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Experimental characterization of the punch through shear strength of an ultra-high performance concrete

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ABSTRACT

The paper describes the quasi-static and dynamic experimental methods used to examine the confined shear strength of an Ultra-High Performance Concrete, with and without the presence of steel fibers in the concrete composition. The experimental setup that employs a hydraulic press allows investigating the concrete shear strength under quasi-static loading regime while dynamic shear strength is characterized by subjecting concrete samples to dynamic loading through a modified Split Hopkinson Pressure Bar set-up. Both methods are based on a so called Punch Through Shear (PTS) test with a well-instrumented aluminum-alloy passive confinement ring that allows measuring the change of radial stress in the shear ligament throughout the test. First, four equally distributed radial notches have been performed on the concrete samples in order to deduce the radial stress in the shear ligament by suppressing self-confinement of the sample peripheral part. However, by analyzing the strain gauge data obtained from the confinement ring, it has been noticed that these were insufficient, especially for fiber-reinforced samples, resulting in subsequently practicing eight radial notches through the peripheral part of the samples. The results obtained from both procedures in addition to post-mortem observations are reported and discussed. It is concluded that the apparent increase of shear strength under dynamic loading compared to the quasi-static response is the consequence of higher radial confinement stresses at high strain-rates that results from an alteration of fracturing in mode I prior to mode II cracking in the ligament.

1. Introduction

Concrete is an extensively used material in both civil and military structures. Its composition, throughout the history, has been evolving in order to assure a great level of structures reliability against various extrinsic factors. Concrete structures such as nuclear power plants, dams, bridges and bunkers, can be exposed to extreme and intensive loadings such as earthquakes, blasting, explosions or projectile-impact. During these dynamic loading conditions, in addition to tensile failure, shear damage modes can also be observed as cratering on the front face and high shear strain close to the crater [1,2]. In other work carried on ultra-high performance concrete, mode II shear fracturing has also been observed during edge-on impact experiments [3,4]. However, when compared to its tensile and compressive strength, the shear strength of ultra-high performance concrete remains relatively unknown and the influence of fibers and strain-rate on the shear strength need to be experimentally investigated in more detail. The Punch Through Shear (PTS) experimental technique was first proposed by Watkins [5], where a cubic specimen of soil-cemented material was performed by one pair of notches on the bottom face considered as the initial crack length in determining the material fracture toughness. The author observed a subcritical tensile crack formation prior to the loading peak after which a pure shear fracture occurs. In further studies carried on rock material [6,7], a cylindrical sample with two cylindrical notches located on the top and the bottom faces of the specimen was introduced in order to derive mode II fracture toughness with the linear elastic fracture mechanics approach. The sample was first subjected to a pure hydrostatic pressure whereas the axial load was added in the second step. The authors finally observed a bilinear relation of material toughness with respect to initially applied confinement pressure. Furthermore, it was also reported that the initiation of, so called, tensile wing cracking occurs at about one third of maximum axial load. This technique was more recently used by Montenegro et al. [8,9] to evaluate the fracture energy of conventional concrete (maximum aggregate size 6 mm) as function of the hydrostatic pressure. It was observed that with the increased initial confinement pressure, the sample shear strength was increased and concrete exhibited a lower overall dilatant behavior through the reduced number of tensile radial cracks in the peripheral zone.

In the present work, quasi-static and dynamic Punch Through Shear (PTS) tests have been conducted with an ultra-high strength concrete, reinforced or not with short steel fibers. A

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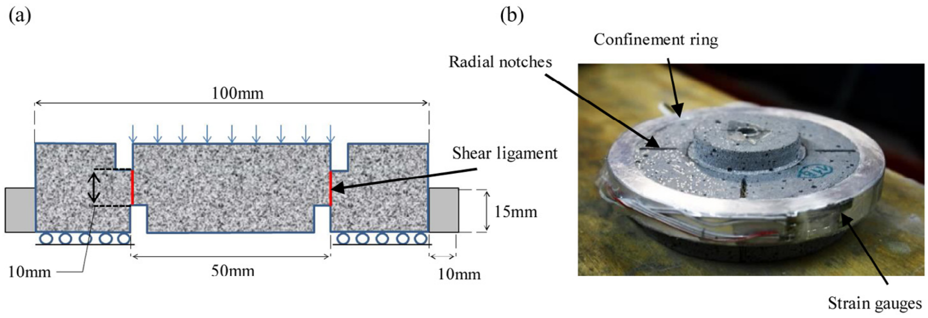

