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Influence of bending test configuration on cracking behavior of FRC

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ABSTRACT

This paper describes an investigation of the influence of the testing configuration for Fiber Reinforced Concrete in bending and aims at evaluating the influence of the test configuration details on the characterization of the material. Two different types of FRC, Steel Fiber Reinforced Concrete (SFRC) and Engineered Cementitious Composites (ECC), were tested and are described in this study. The materials were chosen so that one of them would be strain hardening (ECC) and the other tension softening (SFRC).

Notched and un-notched three- and four-point bending tests were carried out to determine the flexural load-deformation response of FRC. This research focuses particularly on the influence of the appearance and depth of the notch on the cracking behavior of FRC. For this purpose, several specimens, both un-notched and notched with different depths of the notch (25 mm and 45 mm), were tested. The results obtained in the various tests are compared to determine to what extent the notch can affect cracking behavior and the resulting evaluation of the material according to the method described in the standard. Formation of cracking and the crack development has been documented by means of a digital image correlation method.

INTRODUCTION

This paper presents experimental investigations of two particular types of fiber reinforced concrete (FRC), reinforced with steel and polymeric fibers showing a tension softening and a strain hardening post-cracking response, respectively. Strain Hardening Cementitious Composites (SHCC) are also known as High Performance Fiber Reinforced Cement Composites (HPFRCC), or more specifically as Engineered Cementitious Composites (ECC) [1, 2]. Fiber reinforcement mainly enhances the post-cracking properties of concrete and the ductility of the material. The increased ductility is due to the ability of the fibers to transfer tensile forces across the cracked section, leading to a reduction of crack widths at the same load level compared to unreinforced concrete. The extent of this reduction depends on the amount of fibers and on their physical and mechanical properties. The crack width control provided especially by SHCC is desirable from a durability viewpoint as it minimizes ingress of water and contained substances [3].

The motivation of the study presented in this paper was to investigate the influence of the test configuration on the characterization of both SFRC and ECC, using standardized and modified tests and focusing particularly on the effect of the presence and depth of the notch. Specifically, the classification of the ductility level of a fiber reinforced concrete depending on the test method used is investigated.

MATERIAL PROPERTIES AND EXPERIMENTAL PROGRAM

Materials

The experimental program consisted of specimens made of two types of FRC: a tension softening material (SFRC), reinforced with steel fibers, and a strain hardening material (ECC), with polyvinyl alcohol (PVA) fibers. The fibers properties are listed in Tab. 1.

Tab. 1. Properties of PVA and PP fibers

Material name	Fiber type	d [μm]	L [mm]	L/d	Weight [kg/m^3]	Volume fraction [%]	f_t [MPa]	E [GPa]	Tensile strain capacity [%]
ECC	PVA	40	8	200	26	2	1560	40	6.5
SFRC	Steel, Hooked-end	1050	50	45	58.5	0.75	1115	210	-

The SFRC mixture consisted of cement, sand (0-4 mm), coarse aggregate (4-8 mm and 8-16 mm), superplasticizer, water and fibers (0.75% by volume). The ECC mixture contained cement, fly ash, sand (≤0.18 mm), quartz powder, superplasticizer, a viscosity modifying admixture, water and fibers (2% by volume). The specimens were cast in standardized formwork and demolded after 24 to 72 hours after casting. They were moist cured, covered with a wet burlap for 28 days.

Deformation measurements

A digital image correlation method (DIC) was utilized beside classical measurement systems, in order to obtain a more accurate definition of the material behavior. The commercially available DIC evaluation software used in this study was called Aramis (GOM, Braunschweig, Germany). A digital high resolution camera with 60 mm lens was used to take pictures of the specimen surface with a frequency of 0.25 Hz during the loading procedure.

In order to facilitate the measurements, the specimens were prepared applying an adequate contrast in terms of the gray scale distribution of the specimen surface.

Additional details on the DIC technique and software available in the literature [4, 5].

