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ORIGINAL ARTICLE

Simplified DEWS test for steel fibre-reinforced concrete characterisation

Ensaio DEWS simplificado para caracterização do concreto reforçado com fibras de aço

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Abstract: Fibre Reinforced Concrete (FRC) is internationally recognised as a structural material in the *fib* Model Code 2010 and at a national level in the recently published ABNT standard NBR 16935, which establishes the structural design procedure based on post-cracking parameters. This publication should foster an increase in the number of applications of FRC in Brazil in the next years. In this context, many researchers have investigated the use of the DEWS test for the FRC characterisation as an alternative to the three-point bending test (3PBT) usually recommended by standards. The DEWS test is conducted by applying a compressive load on specimens with triangular grooves that induce a pure mode-I tensile fracture. Despite the advantages of the test, such as a smaller specimen and simpler testing procedure to obtain the anisotropic/orthotropic material properties, it still requires transducers to measure crack opening and generate the triangular grooves in the specimen, which is more complex, and labour demanding. This study addresses these issues by proposing a simplified test method and preparation consisting of removing the transducers (correlating the machine stroke and the crack opening) and generating the triangular groves during the casting instead of sawing afterwards. These modifications made the testing procedure much easier to perform. The experimental program assesses the modifications in the DEWS test setup and their influence on the post-cracking characterisation of FRC. Additionally, the effective fibre content and orientation were assessed by performing the inductive test. The results show that FRC characterisation can be successfully conducted using a simpler configuration of the DEWS test. This alternative test presents some advantages in comparison with the 3PBT test for FRC quality control, especially the lower volume of material and the test control by machine displacement.

Keywords: fibre reinforced concrete, mechanical characterisation, indirect tensile test, DEWS.

Resumo: O Concreto Reforçado com Fibras (CRF) é reconhecido internacionalmente como material estrutural pelo *fib* Model Code 2010 e em nível nacional, na recém publicada norma ABNT NBR 16935, que estabelece o procedimento de projeto estrutural baseado nos parâmetros pós-fissuração do compósito. Esta publicação deve propiciar um aumento do número de aplicações de CRF no Brasil nos próximos anos. Nesse contexto, muitos pesquisadores têm investigado o uso do teste DEWS para a caracterização de CRF como alternativa ao ensaio de flexão em três pontos (3PBT) usualmente recomendado pelas normas. O ensaio DEWS é realizado aplicando-se uma carga compressiva em corpos de prova com duplo corte à 45^0 que induzem uma falha em modo-I de fratura. Apesar das vantagens, como uso de corpo de prova menor e procedimento de ensaio mais simples para obter as propriedades anisotrópicas/ortotrópicas do material, ele ainda requer transdutores para medir a

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abertura da fissura e gerar os cortes triangulares no corpo de prova, o que é mais complexo e trabalhoso. Este estudo aborda essas questões propondo um método de ensaio e preparação simplificado que consiste em remover os transdutores (correlacionando o deslocamento da máquina e a abertura da fissura) e gerar os cortes triangulares à 45^0 durante a moldagem em vez de cortar posteriormente. Essas modificações tornaram o procedimento de ensaio muito mais fácil de ser realizado. O programa experimental avalia as modificações na configuração do ensaio DEWS e sua influência na caracterização pós-fissuração do CRF. Além disso, o conteúdo efetivo de fibra e a orientação foram avaliados através da realização do ensaio indutivo. Os resultados mostram que a caracterização do FRC pode ser realizada com sucesso usando uma configuração mais simples. Esse ensaio alternativo apresenta vantagens em comparação ao ensaio 3PBT para o controle tecnológico do CRF, principalmente em relação as dimensões do corpo de prova e controle do ensaio pelo deslocamento do equipamento.

Palavras-chave: concreto reforçado com fibras, caracterização mecânica, teste de tração indireta, DEWS.

