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REVIEW **Open Access**

Test Methods for the Post-cracking Behavior of the FRC in Tension: A State of the Art Review

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Abstract

The knowledge of post-cracking tensile behavior is crucial for the proper use of Fiber-Reinforced Concrete (FRC) in engineering. Although various tests are used to determine FRC's Mode I fracture behavior, each has its limitations in accurately predicting how FRC performs in real-world structures. This underscores the need for further research in this area. The different test methods examined have specific details that can significantly affect results, such as differences in tools, sample sizes and shapes, notch types, and how loads are applied. This paper thoroughly reviews these test methods and discusses their specific characteristics to evaluate FRC's post-cracking behavior. It also explores the inverse analyses procedures for estimating direct tensile behavior from indirect tests and compares results from different test methods.

Keywords Fiber-Reinforced Concrete, Post-cracking behavior, Tensile behavior, Mode I fracture behavior, Inverse analysis

1 Introduction

Steel Fiber Self-Compacting Concrete (SFSCC) has important advantages such as no need for external vibration and resistant capacity after the formation of cracks, which means that it can be used in some structures in which this characteristic is distinguishing, such as tunnels. Currently, some standards contemplate different test methodologies to verify the post-cracking behavior of SFSCC (RILEM TC 162-TDF, 2001; EN, 14651, 2007; CNR-DT 204, 2006). However, this behavior is related to parameters whose exact determination through simplified tests is still difficult to perform. Therefore, a series of tests have been proposed for this investigation, such as prismatic sample bending (RILEM TC 162-TDF, 2001; EN, 14651, 2007; CNR-DT 204, 2006), Round Panel Test (RPT) (Bernard, 2000), Uniaxial Tensile Test (UTT) (RILEM TC 162-TDF, 2001), DEWST (Double Edge Wedge Splitting Test) (di Prisco, Lamperti, & Lapolla, 2010) and the Splitting Test (ST). However, most of these tests still cannot determine with great accuracy the post-cracking parameters of the SFSCC. In addition, they have some limitations. The bending test and the RPT involve samples of significant size, which makes them difficult to handle and a significant consumption of concrete for their production. DEWST needs adaptations that are difficult to execute so that the load is applied properly. The Barcelona test presents difficulties in measuring the circumferential perimeter (Simão, 2019). The test that presents the best results in this investigation is still the UTT; however, its performance involves a major disadvantage, which is the difficulty of execution. These factors make this topic a relevant field of research to be studied.

The fracture constitutes one of the primary contributors to concrete structural failure (Zhang, Wang, Gao, & Wang, 2023). Although crack propagation depends on the material and loading conditions, it is well established that three predominant behaviors exist: Mode I which

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involves tensile stress perpendicular to the plane of the crack, Mode II which involves shear stress acting parallel to the plane of the crack and perpendicular to the crack front, and Mode III which involves shear stress acting parallel to the plane of the crack and parallel to the crack front. Some factors make it difficult to study the fracture parameters for the FRC using known tests. One of these factors is the great tendency for fibers to disperse in the concrete matrix during molding (Molins et al., 2009). The sample molding process of most known tests consists of pouring concrete into the molds from a known guidance (Abrishambaf et al., 2013). With this methodology, the fibers tend to have a preferred orientation. However, significant orientation differences still remain. Furthermore, the quantity and positions of the fibers in the tested sample section are not the same for each sample from the same batch with the same type of concrete, causing a significant dispersion of the results (Abrishambaf et al., 2013; Lappa, 2007; Salehian, 2015). The dimensions of the samples to be tested are an important factor for carrying out the tests (size effect) (Bazant, 1999), which is valid for the SFSCC, because the orientation of the fibers can significantly influence the materials properties (Abrishambaf et al., 2013).

In this context, this paper presents a review of test methods for determining the fracture properties (Mode I) of FRC. The most relevant tests, as well as their particularities and important contributions from the literature for each test are presented.

2 Uniaxial Tensile Test (UTT)

The Uniaxial Tensile Test (UTT) involves applying a uniaxial tensile load to the specimen. However, when assessing the failure properties of plain concrete, this test is often avoided due to its challenging execution. Instead, indirect tests such as the Three- or Four-Point Bending test and the Splitting Test are commonly employed as they are simpler to conduct. Despite the inherent difficulties associated with the UTT, it can still be regarded as a robust testing method (Oliveira, 2010). This is because it tends to present more realistic results than the bending test, since in the first one, only the tensile effort is present in the tested cross-section (Soranakom & Mobasher, 2008). Consequently, it is acknowledged that the UTT is the most suitable method for evaluating the post-cracking mechanical behavior of structural Fiber-Reinforced Concrete (FRC) (Borges L. A., 2017).

The usual boundary conditions for sample under uniaxial tensile test are free rotation and fixed end. None of the boundary conditions can be classified as ideal (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007). The characteristics of these two approaches have important characteristics, as discussed in the literature (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007; Amin, Markic, Gilbert, & Kaufmann, 2018; Salehian, 2015; Zhou, 1988):

- The free-rotating configuration provides a lower tensile strength, a lower fracture energy, a smoother softening curve, and furthermore, after crack formation, a non-uniform strain distribution occurs. This results in a crack opening measurement that is not representative of the sample's actual behavior during testing.
- In fixed-end configuration tests, the strain distribution is uniform during most of the experiment (except during the steep part of the softening curve), the tensile strength is higher, and so is the fracture energy.

There is still no consensus in the literature about the best configuration for performing the UTT, because the main concern in considering the UTT as a pure mechanical test is the test settings that may interfere with the results (Salehian, 2015). When adopting a test methodology to characterize FRC, special care must be taken to ensure that the geometry of the cracked sections remains similar, otherwise the mechanical properties may differ due to the variation in the orientation of the fibers in relation to each other (Oliveira, 2010). For the test to be performed satisfactorily, care must be taken to ensure that the specimen is perfectly aligned in relation to the loading direction. The concrete sample must have an appropriate geometric shape, and in addition, the appropriate use of the acquisition system must be carried out to avoid bending, which can alter the test results (Hordijk, 1991).

As for the shape of the sample for the UTT, there are the dog bone with straight parts shape (Zhao, Xue, Zhang, Tian, & Li, 2019; Zhu, et al., 2019; Kwon, Nishiwaki, Kikuta, & Mihashi, 2014; Blazy, Drobiec, & Wolka, 2021), dog bone with curve shape (Amin, Markic, Gilbert, & Kaufmann, 2018; Van Vliet, 2000; Paegle & Fischer, 2013; Deluce & Vecchio, 2013), cylindrical shaped (RILEM TC 162-TDF, 2001; Cunha, 2010; De Smedt, Vandecruys, Vrijdaghs, Verstrynge, & Vandewalle, 2021; Mudadu et al., 2018), and prismatic shapes (Salehian, 2015; Zhou, 1988; Qing, Yu, & Forth, 2019). Another specimen of the dog bone type without curvatures in the section (dog bone with profile I shape), with rectangular ends and smaller width in the central region, was also used in which the tensile machine applies load through top and bottom flange of the sample (Islam, et al., 2014). One of the objectives of using the dog bone geometry is that the formation of cracks tends to occur in the region of smallest width of the sample (Van Vliet, 2000), so that the results tend to be more homogeneous. The dog bone

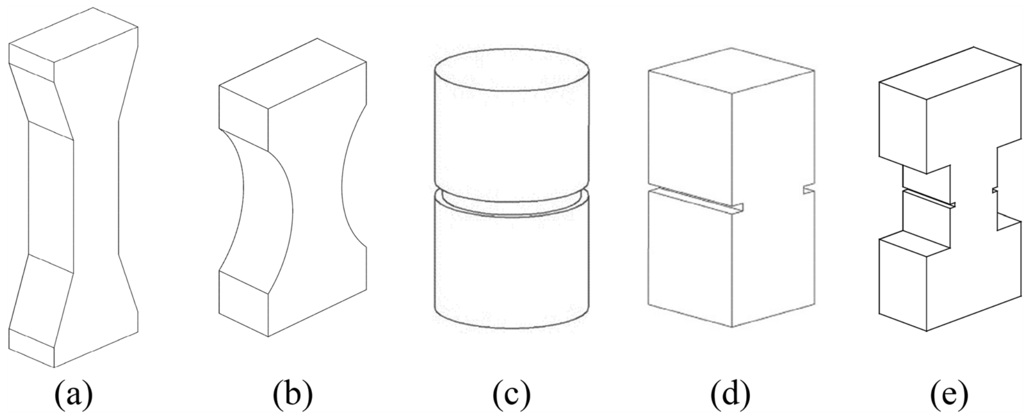

Fig. 1 Shapes of the usual samples for the UTT: **a** dog bone with straight parts shape, **b** dog bone with curve shape, **c** cylindrical-shaped, **d** prismatic shape, and **e** dog bone with profile I shape

