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Uniaxial behavior of circular ultra-high-performance fiber-reinforced concrete columns confined by spiral reinforcement

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HIGHLIGHTS

- Circular UHPFRC columns with varying spiral spacing and concrete strength were tested.
- Circular UHPFRC columns detailed with different code provisions were investigated.
- The efficiency of circular spirals and square hoops on confinement were compared.
- Steel fibers in UHPFRC allowed for gradual spalling and high damage tolerance.
- A design recommendation for spiral reinforcement in UHPFRC columns is proposed.

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ABSTRACT

This paper presents results from the uniaxial tests of six large-scale ultra-high-performance fiber-reinforced concrete (UHPFRC) circular columns confined by spirals. The UHPFRC used in this study had 1.5% of hybrid micro-steel fibers (1.0% of 19.5 mm fibers and 0.5% of 16.3 mm fibers) in the mixture and had compressive strengths varying from 163 to 181 MPa. The effects of the volumetric ratio of spiral reinforcement, compressive strength of concrete, and presence of hybrid micro-steel fibers on the axial load responses, including post-peak deformability, were investigated. In addition, the ductility level reached by circular UHPFRC columns designed according to the minimum spiral reinforcement of current design provisions of the CSA A23.3-14 Standard and the ACI 318-14 Code were evaluated to investigate the applicability of these equations to UHPFRC columns. Test results showed that the combined effect of the minimum spiral reinforcement and steel fibers resulted in sufficient post-peak ductility of the UHPFRC columns. To investigate the efficiency of the shape of the confinement reinforcement, the test results of the circular UHPFRC columns confined by spirals were compared with those from equivalent-sized square UHPFRC columns confined by hoops. The test results demonstrate the superior performance of circular spirals for developing the ductile behavior of UHPFRC columns than the same volumetric ratio of rectilinear hoops. A design recommendation for spiral reinforcement that ensures the ductile behavior of UHPFRC columns in moderate seismic regions is proposed.

1. Introduction

Extensive efforts have been made to improve the strength of concrete for high-rise building applications. However, the increase in strength is accompanied by an inevitable more brittle response that should be addressed. Confining the concrete core by properly detailed and closely spaced transverse reinforcement is the most common and efficient solution to avoid brittle responses of these very high strength concretes [1–8]. In terms of a material approach, the incorporation of steel fibers has been demonstrated as another solution, which can delay cover spalling and improved ductility by providing some additional confinement [9–12]. In particular, the recently developed ultra-high-performance fiber-reinforced concrete (UHPFRC) has shown both superior strength and ductility, and is also characterized by improved fatigue performance and durability compared with normal- and high-strength concretes (NSC and HSC) [13–18]. These outstanding properties are obtained by optimizing the granular mixture without the coarse aggregate,

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Notations

A_g	gross area of column section (mm^2)
A_s	cross-sectional area of steel reinforcement (mm^2)
A_{sl}	cross-sectional area of longitudinal reinforcement (mm^2)
A_{st}	total area of longitudinal reinforcement (mm^2)
A_{cc}	cross-sectional area of concrete core (mm^2)
A_{ch}	area of the concrete core measured to the outside diameter of transverse reinforcement (mm^2)
A_u	area under the concrete load-strain curve up to strain of 0.02
c_x and c_y	core dimensions measured to the centerline of the hoops
d_b	nominal diameter of steel reinforcement (mm)
d_f	nominal diameter of steel fiber (mm)
D_o	diameter of confined core measured to the centerline of the spirals
E_c	modulus of elasticity of concrete obtained from cylinder tests (MPa)
$f\prime_c$	specified compressive strength of concrete from cylinder tests (MPa)
f_r	flexural strength (modulus of rupture) of concrete (MPa)
f_u	ultimate strength of steel reinforcement (MPa)
f_y	yield strength of steel reinforcement (MPa)
f_{yl}	yield strength of longitudinal reinforcement (MPa)
f_{yh}	yield strength of transverse reinforcement
I_{10}	ductility index
k_3	stress block parameter related to the difference between the strength of the column concrete and the strength obtained from a concrete cylinder
K_e	effective confinement index
k_f	concrete strength factor (MPa)
k_f	$f'_c/175 + 0.6 \geq 1.0$
k_p	factor accounting for axial load level (compression)
l_f	length of steel fiber (mm)
$P_{\max}$	maximum axial load carried by RC column (kN)
P_c	maximum axial load carried by concrete (kN)
P_{cc}	maximum axial load carried by confined concrete core (kN)
P_o	nominal axial strength of a column under pure axial load (kN)
P_{oc}	predicted axial load capacity of concrete (kN)
P_{occ}	predicted axial load capacity of core concrete (kN)
P_u	factored axial force (kN)
P_{yield}	axial load at first yielding of longitudinal bars (kN)
R_d	ductility-related force modification factors in the CSA Standard (CSA23.3-14)
$s\prime$	clear vertical spacing between transverse reinforcement
T.I.	toughness index
w_i	clear distance between adjacent laterally supported longitudinal bars
ε_{85}	remaining capacity of the column dropping to 85% of P_{max}
ε_{50}	remaining capacity of the column dropping to 50% of P_{max}
ε_c	peak strain of the concrete corresponding P_c
ε_{cc}	axial strain corresponding P_{cc}
$\varepsilon\prime_c$	strain at the peak stress of the concrete obtained from cylinder tests
ε_u	ulimate strain of steel reinforcement
ε_y	yield strain of steel reinforcement
ρ_{cc}	ratio of the area of longitudinal reinforcement to the area of the confined core
ρ_s	volumetric ratio of transverse reinforcement (spirals or circular hoops)
$\rho_{s(req)}$	volumetric ratio of transverse reinforcement required by design code provisions
ρ_{sl}	volumetric ratio of longitudinal reinforcement
v_f	volume fraction of steel fiber