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1 INTRODUCTION

The publication of the *fib* Model Code 2010 [1] promoted the use of fibre-reinforced concrete (FRC) in structural applications [2]. More recently, the publication of the Brazilian standard ABNT NBR 16935 [3] to design FRC structures has provided normative support for its application in Brazil. Due to the complexity of executing uniaxial tensile tests, standards have traditionally recommended bending tests, such as EN14651 [4] and ASTM C1609 [5], on notched or unnotched beams for material characterisation. The *fib* Model Code 2010 [1] refers to the European standard EN14651 [4] to determine the tensile behaviour of FRC (notched three-point bending test (3PBT)). Similarly, the Brazilian standard ABNT NBR 16940 [6] also proposes a 3PBT. Based on this test, a curve of applied load (F) versus crack mouth opening displacement (CMOD) is obtained.

Despite being the most widely used standard method, the 3PBT involves a complex setup, specialist equipment (closed loop) and relatively big specimens. This becomes particularly evident when a quality program for a major infrastructure project is defined, with the additional challenge of balancing the expectations and/or requirements of the designers and the equipment and resources in most professional laboratories. In addition, the scepticism on the use of FRC as structural material can be directly related to the variability observed in the material characterisation [7]. Pleesudjai et al. [8] reported the number of beams required to comply with the quality control program of a tunnel project, which rose to the staggering figure of 378 beams (ASTM C1609 [5]), representing 4.5 m^3 of FRC.

Quality control programs in major infrastructure projects could significantly benefit from adopting alternative approaches accepted in design recommendations based on indirect tensile tests, which do not require closed-loop equipment and use smaller specimens. Even for obtaining design parameters, the *fib* Model Code 2010 [1] accepts alternative methods if a correlation with the reference test is proved, and the Brazilian standard accepts the double punch test only if indicated by the designer and a correlation with the 3PBT is previously established.

Examples of these indirect tensile tests include the Double Punch test (DPT or BCN) [9], the Montevideo test (MVD) [10] and the Double Edge Wedge Splitting test (DEWS) [11], [12]. Among these, only the DPT have the test procedure established in standards in Brazil (ABNT NBR 16939 [13]) and in Europe (UNE 83515 [14]). Oppositely, the DEWS test exhibits some advantages compared to the DPT test. In the DPT, the failure mechanism commonly presents three radial cracks, although in some cases, four planes can be observed, induced by penetration of two cones formed under the punches. The unpredictable number of fracture planes and the complex failure mechanism are drawbacks of the DPT. This greater behavioural complexity makes obtaining constitutive equations for FRC more challenging once it depends on the inference of the material's internal friction coefficient [15]. The friction problem also occurs with the MVD at an intense level due to the contact between the wedge and the angles positioned on the edge of the notch, making it challenging to obtain constitutive equations [10]. On the other hand, the DEWS test is conducted by applying a compressive load on specimens with triangular grooves, which induces a pure Mode I tensile fracture [11].

The original proposition of the DEWS test presents difficulties associated with specimen preparation, as cutting the triangular grooves demands high accuracy and perfect parallelism of the specimen faces and the installation of transducers to measure the crack opening [11]. These difficulties increase the performing time and costs of the test and, consequently, can be considered a drawback for quality control. MVD and DPT tests have an easier preparation to overcome this last drawback by using stroke displacement [10], [16]. However, both tests present the difficulty of obtaining constitutive equations due to the friction inherent to the test methods. DPT and DEWS were evaluated as alternative tests to characterise the post-cracking tensile response of fibre reinforced sprayed concrete [17]. These authors recognise significant advantages of the DEWS test in comparison with flexural and DPT tests but pointed out the specimen's preparation as a relevant drawback for quality control. Thus, the use of the simplified DEWS test can mean the combination of two major advantages by facilitating the test procedure and the achievement of constitutive equations for FRC structural ability evaluation.

In this scenario, the aim of this paper is to propose and evaluate alterations to the DEWS test setup that result in a simpler but still reliable test for the systematic quality control of the residual tensile strength of FRC.

