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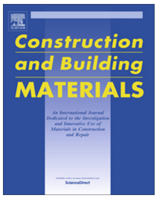

A comparison of existing analytical methods to predict the flexural capacity of Ultra High Performance Concrete (UHPC) beams

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HIGHLIGHTS

- Small-scale UHPC beams were tested to evaluate the ultimate moment capacity.
- The experimental results were used to validate a Finite Element (FE) model.
- Using validated FE model, a series of large-scale UHPC beams were simulated.
- The results of existing analytical methods and the FE model were compared.

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ABSTRACT

Ultra High-Performance Concrete (UHPC) shows enhanced performance and ductility compared to conventional concrete which can be beneficial in the construction industry. Many researchers have performed experimental studies on the structural behavior of the UHPC beams to establish a reliable analytical method to calculate the flexural capacity of the section. However most of these studies were performed through limited specimens due to the high cost of UHPC. The objective of this paper is to compare the accuracy of well-known existing methods to calculate the moment capacity of a reinforced UHPC beam through a parametric study. To that aim, several small-scale beams were constructed and tested to evaluate the flexural behavior and ultimate moment capacity of the UHPC beams. The performance of the tested specimens is discussed regarding the moment capacity, load-deflection curves, crack development and the modes of failure.

The obtained results through the experiments were, then, used to validate the Finite Element (FE) model. Comparing the numerical and experimental results indicates that generally, the proposed numerical model can predict the structural behavior of the UHPC beams reasonably. Hence, the validated FE model was employed as a reference point to evaluate the existing analytical approaches to calculate moment capacity of UHPC beams. A series of large-scale beams with different geometries and reinforcing details were numerically simulated, and the results were compared with the results obtained through the analytical methods. The results showed that some of existing methods can predict the ultimate moment capacity of the UHPC beam with an acceptable accuracy.

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1. Introduction

Ultra High-Performance Fiber Reinforced Concrete (UHPFRC) or known as UHPC is a unique cementitious based material with fine aggregates, silica fume, fibers, superplasticizer and low water/cement ratio. UHPC exhibits an exceptional strength, ductility, and durability that can be an alternative for new constructions. This material has been developed over recent decades, and there are different definitions for UHPC based on various classifications. French Association of Civil Engineering (AFGC) [1] specification defines UHPC as concrete with a compressive strength of more than 21 ksi (150 MPa) and a maximum of 36 ksi (250 MPa).

Several bridges need rehabilitation and using UHPC can increase their durability [2]. The US Federal Highway Administration (FHWA) has been considering the use of UHPC in bridges since 2001. Currently, several bridges (more than 180), in which UHPC was used mostly to connect precast elements, are open to traffic in North America [3,4]. Also using recycled materials in such advanced concrete can improve the sustainability characteristic of UHPC [5]. Considering exceptional properties of UHPC and extending the use of this material in buildings and bridge industry

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Notation

a	depth of a rectangular stress block	f_c	compression strength of UHPC
A_s	area of steel rebar in tension	f_t	the tensile stress of UHPC
b	width of the beam	f_y	yield strength of steel rebar
c	depth to the neutral axis	h	height of the beam
d	depth from extreme compressive fiber to centroid of rebar steel	l_f	length of fibers
d_f	diameter of the fibers	ρ_s	rebar percentage
E_{fs}	modulus of elasticity of fibers	σ_{fy}	fiber yielding stress
E_{UHPC}	modulus of elasticity of UHPC	τ_f	fiber-concrete bond strength
		β_1	stress block parameter

[6–8], in-depth knowledge is required to understand the approach which aids in calculating the moment capacity of UHPC sections.

The moment, shear and compression capacity of a normal strength reinforced concrete is well understood based on which the codes have developed procedures to obtain the moment capacity. Although several experimental and numerical tests have been performed on the flexural behavior of the reinforced UHPC beams, and are documented as a technical reports, there is no general design guideline for the material in the US standards.

The tensile capacity of UHPC is achieved through cement matrix and steel fibers that stitch the cracks. The ductility and tensile strength resulting from the fibers is a characteristic material behavior of UHPC that cannot be ignored. These characteristics change the behavior of the UHPC beams compared to normal strength reinforced concrete ones. Accordingly, the procedures developed in codes for normal strength concrete beams cannot be straightforwardly used for UHPC sections without modifications.

The previous researches on UHPC have dominantly been focused on material properties, and less studies have been undertaken on flexural behavior and moment capacity of a UHPC sections. Several studies are available to summarize the recent UHPC material investigations [9,10]. Some experimental and analytical studies on the structural behavior of the UHPC sections can be found in Refs. [11–16].