Mechanical properties of SFRC and ECC in compression

To measure the basic characteristics of the materials including compressive strength and modulus of elasticity, the standard method prescribed by EN 12390-3 [6] was used. The parameters were obtained using standard cylinders with diameter of 100 mm and height of 200 mm. The tests were carried out with a standard compression machine at a rate of 6 kN/s and deformations measured through two LVDTs attached on both sides of the specimen.

The average compressive strength measured was 57.1 MPa for SFRC and 44.6 MPa for ECC. The average elastic modulus was 34.5 GPa for SFRC and 15.9 GPa for ECC.

Mechanical properties of SFRC and ECC in flexure

Three-point bending test

The notched three-point bending test is a standard test method of fiber reinforced concrete. The 25 mm notched specimens are consistent with EN 14651 [7], RILEM TC-162 TDF [8], the fib Model Code [9], JCI-S-002-2003 [10]. For this study, three-point bending tests according to EN 14651 were conducted. In addition, to investigate the influence of the notch in the FRC specimens, also modified three-point bending beams without notch and with different depth of notch (45 mm) were tested. The geometries of the specimens are shown in **Error! Reference source not found.** and Tab. 2.

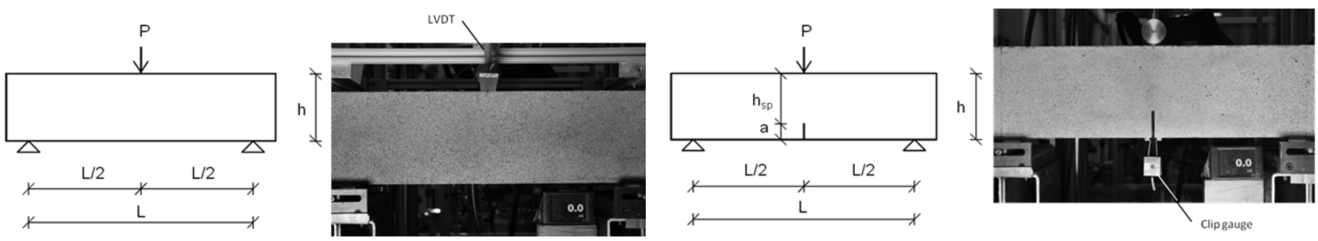

Fig. 1: Three-point bending test

Tab. 2: Geometry of three-point bending beams

Specimen	L [mm]	b [mm]	h [mm]	a [mm]	h_{sp} [mm]	Number of specimens
3P-SFRC_150_0	500	150	150	-	150	4
3P-SFRC_150_25	500	150	150	25	125	4
3P-SFRC_150_45	500	150	150	45	105	3
3P-ECC_25	500	150	150	25	125	6
3P-ECC_45	500	150	150	45	105	3

During the testing procedure, deformation controlled loading was performed at a rate of 0.05 mm/min up to a net deflection of 1.2 mm then the loading rate was changed to 0.2 mm/min. The CMOD was measured using a clip-gauge and the beam deflections were measured by LVDTs. The load and deflection measurements were captured with a frequency of 10 Hz. Additionally, the DIC measurements were taken of one surface of the specimens with a frequency of 0.25 Hz.

Four-point bending test

Various standards (ASTM C1609 [11], DBV - Guide to Good Practice [12], JCI-S-003-2007 [13], CNR-DT 204/2006 [14]) which use a four-point bending test set up are available in order to characterize the flexural behavior of fiber reinforced concrete. In this study, tests according to ASTM C1609 and CNR-DT 204/2006 and a test with modified notch depth were performed. The first one prescribes to use un-notched beams, while the second one prescribes beams with 45 mm notch. Furthermore, modified tests on specimens with 25 mm notch were conducted. The geometries of the specimens are shown in Fig. 2 and Tab. 3.