2 POST-CRACKING PARAMETERS FOR FRC

As mentioned above, the parameters that characterise the competence of the FRC for structural applications are obtained primarily through the 3PBT. The design parameters are the residual flexural tensile strength $f_{R,j}$ (j = 1,2,3,4) corresponding to $CMOD_j$ ($CMOD_1 = 0.5$ mm, $CMOD_2 = 1.5$ mm, $CMOD_3 = 2.5$ mm and $CMOD_4 = 3.5$ mm), calculated by the Equation 1.

$$f_{R,j} = \frac{3 \cdot F_j \cdot l}{2 \cdot b \cdot h_{SP}^2} \tag{1}$$

where F_j is the load corresponding to j, l is the span length, b is the width, and h_{SP} is the distance between the tip of the notch and the top of the beam in the mid-span section.

In both codes, *fib* Model Code 2010 [1] and ABNT NBR 16935 [3], the parameters adopted to design structures with FRC are based on the characteristic residual flexural tensile strengths f_{R1k} (corresponding to $CMOD_1 = 0.5$ mm) and f_{R3k} (corresponding to $CMOD_3 = 2.5$ mm), for the design at service limit state (SLS) and ultimate limit state (ULS), respectively.

On the other hand, the DEWS test results could be achieved from equilibrium considerations [11]. The transverse "splitting tensile" force F_{SP} induced by the applied vertical load P can be calculated by Equation 2:

$$F_{SP} = \mathrm{P} \frac{\cos\vartheta - \mu \sin\vartheta}{\sin\vartheta + \mu \cos\vartheta} \tag{2}$$

where ϑ is the inclination angle of the wedge grooves ($\vartheta = 45°$); and μ is the friction coefficient of 0.06. Consequently, the splitting tensile force $F_{SP} = 0.89$ P.

The tensile stress (f_t) was calculated from Equation 3, where t is the specimen thickness and h_{lig} is the ligament depth.

$$f_t = \frac{F_{SP}}{t \cdot h_{lig}} \tag{3}$$

The referential post-cracking tensile strength values obtained with the DEWS test could also be associated with the SLS and the ULS adopting crack opening displacement (COD) values equal to 0.5 mm and 2.5 mm, respectively. These COD values were adopted to maintain the same crack mouth opening recommended in EN 14651 [3] and NBR 16940 [6]. In this way, it is possible to obtain adequate parallelism of results between both test methods.

3 EXPERIMENTAL PROGRAM

3.1 Materials and mix design

The concrete matrix was composed of Portland cement, siliceous aggregates, tap water and hooked-end steel fibres. Two fibre reinforced concretes T20 and T50 were produced, and the mix design is described in Table 1. The geometric and mechanical characteristics of the steel fibre are summarised in Table 2.

Table 1. Mix design of steel fibre reinforced concretes.

Component	Dosage (kg/m^3)	
	T20	**T50**
Cement CP V-ARI	380	
Granite coarse aggregate (4.8-12.5 mm)	711	
Artificial sand (0-4.8 mm)	968	
Water	224	
Fibre	20	50

Table 2. Geometric and mechanical characteristics of the steel fibre.

Characteristic		Value
Length	l (mm)	35
Diameter	d (mm)	0.75
Aspect ratio	(l/d)	45
Elastic modulus	(GPa)	210
Tensile strength	(MPa)	1225

3.2 Casting and specimen production

For each fibre dosage, 5 cylinders of size ϕ100 × 200 mm were cast to assess the compressive strength and elastic modulus. For the DEWS tests, 24 cubic moulds of 100 mm were used, 12 for each fibre content (T20 and T50). For 6 moulds of each fibre content, two triangular prisms with a 45° inclination were glued in opposite faces to induce the triangular grooves (Figure 1a). The concrete casting was in the axis Z, considering the coordinates shown in Figure 1a. After the cast, the specimens were kept in their moulds for 24 h, covered with plastic to prevent air drying, and remained in a humid chamber for 24 days.

