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Evaluation of post-cracking behavior of fiber reinforced concrete using indirect tension test

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HIGHLIGHTS

- The DEWS test is a reliable instrument for structural parameterization of the FRC.
- The simplified DEWS test was able to identify the anisotropy of the FRC.
- The DEWS test was suitable to evaluate synthetic and steel fibers with low content.
- The susceptibility of the DEWS test to post-peak instability was evaluated.

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ABSTRACT

This paper presents an experimental investigation on the applicability of the novel double-edge wedge splitting (DEWS) testing technique to evaluate the mechanical properties of fiber reinforced concretes (FRCs) with low fiber content. This study aims to validate the DEWS test for the structural evaluation of FRCs with softening behavior, which is also considered by the design codes for structural applications. In this case, the occurrence of post-peak instability is critical. This instability could compromise the residual strength evaluation, especially for the serviceability limit state (SLS). The experimental studies focused on three main aspects affecting the DEWS test response: effect of test displacement rate, effect of fiber content, and orthotropy of FRCs. Two different groups of FRCs (reinforced with steel and macrosynthetic fibers) were mechanically evaluated, both at the SLS and ultimate limit state. The variation of the test displacement rate had no significant impact on the FRC post-cracking pattern. The DEWS test could detect behavioral variations induced by altering the fiber content and fiber orientation on both composites. This variation was more evident for higher crack opening levels because the post-peak instability may compromise the DEWS results in the SLS.

1. Introduction

Tensile strength of unreinforced concrete is low compared to its compressive strength. This justifies the fact that, for long, the design of conventional structures partially or totally ignored the tensile strength of concrete. However, given the advances in the design and production of structures based on fiber reinforced cementitious composites, this concept has been gradually changing [1–3]. The post-cracking behavior of fiber reinforced concretes (FRCs) contributes to the global performance of structural elements, even in the case of low fiber content. Low fiber contents are related to dosages below critical values (approximately 1% by volume for steel fibers [4]) and when FRCs present a softening behavior in the post-cracking region [5]. Therefore, the mechanical behavior of FRCs should not be neglected.

Most uniaxial tensile tests require a complex execution process, which led the standard methods, such as EN14651 [6] and ASTM C1609 [7], to select simpler approaches like bending tests on notched or unnotched beams. Other tests were also proposed as alternatives to bending tests, such as the double punch test (Barcelona test) [8] and small round panel test [9]. However, the bending and punching test responses are quite different from the tensile behavior, which can induce a false behavioral assumption during the design [10], such as the over-estimation of tensile strength. In addition, most conventional approaches do not consider fiber orientation, which makes the extrapolation of composite proper-

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ties to real structural elements more difficult [11]. This has encouraged the development of other methods for FRC characterization such as the multidirectional double punch test [12] that can indirectly assess the degree of effect of fiber orientation, or the wedge splitting test [13], Montevideo test [14], or double-edge wedge splitting (DEWS) test [15] that can perform a direct assignment.

The DEWS test can be used not only to assess the reinforcement orientation but also to obtain the FRC tensile stress–strain relation directly without back analysis [15]. Unlike traditional tensile tests, the DEWS test uses small cubic or even cylindrical specimens, which can be directly extracted from the structure under evaluation. The orientation of the specimens within the structure can be defined to represent critical areas, such as possible preferential fracture planes where high stress concentrations are expected.

It is important to observe, however, that most studies related to the DEWS test [15,16] employed FRCs with high steel fiber content (more than 1.00% by concrete volume). Under such conditions, DEWS results can present a very stable post-cracking behavior that cannot be analogous to FRCs with lower fiber contents, used for example, in pavements or tunnel linings. Moreover, there are no studies addressing DEWS tests applied to FRCs containing macrosynthetic fibers (e.g., polypropylene). Because the employment of macrosynthetic fibers has increased worldwide, leading to the replacement of steel fibers in some cases (e.g., shotcrete in tunnels linings) [17,18], a comparative study involving steel and macrosynthetic fiber reinforcement has become relevant. In this sense, this study furthers the validation of the DEWS test for the structural evaluation of FRCs characterized by presenting softening behavior, as also considered by the design codes for structural applications [2,5,10]. This assessment complements previous analyses and demonstrates the potential of evaluations under the most critical response conditions of FRCs.

In this paper, a simplification of the DEWS test proposed by di Prisco et al. [16] was used to investigate the mechanical properties of two different groups of FRCs: steel fiber reinforced concretes (SFRCs) and macrosynthetic fiber reinforced concretes (MSFRCs), both with low reinforcement ratio. As the DEWS test is an open-loop test method [16], there is a risk of post-peak instability [19]. In that sense, a study was conducted to evaluate the possible effect of displacement rate on the measurements of post-peak strength of FRC. After that, the mechanical characterization of both FRCs was performed in two different orientations, parallel "P" and transversal "T" to the casting direction, in prismatic specimens. The main objective was to analyze the feasibility of the DEWS test application to evaluate the FRC post-peak behavior with low volume fractions of fibers. This quantification was done in terms of tensile strength for different crack-widening levels. Special attention was given to the post-cracking instability and scattering generated in the DEWS test response.

2. Materials and experimental program

2.1. Fiber reinforced concretes

The concrete matrix used in both FRCs (SFRC and MSFRC) was designed to reach a characteristic compressive strength of 30 MPa. A Portland cement type CPII-F32 (containing limestone filler) with the standard 28-day compressive strength of 32 MPa was used in a content of 446 kg/m^3. The aggregates used were artificial sand with particle size ranging from 0.019 mm to 4.8 mm and a coarse aggregate (crushed granite stone) with maximum diameter of 9.5 mm in contents of 701 kg/m^3 and 862 kg/m^3, respectively. Tap water was used for all mixture compositions, which kept the water/cement ratio constant at 0.49. Two types of fibers were used as reinforcement in the aforementioned concrete composites: steel fiber with hooked ends (Dramix®) and macrofiber composed of polypropylene in a monofilament/fibrillated system (Fortaferro®). The length, diameter, aspect ratio, and densities of both fibers are summarized in Table 1. For each type of reinforcement, three different fiber volume fractions were used: 0.25%, 0.38%, and 0.57% (equivalent fiber dosage: 20 kg/m^3, 30 kg/m^3, and 45 kg/m^3) for steel fibers, and 0.50%, 0.75%, and 1.14% (equivalent fiber dosage: 4.7 kg/m^3, 7.0 kg/m^3, and 10.6 kg/m^3) for macrosynthetic fibers. The steel fiber had a tensile strength of 1100 MPa and elastic modulus of 210 GPa, as provided by the manufacturers. On the other hand, the macrosynthetic fiber had a tensile strength of 510 MPa with an elastic modulus of 3.3 GPa, which were obtained in a previous study performed with the same type of macrosynthetic fiber [20]. The FRC properties, in both fresh and hardened states, are presented in Table 2. The compressive strength for each mixture was determined using the average values of two cylindrical specimens of ϕ100 mm × 200 mm.

