Effect of transverse reinforcement detailing on the axial load response of UHPC columns

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Abstract: This paper summarizes the results of a study examining the axial load performance of UHPC columns. As part of the study a total of four large-scale columns having square cross-section are tested under pure axial loading. Parameters considered in this study include the effect of transverse reinforcement spacing and arrangement. The results show that the use of well-detailed transverse reinforcement allows for excellent ductility in UHPC columns, with performance affected by the spacing and configuration of the transverse steel detailing. Reducing the spacing of the ties is found to improve confinement resulting in an enhancement of post-peak column ductility. Performance further improves as the amount of transverse steel within the column cross-section is increased. The results also show that the addition of fibers in UHPC columns allows for gradual cover spalling and controlled failure of core concrete.

Keywords: UHPC, UHPFRC, Columns, Axial, Strength, Ductility, Transverse reinforcement

1. Introduction

Ultra-high performance concrete (UHPC) shows enhanced properties when compared to conventional concrete, including improved compressive strength, post-cracking resistance and toughness. These properties make this material well-suited for heavily loaded structural applications, such as in multi-story building columns, where UHPC could allow for more efficient and resilient columns. Published research on the behavior of UHPC columns is limited and there is a need for further data, particularly in the case of larger-scale column elements. There is also a need to study the effect of transverse reinforcement detailing on confinement in UHPC in order to develop confinement models for UHPC. This paper summarizes the results of a study examining the axial behavior of UHPC columns. As part of the study, four large-scale columns having square cross-section are tested under pure axial loading. Parameters considered include the effect of transverse steel spacing and arrangement on UHPC column response.

2. Background

Table 1 summarizes some of the previous studies which have investigated the axial performance of UHPC columns. Several researchers have examined the behavior of slender UHPC columns, including: Aarup et al. (2005), Redaelli et al. (2014) and others. Research on the behavior of short UHPC columns is limited. In one of the earlier studies, Heshe and Nielsen (1992) examined the effect of transverse reinforcement spacing, longitudinal reinforcement ratio and casting direction on the axial response of smaller-scale UHPC specimens. The researchers concluded that while transverse reinforcement influences axial capacity in UHPC columns, the enhancement in ductility is more important. In addition, the researchers concluded that direction of concrete casting influences the load-bearing capacity of UHPC due the effect of fiber orientation, with capacity being higher when concreting is parallel relative to the loading axis.

The behavior of ultra-high strength concrete columns under axial and cyclic loading has been investigated by Sugano et al. (2007). Parameters considered in this study include the effect of fibers, transverse reinforcement ratio and strength. During the pure axial tests, the researchers observed an enhancement in column strength as the amount and strength of transverse reinforcement increased. Similarly an improvement in ductility with an increase in the ratio/strength of transverse reinforcement was observed. Behavior of the ultra-high strength columns was also studied under seismic loading, with the results confirming that ductility of the ultra-high-strength columns under lateral loads improves with an increase in transverse steel ratio and with the provision of fibers. The behavior of UHPC columns reinforced with high-strength steel has been studied by Teutsch et al. (2008). As part of this study eight UHPC columns were tested under pure axial loading, with seven larger columns tested under eccentric axial loads. Parameters included spacing and configuration of transverse steel as well as the ratio of longitudinal reinforcement. Based on the results, the authors conclude that ductile performance can be achieved in UHPC columns if adequate transverse steel detailing and steel fibers are provided. The authors also noted that the fibers prevented cover spalling in the UHPC columns.

In summary, research on the behavior of UHPC columns confirms the benefits associated with the use of well-detailed transverse reinforcement in UHPC columns. However research has focused on columns having relatively small sections and there is a need for further data, particularly in the case of larger columns.