with straight parts shape (Fig. 1a) is a common geometry and the sample has the same width in this region (Kwon, Nishiwaki, Kikuta, & Mihashi, 2014; Zhao, Xue, Zhang, Tian, & Li, 2019; Zhu, et al., 2019; Blazy, Drobiec, & Wolka, 2021). In the case of the dog bone with curve shape (Fig. 1b), the crack can occur in regions of different widths, which can make the behavior more complex (Van Vliet, 2000). The cylindrical shaped (Fig. 1c) is a standardized test by RILEM TC 162-TDF (RILEM TC 162-TDF, 2001). The dog bone with profile I shape is illustrated in Fig. 1e. In the prismatic sample test (Fig. 1d) and also in the case of a cylindrical sample, to ensure the transfer of load from the test equipment to the sample, the ends of the sample are glued to metallic supports, which are connected to adaptations for connection with the load equipment. In such cases, high-adhesion glue, like a high strength epoxy resin, should be used and the bonding surface should be sufficient to ensure that bonding fails. The sample surfaces must be carefully cleaned by applying solvent; in addition, after applying the glue, it is recommended to use a compression force before carrying out the tensile test (Cunha, 2010; Salehian, 2015). During the execution of the UTT test, it is possible that the glue fails and not the sample itself, which invalidates the test. Therefore, the method of bonding the fasteners to the sample to be tested also significantly influences the results. An experimental investigation was carried out on a micro and macro scale of the SFSCC with different types of fibers (Cunha, 2010). The work involved carrying out the UTT test with cylinders and highlighted the importance of care to be taken when fixing using high-resistance epoxy glue (so that its cure does not harm the geometry of the sample) and the need for the crack to occur from the notch.

The stress–crack opening curve of the UTT (Fig. 2) is an approximation of the softening behavior, the characteristic values for the post-cracking behavior are obtained and the area under the curve represents the fracture energy (Fig. 2) (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007). The supports of the specimen of the UTT to the tensile equipment must be carried out with due care ensuring rotational rigidity (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007; Salehian, 2015; Cunha, 2010).

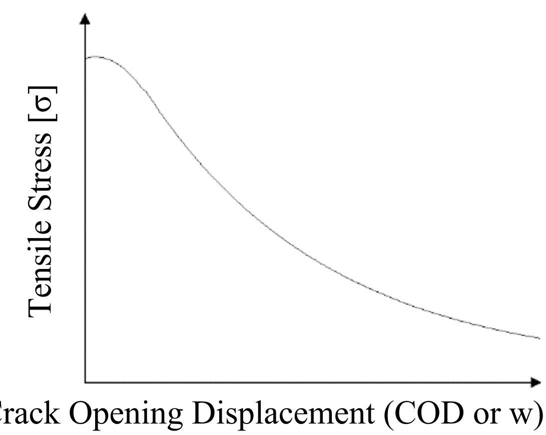

Fig. 2 Typical UTT stress–crack opening curve

A direct method for determining the tensile behavior of SFRC through the formulation of a constitutive model with the purpose of carrying out structural design was proposed (Oliveira, 2010). The main relevance of the work is the identification of the real stress curve—opening of cracks involving high strength and self-compacting concrete with different types and fiber contents, presenting contributions in the orientation parameters and fiber pullout. The Aligned Steel Fiber-Reinforced Cementitious Composites (ASFRC) were investigated using a uniform magnetic field, and the effect on the alignment of steel fibers was examined using an X-ray system and SFRC (Qing, Yu, & Forth, 2019).

The direct tensile test is the one that most realistically determines the tensile strength of an SFRC sample. As the other tests that will be presented below determine this parameter indirectly, the responses from these tests are different. Therefore, it is important to emphasize that, for the purpose of comparing these different tests, it is interesting that the results are taken as a reference for the UTT.

Table 1 shows the main contributions in each type of UTT.

3 Bending Tests

The bending tests are carried out on a specimen in a prismatic geometry that is supported by two supports. A machine applies load to the upper part of the sample according to two possibilities, characterizing the Three- or Four-Point Bending Test (3PBT or 4PBT) (Fig. 3a, b).

This type of test is widely used to indirectly obtain the tensile strength and to evaluate the cracking properties of the FRC (Salehian, 2015; Lameiras R. d., 2016; Cardoso, Lameiras, & Capuzzo, 2021; Toledo Filho, 2001; Medina, 2019; Trindade, Bitencourt Jr, Monte, Figueiredo, & Manzoli, 2020; Malvar & Warren, 1988). An important feature of this test is its simplicity, which is common in indirect tensile tests. The main drawback, however, is the need to employ a relatively complex behavior deduction, which is the inverse analysis procedure for test validation (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007; Carvalho & Lameiras, 2023a). In addition, the sample size makes it difficult to handle during the test and the test results exhibit significant dispersion.

During the bending tests, there are two possible combinations of parameters for monitoring that are used: monitoring the load (*F*) with the displacement (also called deflection, δ) or monitoring the load with the Crack Mouth Opening Displacement (CMOD). Therefore, the use of clip gages (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007) or LVDTs (Linear Variable Differential Transducer) are usual for the CMOD monitoring (Fig. 3c-f). One LVDT can be used on the bottom edge of the beam for both LVDT (Frazão C., 2019) and clip gage (EN, 14651, 2007). But a common methodology in research is to use two LVDTs, each of which is positioned on one side of the sample, parallel to the sample direction (Salehian, 2015; Cardoso, Lameiras, & Capuzzo, 2021; Lameiras, Barros, & Azenha, 2015). In this methodology, the CMOD is obtained directly from the monitoring. The LVDTs can also be positioned to measure deflection vertically (RILEM TC 162-TDF, 2001; Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007; Nour et al., 2015; American Society for Testing and Materials, 2007). In these cases, a correlation equation of these parameters can be used to obtain the CMOD.

In the 3PBT, the intermediate region presents the highest bending moment and the distribution of this

Table 1 Main contributions on the UTT

Reference	Main contribution
Planas et al. (2007)	Establishes recommendations and minimum requirements for proper performance of the UTT
Oliveira (2010)	Proposes a direct and simple constitutive model to obtain the tensile behavior of FRC considering fiber orientation and the specific combination of matrix and fiber properties
Cunha (2010)	Numerical simulation of the UTT with investigation at the micro and macro scale
Salehian (2015)	Performs UTT on prismatic cores obtained from 3PBT samples and develops formulation for inverse analysis to the SFRSCC post-cracking behavior
Amin et al. (2018)	SFRC dog bone specimens are tested with the boundary conditions: fixed–fixed, fixed–rotating, and rotating–rotating
Quing et al. (2019)	Investigated the Aligned Steel Fiber-Reinforced Cementitious Composites (ASFRC) using a uniform magnetic field and the effect on the alignment of steel fibers was examined using an X-ray system and the SFRC
Kwon et al. (2014), Zhao et al. (2019), Zhu et al. (2019), Blazy et al. (2021)	Investigated the UTT for dog bone with straight parts shape
Van Vliet et al. (2000), Paegle et al. (2013), Deluce et al. (2013), Amin et al. (2018)	Investigated the UTT for dog bone with curve shape sample geometry
RILEM TC 162-TDF, Cunha et al. (2010), Mudadu et al. (2018), De Smedt et al. (2021)	Investigated the UTT with cylindrical-shaped sample geometry
Zhou et al. (1988), Salehian (2015), Qing et al. (2019)	Investigated the UTT for prismatic shapes sample geometry
Islam et al. (2014)	Investigated the UTT for dog bone with profile I shape