Fig. 1. Punch Through Shear (PTS) specimen: (a) geometry of the sample used in quasi-static and dynamic experimental procedures, (b) concrete sample with the instrumented confinement ring after quasi-static testing.

well-instrumented passive confining ring has been applied to the PTS samples, instead of a hydraulic pressure, allowing to deduce radial stress in the fractured zone that is supposed to originate from dilating behavior of concrete in a similar way than in quasi-oedometric compression tests [10]. Firstly, the geometry of the specimen will be presented as well as the material composition and mechanical properties of the Ultra-High Performance Concrete that was used throughout all testing procedures. Secondly, an overview of both experimental procedures is given, with presentation and discussion of the results obtained. Finally, post-mortem observations and general discussion on the apparent strain-rate sensitivity and influence of steel fiber reinforcement on shear strength are presented.

2. Concrete sample

2.1. PTS sample

The specimen geometry is shown in Fig. 1a. Inner diameter of the upper notch and outer diameter of the bottom notch coincide perfectly to form a straight cylindrical shear fracture surface. The geometry of the sample was numerically optimized in previous work [11], ensuring an almost perfectly homogeneous shear stress field in the ligament. Moreover, the confining ring is not centered toward the specimen symmetry plane in order to obtain uniform pressure contact between the confining ring and the concrete sample. The aluminum confining ring used for quasi-static and dynamic experimental procedures is 10 mm in thickness and 15 mm in height, instrumented with two strain gauges that form an angle of 135°. The sample is carefully introduced into the confinement ring and the gap between the sample and the confining ring is filled by an epoxy bi-component resin, Chrysor®, commonly used for structural application. Furthermore, equally distributed radial notches through the peripheral part of the specimen are performed in order to avoid specimen self-confinement (Fig. 1b).

The necessity of practicing radial notches was concluded in 3D numerical simulations by comparing the back calculated ligament radial pressure from ring-sample interface pressure with the true radial pressure in the shear ligament.

2.2. Tested material

Although characterized as concrete, UHPC varies in composition compared to conventional concrete and is defined primarily by its material properties. In contrast to conventional concrete, apart from high cement content, sand and water, it contains finely crushed quartz grains and silica fume. The optimized granular mixture of UHPC, where the maximal grain size is approximately 0.6 mm (sand), and extremely low water to binder material (cement and silica fumes) ratio allows casting a finely graded and highly homogeneous concrete matrix with outstanding mechanical properties. The benefit of eliminating coarse aggregates and optimizing the granular mixture in order to obtain a dense and homogeneous concrete matrix has already been pointed out by Richard and Cheyrezy [12]. The use of superplasticizer in order to increase the workability and to allow maximization of the particle packing density is of great importance. In addition, an increase of ductility and fracture energy is obtained by adding a dosage of high tensile steel fibers to the concrete matrix. Generally, the increased tensile characteristics are influenced by different fiber aspects, for example, fiber amount and orientation [13–15]. On the other hand, notable increase of fracture energy was observed up to around 2% of additional volumetric fiber content while a less significant increase was noted for higher volumetric fiber compositions [16].

In the present work, the Punch Through Shear tests have been performed on an Ultra-High Performance Concrete with composition similar to the so-called Ductal® [17,18] concrete, which has been developed for commercial purposes. Two sets of specimens have been considered for shear testing: one which contains 2% volumetric ratio of short steel fibers (0.2 mm diameter and 13 mm in length) and the other without additional fiber reinforcement. The material tested is an Ultra-High Performance Concrete (UHPC) whose composition is listed in Table 1 while the mechanical properties of hardened material are presented in Table 2.

2.3. Casting of concrete samples

The samples used in Punch Trough Shear Testing are notched cylinders with diameter 100 mm and 30 mm in length. After applying

Table 1
Material composition of an Ultra-High Performance Concrete [3].

Composition	Ductal®
Cement [kg/m^3]	730
Silica fume [kg/m^3]	235
Crushed quartz grains [kg/m^3]	220
Sand [kg/m^3]	885
Superplasticizer [kg/m^3]	10
Water [l/m^3]	160
Steel fibers [vol. %]	2%
W/(C + SF)	0.17

Table 2
Mechanical properties of an Ultra-High Performance Concrete [3].

Mechanical Properties	Ductal®
Density [kg/m^3]	2396
Young's modulus [GPa]	55
Quasi-static compressive strength [MPa]	200