Engineering Structures 99 (2015) 388–401

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Behavior of ultra-high performance fiber reinforced concrete columns under pure axial loading

Milad Mohammadi Hosinieh [a], Hassan Aoude [a,*], William D. Cook [b], Denis Mitchell [b]

[a] Department of Civil Engineering, University of Ottawa, Ottawa, Canada
[b] Department of Civil Engineering & Applied Mechanics, McGill University, Montreal, Canada

ARTICLE INFO

Article history:
Received 15 August 2014
Revised 2 April 2015
Accepted 6 May 2015
Available online 23 May 2015

Keywords:
UHPFRC
CRC
Columns
Axial loading
Strength
Ductility
Seismic detailing

ABSTRACT

This paper presents the results of a study examining the axial load performance of ultra-high performance fiber reinforced concrete (UHPFRC) columns. As part of the experimental program six large-scale columns were tested under pure axial loading to examine the effect of UHPFRC and transverse reinforcement detailing on column performance. The results demonstrate that the provision of closely-spaced and well-detailed transverse reinforcement allows for the development of excellent ductility in UHPFRC columns. The results also indicate that spacing and configuration of transverse reinforcement are important factors affecting the axial strength and toughness of UHPFRC columns. The analytical investigation examines the suitability of using existing high-strength concrete and fiber reinforced concrete confinement models to predict the axial response of the columns tested in this research program. The results indicate the need for the development of UHPFRC-specific confinement models.

1. Introduction

Compared to traditional concrete, ultra-high performance fiber reinforced concrete (UHPFRC) shows higher compressive strength, improved toughness and increased damage tolerance. These properties make this class of material well-suited for use in heavily loaded structural components. In columns, UHPFRC can allow for more efficient design of sections, while the provision of fibers can allow for increased ductility and reduced brittleness when compared to high-strength concrete. Current published research on larger-scale UHPFRC columns is limited and there is a need to verify if the strength and ductility necessary for earthquake applications can be achieved through the use of appropriate transverse reinforcement detailing. This paper presents the results of a study examining the axial load performance of UHPFRC columns. As part of the experimental program six large-scale columns constructed with compact reinforced composite (CRC), a UHPFRC mix design originally developed in Denmark [1], are tested under pure axial loading to examine the effect of UHPFRC and transverse reinforcement detailing (configuration and spacing) on column performance. The analytical investigation examines the suitability of using existing high-strength concrete and fiber-reinforced concrete confinement models to predict the axial response of the UHPFRC columns tested in this research program.

2. Literature review

2.1. Compact reinforced composite (CRC)

Compact reinforced composite (CRC) is an ultra-high performance fiber reinforced concrete originally developed by the Danish cement producer Aalborg Portland and currently marketed by CRC Technology and Hi-Con A/S (Denmark) [1]. CRC has very high compressive strength combined with a large volume of steel fibers, which also gives the material improved tensile capacity and toughness. The high compressive strength of CRC is achieved through use of a low water–binder ratio, microsilica and omission of coarse aggregates [2]. Ductility is achieved through the addition of steel fibers at contents of 2–6% by volume of concrete. In the years since initial development, a number of research projects have been carried out to document the properties of CRC. These research projects have investigated the mechanical properties, durability and fire resistance of CRC [2]. A limited number of studies have also been conducted to examine the performance of CRC in structural components such as beams. In terms of applications, CRC is currently marketed for use in precast components such as staircases and balcony slabs, however the high strength and ductility of

* Corresponding author at: 161 Louis Pasteur, Ottawa, Ontario K1N 6N5, Canada. Tel.: +1 (613) 562 5800x6914; fax: +1 (613) 562 5173.
E-mail address: haoude@uottawa.ca (H. Aoude).

http://dx.doi.org/10.1016/j.engstruct.2015.05.009
0141-0296/

CRC makes the material well suited for use in heavily loaded structural applications, such as columns in high-rise buildings.

2.2. Previous research on compressive behavior of UHPFRC

Previous research on the compressive behavior of UHPFRC has focused primarily on material tests on small-scale specimens. In one of the more comprehensive studies, Graybeal [3,4] examined the compressive performance of Ductal, a proprietary UHPFRC, by testing over 1000 cylinder and cube specimens and investigating the effect of curing conditions, specimen geometry and loading rate on the material's behavior in compression. Graybeal concluded that steam curing significantly increases the compressive strength of UHPFRC, along with increased long-term durability. It was noted that the compressive strength of steam-cured UHPFRC is effectively stabilized after 48 h, while UHPFRC treated under ambient conditions can show strength gain for at least 8 weeks after casting. In addition, Graybeal found that the linearity of the ascending branch of the compressive stress strain curve depends on the curing method and the relationship becomes more linear in the case of steam-treated UHPFRC. The study also investigated the effect of cylinder and cube size on the measured compressive strength and reported that results were generally similar for all specimen types. Graybeal also indicated that loading rates between 0.24 and 1.74 MPa/s did not have a significant effect on the compressive behavior of UHPFRC.