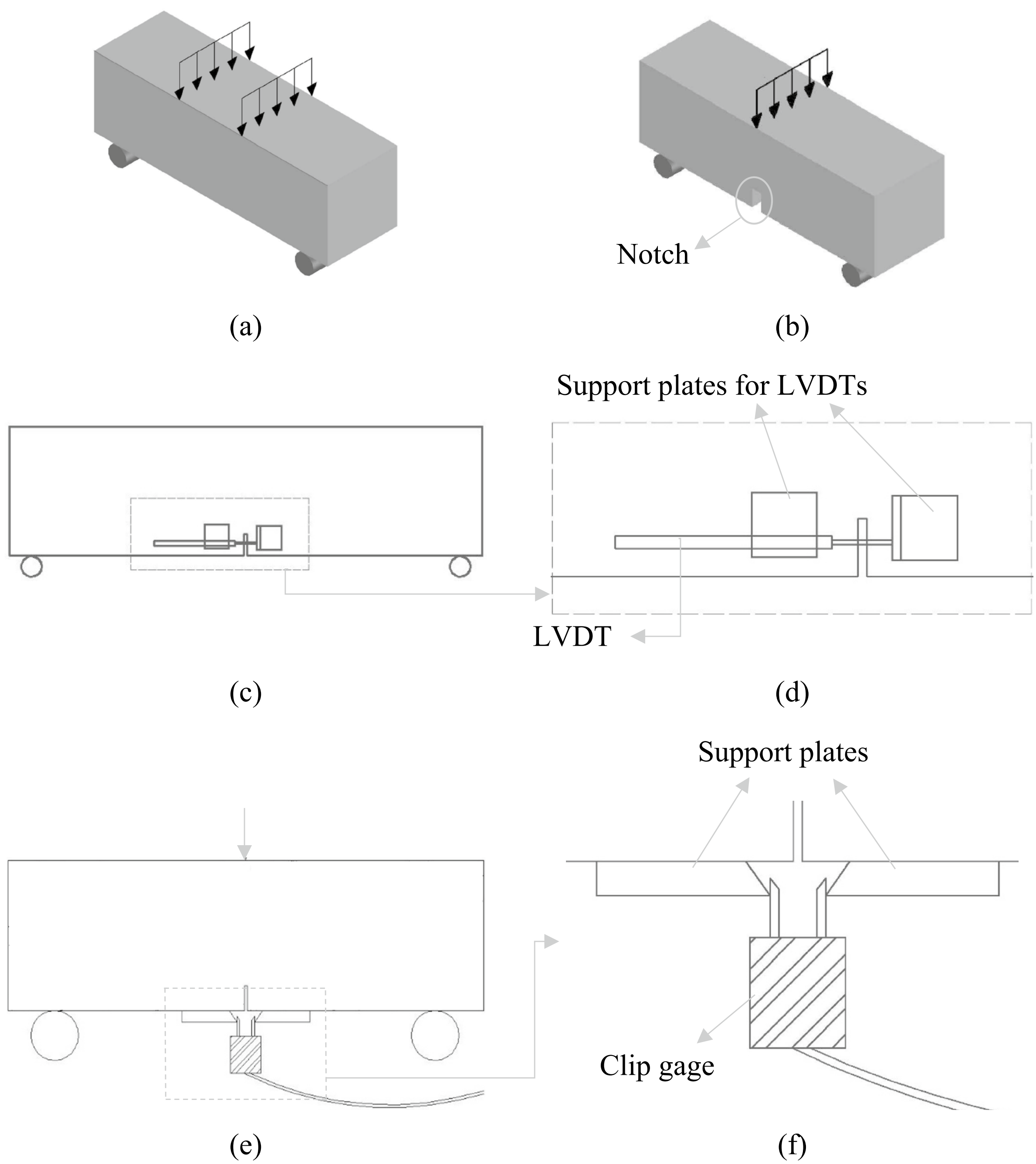

Fig. 3 Bending Tests: **a** Four-Point Bending Test (4PBT) or (**b**) Three-Point Bending Test (3PBT) highlighting the notch in the middle of the span, **c** sample side view with LVDT and (**d**) view of LVDT with backing plates, **e** sample side view with clip gage and (**f**) view of clip gage

moment is influenced by the loading, which occurs in a wedge shape; thus, the positioning of the notch promotes the appearance of a single mid-span crack, which allows analysis of the post-cracking behavior of the FRC in a single cross-section (Salehian, 2015). In addition, the notch promotes a reduction in the dispersion of the results obtained (Medina, 2019). In the 4PBT, there is a region subjected to pure bending (between loads), in which the formation of several cracks can occur. The use of 3PBT and 4PBT for analytical purposes in structural projects is questioned due to the dispersion of results and the differences between cracking mechanisms in tests at material and structural levels (Conforti et al., 2017; Destrée & Mandl, 2008; Medina, 2019; Medina, 2019; Minelli & Plizzari, 2009, 2011).

Despite consisting of a more simplified approach than the UTT test, bending tests have a number of limitations such as the dependence on performing an inverse analysis to determine the stress diagram and crack opening (Medina, 2019). If this analysis is not performed, there is a significant demand for time in the characterization performed only by the test, which is due to the variability of the mechanical properties of the FRC (Trindade, Bitencourt Jr, Monte, Figueiredo, & Manzoli, 2020), and also the composite can present a behavior that is not the real one of the structures (Lameiras, Barros, & Azenha, 2015).

During the performance of the bending test, the load and the crack opening monitored from the notch, also referred as CMOD, are monitored and the resistance to cracking is obtained (f_{cr}). To carry out the test, a transducer is used at the base of the sample, in the region where the notch is located. For carrying out the bending test, it is important that the CMOD measurement can be performed using clip gages or knife gages and it may have plates screwed and fixed to the lower surface of the sample (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007).

Table 2 shows the codes that are highlighted for 4PBT (JSCE, 1984; ASTM C1018-89, 1991; CNR-DT 204, 2006; ACI 544.1R-96, 1996), and for 3PBT (EN, 14651, 2007; fib Model Code 2010, 2012). In 2006, the new standard ASTM 1609 (2012) (ASTM C, 1609, 2012) can begin to be used as an alternative to ASTM C1018-89 (1991), evaluating the flexural performance of FRC using parameters derived from the load–deflection curve (Hamad & Sldozian, 2019).

4 Wedge Splitting Test (WST)

The Wedge Splitting Test (WST) developed by Tschegg (Patent No. 390328, 1986; Tschegg E., 1991) is a test that was developed based on the principle of applying a compressive load to a sample and resulting in the opening of cracks, in a similar way to what occurs in the ST. Experiments were conducted on Steel Fiber-Reinforced Concrete, employing diverse mix proportions and fiber geometries, as well as non-linear fracture mechanics analyses (Löfgren, 2004). The crack width is monitored during the test and the fracture energy of the concrete is determined, similarly to 3PBT and ST. It has been proven that large samples are not required for this test (Abdalla & Karihaloo, 2003). The true specific fracture energy (G_f) of a concrete mix can be determined by testing just a few number of specimens (Karihaloo et al., 2003). The WST can be performed in cylindrical formats (Bruhwiler & Wittman, 1990), but the prismatic format is the most common. The sample is notched and has a rectangular region hollowed out at the top under which the positioning of plates coupled to rollers takes place. During the test, the wedge support moves over the rollers resulting in a tensile force component in the crack opening direction in the notch. An illustration of the WST is presented in Fig. 4.

An inverse analysis procedure based on the analytical hinge model for various multi-linear softening curves is proposed (Skoček & Stang, 2008). A quad-linear curve is used and the results obtained semi-analytically are verified through FEM simulations. The fracture properties of SFRC (Steel Fiber-Reinforced Concrete) were investigated using the WST with different specimen sizes and mix proportions, including various types and contents of fibers (Löfgren et al., 2005) (Table 3).

Table 2 References that address contributions on the 3PBT

References	Main contribution
RILEM TC 162-TDF (2002), EN 14651 (2005) e *fib* Model Code (2012)	Standardized method for 3PBT
JSCE-SF4 (1984), ASTM C1018-89 (1991), CNR-DT 204 and ACI 544.1R-96 (1996)	Standardized method for 4PBT
Minnelli et al. (2011), Conforti et al. (2017) and Medina (2019)	They found that the dispersion of 3PBT is greater than other tests such as panel tests
Planas et al. (2007)	Recommendations for geometry and molding criteria for samples and test setup
Salehian (2015)	inverse analysis for 3PBT with plastic hinge model
Nour et al. (2015)	inverse analysis for 3PBT with procedure based on data fitting algorithm
Carvalho et al. (2023)	Developed a more rational analytical and progressive method for performing the inverse analysis procedure
Lameiras (2016)	Developed a rational numerical and progressive method for performing the inverse analysis procedure
Conforti et al	Design parameters of residual resistances from Model code 2010 (fib Model Code 2010, 2012) can be estimated from ASTM 1609 and JCI-SF4 tests with similar coefficient of variation

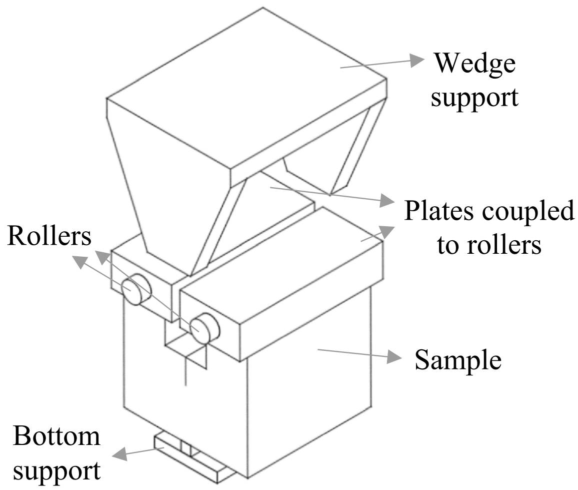

Fig. 4 Sample test setup for Wedge Splitting Test

5 Double Punch Test (DPT) and Barcelona Test (BT)

The Double Punch Test (DPT) was initially used to determine the tensile strength of concrete in cylindrical or cubic samples (Chen, 1970). Some advantages of DPT are: the sample has reduced dimensions, the test is relatively fast, and the fracture surface is considered relatively large, which reduces the dispersion of results (Molins et al., 2009). The DPT with a cube-shaped sample is used to present an efficient way to determine the orientation of fibers in a model that can be used at full scale (Pujadas P., Blanco, Cavalaro, de la Fuente, & Aguado, 2014). For this type of sample, the inverse analysis procedure was also performed (Karrer, et al., 2022). This test is called Multidirectional Double Punch Test (MDPT). An empirical study (Molins et al., 2009) was conducted involving the implementation of both DPT and bending tests on FRC specimens featuring various fiber types, concrete kinds, and fiber volume proportions. A proposed correlation between these two testing methodologies is delineated. The practical application of this correlation to FRC specimens reinforced with steel and polyolefin fibers yields highly promising outcomes. The Barcelona Test (BT) is an extension of the DPT and enhances the establishment of representative figures for the residual tensile strength and toughness of the material, with an average coefficient of variation that falls below 13% (Pujadas P., Blanco, Cavalaro, de la Fuente, & Aguado, 2014). It has been used in other applications, such as quality control of the concrete in segments for lining the subway line (Molins et al., 2009). The test method consists of compressing a cylindrical sample to cause tensile stresses. The application of load is carried out through two steel punches disc shaped at the top and bottom of the sample, so that the alignment between both coincides with the position of the sample axis. The Total Circumferential Opening Displacement (TCOD) in the perimeter direction of the sample and vertical displacement between loading plates were measured. An illustration of the sample is shown in