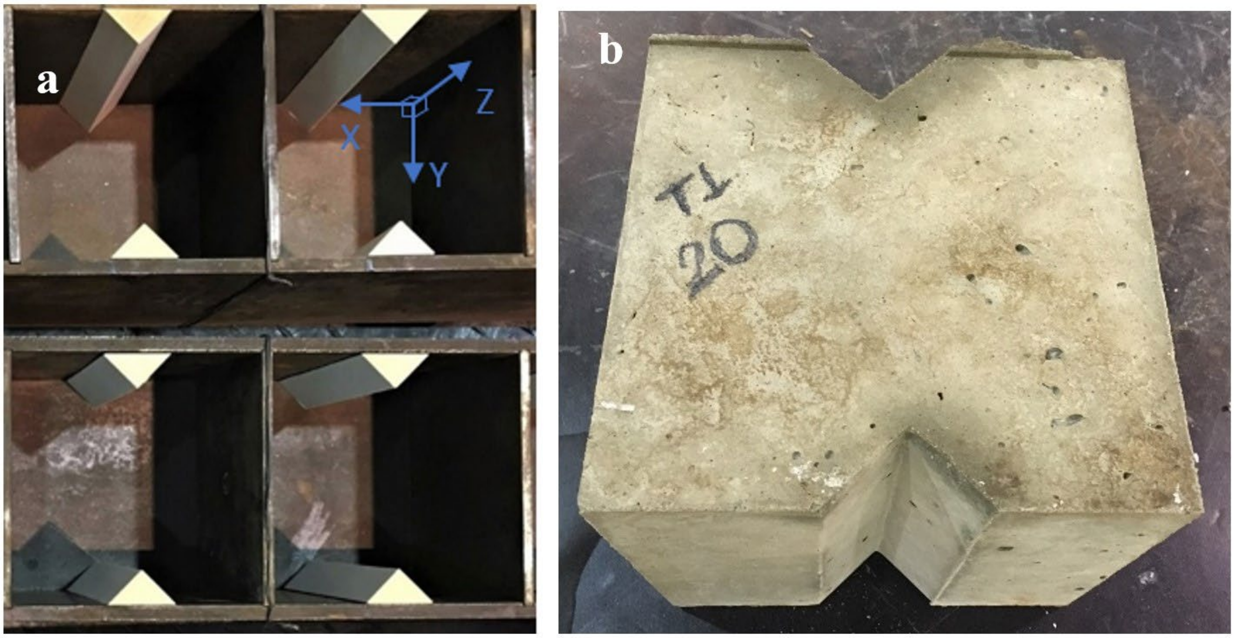

Figure 1. a) Moulds with triangular prims glued in opposite faces; b) Specimen with triangular grooves produced by casting.

For the specimens with triangular grooves not produced by casting, the cut was made one day before testing to generate the grooves (Figure 2). This preparation step is time-consuming and should be done carefully for satisfactory test performance [12].

Figure 2. Cutting the triangular grooves.

For the specimens with moulded triangular grooves, only the two notches starting from the groove vertices were cut. The identification of the specimens is T20-M or T50-M for grooves induced in the mould during cast and T20-C or T50-C for grooves generated by cutting after casting.

3.3 Test methods

3.3.1 DEWS

In the DEWS test, steel rollers are used as a loading device located in the grooves of the specimen (Figure 3). The compressive load applied by the actuator deviates through the grooves, inducing a uniaxial tensile stress state at the "ligament" (vertical fracture surface) [11]. To reduce friction, brass platens were glued to the groove edges, and the contact surfaces were lubricated with graphite, which resulted in a friction coefficient $\mu = 0.06$ [11].

Figure 3. View of the DEWS test setup.

The tests were performed employing a servo-hydraulic machine, and the actuator displacement was used to control the test speed of 0.12 mm/min [12]. To measure the crack opening displacement (COD) in the DEWS test, Prisco et al. [11] used six linear variable differential transformers (LVDTs) attached to the specimens (three per side). To simplify the procedure of measuring the COD, Borges et al. [12] propose a test configuration using two transducers attached to opposite faces of the specimen, measuring the average COD at the middle height of the specimen. Recently, Pereira et al. [18] performed some experimental DEWS tests to correlate the vertical displacement of the machine and COD, as depicted in Figure 4.