Deformation controlled loading was applied with a loading rate of 0.05 mm/min up to a net deflection of 0.5 mm, then the loading speed was increased to 0.25 mm/min. CMOD was measured using clip-gauge and the net deflection of the specimen was measured by LVDTs. The load and deflection measurements were captured with a frequency of 10 Hz. The DIC measurements were taken from one surface of the specimen with a frequency of 0.25 Hz.

Tab. 3: Geometry of four-point bending beams

Specimen	L [mm]	b [mm]	h [mm]	a [mm]	h_{sp} [mm]	Number of specimens
4P-SFRC_0	450	150	150	-	150	4
4P-SFRC_25	450	150	150	25	125	4
4P-SFRC_45	450	150	150	45	105	3
4P-ECC_0	450	150	150	-	150	5
4P-ECC_25	450	150	150	25	125	6
4P-ECC_45	450	150	150	45	105	3

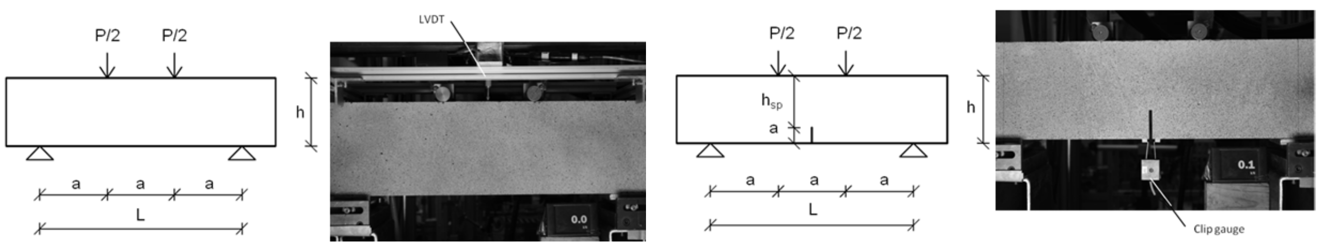

Fig. 2: Four-point bending test

RESULTS AND DISCUSSION

Three-point bending test

The load-CMOD response of the SFRC specimens shown in Fig. 3 indicates a deflection softening behavior with a first peak load similar to the post-cracking peak load except for one beam with 25 mm notch, which shows a deflection hardening behavior. It can be seen that the scatter in the results is relatively small in each type of SFRC three-point bending test (Fig. 3 (a) and (c)). This fact may be explained taking into account that three-point bending SFRC beams present the highest bending moment in the middle of the span length and this fact favors the formation of only one crack with branches in all specimens both with notch and without.

The ECC curves present a strain hardening behavior and show a higher peak load than SFRC specimens. It can be noticed that the scatter in the data is more significant than the one in SFRC due to the formation of multiple cracks.

The typical cracking behavior under three-point bending for ECC and SFRC in flexure is shown in Fig. 4. Although the cross-section of the beam has been reduced at the location of the notch in the middle of the beam where the bending moment is the highest, multiple cracking and branching of cracks have been observed. The branching of the crack in SFRC beams starts after the peak load is reached (Fig. 4 (c) and (d)), for both 25 and 45 mm notched specimens, as the material is deflection softening and the peak load is reached almost immediately before the first crack forms (Fig. 4 (a) and (b)). In ECC the peak load is reached at larger deflections and multiple cracking occurs before the peak load is reached (Fig. 4 (e) and (f)). Also cracks due to shear stresses in the beam can be observed both in the 25 mm and 45 mm notched specimens. As a result in ECC, not all the beam deformation can be captured by the clip-gauge placed at the notch because the left and the right side of the beams deform additionally to the notch opening. The depth of the notch seems not to influence the behavior of the material: crack pattern and shape of the curves are very similar with both 25 and 45 mm.