2.2. Casting and specimen production

At first, concrete mixtures were placed in prismatic molds measuring 100 mm × 100 mm × 350 mm (width × height × length). The casting process was conducted from the side (100 mm × 100 mm), leaving the concrete free to flow along the length of the mold (350 mm) (Fig. 1). The casting direction (or flow direction) was considered as reference to the orientation of the mechanical tests. Concrete consolidation was then performed using a vibratory table (60 Hz) for 15 s. For each fiber content, a batch of 45 L of concrete was created. The specimens were covered in their molds for 24 h prior to moist curing for 111 days in a curing chamber with 100% relative humidity and temperature of 23 ± 1 °C. Such an advanced age minimized possible strength variations associated with the age of concrete.

The specimens were prepared by cutting cubes of 100 mm × 100 mm from the aforementioned prisms (Fig. 2a). Then two triangular grooves, with a 45° inclination, were cut along two opposite sides of the cubes (Fig. 2b). In addition, two notches of 5 mm depth and 2 mm width (saw-blade thickness) were made in the specimens, starting from the groove vertices to force the appearance of cracks on the desired vertical plane (Fig. 2c). This preparation step consumes a longer time compared to other types of tests, such as the flexural or double punching type tests. In addition, it is important to note that cutting should be done carefully for satisfactory performance of the test. This time-consuming and labor-intensive requirement could be considered a drawback for DEWS.

During the test, the load is applied to the specimen through a steel cylinder directly accommodated into the groove. The same process is done at the bottom of the specimen, where the steel cylinder provides support to the test set up (Fig. 3). As reported by di Prisco et al. [15], through the grooves, the compressive load applied by the actuator deviates, inducing a uniaxial tensile stress state at the "ligament" (vertical fracture surface). Before testing,

Table 1
Properties of steel and macrosynthetic fibers.

Properties	Steel fiber	Macrosynthetic fibers
Geometry aspects	Hooked end	Monofilament/fibrillated system
Length (mm)	30	54
Diameter (mm)	0.61	0.32
Aspect ratio	49	168
Tensile strength (MPa)	1100*	510.8 [20]
Elastic modulus (GPa)	210	3.39 [20]
Density (kg/m^3)	7.85	0.91

* Value provided by manufacturers.

Table 2
Properties of tested FRCs.

Mixture	Slump (mm)	fc (MPa) (standard deviation)
SFRC_0.25	75	46.0 (1.0)
SFRC_0.38	125	45.9 (0.5)
SFRC_0.57	50	44.66 (0.04)
MSFRC_0.50	55	40.2 (1.6)
MSFRC_0.75	30	42.3 (0.2)
MSFRC_1.14	0	38.6 (2.0)

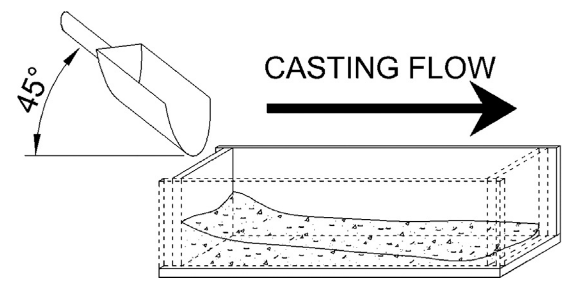

Fig. 1. Scheme of prisms casting.

the cube faces were regularized by grinding. Two steel plates of 0.9 mm × 15 mm × 100 mm (thickness × width × length) were attached to the groove surfaces using body filler as glue.

Given the geometry of the specimens, the load provided by the testing machine cannot be considered as the load in the specimen fracture surface (splitting tensile). Thus, it is necessary to convert the recorded load (P) into "effective load," which actually works in the system (P_{ef}). From equilibrium considerations, di Prisco et al. [15] achieved the following:

$$P_{ef} = P\frac{(\cos\theta - \mu\sin\theta)}{(\sin\theta + \mu\cos\theta)} \quad (1)$$

where θ is the angle between the groove surface and center line of the notch (i.e., 45°), and μ is the coefficient of friction between two steel surfaces. The coefficient of friction was kept constant at 0.15, considering steel–steel sliding without lubricant. This value was obtained by means of an inclined plane to measure the static friction coefficient between the steel cylinder and steel plate. To reduce the friction effect, the contact surfaces (steel cylinder and steel plate) were carefully cleaned before starting a new test. The resulting tensile stress (σ) can be found through Eq. (2) [15] below:

$$\sigma = \frac{P_{ef}}{b\ h_{lig}} \quad (2)$$

where b is the depth of the specimen and h_{lig} is the height of the ligament.

2.3. Test details

The DEWS test was performed in an electromechanical EMIC universal Brazilian testing machine model DL 10000. The specimens were tested in two different orientations, parallel (P) and transversal (T), based on the casting flow direction. Six cubic specimens with edges measuring 100 mm were tested for each particular condition, i.e., for each fiber volume fraction and sample orientation. Di Prisco et al. [15,16] also employed an open-loop