resulting in a more homogeneous internal structure of the matrix, and by incorporating a high volume of micro-steel fibers [14,15]. In order to use these superior properties of the UHPFRC for high-rise building applications, there have been some research studies [19–24] on UHPFRC columns confined by transverse reinforcement. However, these available tests are predominantly for square UHPFRC columns [19–23]. Some research on circular UHPFRC columns has also been reported, but the columns were confined externally with steel tubes [25] or fiber-reinforced polymer (FRP) tubes [24,26–31]. There is a lack of test data on circular UHPFRC columns confined by spirals. Zohrevand and Mirmiran [28] studied the effects of external confinement provided by FRP tubes for UHPFRC columns, including a companion UHPFRC column confined by spirals. Yang et al. [32] also studied the confinement effects of UHPFRC columns confined by circular spirals. However, they studied the response of small cylindrical specimens with a size of $\phi 102 \times 203$ mm without any longitudinal bars, which cannot simulate the actual stress-strain behavior of confined UHPFRC columns. Furthermore, there is no study that has evaluated the applicability of current seismic design provisions for spiral reinforcement for practical UHPFRC columns.

Although UHPFRC columns having steel fibers and confined by square hoops showed improved performance compared to the similar-strength columns without steel fibers [8], they required a significant amount of transverse reinforcement (more than approximately 4%) to ensure the ductile behavior of the columns due to the significantly high compressive strengths of these concrete [21,23]. Previous studies [4,33–35] have established the fact that circular spirals are more effective in confining concrete than rectangular hoops owing to their geometric shape. Circular spirals produce uniform and continuous pressure around the circumference of the core, whereas, rectangular hoops produce non-uniform pressure, which peaks at locations of the transverse legs of tie steel [4,5]. In particular, Hatanaka and Tanigawa [34] reported that the lateral pressure produced by a square perimeter tie is about 0.3–0.5 times the pressure provided by a circular spiral. Bjerkeli et al. [33] reported that the ratios of peak stresses for the confined concrete to the unconfined concrete varied from 0.85 to 1.9 for rectangular columns with hoops, but they increased to 0.9–3.5 for the circular columns with spirals. The corresponding ratios of the strains at peak stresses for the confined concrete to the unconfined concrete varied from 1.05 to 1.5 for the rectangular columns with hoops, but they increased to 1.25–1.55. These beneficial effects of circular spirals compared to rectangular hoops in UHPFRC columns need to be studied.

Accordingly, this paper presents uniaxial test results of circular UHPFRC columns confined by spirals. The objectives of this research are: (1) to evaluate the effects of the volumetric ratio of spiral reinforcement, the compressive strength of the concrete, and the presence of hybrid micro-steel fibers on the axial load response UHPFRC columns confined by spirals; (2) to examine the axial load responses and ductility levels reached by circular UHPFRC columns designed according to the minimum spiral requirements of different code provisions (2014 ACI 318 Code