Three-point bending notched specimens present the point load and the notch at the same cross section and as consequence the section acts as a disturbed region with a combination of shear stresses, vertical normal stresses and the disturbance caused by the notch at the same time. As a result, the material characteristics obtained by notched three-point bending test are not totally representative when more than one single crack is

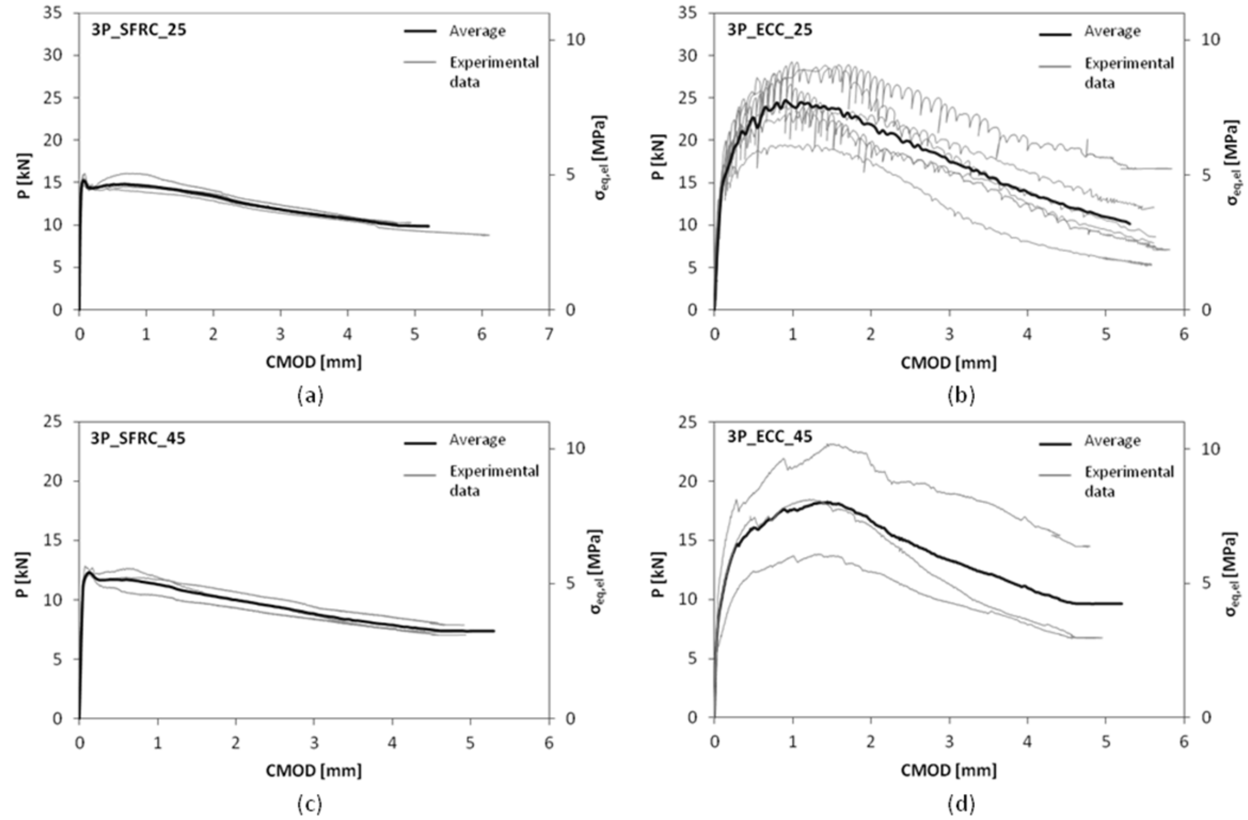

Fig. 3: Load – mid-span deflection and load – CMOD relationship of three-point bending beams