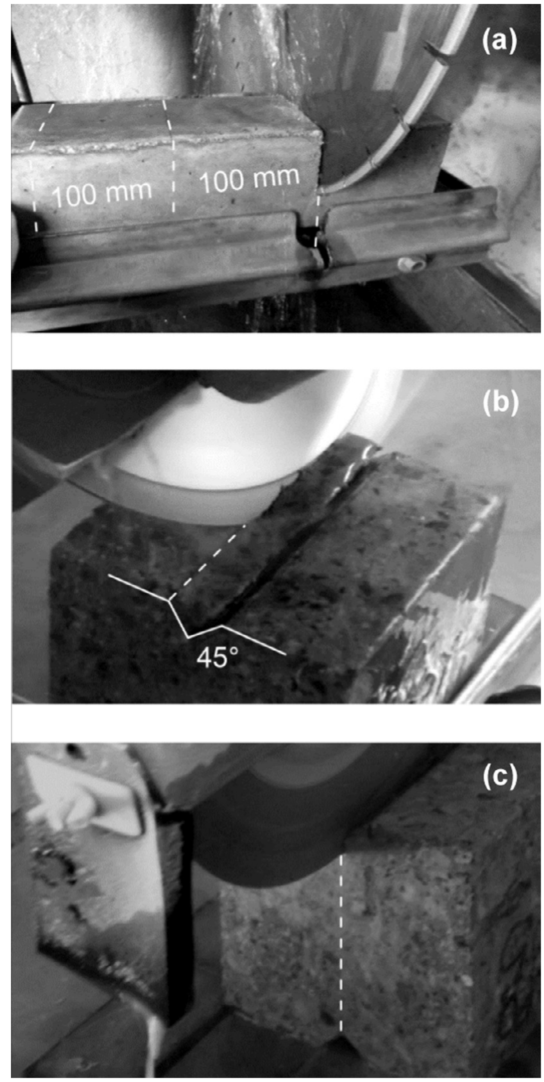

Fig. 2. Specimen preparation: (a) Cutting prisms into cubes, (b) creating grooves, and (c) creating notches.

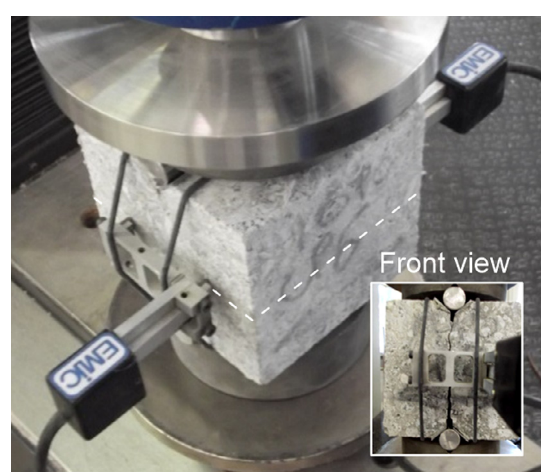

Fig. 3. DEWS test setup. Details of the used measurement system attached to the horizontal midplane of the specimens.

system but varied the actuator displacement rate as a function of crack propagation stage. Furthermore, the authors used six linear variable differential transformers (LVDTs) attached to the specimens (three per side) to measure the crack opening displacement (COD). The simplification proposed here makes use of two transducers, each one attached individually on opposite faces of the specimen (Fig. 3). The transducers were positioned at the middle height of the specimen to measure the average COD. Thus, the recorded COD values presented in this study represent the average of two measurements taken on opposite faces of the cubes. A gauge length of 50 mm was adopted to measure the COD in the experiments. The proposed simplification and the test setup can be adapted in a majority of laboratories in Brazil. It could be justified by the fact that, using low fiber content, a single crack is expected with the reduction of stress applied in both sides of the specimens and the crack surfaces distortions could be neglected. This assumption is due to the fact that FRCs with low fiber content present a softening behavior and, in this condition, both sides of the specimens work as rigid bodies after cracking. Therefore, the COD measured at the middle height of the crack could be considered very close to the average COD in each side. The differences in measurements taken from LVDTs are generated by the origin of the crack, which starts at one end of the ligament surface, as well as the fact that the distribution of fibers in the section of the crack is not completely homogeneous. This heterogeneity generates a load capacity distribution that allows a certain level of rotation of the specimen with respect to the ligament surface, which generates variations in the values measured in both LVDTs.

Preliminary DEWS tests were performed to assess the effect of displacement rate on the referred test results. After preliminary experiments, the DEWS test, in its original procedure (proposed by di Prisco et al. [15,16]), proved to be time consuming. In this context, an experimental investigation was performed to compare the results obtained with the originally proposed minimum displacement rate (0.2 μm/s, i.e., 0.012 mm/min [15,16]) with results using a displacement rate 10 times greater (0.12 mm/min). In that sense, ordinary concrete (compressive strength around 30 MPa) was prepared with a steel fiber content of 0.25% (20 kg/m^3) and casted in the form of prisms, as described in Section 2.2. The referred comparison was conducted with specimens being loaded in transversal direction to the casting flow.

The capability of DEWS test in differentiating the used fiber volume fractions and material anisotropy was measured in terms of maximum tensile strength and residual tensile strength. The latter was determined in two different crack-opening levels: 0.5 mm and 2.5 mm. Such COD levels were adopted on the basis of the fib Model Code [2,21] and were intended to represent the serviceability limit state (SLS) (f_{R1}) and ultimate limit state (ULS) (f_{R3}), respectively, for the composite (although derived from a different test). Naturally, the results obtained with the DEWS and flexural tests are not directly correlated since the type of fracture involved is different. In the bending test, crack width is measured at the mouth, while in the DEWS test, a practically uniform crack opening is obtained along the ligament. This proposition leads us to believe that the real SLS and ULS in the DEWS test is obtained for half of the crack openings employed for the beams (0.5 mm and 2.5 mm). However, the authors decided to characterize the post-cracking performance of the composites at the same crack-opening levels adopted in the fib Model Code [2,21]. It is known that results from different types of tests (direct tension, flexural, and panel tests) present quite distinct responses; however, the direct tension tests are considered as more representative of the design of structures using the FRC [10,21]. In that sense, the DEWS test could provide a result that could be more directly used to evaluate the capacity of FRCs to be used as a structural material.