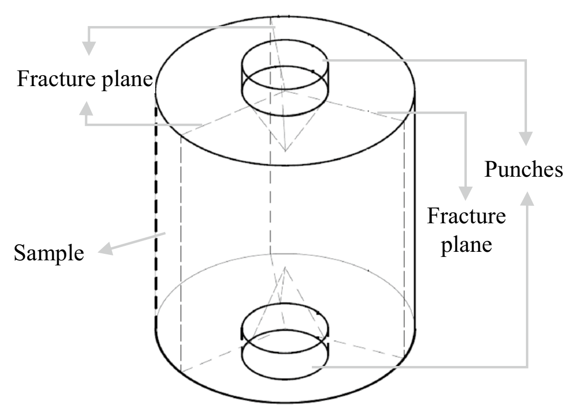

Fig. 5 Barcelona Test sample illustration with crack lines

Table 3 Main contributions to WST

Reference	Main contribution
Tschegg (1986)	Initial conception for the WST
Bruhwiler et al. (1990)	WST is carried out with cylindrical shape
Abdalla et al. (2003)	The specific fracture energy is determined by WST comparing with 3PBT
Karihaloo et al. (2003)	Found that the so-called true specific fracture energy can be determined by testing just a few samples
Löfgren (2004)	Conducted experiments for the WST (Wedge Splitting Test) for the FRC (Fiber-Reinforced Concrete), considering variations in mix proportions and fiber geometries, as well as non-linear fracture mechanics analyses
Skoček et al. (2008) and Löfgren et al. (2005)	Proposed an inverse analysis for WST

Fig. 5. The solid lines represent the sample and punches. The dashed lines on fracture plane directions represent the crack lines. The other represents the hidden part of the punches and of the sample.

The BT has demonstrated its high suitability for the evaluation of the tensile properties of FRC, but the requirement to measure the TCOD of the specimen necessitates the use of a costly circumferential extensometer (Pujadas P., Blanco, Cavalaro, Fuente, & Aguado, 2013). Therefore, an extensive experimental program is undertaken to determine relationships between circumferential and axial displacement (Malatesta et al., 2012). The results of these authors suggest the possibility of using axial displacement instead of circumferential displacement, bringing more simplicity to the test. In this same line of work, a new analytical model to convert the displacement into the TCOD is developed and validated for a wide range of FRC (Pujadas P., Blanco, Cavalaro, Fuente, & Aguado, 2013).

It has been demonstrated that it is possible to predict the 3PBT based on BT with a confidence margin, despite the wide variety of fiber type, fiber content, and rheology considered (Galeote et al., 2017) (Table 4).

6 Splitting Test (ST)

Initially, the Brazilian Test was used to determine the characteristic tensile parameters (first crack and ultimate strengths, as well as toughness indexes) of FRC (Nanni, 1988). As already shown, the use of UTT has important disadvantages, especially the difficulty of carrying out them. Indirect tests, such as the 3PBT, require the inverse analysis procedure to determine the tensile behavior. With a view to overcome these difficulties, the test known as the Brazilian Test or Splitting Tensile Test (STT), or simply Splitting Test (ST) (Carmona & Aguado, 2012; Ozyurt et al., 2007) (Fig. 6a, b) is performed. This test is similar to the diametral compression test used in plain concrete, the so-called Brazilian Test, which is used to determine the characteristic tensile parameters (first crack and ultimate strengths, as well as toughness indexes) of FRC. However, the ST is aimed at the FRC, being indicated for investigating its post-cracking behavior, while the diametral compression test is indicated only for determining the tensile strength of plain concrete.

The ST can be considered simple, in addition to the fact that cores can be extracted from slabs or beams through concrete core drilling (Lameiras, Barros, & Azenha, 2015). The testing carrying out occurs in such a way that a cylindrical sample in FRC is compressed in the diametrical direction and the stresses propagate in such a way that in the direction perpendicular to the plane of compression, a tensile stress occurs. In this direction, the Crack Opening Displacement (COD) is monitored as a function of the applied load by the test machine and the tensile behavior is studied. In the case of non-homogenization of concrete, the tensile stress field results in a cracking surface that is hardly uniform, so the accuracy of the tensile behavior of these cement-based materials through the crack test is questionable (Salehian, 2015).

Based on ST, the Modified Splitting Tensile Test (MSTT) was proposed (Abrishambaf et al., 2013). In this test, a notch is introduced into the sample (Fig. 6c–d), at the intersection between its faces and the loading plane, with the aim of inducing the formation and propagation of cracks in the region of the notch. σ-w relations with numerical simulations (inverse analysis) were obtained for ST (Abrishambaf et al., 2015).

Based on DEWST and the shape of the MSTT sample, another test (Fig. 6e, f) was proposed (Lameiras, Barros, & Azenha, 2015). This test has a new cylindrical sample format with a notch similar to that present in the MSTT sample and also with the wedge-shaped adaptation of the DEWST. The purpose of introducing the new shape is to promote stress redistribution and make the intermediate section of the sample subject only to tensile stresses, overcoming the shortcomings of DEWST and MSTT by inducing even more crack formation in the compression plane and also single crack formation (Table 5).

Table 4 Main contributions to DPT and BT

Reference	Main contribution
Chen (1970)	Development of DPT to determine the tensile strength of concrete
Molins et al. (2009)	Proposed a correlation between DPT results and Bending Tests for the FRC
Malatesta et al. (2012)	Determined relationships between circumferential and axial displacement based on experimental results
Pujadas et al. (2013)	Proposed analytical model to convert the displacement into the TCOD and validated for a wide range of FRC
Pujadas et al. (2014)	The cube-shaped sample is used to present an efficient way to determine the orientation of fibers
Galeote et al. (2017)	Determines a correlation between BT and 3PBT
Karrer et al. (2022)	Perform inverse analysis procedure from the results of DPT conducted on cubes

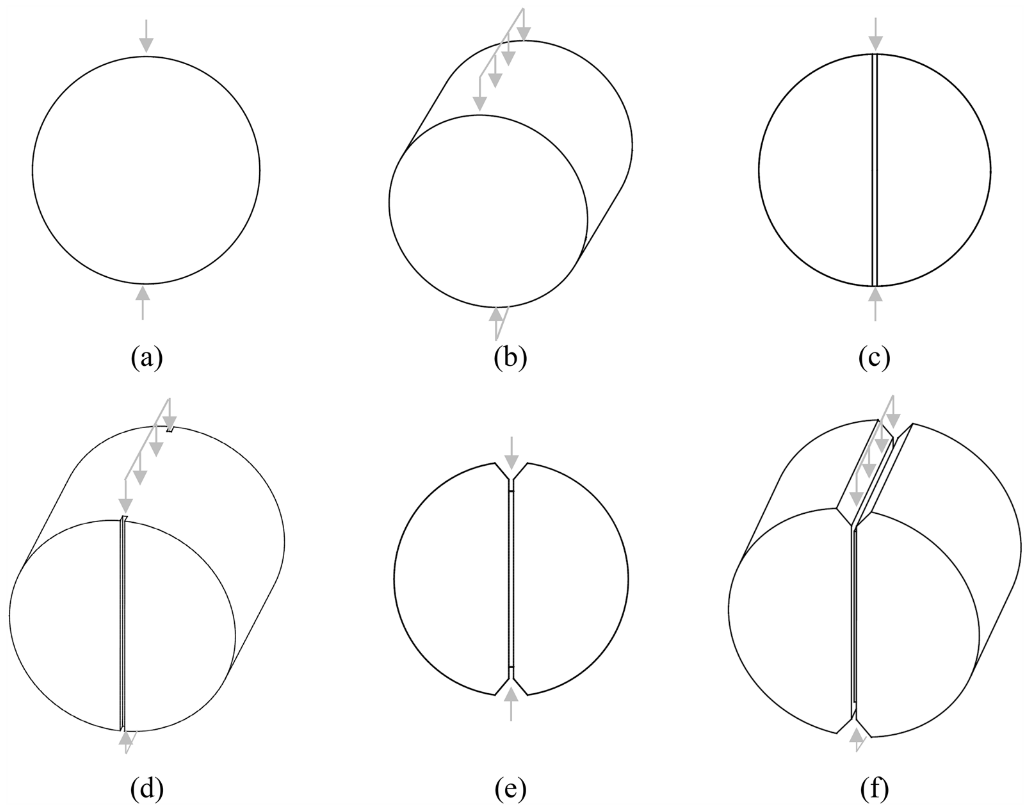

Fig. 6 Sample formats for the ST (front view and three-dimensional perspective, arrows represent the loading orientation during testing): **a** and **b** traditional test without notch (Carmona & Aguado, 2012; Ozyurt et al., 2007), **c** and **d** MSTT (Abrishambaf et al., 2013), and **e** and **f** test proposed with V-notches (Lameiras, Barros, & Azenha, 2015)

