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Cracking and load-deformation behavior of fiber reinforced concrete: Influence of testing method

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ABSTRACT

The characterization of the tensile behavior of cementitious materials has been a long-standing research topic and a general consensus on how to accomplish this task has not yet been reached. Many standardized tests are available but each with different test set-up and prescriptions on the definition of measured and derived parameters, including toughness, elastic properties and strength. This paper discusses a number of test procedures for selected material properties including tension and flexure. A comparative experimental study was carried out using two distinct fiber reinforced cementitious composites with strain hardening and strain softening behavior. Digital Image Correlation was utilized in the experimental program to detect and quantify the formation of cracks. Results show that the different test methodologies valuate specific aspects of material performance. The outcome of these evaluation procedures is compared and critically analyzed.

1. Introduction

The description of testing and characterization procedures for fiber reinforced cementitious composites (FRCC) in the recent publication of the fib Model Code 2010 [1] emphasizes the significance of defining suitable material parameters, including the post-peak tensile behavior of FRCC, to be utilized in the design of structural members. Dimensioning and verifying the load capacity of any structural element made with randomly distributed fibers, with or without traditional reinforcement, requires the determination of equivalent elastic post-cracking strengths of the FRCC material. There are many standard methods available to derive the post-cracking response of FRCC. Among several tests for characterizing FRCC in tension, it is possible to distinguish three main test categories, characterized by different set-up and stress fields generated:

- Uni-axial tension tests, with a prescribed single crack or possible multiple cracking;
- Flexural beam tests, performed on notched or un-notched prisms, under three or four-point loading;
- Flexural plate tests (square panel with continuous support or round panel with 3 point supports);

In the first group of test methods, the single-crack notched [2] coupon test and the dog-bone test [3,4] are intended to determine the local and global tensile behavior of a FRCC material with special emphasis on strain-hardening materials. In the second group of tests, among many different beam types and loading configurations, the most common are the three or four-point bending test, with or without notch. The notched three-point bending test according to EN 14651 [5] and the un-notched four-point bending test according to ASTM C1609 [6] and DAfStb [7] are the most often utilized. In the third group of tests, the round determinate panel (RDP) according to ASTM C1550 [8] was developed especially to measure the energy absorption, utilized in sprayed fiber reinforced concrete applications. A recent publication suggests expanding the utilization of the RDP test to a mechanical characterization of the material [9], implementing set-up through closed-loop control and crack width measurements.

To evaluate advantages, disadvantages and specific features of different test methodologies, experimental tests on two FRCC materials were conducted including two tensile tests, two types of

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beam tests and a round panel test. Furthermore, in the case of ASTM C1609 beams and ASTM C1550 round panels, the influence of alternative specimen geometries was also considered to investigate any influence of specimen size and slenderness on the results of the material characterization.

The consistency and reliability of the test results were evaluated in terms of scatter of the test results, stress disturbance (compared to the stress filed according to beam theory) due to concentrated load and notch, influence of fiber orientation, fiber type, fiber properties as well as specimen size.

The objective of this paper is to investigate the suitability of the main types of test methods to accurately characterize FRCC materials in tension, including not only common tension softening materials, but also materials with a hardening response. Furthermore, the usefulness of the obtained results with respect to structural design is evaluated.

2. Material descriptions and experimental methods

The two types of materials used in this investigation were a steel fiber reinforced concrete (SFRC) with a softening behavior in tension and a representative strain hardening material known as Engineered Cementitious Composite (ECC). In addition to the standardized test methods above mentioned, a digital image correlation (DIC) technique was used in the experimental program to continuously measure specimen deformations and to detect and quantify the formation of cracks. The test methods are divided in three categories including 1) uniaxial tensile tests, 2) flexural beam tests, and 3) flexural plate tests.