3. Results and discussions

3.1. Effect of displacement rate on DEWS test results

The stress versus COD curves for FRCs tested in both displacement rates (0.012 mm/min and 0.12 mm/min) are presented in Fig. 4a and b, respectively. The increase in displacement rate has no significant effect on the FRC first crack strength, as observed from the values in Table 3, which show a difference of 6% in average values. Although the average post-cracking strength increased with higher displacement rate, the results showed a wide reduction in scattering. The average coefficient of variation was 65% for the lowest displacement rate and 28% for the highest. The very high coefficient of variation can be justified by very low average residual strength due to the low fiber content used in this study. As the standard deviation is relatively uniform, this ends up inducing high coefficients of variation associated with low fiber contents. For this reason and to avoid underestimating the structural capacity of the material, especially for low contents, according to the fib Model Code 2010 [21], the characteristic value of residual strength was 70% of the average value, ignoring the statistical parameters associated with the measurement of sample variability. A wide scattering could be considered as an intrinsic factor associated with FRCs during evaluation using small specimens,

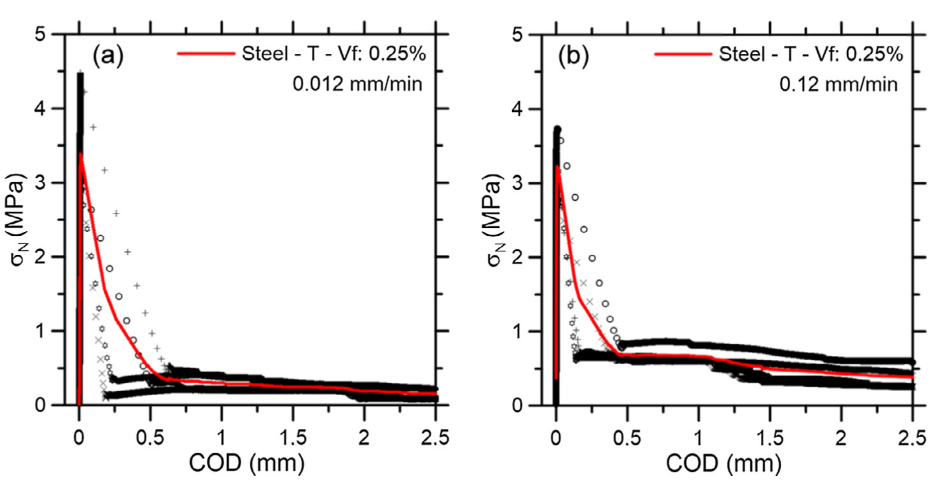

Fig. 4. Effect of displacement rate on DEWS test results: (a) 0.012 mm/min and (b) 0.12 mm/min. Tests transversal (T) to the casting direction. Red curve represents average of all specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Effect of displacement rate on DEWS tests results.

Displacement rate (mm/min)	Tensile strength (MPa)	Residual strength 0.5 mm (MPa)	Residual strength 2.5 mm (MPa)
0.012	3.4 (0.7)	0.5 (0.4)	0.15 (0.08)
0.120	3.2 (0.4)	0.7 (0.1)	0.4 (0.2)

Note: Values in brackets indicate standard deviation.

such as DEWS [22]. In terms of testing time consumption, the highest displacement rate seems to be closer to the time used in conventional tests for FRC characterization, such as bending tests. Based on such results, the highest displacement rate (0.12 mm/min) was adopted as the standard speed for all other DEWS tests performed in the present study.

3.2. Capability of DEWS test differentiating fiber volume fraction and material anisotropy

Fig. 5 shows the representative nominal stress versus COD curves from SFRCs (fiber volume fraction (Vf): 0.25%, 0.38%, and 0.57%) in the direction transverse to the casting flow. Similarly, Fig. 6 shows the tensile response of the same SFRCs obtained in the direction parallel to the casting flow. The experimental curves were divided according to the fiber content and loading direction (transversal and parallel to the casting direction). As described in Section 2.3, the tests were conducted at the age of 111 days. All specimens presented a strain softening behavior under indirect tension as expected. The predominant failure mode consisted of a single vertical crack for all used reinforced ratios as expected.

As observed in Figs. 5 and 6, after the crack formation (end of the elastic phase), a nonlinear descending branch appears in the curves. This drop till ~0.5 mm, typically wide, reflects instabilities of the cracking process associated with low fiber contents used as reinforcement in the FRCs as well as used displacement rate (Section 3.1). The post-peak instability proved to be higher for the steel fiber content of 0.25% in the transverse direction and 0.25% and 0.38% in the parallel direction. This brings uncertainty to the SLS residual strength determination. The third phase of the curves is characterized by a long lateral descending plateau that extends up to 2.5 mm (end of measurements). Consequently, for the ULS, there was no direct effect of instability.

As expected, the increase in Vf had no effect on the FRC first crack strength. At this stage, concrete matrix governs the composite strength, while the contribution of fiber reinforcement (below the critical volume) may be neglected. Table 4 summarizes the average experimental results of tensile strength obtained by the DEWS test at the first crack, and for the COD values of 0.5 mm (SLS) and 2.5 mm (ULS). Each value represents the average of six measurements.

Even for small increases in steel fiber content, the DEWS test is sensitive regarding the tensile strength assessment in the loading transversal direction. The composites reinforced with 0.25%, 0.38%, and 0.57% of steel fibers generated tensile strength values of 0.97 MPa, 1.31 MPa, and 1.83 MPa, respectively, at the SLS

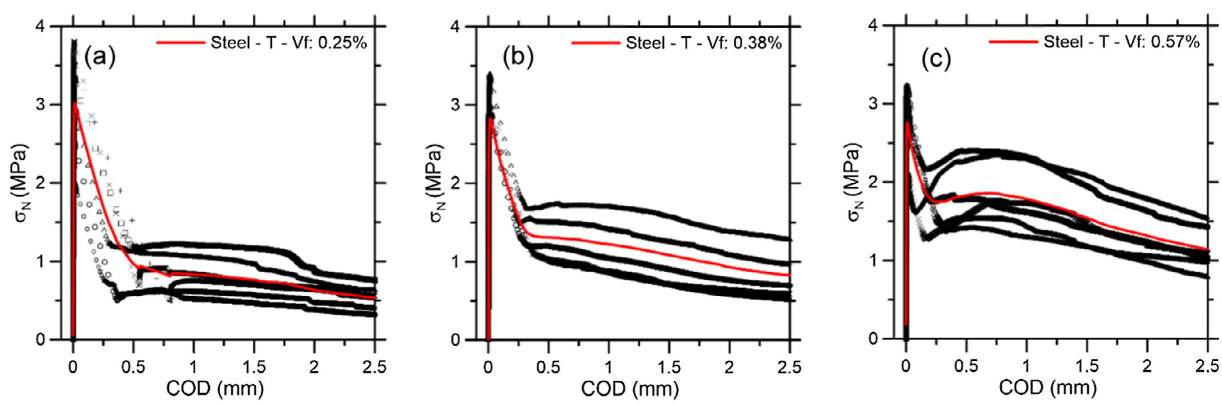

Fig. 5. Tensile strength obtained by DEWS test on SFRCs with different Vfs: (a) 0.25%, (b) 0.38%, and (c) 0.57%. Tests transverse (T) to the casting direction. Red curve represents average of all specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

