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Torsional behavior of ultra-high performance concrete squared beams

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ABSTRACT

This paper presents experimental results on the torsional behavior of ultra-high performance concrete (UHPC) beams. Thirteen beam specimens with 300 × 300-mm cross section were cast from UHPC with the compressive strengths greater than 150 MPa. The experimental parameters were the specimens' volume fraction of steel fibers, transverse reinforcement ratio, and longitudinal reinforcement ratio. The test results indicated that the beams' initial cracking and ultimate torsional strength increased as the volume fraction of steel fibers increased. The ultimate torsional strength and torsional stiffness after initial cracking increased as the stirrup ratios increased, and ultimate torsional strength increased as the longitudinal rebar ratios increased. The effect of the quantity of transverse and longitudinal reinforcement on the angle of the diagonal compressive stresses was investigated. The results of this study provided valuable data that could be used in future studies to develop computational models of the torsional behavior of UHPC beams and predict their ultimate strength.

1. Introduction

Torsion can be a significant issue in concrete structural members, such as eccentrically loaded beams, spandrel beams, and curved girders. These members must be able to resist torsion, and design for torsion has become more important in concrete design [1–7]. Certain tests of high-strength reinforced concrete beams subjected to torsion have been reported in the literature [8–11]. However, there are limitations to the use of conventional and high-strength concrete in torsion scenarios, including its low tensile strength and ductility. According to the experimental work by Bernardo and Lopes [12], the torsional ductility in high-strength concrete was low and the reinforcement ratio where ductility still occurred was very narrow. In addition, the test results in the work of Rasmussen and Baker [10] showed that the cracking of a high strength concrete beam was more brittle than for a normal strength concrete beam. To improve the low tensile strength and ductility of concrete steel fibers can be used. When steel fibers are added to a concrete mix, they change the concrete from a brittle material to a ductile one.

Steel fiber-reinforced concrete has been increasingly applied in this situation, and research efforts have been focused on the study of steel fiber-reinforced concrete. The addition of steel fibers has increased the ductile behavior [13–15], tensile strength [16], shear strength [17–18], and torsional strength of concrete beams [19]. Gunneswara and Seshu [20] and Narayanan and Kareem-Palanjian [21] investigated the effects of steel fiber-reinforced concrete on the torsional behavior of beams, while Mansur [22] and Chalioris and Karayannis [23] studied the torsional characteristics of fiber-reinforced concrete, the results of which have revealed the advantages of fiber-reinforced concrete in torsion scenarios. Karayannis [24] and Karayannis and Chalioris [25] also developed a nonlinear numerical method for studying the torsional behavior of steel fiber-reinforced concrete beams.

Ultra-high strength concrete reinforced with steel fibers was developed more recently [26]. Richard and Cheyrezy [27] and Behloul [28] studied the use of reactive powder concrete, which is a form of ultra-high performance concrete (UHPC). UHPC is an advanced cementitious composite that consists of a dense, high-strength matrix and steel fibers. It is a promising material in construction and infrastructure rehabilitation because of its remarkable properties, which include high tensile strength, high ductility [29], and low permeability [30]. Compared to conventional concrete, UHPC possesses significantly increased tensile strength [31] and post-cracking behavior [29,32]. It has also been found that the high ductility of UHPC results from the bridging effect of fibers across cracks and that the use of UHPC can limit the amount of rebar needed in a structure.

Most studies on UHPC have focused on special concrete materials with characteristics that differ from those of conventional

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concrete at the material level. However, few experimental test results are available on the torsional behavior of UHPC beams. Therefore, more information is needed to explore the structural behavior of UHPC beams subjected to torsion.

With this need in mind, the purpose of this study was to explore the torsional behavior of UHPC beams with compressive strengths greater than 150 MPa, and this paper describes the experiments performed on this topic. The experimental parameters included steel fiber content, longitudinal steel reinforcement, and transverse reinforcement. The experimental test results from the static loading of the UHPC beams revealed the characteristics of the torsional behavior of UHPC. The investigation of torsional behavior included the consideration of cracking, failure patterns, and torsional capacity measurements.

2. Research significance

Experimental studies of the torsional characteristics of UHPC beams have been extremely limited in the literature. This study investigated the characteristics of the structural behavior, cracking and failure patterns, cracking torsional strength, and ultimate torsional strength of ultra high-performance concrete beams with squared solid sections when subjected to torsion. The experimental data presented in this paper provide valuable information on understanding the strength and structural behavior of ultra-high-strength concrete squared beams reinforced with steel fibers. These data could also be useful for the development of design equations that can predict the torsional strength of UHPC beams in the future.

