52% were used in the study.

Table 1 Concrete mix proportions

Total cementing material (kg/m ³)	900
Silica Fume %	17.5%
Water/Binder Ratio	0.23
Water/Cement Ratio	0.27
Fine Aggregate %	60%
- Coarse Sand %	70%
- Dune Sand %	30%
Coarse Aggregate %	40%

The behavior of medium scale reinforced concrete columns made with the produced concrete is investigated, taking into account the effect of different fiber volume and different transverse steel (stirrups). Eight columns were made with dimensions 150x150mm in cross section and 470mm in height. Two columns were made with no fibers as control columns, the remaining six columns were divided into 3 groups each included 2 columns; the fiber volume in the 3 groups was 0.08%, 0.12% and 0.52%. The main reinforcement of the columns was 4 bars 12mm in diameter. The stirrups used are 8mm in diameter. The steel reinforcement used for longitudinal and transverse reinforcement has yield strength of 425MPa. The transverse reinforcement (i.e. stirrups) was varied among the two columns in each group. In one column the maximum spacing of 150mm was used and in the second column the spacing between the stirrups was 75mm. The ID of the columns is C-X-150, or C-X-75, the (X) digit denotes

the fiber volume percentage in the mix, the third number indicates the spacing between the stirrups (150mm or 75mm). Figure 1 is a schematic diagram of the columns' details and test setup.

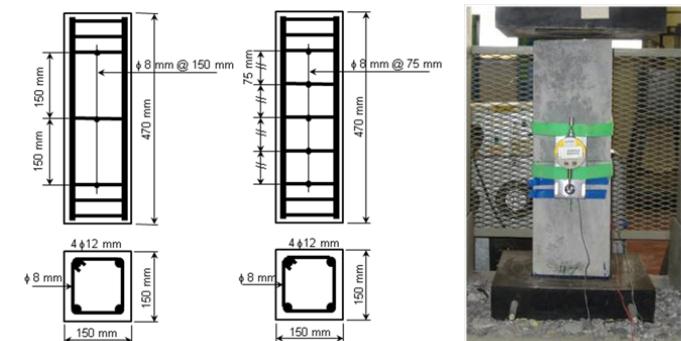


Figure 1 Details of tested columns and test setup.

Concrete strain versus applied load for tested columns is shown in Figure 2. The main reinforcement strain for tested is shown in Figure 3. While, Figure 4 show the stirrups' strain with applied load for columns. The strain gauge of the main reinforcement for column C-0.12-150 failed to measure any strain due to its damage during casting. As the fiber volume fraction increases up to 18%, however, with the lowest fiber volume fraction there is no significant improvement. Also, as the fiber volume increases the concrete strain at failure increases with the highest increase with fiber volume fraction of 0.52%, indicating better ductility and deformability of the concrete.

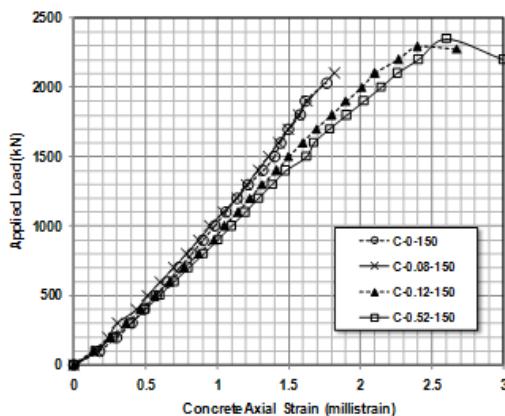


Figure 2 Axial deformation versus applied load for columns.

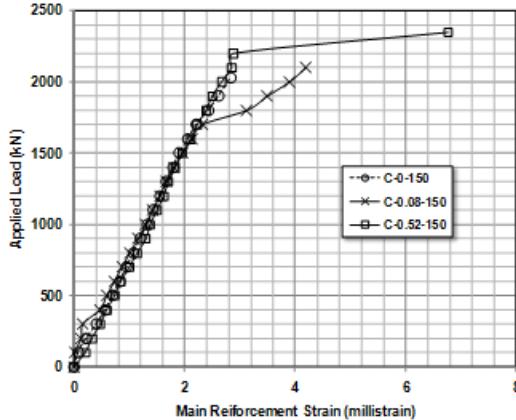
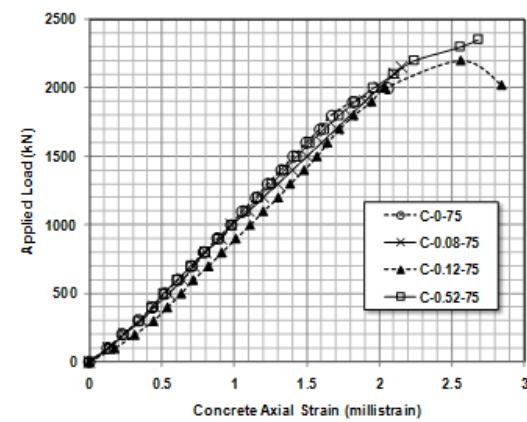
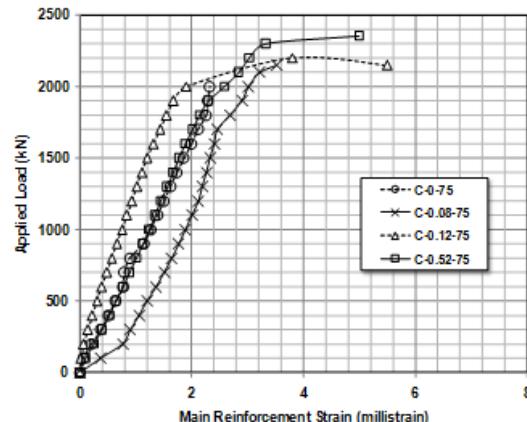