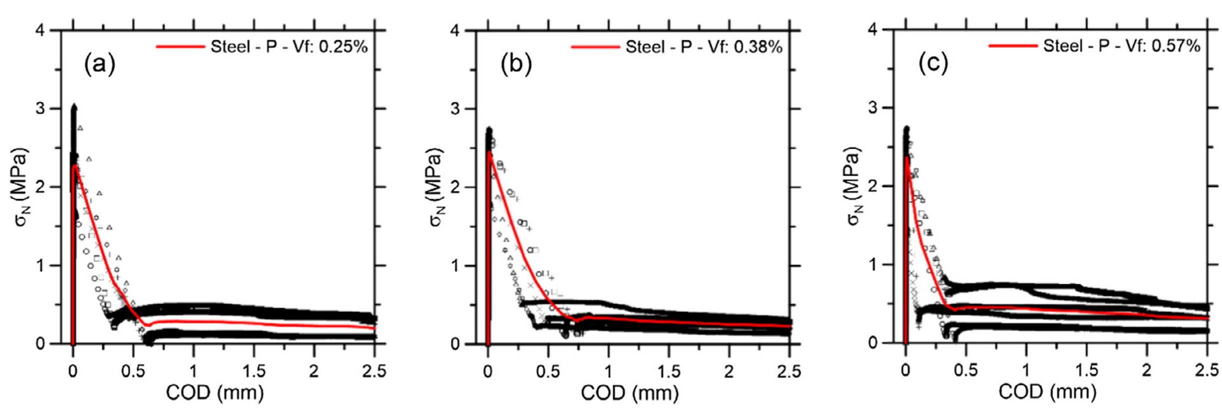

Fig. 6. Tensile strength obtained by DEWS test on SFRCs with different Vfs: (a) 0.25%, (b) 0.38%, and (c) 0.57%. Tests parallel (P) to the casting direction. Red curve represents average of all specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Average results of DEWS tests for SRFCs.

Mixture Transversal to the casting direction	Peak load (kN) Average value (Standard deviation – Coefficient of variation %)	Maximum tensile strength (MPa)	Residual strength 0.5 mm (MPa)	Residual strength 2.5 mm (MPa)
SFRC_0.25_T	21 (5–22%)	3.0 (0.7–22%)	1.0 (0.4–38%)	0.5 (0.2–30%)
SFRC_0.38_T	20 (4–21%)	2.9 (0.6–21%)	1.3 (0.3–21%)	0.8 (0.3–35%)
SFRC_0.57_T	19 (3–17%)	2.8 (0.5–17%)	1.8 (0.4–22%)	1.1 (0.3–25%)
Parallel to the casting direction	Average value (Standard deviation – Coefficient of variation %)			
SFRC_0.25_P	16 (3–17%)	2.4 (0.4–19%)	0.40 (0.09–23%)	0.2 (0.1–60%)
SFRC_0.38_P	17 (2–14%)	2.5 (0.4–15%)	0.6 (0.3–47%)	0.23 (0.06–26%)
SFRC_0.57_P	17 (3–21%)	2.4 (0.5–21%)	0.5 (0.2–51%)	0.3 (0.1–45%)

(COD: 0.5 mm) (Table 4). In relation to the tensile strength at the SLS obtained with a Vf of 0.25%, the increase in fiber content to 0.38% and 0.57% resulted in increase in tensile strength of 35% and 89%. Such effect results from the higher number of fibers oriented across the “ligament,” i.e., orthogonal to the loading direction.

Regarding the residual strength associated with ULS (2.5 mm) in the transversal direction, the increases generated by Vfs of 0.38% and 0.57% in relation to the minor fiber content (0.25%) were 50% and 111%, respectively.

The large scattering observed in the SFRC post-cracking response, which was more pronounced in the transversal direction (Fig. 5), results in part from the reduced number of fibers (below the critical volume) controlling the cracking process. Furthermore, it is known that different factors such as the straightening of the hooked end [23], variations in the pull-out angle (orientation) [24], and rupture of fibers [25] can disturb the composite post-cracking response, which can be accentuated in the case of low fiber volume, as is the case in the present study. Another important aspect to be observed is that all these factors interfering within the process variability have a greater effect on the result when the area of the cracked region is smaller, such as the case of the DEWS test in relation to the conventional prism flexural tests.

The anisotropic behavior of SFRCs is clear when comparing the responses of the specimens tested in the transversal and parallel directions. SFRCs in the parallel direction presented residual strength values lower than those in the transversal direction due to the alignment of the fiber in parallel to the “ligament” (Fig. 6). From Table 4, it can be observed that no higher residual strengths (SLS and ULS) were obtained for larger fiber dosages in the parallel direction. Such results, contrary to that observed in the transversal direction, reveal the sensitivity of the DEWS test to the reinforcement orthotropy. With low number of fibers bridging the crack orthogonally in the parallel direction, the increase in fiber content becomes imperceptible in terms of residual strength.