3. Material properties

3.1. Materials and mix proportions

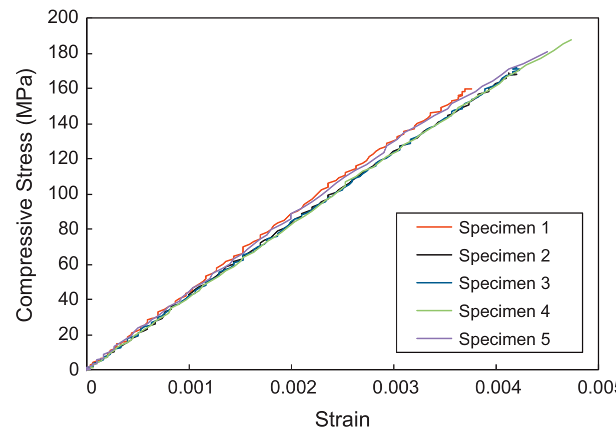
The UHPC investigated in this study was a type of reactive powder concrete [27]. Coarse aggregates were not included, and the fine aggregates consisted of sand with a diameter of less than 0.5 mm, which was the largest component of the UHPC. Portland cement was used as the binder, and the filler material was crushed quartz with an average diameter of 10 μm and a density of 2600 kg/m^3. The silica fume, which was the smallest of the UHPC components, had a diameter sufficiently small to fill the interstitial voids between the cement and crushed quartz particles. The workability provided by the low water-to-cement ratio of the concrete was maintained by the addition of a high-performance water-reducing agent, a polycarboxylate superplasticiser with a density of 1060 kg/m^3. The steel fibers used for this concrete were straight steel fibers with a diameter of 0.2 mm, and two different lengths of 16.5 and 19.5 mm were used together for each batch. The fibers had a density of 7500 kg/m^3 and a yield strength of 2500 MPa, and they were added in volumes of 1% and 2% of the total mix volume. The proportions of the components in this UHPC mixture are expressed in terms of their weight ratios in Table 1.

3.2. Mechanical properties of materials

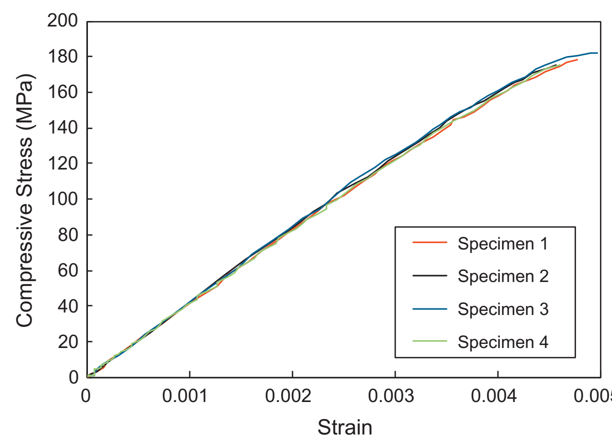
The compressive strength of the UHPC was determined by the compressive testing of cylindrical specimens with a diameter of 100-mm and height of 200 mm. The specimens were fabricated simultaneously with each batch of test beams. A specially designed axial deformation-measuring device was used for the compressive strength test. Two parallel rings were rigidly attached to the cylinders, leaving 100-mm spaces between the attachment points. The upper ring held three linear variable displacement transducers (LVDTs), the ends of which were supported by the lower ring. In

Table 1
UHPC mix proportion by weight ratio.

Water-binder ratio	Cement	Silica fume	Filler	Fine aggregate	Water-reducing admixture	Steel fiber by volume of concrete
0.2	1.0	0.25	0.3	1.1	0.02	0%, 1.0%, and 2.0%



(a) UHPC containing a steel fiber volume fraction of 1%



(b) UHPC containing a steel fiber volume fraction of 2%

Fig. 1. UHPC compressive stress–strain.

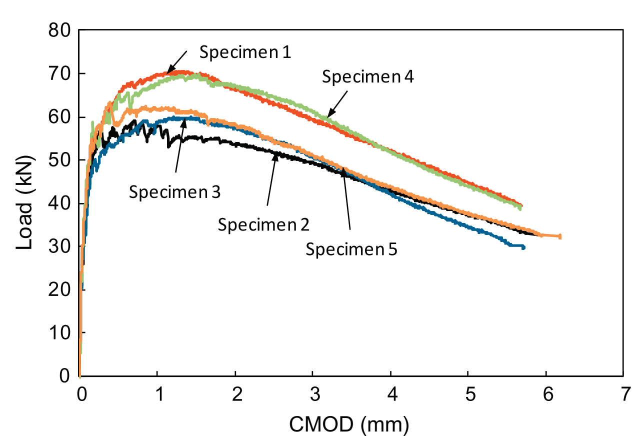


Fig. 2. Load–CMOD curves (steel fiber content of 2%).