Nielsen [5] examined the mechanical properties of Compact Reinforced Composite (CRC), with a focus on the material's behavior in tension and compression. To study compressive behavior, a series of cylinders were tested and the effect of fiber properties and "fiber reinforcing index" ($\upsilon_f * l_f/d_f$) on performance was investigated (where υ_f is fiber content and l_f/d_f is the ratio of the fiber length and diameter). As expected the material showed a brittle response without provision of fibers, with linear behavior up to peak followed by sudden explosive failure. Through the addition of fibers compressive capacity increased, and the ascending branch became more non-linear with a stable and less brittle post-peak failure. The study also found that increasing the fiber reinforcing index increased peak stress and overall toughness in compression. Nielsen [5] showed that the parameters of the stress–strain curve (peak stress, peak strain, modulus of elasticity, etc.) are directly related to the "fiber reinforcing index" ($\upsilon_f * l_f/d_f$) and suggested that the effect can be considered using simple linear relationships as follows:

$$X_f = X + a\left(\upsilon_f \frac{l_f}{d_f}\right) \quad (1)$$

where X is the parameter being studied (e.g. stress, strain) for the case without fibers, X_f is parameter after addition of fibers and a is a constant which depends on the studied parameter.

2.3. Previous research on axial performance of UHPFRC columns

2.3.1. Summary of previous research on UHPFRC columns

Published research related to the axial performance of UHPFRC columns includes studies on short and slender columns; some of the previous studies are summarized in Table 1. It is noted that there is limited published research on the axial performance of larger-scale short UHPFRC columns reinforced with conventional steel reinforcement. The increased bearing capacity of UHPFRC can allow for columns with reduced building foot-prints, which can result in columns with high slenderness. The axial load behavior of slender UHPFRC columns has been investigated by Aarup et al. [6], Heimann et al. [7], Empelmann et al. [8], and Redaelli et al. [9]. As an alternative to conventional steel reinforcement, researchers have also studied the potential of using cast-in-place FRP and steel tubes to enhance the axial performance of UHPFRC columns [10,11]. The research related to short UHPFRC columns reinforced with conventional reinforcement is summarized in the section that follows.

2.3.2. Previous research on axial performance of short UHPFRC columns

Heshe and Nielsen [12] studied the pure axial behavior of twenty-four small-scale UHPFRC columns having rectangular cross-section of 130 mm × 158 mm. The test variables in this study included transverse reinforcement spacing and amount of longitudinal steel reinforcement. The authors of this study concluded that although confinement influences axial capacity in UHPFRC columns, the enhancement in ductility is more considerable. In addition, the authors mentioned that the direction of concrete placement has a noticeable effect on the capacity due the influence of fiber orientation, with the capacity being higher when concreting is parallel to the loading axis.

Sugano et al. [13] tested nine UHPFRC columns having square section of 200 mm × 200 mm under pure axial loading. It is noted that the columns in this study were reinforced with high strength transverse steel ties. The variables in this study included concrete strength (f'_c = 120, 160, 200 MPa), fiber content (υ_f = 0% or 2%) as well as strength (f_y = 700 MPa and 1400 MPa) and spacing of transverse reinforcement (s = 35, 45, 55 mm). For the case of the fiber-reinforced specimens, the authors observed an increase in the confined strength as the amount or strength of the transverse reinforcement increased. Compression ductility was discussed in terms of the ratio of peak confined strain to peak unconfined strain, with ductility improving as the amount or strength of the transverse reinforcement increased. In addition to the axial tests, the behavior of UHPFRC under simulated earthquake loading was studied by testing six companion columns under reversed-cyclic loads; the results showed that an increase in confinement and provision of fibers improved the ductility of the columns under lateral loads.

The behavior of UHPFRC columns reinforced with high-strength longitudinal steel reinforcement has been investigated by Steven and Empelmann [14]. As part of this study, eight UHPFRC columns having dimensions of 200 mm × 200 mm × 600 mm were tested under pure axial loading, with a further seven columns having dimensions of 250 mm × 250 mm × 1250 mm tested under eccentric axial loads (with eccentricity, e_o, ranging from 5 mm to 75 mm) [14]. The variables in the test program included configuration and spacing of the transverse reinforcement as well as ratio of high-strength longitudinal steel reinforcement. The authors noted that ductile performance can be achieved in UHPFRC columns if adequate transverse steel reinforcement and steel fibers are provided. The authors also noted that the provision of fibers prevented cover spalling in the columns. Based on the experimental findings, the authors proposed equations to predict the design bearing capacity and ductility of concentrically and eccentrically loaded UHPFRC columns. In a related study, Empelmann et al. [15] conducted a parametric study to investigate the feasibility of using UHPFRC in heavily loaded building columns. As part of the investigation, the authors presented a case study where traditional concrete and UHPFRC were considered for the design of ground-story columns in a 42-story high-rise building. Due to architectural constraints the square cross-sectional dimensions were limited to 762 mm, and the columns were to carry a design axial load of 30,000 kN. When considering conventional concrete the design required the use of a steel–concrete composite section, while the use of UHPFRC, with its superior bearing capacity, allowed for columns with conventional steel reinforcement, resulting in savings in material and construction costs.