The average residual tensile strength values at the SLS obtained in the transversal direction (Fig. 7a) for steel fiber contents of 0.25%, 0.38%, and 0.57% were 143%, 126%, and 307%, respectively, greater than those obtained for the same Vfs in the parallel direction. Since the residual strength at the SLS and ULS remains unchanged in the parallel direction for all Vfs (Fig. 7b), such a difference becomes more evident as Vf increases. With relation to the residual strength at the ULS, the values obtained in the transversal direction for steel fiber contents of 0.25%, 0.38%, and 0.57% were 170%, 252%, and 268%, respectively, greater than those observed for the parallel direction using the same Vfs. Such results clarify

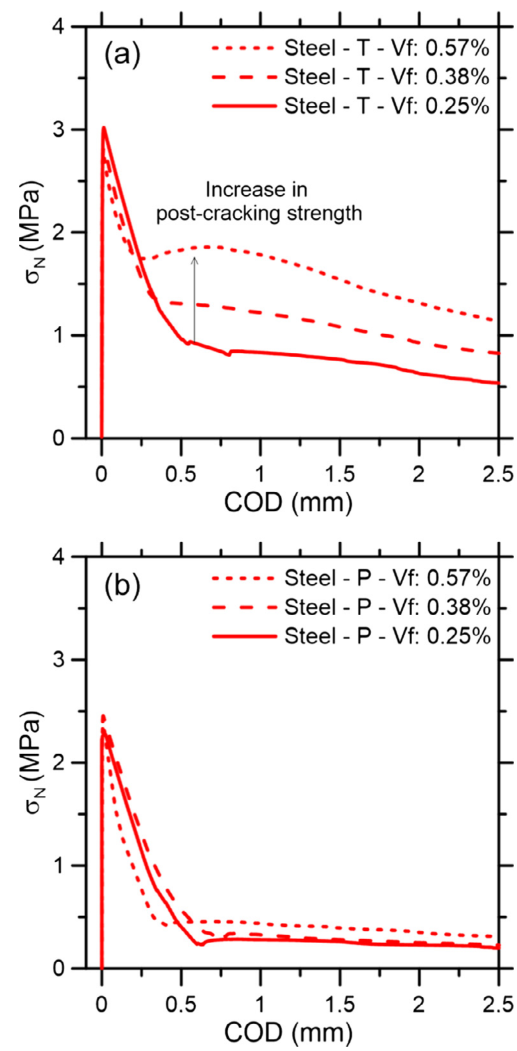

Fig. 7. Average stress versus COD curves obtained from SFRC. (a) Tests transversal (T) to the casting direction and (b) tests parallel (P) to the casting direction.

that flow-induced fiber orientation can be used to improve the SFRC tensile strength behavior in critical zones (susceptible to cracking) [26].

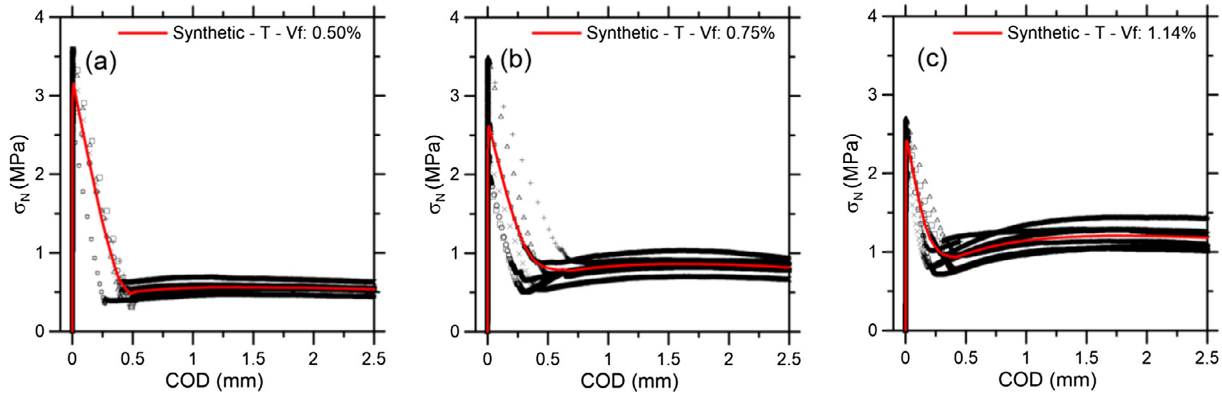

Fig. 8. Tensile strength obtained by DEWS test on MSFRCs with different Vfs: (a) 0.50%, (b) 0.75%, and (c) 1.14%. Tests transverse (T) to the casting direction. Red curve represents average of all specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

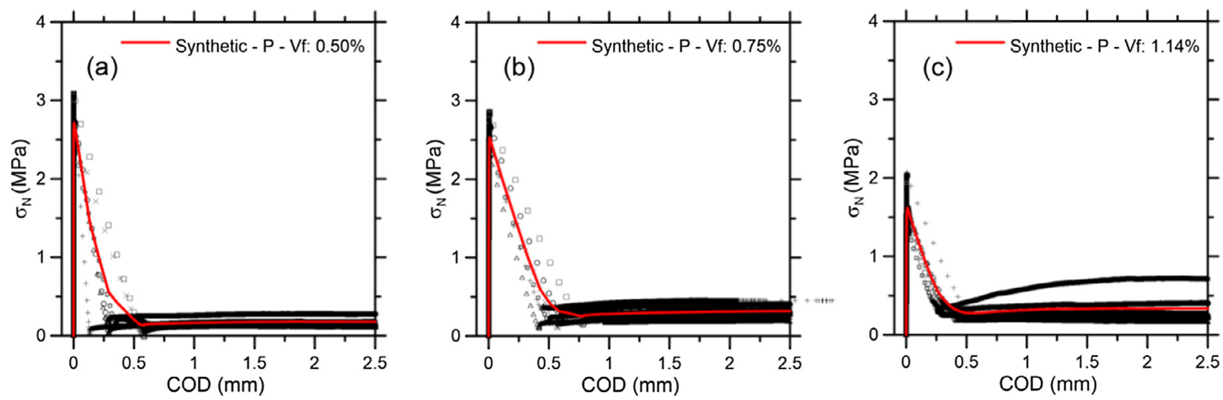

Fig. 9. Tensile strength obtained by DEWS test on MSFRCs with different Vfs: (a) 0.50%, (b) 0.75%, and (c) 1.14%. Tests parallel (P) to the casting direction. Red curve represents average of all specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

From Figs. 8 and 9, it can be observed that MSFRCs showed a higher level of instability extension. Only the higher fiber content became free of instability effect in the COD range of 0.5 mm. Therefore, macrosynthetic fibers were more susceptible to the test instability with more uncertainty regarding the SLS residual strength determination. Instability extension is the measure in the COD axis between peak load and the instant when the acquired data become constant.