Table 5 Main contributions to ST

Reference	Main contribution
Nanni (1988)	Used the test to determine the characteristic tensile parameters (first crack and ultimate strengths, as well as toughness indexes) of FRC
Ozyurt et al. (2007) and Carmona et al. (2012)	Proposed an adaptation of the Brazilian Test to evaluate the post-cracking behavior of FRC
Abrishambaf et al. (2013)	Studied ST sample with straight notches in the plane of crack propagation
Abrishambaf et al. (2015)	Obtained σ–w relations with numerical simulations (inverse analysis) of the ST
Lameiras et al. (2015)	Studied ST sample with straight notches in the plane of crack propagation and with V-notch

7 Round Panel Test (RPT)

The Panel Tests are experimental indirect approach considered very effective for determining the mechanical properties of concrete, special in relation to the use of fiber reinforcement (Rambo, 2012). There are three different approaches for this test. A Square Panel Test (SPT) with a square panel sample and simple support was proposed by a standard (EFNARC, 2002). This test is performed with a square loading platen and a leaked square support (Fig. 7a). A disk-shaped sample was employed by other authors since the 2000s (Bernard, 2000; Mobasher & Destreé, 2010). In this approach, the supports are also simple and are positioned close to the edge of the sample (Fig. 7b). The test with this sample geometry has been called the RPT. The ASTM C 1550–05 (ASTM C1550-05, 2005) standard suggests different supports for the RPT. To carry out the test, the sample consists of a disc-shaped plate with a diameter of 800 mm and a thickness of 75 mm which is supported on three pivots positioned at the ends of the disk, forming a 120° inclination (Fig. 7c)

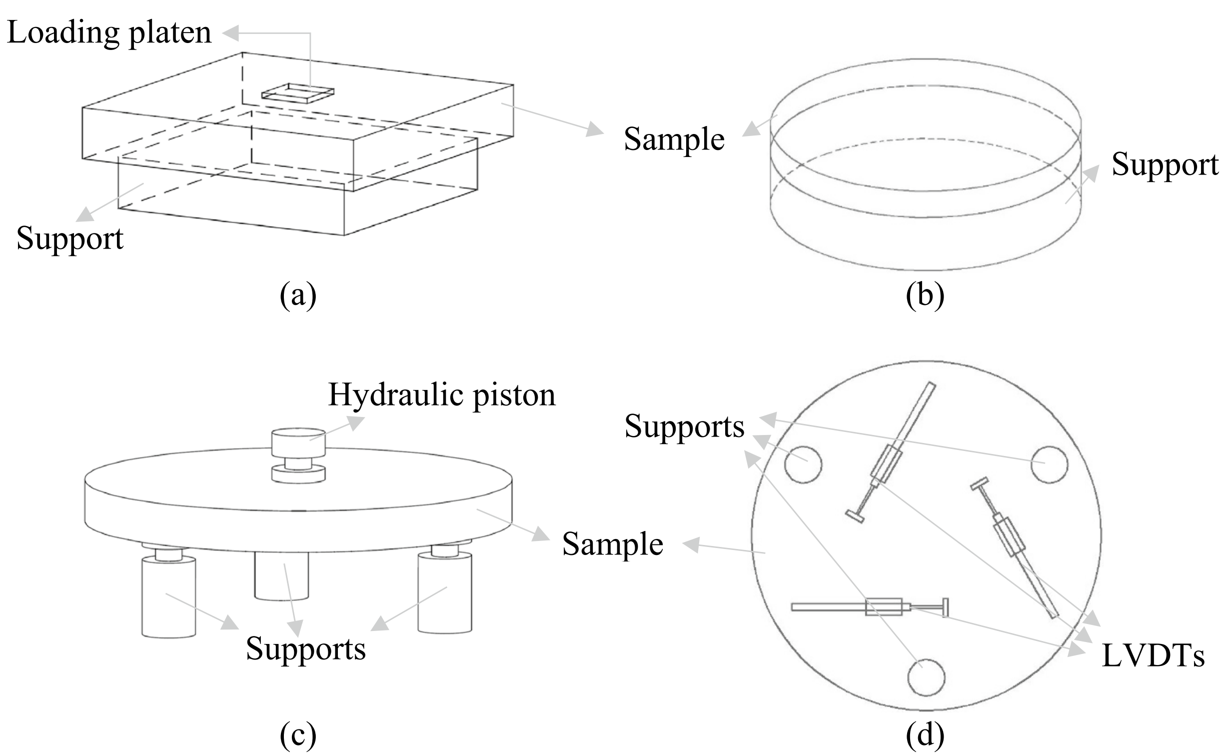

Fig. 7 Illustration of the samples of: **a** SPT, **b** RPT with simple support (RPT-WSS), **c** RPT with three pivots (RPT-WTP), and (**d**) bottom view of RPT-WTP with LVDTs

and subjected to static load, with this load and deflection being monitored. The result of a test is a load–deflection record indicating resistance to load between the onset of loading and a central deflection of at least 40 mm (ASTM C1550-05, 2005). Some authors (Medina, 2019; Minelli & Plizzari, 2010a; Frazão, Barros, & Bogas, 2021; Frazão, Barros, & Bogas, 2019) perform this test by monitoring the load and width of the three developed cracks in the fracture plane that occurs between the pivots and the center of the sample by positioning three LVDTs (Fig. 7d); however, this makes the test more complex. This approach has the advantage of determining fracture energy more accurately because this parameter is related to crack opening and not to deflection.

The load and displacement are monitored on the SPT and on the RPT with simple support (RPT-WSS). The RPT with three pivots (RPT-WTP) is the most used proposal. In this case, the load is applied in the center of the disc, thus causing three regions of cracking, which total a larger cracked region than in the case of other tests used to evaluate the behavior of the SFRC, making it possible to determine the predominant orientation of the fibers and that the material can best be treated as a homogeneous and isotropic material (di Prisco et al., 2009). The load and Crack Mouth Opening Displacement (CMOD) are monitored. The CMOD is monitored through three LVDTs positioned at the bottom of the sample in the region where cracks are expected to occur. During the test, the energy absorbed by the sample is evaluated based on the deflection of the central region. Sample performance is evaluated based on the energy absorbed when loading the plate with selected values of center deflection. However, this characteristic makes it difficult to compare the results of other tests for the same concrete considering the different geometries of the samples in the different types of tests. Therefore, an inverse analysis procedure may be necessary. This procedure was carried out applying the plastic hinge model (Salehian, 2015) and also with the data fitting algorithm procedure (Nour et al., 2015).

The main disadvantage of the test is that the specimen itself is too large and heavy to be handled easily and is not sized for many commonly used testing machines. Due to the difficulties in carrying out the test, especially that of mobilizing samples with significant weight, a sample of reduced dimensions was proposed (Minelli & Plizzari, 2010a, 2010b) for the RPT: 600 mm in diameter, 60 mm thick, weighing 40 kg. One advantage is the reduced weight of the samples, which now have a more suitable size for the use of a test machine and more reliable results

(Minelli & Plizzari, 2015). This new test is known as Small Round Determinate Panel (SRDP). In addition, the most recent works on this test show a great advantage, which is the low dispersion of the results. Despite this, SFRC samples with larger fracture areas demonstrate diminished dispersion (Sorelli et al., 2005). This is due to the fact that the crack's surface area is much larger than in other tests, which reduces the major problem of tests for characterizing the post-cracking behavior of concrete with fibers, which is the high dispersion of the results. Table 6 shows papers that address contributions on this test.

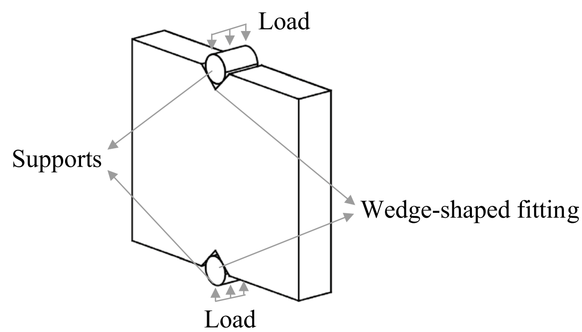

Fig. 8 Sample illustration for performing the DEWST

8 DEWST (Double Edge Wedge Splitting Test)

DEWST can be defined as a typical indirect tensile test in which a prismatic specimen with wedge-shaped openings on two opposite faces receives a compressive load (Agra, Serafini, Figueiredo, & Berto, 2019). The test was first proposed by di Prisco et al. (di Prisco, Lamperti, & Lapolla, 2010). The wedge-shaped fitting is made on surfaces with a 45° inclination to the faces. The faces that present wedges correspond to the region where the load is applied (Fig. 8). This adaptation promotes redistribution of efforts and makes the intermediate section subject only to tensile stresses, which in this way makes the measured resistance approach a value that would be obtained if a UTT were performed (Pereira, Monte, Bitencourt Júnior, & Figueiredo, 2019).