Due to the complicated character of developing a Finite Element (FE) model, a simplified analytical procedure can facilitate the design process. The developed analytical procedure should provide basic assumptions to calculate the moment capacity of the UHPC beams.

The objective of this research is to evaluate the existing methods to calculate the ultimate moment capacity and understand the flexural behavior of a reinforced UHPC beam section. To do so, several small-scale UHPC beams with different percentage of longitudinal reinforcement and effective depth were tested. The results of these experimental tests were used to validate the FE models. The material properties of UHPC adopted in this model were based on the material properties used in an earlier research [17]. The FE model was able to predict the behavior of the tested beams including load-deflection curves, ultimate capacity, and mode of failure with a good agreement. This model was able to predict the behavior of UHPC specimens with different geometries, loading conditions, and reinforcing details with a reasonable accuracy, and was considered as a reference point. Then it was used as a benchmark for a parametric study on large-scale beams to evaluate the existing analytical method.

2. Experimental program

Twelve small-scale UHPC beams were fabricated and tested under three-point loading. Construction of the specimens was undertaken in several stages. In the first stage, the forms were oiled and the steel bars were placed in their positions in the forms. Plywood blocks with holes drilled in them were used to support the steel bars. As the casting direction may affect the fiber orientation, all specimens were cast horizontally and trowel finished [18–20]. After casting, the specimens were covered with polythene sheets for 72 h. and then de-molded. The specimens were kept moist for one week after casting to control the rate of moisture loss and hence prevent premature shrinkage cracking. Then they were cured in an air-dry condition until the test. Prior to test, the beams were painted in white to facilitate tracing of the cracks.

All specimens designated as S$h \times b$- $\rho_s - d/h$ (D) where: h and b specify the height and the width of the beam in inch, respectively. ρ_s shows the percentage of rebar in tension and d/h presents the ratio of effective depth to the height of the section (see Fig. 1). As some specimens had the same geometry and rebar percentage and were cast as alternate specimens, (D) at the end of the specimen's names shows the duplicate specimen results. For example, S6 × 6-1.7-0.85 shows the specimen with the width and height of 6 in. (15.2 cm), 1.7% of rebar ratio and $d/h = 0.85$ ($d = 5.1$ in.). Also, Specimen S6 × 6-0-0 and S6 × 6-0-0D show the specimens without rebar reinforcement. Based on previous studies [21], the development length in UHPC is much less than regular concrete and there were no need for the mechanical anchorage.

The total length and load span of the beams were 20 in. (50.8 cm) and 18 in. (45.7 cm), respectively. To compare the results, all tested specimens had similar material and width and longitudinal reinforcement provided reinforcement ratios of 0–2.6%. The specimens were designed to show flexure and shear behavior under center-point bending test loading approach for tensile based on AFGC [1].

2.1. Materials

The UHPC used in this study was composed of a blended premix powder, water, superplasticizer, and 2% steel fibers by volume which is the most common ratio suggested by commercial UHPC companies in North America. The premix powder included cement, silica fume, ground quartz, and sand. The fibers were 0.5 in. (13 mm) long with a diameter of 0.2 mm respectively, with a tensile strength of 400 ksi (2800 MPa). Flow table test was performed according to ASTM C1437 [22], to obtain the rheology of the UHPC. Static and dynamic flowability of UHPC was measured 8 in. (20 cm), and 10 in. (25 cm), respectively.

The compressive and tensile strength of UHPC were obtained through testing cylinder specimens (3 × 6 in. (7.5 × 15 cm)) and dog-bone test, respectively. The mean compressive (f_c) and tensile (f_t) strength of the tested beams were 21 ksi (145 MPa) and 1.4 ksi (9.6 MPa) respectively.

All steel reinforcements were from one heat in manufacturing. Tension tests performed on three representative specimens resulted in an average yield strength of 68 ksi (469 MPa) and ultimate strength of 113 ksi (780 MPa).

2.2. Testing procedure and loading

The test was conducted at the age of 150 days after casting. The load was applied constantly at the middle of the beam. Fig. 2 illustrates the loading setup. Load cells and pressure transducers were used to measure the load at each level of loading. The deflection was measured by the potentiometers installed at the mid-span of the beams. The applied load, deflection, and crack tracing were recorded after each load increment. To observe the post-peak behavior of the specimens, the loading was continued up to either the failure of the beam or 1-inch (2.54 cm) deflection.

3. Analysis and discussion of experimental results

The behavior of the specimens including crack patterns, mode of failure, load-deflection relation, and ductility are discussed in the following sections.

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