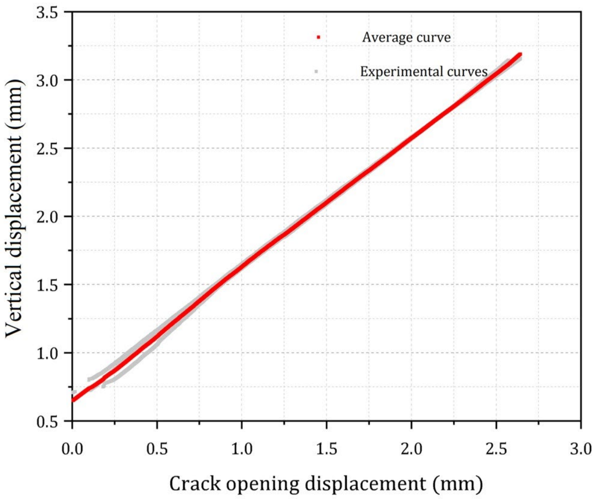

Figure 4. The relationship between vertical displacement (mm) and crack opening displacement – COD (mm) (adapted from Pereira et al. [18]).

Based on these results and using linear regression ($R^2 = 0.9997$), these authors proposed Equation 4, in which the COD can be obtained directly from the measure of the vertical displacement of the machine without the need for transducers.

$$D = 0{,}963 \times COD + 0{,}650 \tag{4}$$

Therefore, the residual strengths $f_{0.5}$, for COD = 0.5 mm, and $f_{2.5}$, for COD = 2.5 mm, can be obtained by means of the DEWS tests.

It is essential to mention that Equation 4, proposed by Pereira et al. [18], was obtained from a steel fibre-reinforced concrete with 40 MPa (compressive strength) and fibre content of 35kg/m^3. However, adopting the hypothesis that vertical displacement versus COD is a geometric relationship derived from a rigid body motion of the specimen, this equation can also be used for other concretes with distinct compressive strengths and fibre contents. In addition, it is also important to note that assuming this hypothesis, the theoretical relationship between vertical displacement and COD can be written as: D = 1.0 x COD + 0.0. The slight discrepancy between Equation 4 from the theoretical relationship is due to imperfections and accommodations in the test, which can be due to the concrete strength and stiffness, any specimen rotation after cracking, or the friction between the steel rollers and brass platens glued to the groove edges. The term 0.65 in Equation 4 represents the elastic strain of the specimen before concrete cracking.

3.3.2 Inductive method

Before the mechanical DEWS tests, the inductive method (non-destructive test) [19] was used to assess the content and the distribution of steel fibres in the specimens. This evaluation was performed to test if any significant difference can be attributed to the method of producing the grooves.

The inductive method [19] is based on the inductance change produced when a steel fibre reinforced specimen is exposed to a magnetic field. The equipment is composed of an impedance analyser and a coil (Figure 5). The magnetic field generated in the coil by the current flow is altered by the ferromagnetic nature of the steel fibres, which increases the permeability of the medium and produces an inductance variation measured by the analyser.

Figure 5. Coil and impedance analyser.

The test is compatible with cubic and cylindrical specimens. When the cubic specimen is used, the specimen is placed inside the coil, and the inductance is measured in the main directions perpendicular to its faces. For a given set of axes, each measurement will represent ΔLx, ΔLy and ΔLz for the axis X, Y and Z, respectively.

Torrents et al. [20] show that the summed inductance (ΔL) for the three axes holds a linear relation with the fibre content. Consequently, a calibration curve for the type of fibre being used is needed to determine the content of fibre (C_f). This calibration can be made by crushing the specimen after measuring the inductance in the axis X, Y and Z, or by using a known content of fibres (the same fibre used in the experiment) in polystyrene pieces (Figure 6).