Table 1. Some of the previous tests on UHPC columns

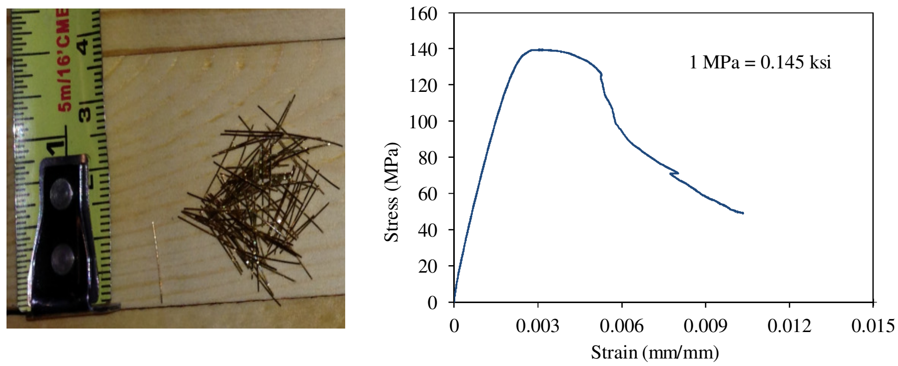
Type of column	Slender columns		Short columns		
Researchers	Aarup et al. (2005)	Redaelli et al. (2014)	Heshe and Nielsen (1992)	Sugano et al. (2007)	Teutsch et al. (2008)
# of columns tested	61	7	24	9	15
Cross-section & Dimensions (mm x mm)	Square 80x80 200x200	Circular 240 dia.	Rectangular 130x158	Square 200x200	Square 200x200 250x250
Concrete Strength (MPa)	137-154	130	173-184	159-222	139-152

*Note: 1 MPa = 0.145 ksi, 1 mm = 0.0394 in.

3. Testing Methods

3.1 Description of Specimens

As part of the experimental program four large-scale UHPC columns were tested under pure axial loading. All columns were constructed with compact reinforced composite (CRC), a proprietary UHPC developed in Denmark and currently marketed by CRC Technology and Hi-Con A/S (Aarup 1998). In order to improve toughness and ductility, short high-strength steel fibers were added to the CRC mixtures at a volumetric ratio of 2.5%. Figure 1a shows the high-fibers used in this study which had length of 13 mm (0.5 in), aspect-ratio (length/dia.) of 43, and tensile strength of 3150 MPa (457 ksi). A sample stress-strain curve of the CRC used in the the columns, obtained by testing 100 x 200 mm (4 x 8 in) cylinders, is shown in Figure 1b.



(a) High-strength fibers (b) Sample compressive stress-strain curve

Figure 1. High-strength steel fibers and sample results from standard tests on cylinders

* Note: 1 MPa = 0.145 ksi

As shown in Figure 2, the columns had dimensions of 250 x 250 x 1000 mm (10 x 10 x 40 in) and were reinforced with either 8-15M or 12-15M longitudinal reinforcing bars (diameter = 16 mm [0.6in] and Area = 200 mm^2 [0.32 in^2]) and 10M ties (diameter = 11.3 mm [0.4 in] and Area = 100 mm^2 [0.16 in^2]). A clear concrete cover of 10 mm (0.4 in) was provided in all columns. The 15M longitudinal bars had average yield strength (f_y) of 455 MPa (66 ksi), while the transverse 10M reinforcement had average yield strength of 453 MPa (66 ksi). As shown in Table 2, the two primary variables in the study include the spacing and configuration of the transverse steel. In the case of the C3 series, the columns were reinforced with 8 longitudinal bars with 10M hoops and cross-ties (see Figure 2b). Tie spacing of 120 mm (4.7 in) and 40 mm (1.6 in) were used in columns C3-120 and C3-40, corresponding to the requirements for "moderately ductile" and "ductile" columns in the Canadian CSA A23.3 standard, while an intermediate spacing of 60 mm (2.4 in) was used in column C3-60. Column C4-60 contained 12–15M reinforcing bars, while transverse reinforcement consisting of 10M double hoops, spaced at 60 mm (2.4 in), which also reflects "ductile" column design requirements (see Figure 2c). All columns were cast vertically (with casting parallel to the loading axis).