As shown in Fig. 8, the load is applied in the direction of the line that intersects wedges. LVDTs are placed on major faces to measure COD in the direction perpendicular to the applied load. In addition, the force applied during the test is monitored. The wedge-shaped adaptation can be performed by means of fixing metallic plates to minimize the friction between the roller of the equipment that applies load and the tested sample. The initial proposal of the DEWST consists of using six transducers, three positioned on one of the faces of the sample and the other three on the opposite face. (di Prisco, Lamperti, & Lapolla, 2010; di Prisco et al., 2013). Another test proposal consisted of an simplification using only two transducers, one positioned on each side of the sample, positioned at the middle height (Borges et al., 2019). According to the authors, this is justified in situations of low fiber content and a softening behavior because both sides of the specimens work as rigid bodies after cracking.

The DEWST was validated using non-linear finite element analysis (di Prisco et al., 2013). The authors conclude that the test does not require the inverse analysis procedure to be carried out because, despite being an indirect test, its results represent well the behavior of tensile stress versus crack opening "'constitutive relationship'" of the material.

An important advantage of DEWST is that it can be used as a less difficult execution alternative in relation to UTT, this is because it prevents the compressive stresses from becoming highly localized, consisting of a compression test that simulates a tensile behavior in the sample middle section (di Prisco, Lamperti, & Lapolla, 2010). However, making cuts to form the wedge region is not simple (Pereira, Monte, Bitencourt Júnior, & Figueiredo,

Table 6 Main contributions on the RPT and SRDP tests

Reference	Main contribution
Bernard (2000)	RPT trial studies highlighting single supports
ASTM C1550-05	Standardization of panels with a diameter of 800 mm
EFNARC, 2002	Square Panel Test (SPT) standardization
Solleri et al. (2005)	It found that SFRC samples with a larger fracture area show less dispersion
Minelli and Plizzari (2010a) and Minelli and Plizzari (2010b)	Use of panels with a diameter of 600 mm with less weight and dispersion of results
Soltanzadeh et al. (2019)	The authors (Soltanzadeh, et al., 2019) tested smaller samples similar to Minelli and Plizzari (2010a and 2010b) and estimated the post-cracking response of SFRSCC using numerical approaches
Minelli e Plizzari (2015)	Proposed an analytical methodology to determine the stress relationship with crack opening
Nour et al. (2015) and Salehian (2015)	Performed inverse analysis for the RPT

2019). Adaptations in the molding process were tested so that the mold itself contemplates the V-shaped notches (Monte, Pereira, Figueiredo, Blanco, & Bitencourt Júnior, 2023). According to the authors, this process simplified the test because it no longer requires complex cuts for the proper geometry of these notches. The authors also conclude that the axial deflection can be monitored and used for the composition of the test results instead of using transducers. This further simplifies testing.

The test shows the possibility of characterizing concrete reinforced with steel fibers, allowing to determine the residual tensile strength, including associating it with different levels of cracking of the composite (Agra, Serafini, Figueiredo, & Berto, 2019). It has been shown that employing DEWS to characterize the post-crack tensile properties of SFRC after exposure to elevated temperatures reduces variability and aids in result interpretation by minimizing frictional interaction between the apparatus and the specimen (Serafini, Agra, Salvador, de la Fuente, & Figueiredo, 2021).

A comparison of 3PBT with DEWST in samples of high-performance FRC was made (di Prisco et al., 2013) and found that in addition to DEWST allowing the investigation of tensile behavior both pre-peak and post-peak, the test proved to be a very reliable indirect test (Table 7).

9 Semicircular Bending Test (SCBT) and Modified Semicircular Bending Test (MSCBT)

A recent test proposal was to evaluate the FRC post-cracking parameters performing the bending procedure in samples with semicircular shape. This test is called Semicircular Bending Test (SCBT). It is similar to 3PBT, but the sample is semicircular in shape (Fig. 9).

This test approach has been studied relatively commonly for rocky materials (Lim, Johnston, Choi, & Boland, 1994a; Aliha & Ayatollahi, 2011; Kuruppu et al., 2014; Lim et al., 1994b) with the aim of investigating fracture-related properties of this material. Other different materials were also studied through this test: synthetic polymers (Ayatollahi et al., 2006), asphalt concrete (Arabani & Ferdowsi, 2008), a manufactured mixture from asphalt concrete and Portland cement concrete (Mirsayar et al., 2017), reactive powder concrete (RPC) (Su et al., 2019). For the FRC, a study was carried out with force-CMOD monitoring and involving a geometric modification of the SCBT (Carvalho & Lameiras, 2023b), the so-called MSCBT. Initially, a computational tool for performing the inverse analysis procedure usually used for the 3PBT is employed for experimental MSCBT results (Carvalho & Lameiras, 2023b). The SCBT was also applied to Fiber-Reinforced High-Strength Concrete (FRHSC) (Aziminezhad, Mardi, Hajikarimi, Nejad, &

Table 7 Main contributions on the DEWST

Reference	Main contribution
di Prisco et al. (2010)	First proposal for DEWST
di Prisco et al. (2013)	Demonstrated the reliability of DEWST compared to 3PBT with inverse analysis
Agra et al. (2019)	Evaluated the effects of fire on the residual tensile strength of Steel Fiber-Reinforced Concrete using the DEWST
Borges et al. (2019)	Use of only two transducers for DEWST
Serafini et al. (2021)	Used the DEWST to characterize the design post-cracking parameters of Fiber-Reinforced Concrete subjected to high temperatures
Monte et al. (2023)	Use shaped molds contemplating the V-shaped notches so as to not need complex cuts in the test. They conclude the possibility of performing tests with monitoring of axial deflection instead of using transducers

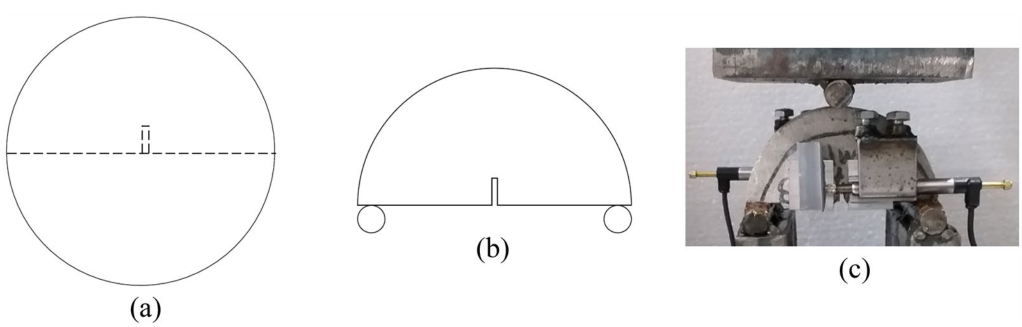

Fig. 9 Illustration of the cores extracted for the SCBT test: **a** Cylinder after extraction and with the hatched line representing the cut to obtain a semicircular sample, **b** SCBT sample after notch cutting with supports, and **c** illustration of SCBT setup

Gandomi, 2020). Different fibers were used (glass, polypropylene, and steel). The fracture parameters are studied using finite element software for the SCBT (Hosseini, Hajikarimi, Hosseini, Aliakbari, & Nejad, 2023). However, in these two works (Aziminezhad, Mardi, Hajikarimi, Nejad, & Gandomi, 2020; Hosseini, Hajikarimi, Hosseini, Aliakbari, & Nejad, 2023), the authors performed the monitoring only in force–displacement and not in force–CMOD.

The SCBT has shown important advantages. The test is carried out with the sample submitted to bending in a similar way to the 3PBT. This procedure is considered simple and fast (Carvalho & Lameiras, 2023b; Aziminezhad, Mardi, Hajikarimi, Nejad, & Gandomi, 2020; Molenaar, Scarpas, Liu, & Erkens, 2002) because it does not require as much care with alignment and proper load distribution as in the case of the UTT. The SCBT samples have reduced dimensions, which greatly facilitates handling, speeds up the execution of the test, and facilitates the storage of the samples, occupying less space in the laboratory. 3PBT, RPT, and UTT samples are generally larger. Another important advantage of this test is that samples can be extracted from larger structures using concrete core cutting machine. This contributes to real structures because with this advantage, it is possible to evaluate the real behavior of the structure by performing tests on a structural specimen (Table 8).