Figure 6. Piece of polystyrene with a known content of fibre.

The parameter used to assess the contribution of the fibres in a certain direction is the average orientation number (η_i), given by the average of the cosine of the angle formed between the fibres and a line parallel to the direction of consideration. Cavalaro et al. [19] defined Equation 5 to assess the orientation number for FRC:

$$\eta_i = 1.03 \cdot \sqrt{\frac{\Delta L_i \cdot (1+2\cdot\gamma) - \Delta_L \cdot \gamma}{\Delta_L \cdot (1-\gamma)}} - 0.1 \quad (5)$$

where:

- η_i is the orientation number for each i axes.
- ΔLi is the variation in inductance in each axis, in Henry.
- ΔL is the summed inductance for the three axes, in Henry.
- γ is the shape factor equal to 0.05 for the fibre employed.

The orientation number can be used to estimate the relative contribution of the fibres in a direction i ($\mathrm{C_i}$), using Equation 6.

$$\mathrm{C_i} = \frac{\eta_i}{\sum_{i=x,y,z}\eta_i} \tag{6}$$

4 RESULTS AND DISCUSSIONS

4.1 Compressive strength and elastic modulus

The average and standard deviation results at 28 days of the compressive strength (f_{cm}) and elastic modulus (E_{cm}) are presented in Table 3.

Table 3. Mechanical properties of the FRCs with their respective standard deviation.

	f_{cm} (MPa)	E_{cm} (GPa)
T20	38.9±2.0	25.402±0.008
T50	35.9±0.4	25.76±0.02

For the relatively low fibre content (less than 1%), the fibre has no expected effect on compressive strength or elastic modulus. The results presented in Table 3 denoted a slight reduction of the average compressive strength when 50 kg/m^3 of fibres were added, which can be related to the impact of the fibre addition in the concrete consistency and, consequently, more difficulty in casting the specimens. However, an ANOVA analysis showed a non-significant difference between T20 and T50 compressive strengths. The null hypothesis for the test that the two means are equal was accepted with a p-value of 0.176 (considering significance level of 0.05).

4.2 Fibre content, orientation number and relative contribution of the fibres

Figure 7 shows the calibration curve, represented by the amount of inductance (ΔL) measured and the mass of fibres introduced in the polystyrene pieces.

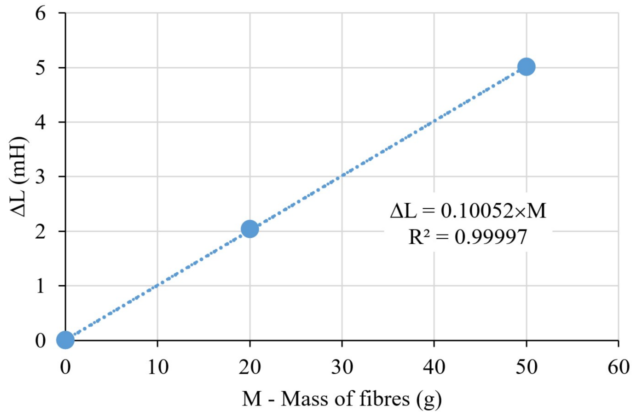

Figure 7. Calibration curve obtained for the fibre used.

The calibration equation ($\Delta L=0.10052\times M$) allows the determination of the mass of fibres in each DEWS specimen, measuring the inductance variation in each axis. Table 4 presents the nominal values of fibre content, the average fibre content calculated with the inductive method.

Table 4. Fibre content nominal values and average result measured with the inductive method and their respective standard deviation.

	Fibre content	
	Nominal (kg/m^3)	**Measure with inductive (kg/m^3)**
T20-M	20	25±2
T20-C		27±1
T50-M	50	57±2
T50-C		56±7

The results in Table 4 showed no significant difference between the fibre content of specimens with triangular grooves produced during the cast or cut after the cast. Thus, the results can be considered comparable because the fibre content is equivalent in both situations. Moreover, the inductive method revealed that the real fibre contents are significantly higher than the nominal values (30% for T20 and 13% for T50). The inductive method also assesses the estimation of the fibre orientation in the specimen, the orientation number (η_i) and the relative contribution of the fibres in a certain direction (C_i) (Table 5).