Table 2. Column design details and average concrete properties

Column ID	Cross section mm x mm (in. x in.)	Long. steel	Transverse steel	Tie spacing s mm (in.)	Fiber content v_f %	Compressive Strength, f'_c (MPa)
C3-40	250 x 250 (10 x 10)	8–15 M	10 M (3 legs)	40 (1.6)	2.5	130.0
C3-60				60 (2.4)	2.5	124.6
C3-120				120 (4.7)	2.5	126.8
C4-60		12–15 M	10 M (4 legs)	60 (2.4)	2.5	134.9

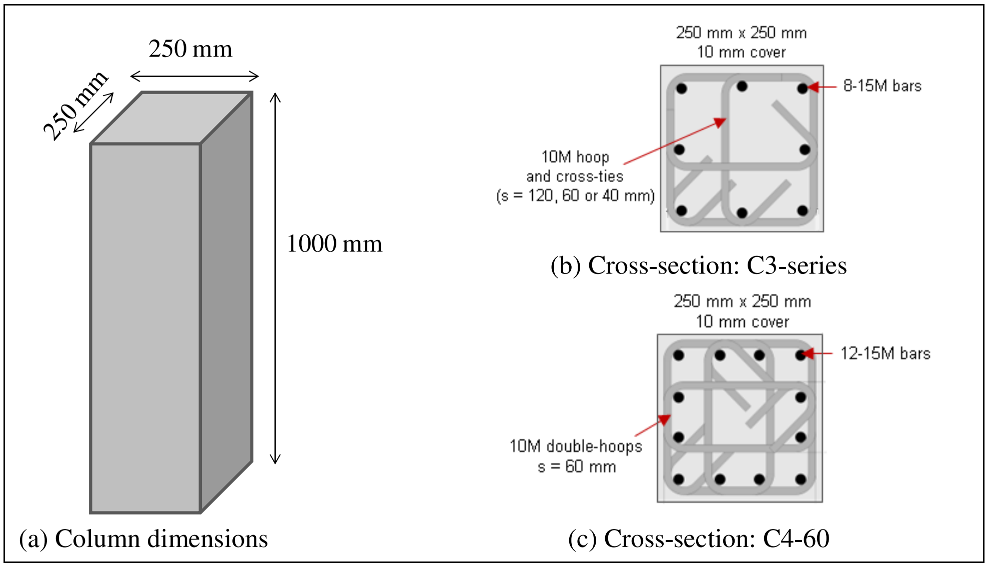


Figure 2. Column dimensions and design details

* Note: 1 mm = 0.0394 in.

3.2 Test Procedure

The columns were tested under pure axial loading using a universal testing machine with a maximum capacity of 11,400 KN. Figure 3 shows the setup used in the column tests. Axial load was recorded by the machine load-cell, while axial strains were obtained using four linear variable differential transducers (LVDTs) attached on the column faces over a gauge length of 925 mm (3 ft). The LVDTs were mounted on special steel collars that were constructed to confine the end regions of the columns. The initial rate of testing was 3 KN/s (0.68 kips/s) up to a load of 7000 KN (1575 kips) after which loading switched to displacement-control at a rate of 0.0024 mm/s (0.001 in/s). This rate was gradually increased to 0.007 mm/s (0.003 in/s) in the later stages of testing.