Unlike the aforementioned SFRCs, MSFRCs presented a "flat" ductile post-cracking behavior (between 0.5 mm and 2.5 mm). Such a feature reflects in part the fiber geometry, which greatly differs from steel fibers with respect to aspect ratio and anchorage. Compared with steel fibers, synthetic fibers have an increased amount of fibers per cubic meter of concrete. The synthetic fibers used in this study are capable to self-fibrillate, increasing their surface area and consequently, improving the fiber–matrix interaction. Because of the flat behavior, the obtained values of residual tensile strength at the SLS and ULS are similar to each other within each tested group (Table 5). As described above, the tests were conducted at the age of 111 days.

Similar to SFRCs, the DEWS test could recognize reinforcement orientation on the MSFRCs. From Table 5, it can be seen that in the transversal direction, higher residual strengths (SLS) are obtained for larger fiber contents. MSFRCs reinforced with 0.50%, 0.75%, and 1.14% of fibers generated tensile strength values at the SLS (COD: 0.5 mm) of 0.53 MPa, 0.71 MPa, and 0.98 MPa, respectively (Table 5). With regard to the tensile strength at the SLS obtained with a Vf of 0.50%, the increase in fiber contents to 0.75% and 1.14% resulted in tensile strength enhancements of 34% and 85%, respectively. Greater values were obtained for the residual strength at 2.5 mm (ULS). Compared to the tensile strength at the ULS obtained using a Vf of 0.50%, the residual strengths obtained for Vfs of 0.75% and 1.14% were higher by 52% and 119%, respectively. The analysis of Fig. 8 and the standard deviation values in Table 5 indicate that the scattering of MSFRC curves was lower than that previously shown for SFRCs, which will be further addressed in Section 3.3.

Similar to SFRCs, fiber orientation strongly affected the post-cracking response of MSFRCs (Fig. 10). When subjected to splitting tension, MSFRCs tested in the parallel direction did not present significant differences in the residual strength values (SLS and ULS) with increasing fiber content.

As is widely known, the addiction of fibers does not significantly increase the tensile strength, as the results clearly show. On the contrary, Figs. 8 and 9 show a decrease in tensile strength. Considering the scattering results, a Tukey test did not indicate significant differences between 0.5% and 0.75% (both cases T and P) and between 0.75% and 1.14% (only T). The use of high content of synthetic fibers may decrease the peak load, because it causes a reduction in workability and entrapping air during specimen cast [27].

3.3. Scattering and efficiency of DEWS test

The scattering observed in the tensile strength curves (transversal direction), between 0.5 mm and 2.5 mm, was statistically different compared to SFRCs and MSFRCs (p-value < 0.05 by test-F).

Table 5
Average results of DEWS tests for MSFRCs.

Specimen	Peak load (kN)	Maximum tensile strength (MPa)	Residual strength 0.5 mm (MPa)	Residual strength 2.5 mm (MPa)
Transversal to the casting direction	Average value (Standard deviation – Coefficient of variation %)			
MSFRC_0.50_T	22 (3–13%)	3.2 (0.4–13%)	0.53 (0.09–17%)	0.54 (0.06–11%)
MSFRC_0.75_T	18 (5–28%)	2.6 (0.7–27%)	0.7 (0.1–17%)	0.8 (0.1–12%)
MSFRC_1.14_T	16 (2–32%)	2.4 (0.2–10%)	1.0 (0.2–16%)	1.2 (0.2–13%)
Parallel to the casting direction	Average value (Standard deviation – Coefficient of variation %)			
MSFRC_0.50_P	19 (2–10%)	2.7 (0.2–8%)	0.17 (0.06–35%)	0.18 (0.05–28%)
MSFRC_0.75_P	18 (1–8%)	2.6 (0.2–7%)	0.2 (0.1–48%)	0.3 (0.1–31%)
MSFRC_1.14_P	11 (2–15%)	1.6 (0.2–15%)	0.3 (0.1–36%)	0.3 (0.2–61%)

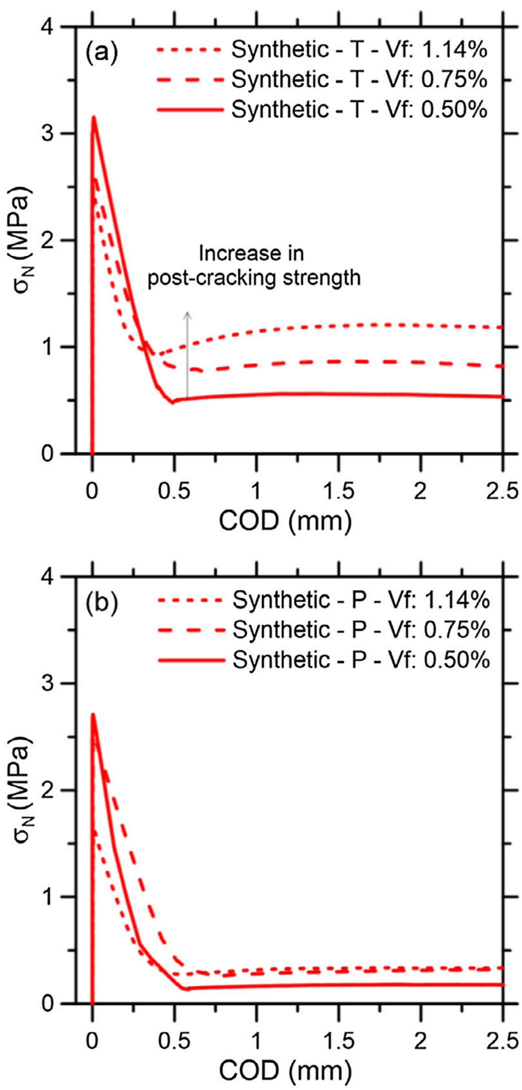

Fig. 10. Average stress versus COD curves obtained from MSFRC. (a) Tests transversal (T) to the casting direction and (b) tests parallel (P) to the casting direction.

Comparing the variances between both produced composites (MSFRCs and SFRCs), the variance in SFRCs was 243% higher than that in MSFRCs. In SFRCs, the pull-out process up to 2.5 mm is governed by the alignment of the hooked-end fibers. This process induces stress oscillations, which is quite visible for the produced SFRCs due to the low reinforcement ratios (0.25%, 0.38%, and 0.57%). Given the self-fibrillating ability of macrosynthetic fibers, lower scattering bands are observed for MSFRCs.