10 Other Tests

The test called Montevideo (MVD) was proposed (Segura-Castillo et al., 2018) based on tests: BT, DEWST, and mainly on WST. The main advantage of this test is its simplification compared to WST. The loading device is simpler, consisting of a solid wedge. In addition, the sample only has a simple notch, avoiding the need to perform the more complex groove and notch cuts for sample preparation, as in the case of the WST. Another modification to WST (MWST) is proposed (Neuner, Smaniotto, & Hofstetter, 2022). There is also no traditional WST slot in this approach and the wedge is similar to traditional WST. Interconnected claws are used to affix the testing apparatus. This configuration is inserted directly into the initial notch of the sample. Through the claws, the force of division is immediately conveyed into the sample via the adjacent facets of the initial notch. In addition, a prestressing system employing steel cables positioned at the anterior and posterior facets enables the application of minor compressive pre-stressing on the sample, aiming to enhance the behavior of crack propagation during the test (Fig. 10) (Table 9).

11 Inverse Analysis

The inverse analysis methodologies transform a load–deflection or load–CMOD reaction into a stress–crack width relationship (Montaignac et al., 2012). The closed-form solutions are used to avoid the inverse analysis procedure. They are the analytical and direct solutions for determining the properties and behavior of FRC. These solutions are expressed with mathematic equations that can be solved directly, without the need for iterations or numerical. Closed-form solutions were used to generate moment–curvature diagrams for FRC through 3PBT and 4PBT (Soranakom & Mobasher, 2007). The model provides the underestimated uniaxial tensile response in relation to the flexural response. The curvature distribution along a beam was integrated up to the mid-span, resulting in closed-form solutions for the mid-span deflections during the 3PBT and 4PBT. For the authors, the 4PBT is more comparable to the UTT than the 3PBT.

The inverse analysis methodology for FRC can be pursued via two distinct approaches (Carvalho & Lameiras, 2023b): analytical and numerical. Within the numerical approach, essential input data encompassing geometric boundary conditions and material behavior laws are derived through numerical simulations. Nonetheless, this approach suffers from drawbacks, including the high

Table 8 Main contributions on the SCBT and MSCBT

Reference	Main contribution
Lim et al. (1994a); Lim et al. (1994b); Aliha & Ayatollahi (2011); Kuruppu et al. (2014)	The SCBT was studied for rocky materials
Ayatollahi et al. (2006)	The SCBT was studied for synthetic polymers
Arabani and Ferdowsi (2008),	The SCBT was studied for asphalt concrete
Mirsayar et al. (2017)	The SCBT was studied for a manufactured mixture from asphalt concrete and Portland cement concrete
Su et al. (2019)	SCBT was conducted on reactive powder concrete (RPC) to explore the fracture characteristics under Mode I
Aziminezhad et al. (2020)	SCBT applied for FRHSC with different fibers kind (glass, polypropylene, and steel)
Hosseini et al. (2023)	Fracture parameters are studied using finite element software for the SCBT
Carvalho and Lameiras (2023b)	Force–CMOD monitoring and geometric modification for SCBT (MSCBT). The inverse analysis procedure usually used for the 3PBT is employed for experimental MSCBT results

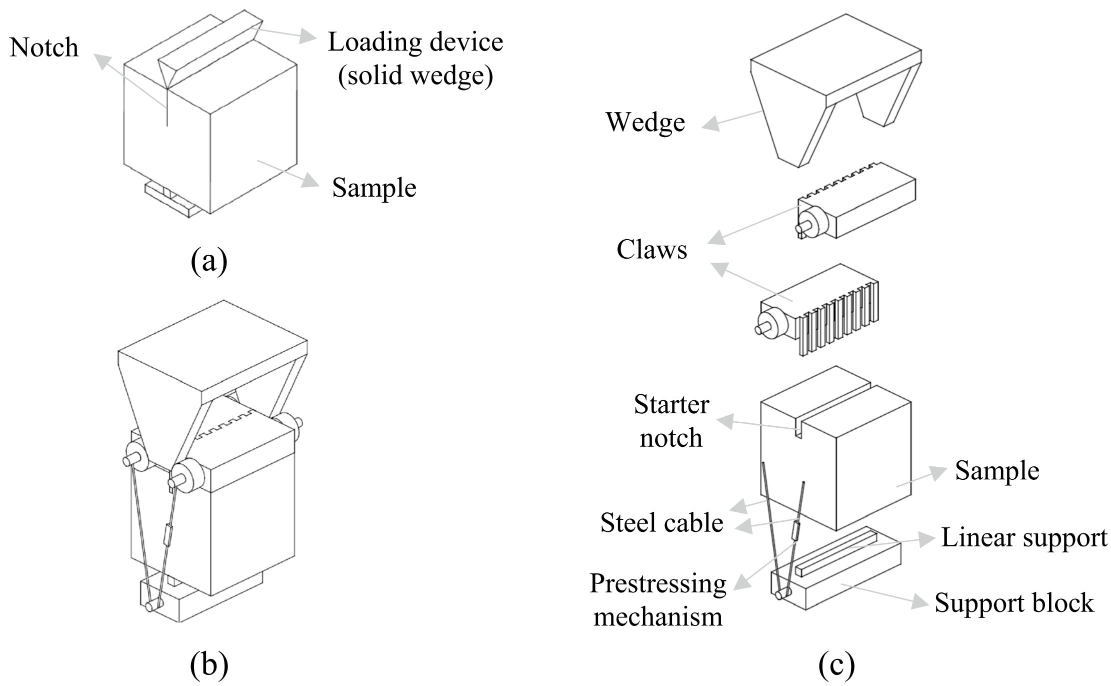

Fig. 10 Modifications: **a** MVD test, **b** MWST test setup, **c** description of the elements of the MWST apparatus

computational expenses and the necessity to employ a numerical model, such as the Finite Element Method (FEM). Previous research has extensively employed this approach in its traditional form to investigate Steel Fiber-Reinforced Concrete (SFRC) (Abrishambaf et al., 2013; Cunha, 2010; Azevedo, Barros, Sena-Cruz, & Gouveia, 2003; Löfgren, Stang, & Olesen, 2004; Gao, Ding, Yuyang, & Chen, 2021; Roelfstra & Wittmann, 1986; Zhang & Li, 2004), FRC incorporating recycled fibers (Frazão C., 2019; Blasi & Leone, 2022), and specimens featuring varying notch depths and sizes (Santos & Forti, 2022). Some studies have underscored the significance of analytical methodologies that focus on the incorporation of plastic hinges (Olesen, 2001; Salehian, 2015). The inverse analysis procedure starts from the knowledge of concrete and fiber properties and the experimental response of the 3PBT to estimate the tensile response (σ–COD) (Fig. 11) (Carvalho & Lameiras, 2023a).

Table 9 Main contributions on the others tests

Reference	Main contribution
Segura-Castillo et al. (2018)	The Montevideo (MVD) test was proposed
Neuner et al. (2022)	The MWST was proposed

This encompasses various approaches that center around the optimization of parameters through probabilistic methods (Stephen et al., 2019). In addition, employing this numerical approach, a recent study (Lameiras R. d., 2016) conducted an inverse analysis procedure utilizing a graphical analysis process. Initially, relationships are established to characterize the defining parameters of post-cracking behavior and boundary conditions. Subsequently, simulations utilizing an FEM-based program are executed.

For the model of the bending test of a sample with FRC behavior, when the stresses significantly exceed the cracking stress, a non-linearity of the stress–strain behavior occurs, due to the increase in the moment, and thus, the simple consideration of constitutive relationships applied directly to the structural element have no correlation with the actual behavior of cracking and deformations (Salehian, 2015). Therefore, it is necessary to optimize these relationships, considering the behavior of this type of concrete in its post-cracking state. This sub-item shows the contribution of some authors to the formation of numerical models to consider this behavior.

An analytical expression (Zhang & Stang, 1998) which was substantiated by FEM and experimental outcomes is currently employed as it satisfactorily predicts the load–displacement feedback for any arbitrary tensile stress (σ) vs. COD diagram. Nonetheless, there is a deficiency of

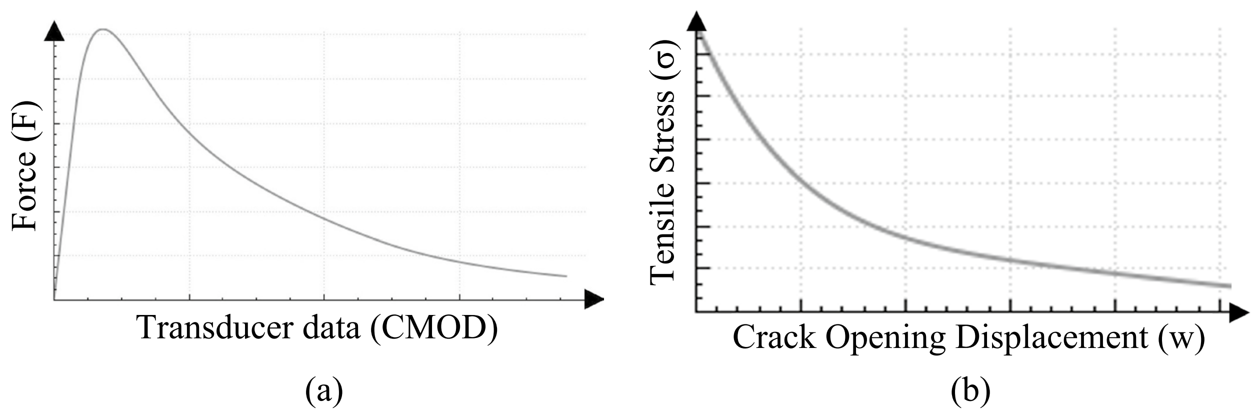

Fig. 11 inverse analysis procedure (Carvalho & Lameiras, 2023a): **a** force (F)—Crack Mouth Opening Displacement (CMOD) and (**b**) stress (σ)—Crack Opening Displacement (w) curve analysis (represents the UTT)

such an analytical formulation for FRC panels to the best of our understanding. The ideal bending behavior of FRC beams optimizes the bonding properties of the aggregate/matrix and fiber/matrix interfaces. The study indicated that it is possible to obtain satisfactory predictions for full structural performance in bending, such as load–CMOD and load–deflection for a sample under 3PBT.