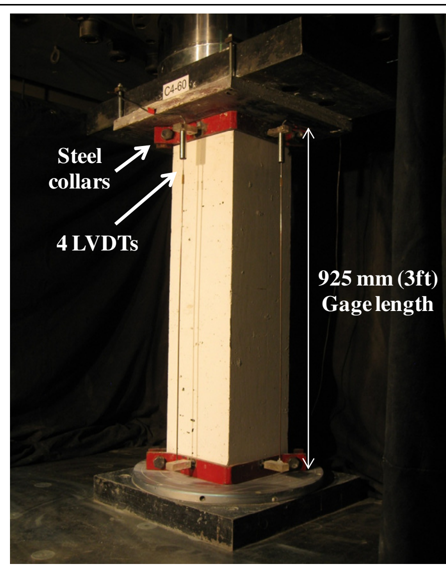


Figure 3. Column instrumentation and test setup

4. Discussion of Results

4.1 Summary of Results

Figure 4 plots the experimental load-strain response of all specimens tested in this study. Table 3 provides a further summary of the results and reports several parameters including: maximum axial load (P_{max}), maximum axial strain (ε_{max}) and the strain corresponding to 85% drop in peak capacity (ε_{c85}). The maximum loads are compared to the nominal axial strength computed using the ACI 318 Code (P_o) to obtain the ratio P_{max} / P_o , where $P_0 = 0.85f_c'A_c + f_yA_{st}$, with A_c and A_{st} equal to the area of concrete and longitudinal steel in the column cross-section, respectively.. Similarly the strain values are normalized with the strain of the unconfined CRC (ε_{co} = 0.0028, as obtained from the cylinder tests). The table also reports a toughness parameter (A_u), which corresponds to the area under the concrete load-strain curves up to strain of 0.02. Discussion on the effect of the test variables is provided in the sections that follow.

Table 3. Summary of experimental results and parameters

Column ID	P_{max} (KN)	ε_{max}	ε_{c85}	$\frac{P_{max}}{P_o}$	$\frac{\varepsilon_{max}}{\varepsilon_{co}}$	$\frac{\varepsilon_{c85}}{\varepsilon_{co}}$	A_u (KN)
C3-40	10965	0.0072	0.0095	1.47	2.61	3.42	145
C3-60	9670	0.0061	0.0069	1.35	2.20	2.47	112
C3-120	9070	0.0043	0.0057	1.25	1.56	2.06	87
C4-60	10246	0.0067	0.0109	1.29	2.41	3.94	139

* Note: 1 KN = 0.225 kips

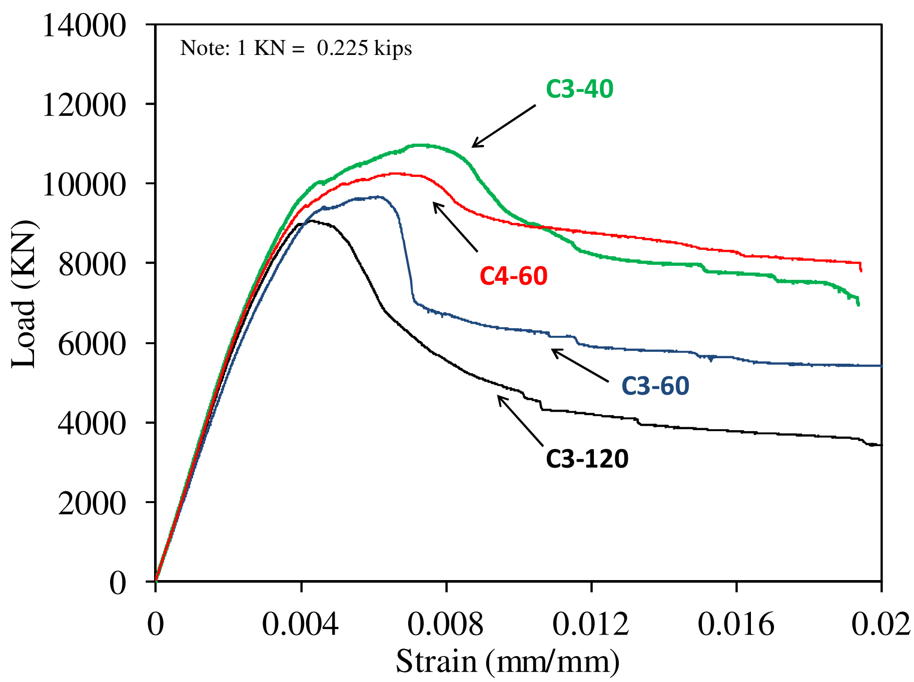


Figure 4. Experimental load-strain results for columns tested in the research program