Table 6
Average number of manually counted fibers in DEWS fractured specimens.

Testing direction	SFRC			MSFRC		
	0.25%	0.38%	0.57%	0.50%	0.75%	1.14%
Parallel	13 (5)	13 (3)	17 (8)	21 (5)	28 (7)	26 (3)
Transversal	24 (10)	32 (8)	40 (7)	33 (6)	40 (10)	40 (7)

Note: values in brackets refers to standard deviation.

To better understand the scattering obtained with steel and synthetic reinforcement, the number of fibers crossing the "ligament" of the tested specimens was determined through manual counting (Table 6). The total number of fibers crossing the cracked surface in MSFRCs was at least 1.36 times greater than that in SFRCs. This considerable increase in the number of fibers orthogonally oriented with respect to the loading direction contributes to a more stable post-cracking branch and, consequently, lower scattering. In addition, as reported by Buratti et al. [27], the distribution of fibers crossing the fracture surface is more homogeneous in the case of macrosynthetic fibers. Stiff fibers (e.g., SFRCs), in contrast, are less likely to spread homogeneously during the casting process. In terms of coefficient of variation, the scattering obtained with the post-cracking strength value of SFRCs (transversal direction) was ~97% greater than that of MSFRCs. However, the scattering is also a consequence of the number of fibers (Table 6), which varies considerably between specimens with low fiber content [22].

The coefficients of variation obtained in the study were higher than those usually found for FRC qualification. Surveys presented in a previous study [10] have exhibited coefficients of variation of FRC characterization tests in the ranges up to 25%. In this test program, these coefficients were much higher, but it is important to note that this parameter depends on the level of average residual strength. In that sense, as the residual strengths of the DEWS test performed with low fiber content decreases, especially for higher levels of COD, the coefficients of variation are not considered in absolute terms for direct comparison. However, the greater variability requires an even more careful execution of the test. Because relatively high scattering observed on the SFRC post-

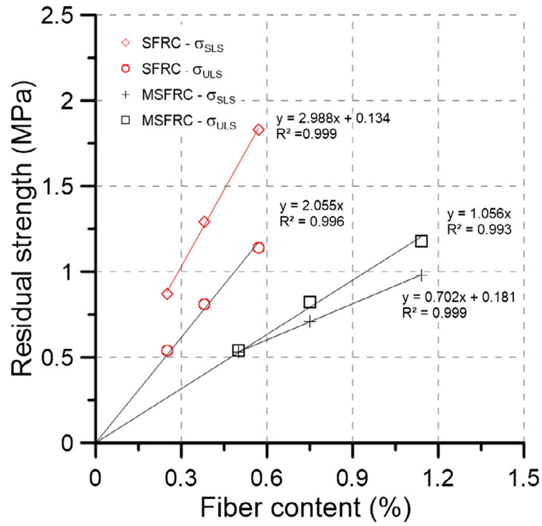

Fig. 11. Relation between average transversal (T) residual strength and fiber content.

cracking response obtained from small specimens cannot underestimate the structural capacity of this type of composite from the design perspective, the actual variation of the sample could be neglected. This affirmation is particularly important when considering a structure where a significant redundancy is guaranteed and the average mechanical behavior, instead of the characteristic one, governs the structural response [2,10].

The multiaxial approach, which is a characteristic of the DEWS test, was very effective in assessing the reinforcement orientation of MSFRCs and SFRCs for all fiber volume fractions. The correlations presented in Fig. 11 showed that the DEWS test is sensitive in detecting the increases in composite fiber volume fraction in all conditions. Even in the SLS zone, where the instability could negatively affect the correlations, the results presented very high coefficients of correlations when considering average values. Therefore, the simplified DEWS test used in this study is very useful to parameterize FRCs even when low Vfs are used [28]. It is important to consider that, as the post-cracking performance of SFRCs and MSFRCs depends on the matrix, fibers, and interaction of both, the equations proposed here should not be extrapolated for any type of fiber or composite.

Finally, despite the difficulties associated with the preparation of specimens and the relative dispersion of post-cracking results, the DEWS test is a very interesting method to provide constitutive equations for parameterization of FRCs. One of the most important aspects is that the derivation of these constitutive equations, in the case of the DEWS test, does not depend on the estimation of values such as failure angle values, internal kinetic friction coefficient, and number of cracks, as observed in the double punching test [29]. Consequently, the greater experimental difficulty associated with the execution of DEWS can be clearly outweighed by the greater effortlessness of analysis.

4. Conclusions

The present work investigated the tensile behavior of two different fiber reinforced composites, SFRC and MSFRC (both with low fiber contents), by using a simplified DEWS test.

A displacement rate 10 times greater than the minimum, initially proposed for the DEWS test, provided a wide reduction in the scattering of the average post-cracking strength. Moreover, the duration of the test procedure was reduced and brought closer to the conventional bending test procedure. However, the range of residual strength variation was higher than that in other types of tests used for FRC characterization. Therefore, the use of DEWS for quality control may require a larger number of specimens to guarantee reliable results.

The orthotropic behavior of both FRCs (SFRC and MSFRC) was clearly identified by altering the DEWS test orientation. The DEWS test could detect behavioral variations induced by altering fiber content on both the composites. These variations, however, were more evident and reliably measured with higher level of crack opening, associated with the ULS, where the effect of post-peak instability was not observed.

The low level of crack opening associated with the SLS zone proved to be susceptible to instabilities associated with lower fiber contents and, especially, for macrosynthetic fibers due to the reduced residual strength. However, it is possible to affirm that the DEWS test can be used to evaluate FRC in the concerned critical situations. However, when the gap between the matrix and residual strength is very high, a closed-loop system will provide results without the negative effect of instabilities. The DEWS test is more labor intensive, but this disadvantage can be compensated by the fact that it is possible to obtain constitutive equations from its results without estimating uncertain parameters, which is a shortcoming of other types of tests.

Steel fiber reinforcement, in general, was more efficient in terms to post-peak load-bearing capacity, resulting in larger values of residual tensile strength. However, the use of macrosynthetic fibers resulted in a less scattered post-cracking performance, especially because of their self-fibrillating capacity that produces a large number of fibers in the cracked area of the specimen.

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Conflict of interest

The authors declare that they have no conflict of interest.

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