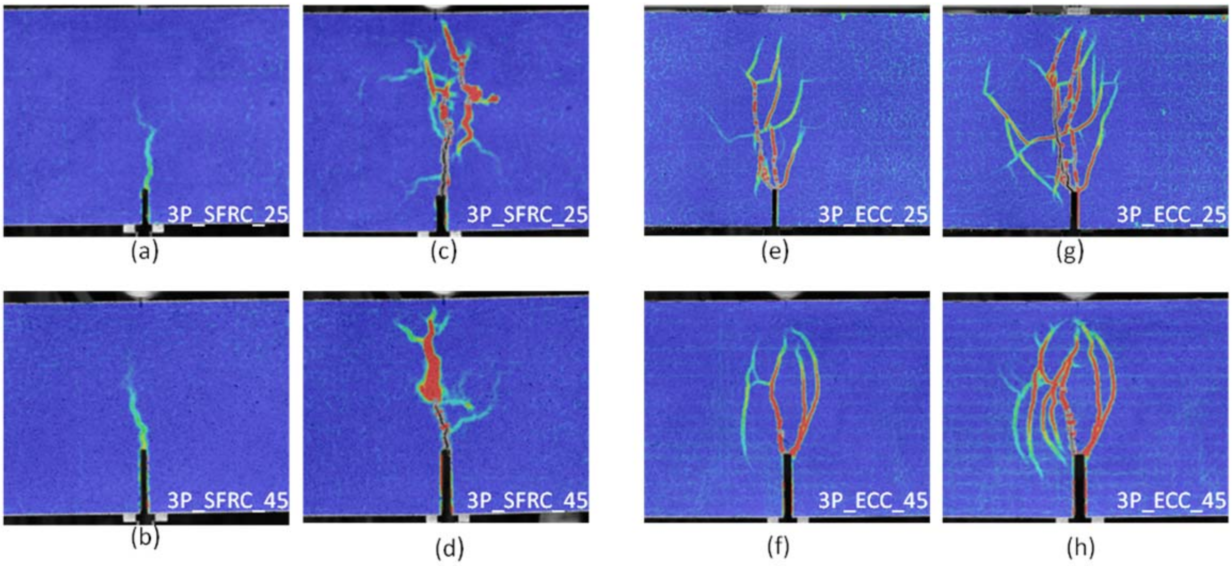

Fig. 4: Cracks distribution of FRCC beams under three-point bending: (a) 3P_SFRC_25 at peak load, (b) 3P_SFRC_45 at peak load; (c) 3P_SFRC_25 at CMOD of 2,5mm; (d) 3P_SFRC_45 at CMOD of 2,5mm; (e) 3P_ECC_25 at peak load; (f) 3P_ECC_45 at peak load; (g) 3P_ECC_25 at CMOD of 2,5mm; (h) 3P_ECC_45 at CMOD of 2,5mm

originating from the notch or its vicinity in FRC with deflection hardening behavior. In conclusion, the notched three-point bending test does not seem to be a representative test method for material characterization for materials with a hardening behavior in flexure.

Four-point bending test

Fig. 5 shows the load-deflection and load-CMOD curves of four point bending tests. It can be seen that the scatter in the data is significant, especially compared to three-point bending results. This can be explained considering the evolution of the moment in four-point bending specimens, which presents a constant moment section that allows the formation of more branches and cracks.

The notched tests show a significant scatter in the results, both for peak and residual load, whereas in the un-notched SFRC tests the peak load reached by all the specimens is almost the same, while there is a significant difference between the residual load at L/600 and L/150 (Fig. 5 (a)). A significant scatter can be noted also in ECC un-notched specimens. In 25 mm notched ECC beams the scatter of the peak load is small and it is higher at CMOD of 3.5 mm, while in 45 mm notched ones there is higher variation between the peak load and less between the residual load.

Although the residual strength at a mid-span deflection of L/150 or CMOD of 3.5 mm is similar for both materials, the peak strength of ECC is in general much higher than that of SFRC. This indicates that even though ECC can hold higher maximum load, the post-peak behavior of SFRC is more stable and with additional deflection or crack opening of the beam, flexural strength reduction is less rapid. This is due to different fiber properties and bond to the cementitious matrix: the bond between matrix and steel fibers can hold less that the fiber strength is so the fibers are slowly pulling out instead of rupturing while the PVA fibers has a very good bond between them and cementitious matrix, so with additional crack opening the fibers are rupturing resulting in more rapid loss in load carrying capacity.