4.2 Effect of Tie Spacing

UHPC columns C3-120, C3-60 and C3-40 had tie spacing of 120, 60 and 40 mm (4.7, 2.4 and 1.6 in), respectively. Examining the results in **Figure 4** it is clear that by reducing the tie spacing from 120 to 40 mm (4.7 to 1.6 in), the strength and ductility of the UHPC columns is improved. Column C3-40 shows the largest capacity (P_{max}=10,965 kN [2467 kips]) among all specimens tested in the study, with a P_{max}/P_o ratio of 1.47. Similarly the normalized strain $\varepsilon_{max}/\varepsilon_{co}$ reaches a maximum value of 2.61 for this column. Specimen C3-120, which had the largest tie spacing, and therefore the lowest confinement, reaches a maximum load of P_{max} =9,070 kN (2041 kips) with normalized load and strain values of P_{max}/P_o =1.25 and $\varepsilon_{max}/\varepsilon_{co}$ = 1.56. Column C3-60 shows intermediate values of peak load and strain. It is important to note that the axial capacity of all columns remains well above the nominal capacity predicted by the ACI-318 code, even in the case of the nominally confined C3-120 column, an indicator of the positive influence of the fibers in enhancing the load-bearing capacity of UHPC. In terms of post-peak ductility, the normalized post-peak strain $\varepsilon_{c85}/\varepsilon_{co}$ improves by 66% when reducing the tie spacing from 120 to 40 mm (4.7 to 1.6 in), indicating an important enhancement in post-peak ductility as the transverse reinforcement spacing is reduced. Likewise, the measured area under the concrete load-strain curves (A_u) increases gradually as the tie spacing is reduced from 120 to 40 mm (4.7 to 1.6 in), with values of 87, 112 and 145 KN (19.6, 25.2 and 32.6 kips) for columns C3-120, C3-60 and C3-40, respectively. In summary, the results clearly demonstrate that both axial strength and ductility are improved in UHPC columns as confinement is increased through the reduction of transverse reinforcement spacing.

4.3 Effect of Tie Configuration

UHPC columns C3-60 and C4-60 had the same tie spacing of 60 mm (2.4 in) but were detailed with two different tie configurations, allowing for an investigation into the effect of transverse reinforcement arrangement on UHPC column response. The results in Table 3 reveal that the peak capacity of the columns, P_{max} increases modestly from 9,670 to 10,246 kN (2176 to 2305 kips) when going from configuration C3 to C4, with a corresponding increase in normalized strain, $\varepsilon_{max}/\varepsilon_{co}$ of 2.20 to 2.41, respectively. Examination of the load-strain response in Figure 4, shows that while both columns show excellent post-peak ductility, the sudden drop in capacity after peak in specimen C3-60 is more gradual in specimen C4-60. This translates in a significant increase in the ductility strain ratio $\varepsilon_{c85}/\varepsilon_{co}$ of 60% for column C4-60, with overall toughness (A_u) also increasing by a factor of 24%. In summary, the results show that increasing confinement in UHPC columns through improvement of cross-section detailing results in an enhancement in overall toughness and post-peak ductility, with a limited effect on peak load-carrying capacity.

4.4 Controlled failure process

One of the interesting observations in this research program, is that despite the high-strength of UHPC, controlled failure of core and cover concrete is possible in UHPC columns, due to the provision of fibers. Figure 5a shows the staged failure response for column C3-40. During the various stages of loading up to failure, it is observed that cracking is well distributed on the cover surface. This is in contrast to the brittle and explosive cover failure reported by numerous researchers for conventional high-strength concrete columns. Thus with fiber-reinforced UHPC cover spalling is gradual; in fact the cover remained attached to the specimens throughout testing due to the ability of the fibers to bridge the cover shell at the core-cover interface. Similarly, the provision of fibers and closely spaced transverse reinforcement allowed for gradual failure of core concrete in the UHPC columns. Figure 5b which shows the core integrity in column C3-40 at the end of testing (after manually detaching the cover).

(a) Gradual failure of the UHPC cover (b) UHPC core integrity

Figure 5. Controlled failure of cover and core in UHPC columns (Column C3-40)

5. Conclusions

As part of this study four large-scale UHPC columns having square cross-section were tested under pure axial loading. The following conclusions can be drawn from this study:

- Reducing the tie spacing in UHPC columns results in improved confinement which leads to increased strength and ductility;
- Improving the detailing of the transverse steel within the column cross-section further enhances confinement, and results in an increase in post-peak toughness;
- The provision of fibers in UHPC columns allows for gradual and controlled cover spalling with well distributed cracking on the cover surface, even at very large strains;
- The provision of fibers and closely spaced transverse reinforcement results in gradual and controlled failure of core concrete in UHPC columns.

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