Table 5. Orientation number and relative contribution of the fibres in each direction with their respective standard deviation.

	Orientation number per axis			Fibre contribution per axis		
	η_X (%)	**η_Y (%)**	**η_Z (%)**	**C_X (%)**	**C_Y (%)**	**C_Z (%)**
T20-M	52±3	52±4	47±4	34±2	34±1	31±1
T20-C	58±8	54±3	51±3	36±3	33±1	31±2
T50-M	89±5	91±3	77±6	35±1	35±1	30±2
T50-C	85±8	90±8	79±10	33±2	36±2	31±2

As can be seen in Table 5, the η_i and C_i results are similar for the specimens with triangular grooves moulded or cut. Consequently, producing the grooves in the casting process does not induce fibre orientation.

4.3 Post-cracking characterisation – DEWS tests

The results of the DEWS tests are load and vertical displacement. The tensile stress and COD results were calculated using Equations 3-4. The stress *vs.* COD curves for the fibre content of 20 kg/m^3 with triangular grooves moulded (T20-M) or cut (T20-C) are presented in Figures 8 and 9, respectively.

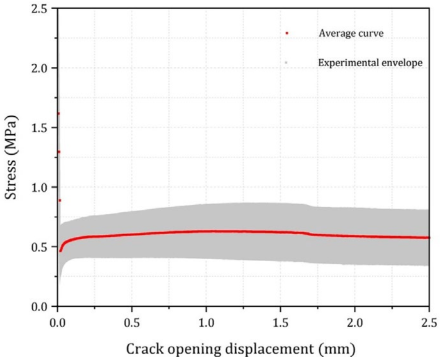

Figure 8. Stress *vs.* COD curves for DEWS tests with 20 kg/m^3 of steel fibres and triangular grooves moulded (T20-M).

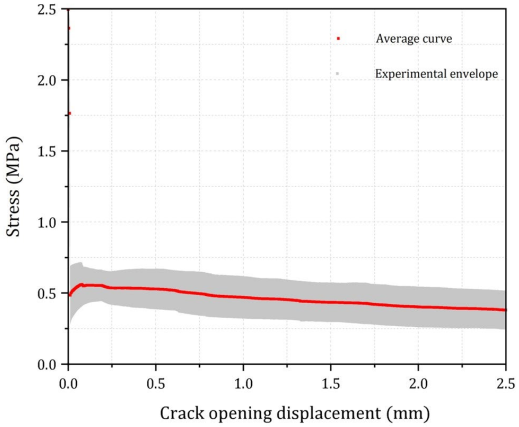

Figure 9. Stress *vs.* COD curves for DEWS tests with 20 kg/m^3 of steel fibres and triangular grooves cut (T20-C).

The experimental envelope of the tests with triangular grooves moulded is wider than those produced by cut. Such an outcome cannot be attributed to the method used for inducing the triangular grooves since this pattern does not occur for the specimens containing 50 kg/m^3 (see Figures 10-11).

The stress *vs.* COD curves for the fibre content of 50 kg/m^3 with triangular grooves moulded or cut are presented in Figures 10 and 11, respectively.

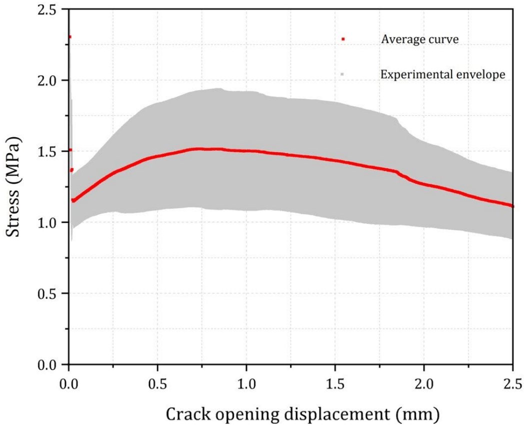

Figure 10. Stress *vs.* COD curves for DEWS tests with 50 kg/m^3 of steel fibres and triangular grooves moulded (T50-M).