Figure 3 Strain of main reinforcement versus applied load for columns.



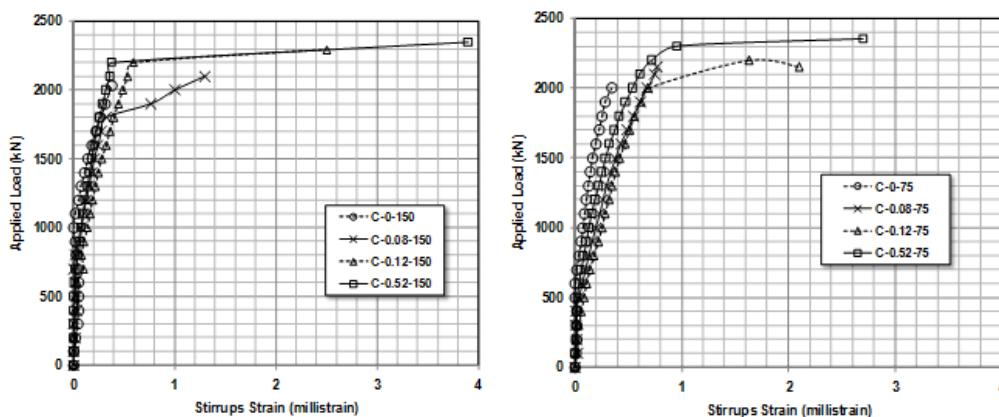


Figure 4 Strain of stirrups versus applied load for columns.

There is a significant improvement in the strain in the reinforcement and stirrups as the fiber volume fraction increases this is due to the confinement action of the fibers. It should be noted that the strain in the stirrups at failure reached or exceeded the yield strain value for $Vf=0.12\%$ and 0.52% , indicating full activation of the stirrups action due to the better ductility and deformation of the concrete. With reference to Figure 4, stirrups' strain with applied load, it is noted that the strain in the stirrups is very small up to almost the failure load for columns C-0-150, C-0-75, C-0.08-150- and C-0.08-75, which indicates that the stirrups are not fully activated and its confinement effect is not significant. On the other hand, when the steel fibers volume fraction increases, ($Vf=0.12\%$ and 0.52%) led to a significant increase in the concrete deformability, therefore increasing the strain in the stirrups indicating activation of the stirrups' effect in confining the concrete. This effect is noticed in the higher failure load and the significant increase in the main reinforcement strain and concrete deformation at failure. It is also noted that reducing the stirrups' spacing has no significant effect in improving the behavior of the column.

The effect of fiber inclusion and fiber volume fraction was also observed on the failure mode of the tested columns, Figure 5. Columns with no fibers experienced spalling of the concrete cover and sudden failure and little vertical cracks.¹² Columns with fibers showed more ductile failure mode as the fiber volume fraction increases and little or no cover spalling of the cover, besides numerous cracks development, as shown in Figure 5.

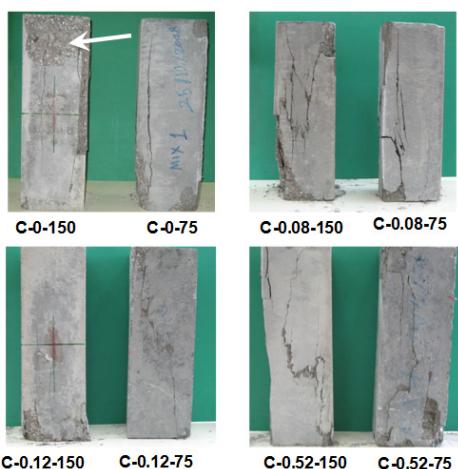


Figure 5 Failure modes of tested columns.

Conclusion

- Inclusion of steel fibers
- Increased the deformability (i.e. axial deformation) and load carrying capacity of ultra-high-strength concrete especially at high fiber volume fractions.
- At high fiber volume fraction the high deformability of the concrete activated the confinement exerted by the stirrups.
- For UHS-FR-SCC reducing the spacing between the stirrups did not significantly improve the confinement.
- For high fiber volume fraction the effect of increasing the spacing between the stirrups needs to be further investigated.

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Conflict of interest

The author declares no conflict of interest.

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