Also based on the force balance in the critical section, an analytical model was developed to determine the post-cracking behavior for FRC of the same thickness subjected to bending (Nour et al., 2011). The model was based on the Monte Carlo method and experimentally validated and the results were satisfactory. An inverse analysis procedure to characterize the stress vs. COD for the 3PBT beam model was developed (Nour et al., 2015) based on models (Nour et al., 2011; Zhang & Stang, 1998). The proposed methodology entails a staged analysis approach, comprising an initial parameter estimation phase followed by subsequent curve adjustment procedures. The results were experimentally validated. The analysis was carried out in three stages. In the first, an initial guess is made of the multilinear softening diagram of the sample based on the analytical response corresponding to the target curve. In the next two steps, the diagram goes through adjustment, finally an analytical solution within an iterative process.

To determine a model for the flexural behavior of beams, several studies in the literature have relied on considering the rotation of a central element, known as the plastic hinge model (Fig. 12). For this model, a method to satisfactorily reproduce the behavior of FRC with and without conventional reinforcement was developed (Montaignac et al., 2012). According to the authors, the plastic hinge length (L_h) is influenced by various factors, such as the fraction, type, and volume of fibers, characteristic strength of concrete, geometry of the cross-section, presence or absence of structural

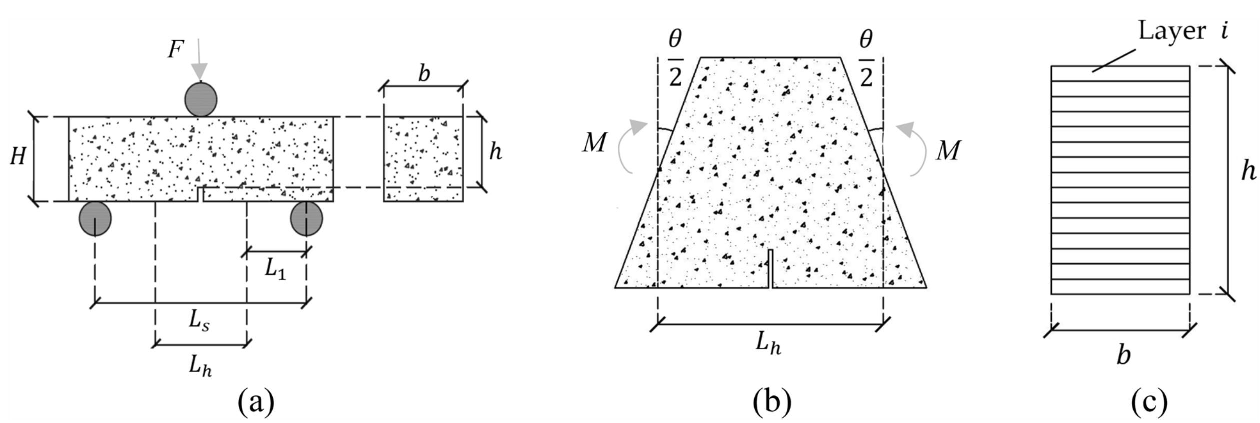

Fig. 12 Representative scheme of the beam under the 3PBT test, highlighting: **a** overview of the test with dimensional parameters, **b** plastic hinge element with plastic hinge length (L_h), and (**c**) layering of the cross-section. Adapted from Carvalho and Lameiras (2023a) and Salehian (2015)

reinforcement, and loading conditions. However, the conducted work concludes that employing a single value of L_h for all loading stages corresponds to favorable experimental outcomes, as the most relevant factor governing the behavior is the maximum crack width. For FRC without conventional reinforcement, the authors used $L_h = 2h$ as the maximum crack width. Other literature has used other values for this parameter: $L_h = h/2$ (RILEM TC 162-TDF, 2001; Massicotte, 2004; Ulfkjaer, Krenk, & Brincker, 1995; Kooiman, 2000; Iyengar, Raviraj, & Ravikumar, 1998; Pedersen, 1996), $L_h = 2h/3$ (AFGC-SETRA, 2002), $L_h = h$ (CNR-DT 204, 2006; Salehian, 2015; FIB, 2010), and $L_h = 2h$ (Montaignac et al., 2012; Strack, 2008).

During the execution of the bending tests, there are two possible combinations of parameters for monitoring that are used: monitoring the load (*F*) with the displacement (also called deflection, δ) or monitoring of the load with the CMOD. *F* is monitored from the universal testing machine itself or through a load cell positioned between the upper surface of the sample and the machine's piston. The CMOD is monitored by means of an acquisition system and corresponds to the crack opening measured precisely in the region of the notch where the crack starts. Therefore, the use of clip gages (Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007) or LVDTs are usual for the CMOD monitoring (Fig. 3c–f). Only one LVDT can be used on the bottom edge of the beam for both LVDT (Frazão C., 2019) and clip gage (EN, 14651, 2007). But a common methodology in research is to use two LVDTs, each of which one is positioned on one side of the sample, parallel to the sample direction (Salehian, 2015; Cardoso, Lameiras, & Capuzzo, 2021; Lameiras, Barros, & Azenha, 2015). In this methodology, the CMOD is obtained directly from the monitoring. The LVDTs can also be positioned to measure deflection vertically (RILEM TC 162-TDF, 2001; Planas, V. Guinea, Jaime C. Galvez, Beatriz Sanz, & Adel M. Fathy, 2007; Nour et al., 2015; American Society for Testing and Materials, 2007). In these cases, a correlation equation of these parameters can be used to obtain the CMOD.

12 Comparing Different Tests

The behavior of FRC can be evaluated through the shape of the load vs. cracking opening diagrams or tensile stress vs. COD diagrams (in the case of UTT), which can be obtained through the tests presented in this study. However, when the objective is to compare different methods to determine the post-cracking behavior of FRC in tension, the specificities of each test such as sample geometry, fracture surface, and molding conditions must be taken into consideration.

An experimental program aimed at comparing different tests was conducted (Montaignac et al., 2012) for SFRC with three types of standardized characterization tests: direct measurement using the Uniaxial Tensile Test (UTT) (RILEM TC 162-TDF, 2001) on notched core-cylinders, indirect measurement by applying inverse analysis procedures on the notched beam test (or 3PBT) (EN, 14651, 2007), and on the ASTM C1550 RPT (ASTM C1550-05, 2005). The authors' significant findings were: The mean post-cracking energy derived from inverse analysis in 3PBT and RPT were very similar to that obtained through the UTT. The ratios between the fracture energies of the 3PBT and the RPT in comparison to the UTT were below 20% for the five concrete mixes analyzed. Given the variability in the properties of uniaxial tension tests, with only five specimens per mix, energy ratios approaching 1.0 suggest that inverse analysis yields comparable cracking energy values across all three tests. The authors also concluded that the range of 0–1 mm for crack opening is sufficient for the comparison of the analyzed tests.

Another study conducted an experimental program with UTT in comparison with 3PBT (Amin et al., 2015). An inverse analysis procedure was developed for 3PBT. The tensile stress vs. COD results obtained by inverse analysis of 3PBT fit within the scatter range of experimental results from UTT. This demonstrates that the post-cracking behavior of SFRC can be directly obtained from UTT or indirectly, through the inverse analysis procedure of 3PBT. Evidence was found through the reverse analysis procedure that the *fib* Model Code 2010 (2012) may overestimate the residual tensile strength, which forms the basis of physical models for SFRC (Montaignac et al., 2012; Amin et al., 2015).

13 Final Remarks

This work aims to present a review on the methods of testing for the determination of FRC fracture parameters. The characteristics, advantages, disadvantages, and main contributions involving each test were presented and discussed.

The procedure for determining FRC fracture parameters is not yet fully understood. The known test methods for the FRC present difficulties as a challenge to be overcome for future works. As perspective for future work, some promising tests were presented. The SCBT showed advantages such as simplicity and speed of execution and the possibility of obtain samples from real structures. New notch types have been developed for the Splitting Test, preventing unexpected sample rupture. Different geometries are studied for the UTT. A new geometry for the RPT was shown, still maintaining a large fracture surface.

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Author contributions
Carvalho, PPM: conceptualization, data curation, writing, formal analysis, review; Lameiras, RML: supervision, data curation, methodology, review.

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Availability of data and materials
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Declarations

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Consent for publication
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Competing interests
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Publisher's Note

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