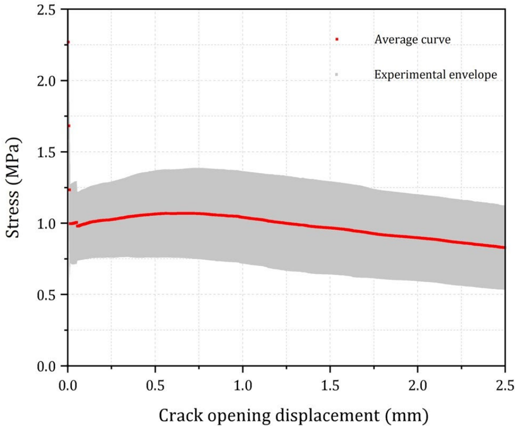

Figure 11. Stress *vs.* COD curves for DEWS tests with 50 kg/m^3 of steel fibres and triangular grooves cut (T50-C).

The curves of the tests with triangular grooves moulded suggest better performance than those produced by cut. Despite the scatter in the results, statistical tests did not reveal significant differences between the average residual tensile strengths obtained in specimens with moulded or cut grooves. A summary of the residual tensile strengths ($f_{0.5}$ for COD = 0.5 mm and $f_{2.5}$ for COD = 2.5 mm), with their respective standard deviation is presented in Table 6. Also, the average values were compared by a t-test with a significance level of 5%. The null hypothesis is that the average values are equal, independent of the method to produce the triangular grooves, and it is rejected for p-values below 0.05.

Table 6. Residual tensile strength: average, standard deviation and p-value in two-sample t-test.

	$f_{0.5}$		$f_{2.5}$	
	MPa	**p-value**	**MPa**	**p-value**
T20-M	0.61±0.20	0.372	0.54±0.23	0.109
T20-C	0.52±0.14		0.33±0.16	
T50-M	1.36±0.24	0.215	0.92±0.12	0.487
T50-C	1.11±0.33		0.83±0.24	

The results in Table 6 indicate that the average residual tensile strengths $f_{0.5}$ and $f_{2.5}$ are higher when the triangular groove is moulded. This may be associated with changes in fibre local orientation at the triangular grooves for moulding the specimens, which is minimised by the fact that there are notch cuts in both situations, which reduces the wall effect. Also, the cuts of triangular grooves can produce material damage in the specimens. However, considering the variability of residual strength obtained in the experimental tests, it can be noted that there is no statistical difference between the average results (p-value is above 0.05). In further studies, it is important to investigate the influence of the cuts in the post-cracking behaviour.

5 CONCLUSIONS

This paper addresses some of the issues identified as hindering the universal use of the DEWS test as a method for FRC characterisation. The results of the experimental program suggest that the modifications proposed in the test setup simplify the execution of the test without compromising its reliability for evaluating the mechanical behaviour of FRC. Based on the analysis conducted in this study, the following conclusions are drawn:

- Moulding the triangular grooves in the DEWS specimen while casting is feasible and significantly reduces the preparation steps.
- The fibre content of specimens with moulded and cut triangular grooves is similar. Also, the production of the grooves during the casting process does not affect the overall fibre orientation in the specimen, although some local influence could occur at the triangular grooves regions.
- The fact that the notches are sawed in the two situations of production of specimens minimises the wall effect of orientation of the fibres in the superior and inferior extremes of the ligament section.
- The deformation in the DEWS test can be measured using axial displacement instead of transducers, thus simplifying the execution and facilitating the adoption of the test in quality control laboratories.
- The residual tensile strength obtained in specimens with moulded and cut triangular grooves is comparable in terms of average and scatter. Hence, cutting the grooves is recommended only if the DEWS test will be used in cores drilled from real structures.

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