2.1. Materials

The strain hardening ECC was reinforced with 2% by volume polyvinyl alcohol (PVA) fibers, equivalent to 26 kg/m^3. The ECC matrix consisted of 856 kg/m^3 fly ash, 428 kg/m^3 cement, 320 l/m^3 water, 150 kg/m^3 sand (max. grain size 0.18 mm), 150 kg/m^3 quartz powder and chemical admixtures. The tension-softening material was a SFRC consisting of 300 kg/m^3 cement, 792 kg/m^3 sand (0–4 mm), 308 kg/m^3 aggregate (4–8 mm), 703 kg/m^3 aggregate (8–16 mm), 145 l/m^3 water, chemical admixtures and 55 kg/m^3 steel fibers (Dramix 3D 45/50) (0.7% by volume). The specimens were demolded 24–48 h after casting and were wet cured at 18 ± 2 °C. The specimens were covered with wet burlap and plastic sheets during curing for 28 days prior to testing. Table 1 lists the properties of fibers adopted.

Compressive strength and secant modulus of elasticity were obtained using standard compression cylinders with a diameter of 100 mm and height of 200 mm. Six specimens of each material were loaded to failure in compression with a loading rate of 6.28 kN/s. The average compressive strength was 47.5 MPa, and 57.1 MPa for ECC and SFRC, respectively. The average secant elastic modulus in compression was 18.0 GPa in ECC and 34.5 GPa in SFRC.

2.2. Deformation measurements

A DIC system was used to measure deformations of the front surface of the specimens in the region of interest. Deformations of selected specimens were additionally verified by an arrangement of LVDTs positioned on the back and on the sides of the specimens.

A digital single-lens reflex camera (24 and 36 megapixel) with a 60 mm macro lens for two dimensional measurements was utilized to provide quantitative and qualitative information on the surface deformations of the specimen. Details of the measurement regions are illustrated in the figures below for each test separately. Digital images were recorded at specific intervals as described below for each test. A commercially available DIC software called Aramis [10] was used to process the images taken during the loading procedure, providing full field deformation measurements of the surface of the specimen, as shown in Fig. 1.

The loading state in each image is correlated by synchronizing the time on the loading machine and that in the image file. In order to achieve adequate contrast in the gray-scale of individual objects, black and white spray paint was used to apply a stochastic spackle pattern on the specimen surface.

The photogrammetry system tracks movements of small areas (called facets) of the specimen surface corresponding to 15 by 15 pixel square areas; the step of the facets defined in the testing program was 13 pixels. For the most precise measurements, the optimal size of the gray-scale dots should be around 1/3 to 1/2 of a facets size. Additional details on the DIC technique and equipment are available elsewhere [10,11].

2.3. Uni-axial tensile tests

Typically for cementitious materials the tensile strength of concrete is given as a percentage of compressive strength; alternatively, the tensile strength can be determined through split cylinder test (e.g., ASTM C496 [12], EN 12390-6 [13]). While the split cylinder test provides sufficient information for brittle cementitious materials, where post-cracking tensile strength is negligible compared to the cracking strength, significant post-cracking strength gain and deformations are evident in ECC and in tension hardening composites, making the split cylinder test unsuitable and therefore requiring new test methods.

2.3.1. Single-crack notched coupon test

The basic tensile material property for FRCC can be measured from a single crack. To isolate a single crack and to avoid multiple cracking, an alternative test method for tension softening as well as strain hardening FRC was developed by Pereira et al. [2], where the formation of a single, localized crack was consistently verified and a relationship between applied tensile load and crack opening was established.

The tensile stress-crack opening response of ECC was determined using notched coupon specimens with a representative cross section of 8 mm × 30 mm. The size of the notched coupon specimen and the test setup are shown in Fig. 2 and Table 2. The notch reduced the tested area of specimen by 60% to generate a single crack in the specimen even for a strain hardening material. Deformation controlled tensile tests (0.3 mm/min loading rate) were conducted using clip-gauges to measure the opening of the predefined single crack at notch. The deformation was applied to the specimen through hydraulic grips providing fixed support at both ends of the specimen [2and14]. The specimen geometry used

Table 1
Properties of fibers.

Material name	Fiber type	∅, µm	L, mm	L/∅	f_t, MPa	E, GPa	Tensile strain capacity, %
PVA-ECC	PVA	40	8	200	1560	40	6.5
SFRC	Steel, hooked-end	1050	50	45	1115	210	–