Fig. 6 (a)-(f) shows the crack pattern of SFRC beams. It can be seen that only one big crack with branches is originated, both in un-notched and notched specimens. The crack presents more branches compared to three-point bending specimen and both the 25 mm and 45 mm notched beams show that the branching of the crack starts before the peak load is reached (Fig. 6 (b) and (c)), unlike in the un-notched specimens (Fig. 6 (a)). This fact could explain the significant scatter of the peak load that can be noticed in Fig. 5 (c) and (e), compared to Fig. 5 (a).

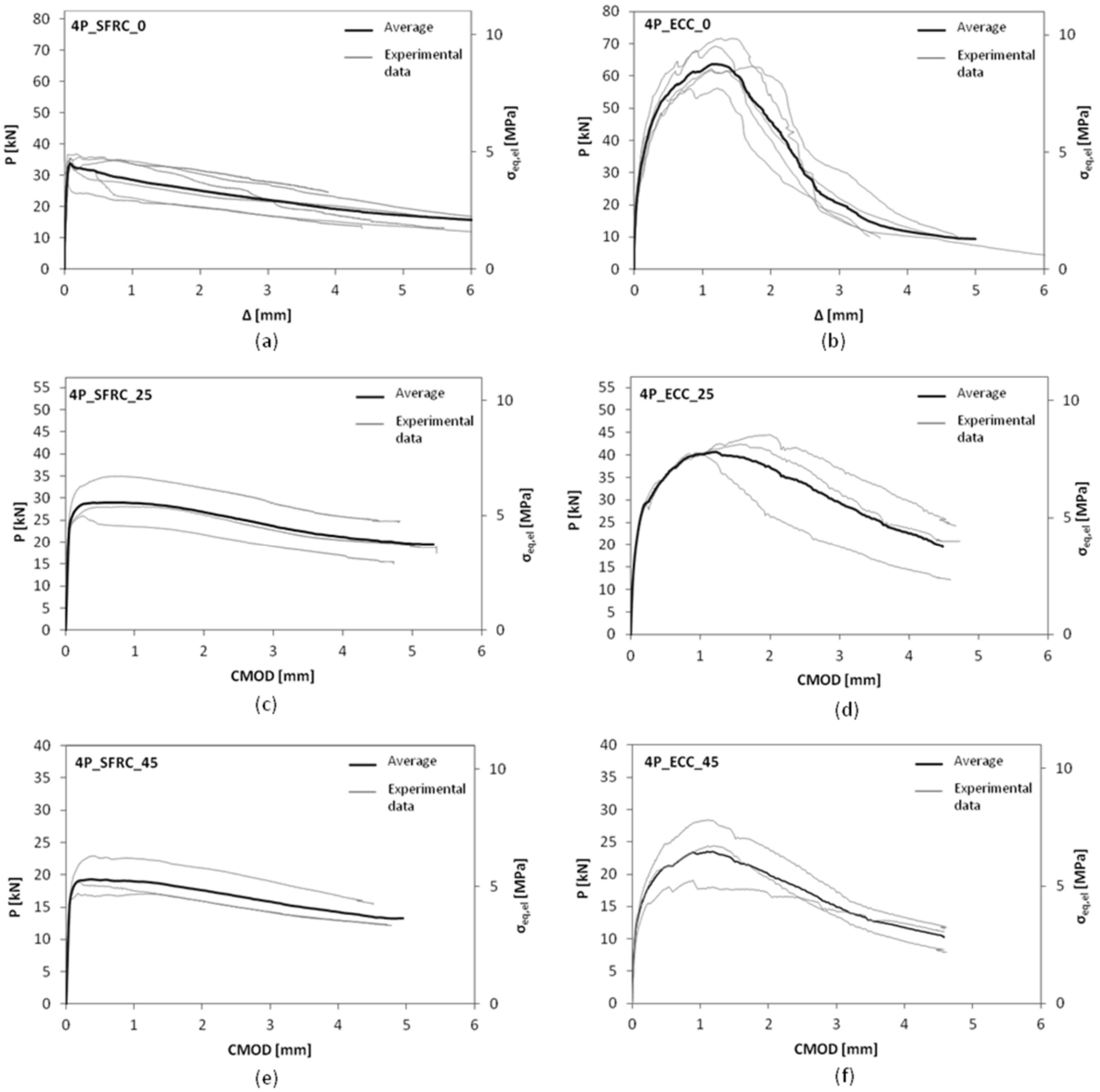

Fig. 5: Load – mid-span deflection and load – CMOD relationship of four-point bending beams

Fig. 6 (g)-(i) shows the flexural cracks that formed at the ultimate stage in ECC specimens. Multiple cracks can be observed in all types of specimens. While the CMOD in a notched specimen is supposed to represent the width of a single crack induced in a notched section, the deflection recorded by the LVDT in un-notched specimen is a result of the crack propagation process of several cracks. Considering a material like ECC, which presents multiple cracking, un-notched specimens are preferred, because they better represent the behavior of the material. However, the problem of the shear stresses has to be considered in un-notched beams: many cracks were located beyond the loading points with a typical mixed shear-flexure pattern (see Fig. 6 (g)). This affects the results because the deflection takes into account also the contribution of the shear cracks that appeared outside the pure bending region, i. e. the center segment between the loading points.

In Fig. 6 (h) it can be noticed that the shear affects also the crack pattern in the 25 mm notched specimens. Numerous cracks appeared outside the pure bending region and significant deformations occurred in the side parts of the beam. This behavior does not appear in the 45 mm notched beams (Fig. 6 (i)), where the multiple cracking is limited and there are shear crack do not occur. This can be explained by the fact that the section is more weakened in this case compared to beams with 25 mm notch and it limits the influence of the shear.

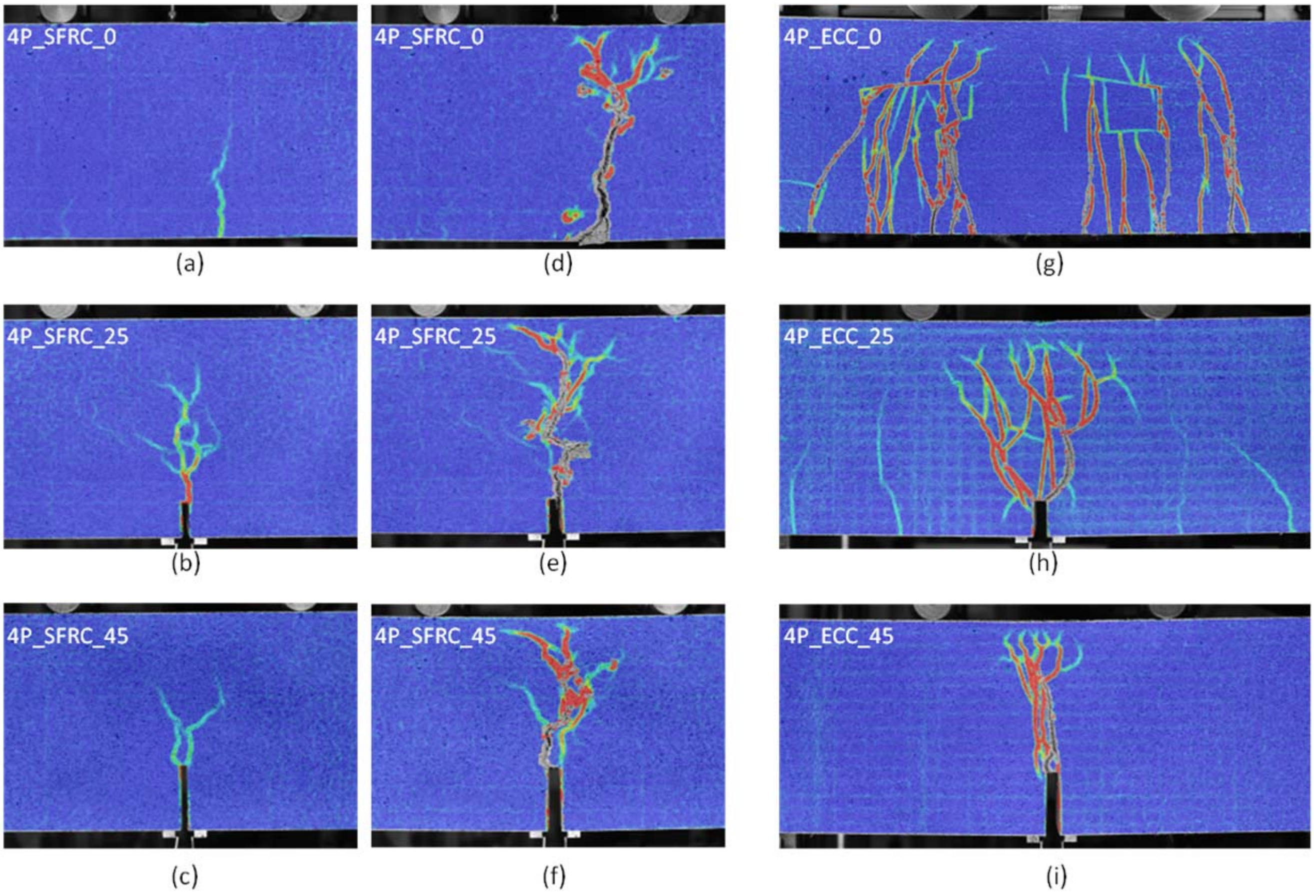

Fig. 6: Cracks distribution of FRCC beams under four point bending: (a) 4P_SFRC_0 at peak load; (b) 4P_SFRC_25 at peak load; (c) 4P_SFRC_45 at peak load; (d) 4P_SFRC_0 at deflection of L/150; (e) 4P_SFRC_25 at CTOD of 2.5 mm; (f) 4P_SFRC_45 at CTOD of 2.5 mm; (g) 4P_ECC_0 at deflection L/150; (h) 4P_ECC_25 at CTOD of 2.5 mm; (i) 4P_ECC_45 at CTOD of 2.5 mm

CONCLUSIONS

Various test methods can be used to characterize the behavior of FRC in bending. In this study some of the most significant standardized test methods were presented and discussed in order to find out how their configuration details can affect the characterization of the tested material.

Three-point bending tests with notched specimen are not suitable as unexpected crack formation occurs in the vicinity area of the notch as a result of a disturbed stress region due to the presence of notch and the point load acting at the same section and also due to the influence of the shear stresses. As a consequence, the material characteristics obtained by this test are not generally representative of the FRC evaluated using the notched three-point bending test. This conclusion is valid for both notch depths (25mm and 45mm) as the depth does not seem to influence the results: crack pattern and shape of the curves are very similar with both 25 and 45 mm and both materials.

The four-point bending un-notched set up favors a crack propagation starting from the weakest cross section between the load points where the moment is constant, whereas the notch favors a stable propagation of the crack, which cannot develop in the weakest section, but is forced to initiate at the notch at mid-span of the beam. This fact can lead unrepresentative test results. Furthermore the CMOD cannot be used to describe the behavior of the material when multiple cracking occurs. In ECC notched specimens, the depth of the notch has a significant influence on the cracking behavior. While the 25 mm notched specimens show a crack pattern highly affected by shear, the 45 mm notched specimens exhibit limited multiple cracking and no shear cracks. For this reason the higher depth of the notch is preferable. However, for materials characterized by multiple cracking, un-notched specimens are recommended as they provide most representative test results. Nevertheless the problem of the deformations due to shear cracking has to be taken into account.

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