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Influence of the instability of the double punch test on the post-crack response of fiber-reinforced concrete

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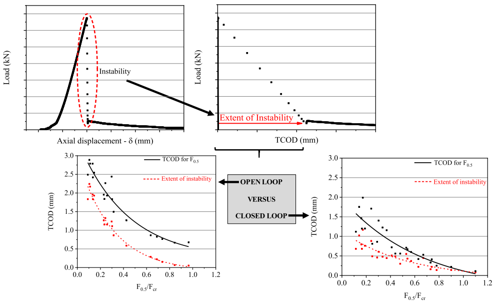
HIGHLIGHTS

- The suitability of DPT as an alternative method for FRC quality control is endorsed.
- The DPT post-peak instability in the determination of residual strength is evaluated.
- The DPT performed with closed and open loop control systems are compared.
- Instability is proportional to the distance between matrix and residual strengths.

GRAPHICAL ABSTRACT



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ABSTRACT

The characterization of the post-crack behavior of fiber-reinforced concrete (FRC) is essential in order to properly design and apply this composite. Although beam tests (3 and 4 points) are standardized for this purpose, a simpler methodology is necessary to be designated as a regular quality control method. In this context, the research presented in this paper focuses on the evaluation of the double punch test (DPT) as an alternative method to control the mechanical behavior of FRC. Tests were performed in open and closed-loop test machines to verify if the instabilities caused after the matrix cracks compromise the determination of residual strength. Results showed that when open-loop test machines are employed, post-crack instability is greater. However, it does not influence the determination of residual strength negatively. Therefore, the DPT performed in open-loop test machines may be used for the routine analysis and characterization of FRC.

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1. Introduction

The use of fiber-reinforced concrete (FRC) for structural purposes has been expanded with the development of concepts of fracture mechanics to describe its mechanical behavior [1]. However, the technological control of the FRC is more challenging than the technological control of the conventional concrete, essentially due to the complexity of the tests. Therefore, it is necessary to develop a methodology to characterize the mechanical behavior of FRC for quality control programs based on the execution of easy-to-use tests with reliable results [2,3].

The main challenge in FRC control tests involves the parameterization of the post-crack behavior, where the residual strength of the FRC must be determined with highest achievable precision [4]. Several experimental methods have been developed

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to characterize the post-crack behavior of FRC, such as the bending tests recommended in EN 14651 [5] and ASTM C1609 [6]. The *fib* Model Code 2010 [7] prescribes the bending test of notched specimens [5] as a reference for the parameterization of FRC behavior for structural applications. However, this test demands complex and expensive closed-loop equipment to determine the deformation of the specimen. Alternatively, other test methods may be applied once a proven correlation with the reference method is provided.

The double punch test (DPT) normalized by the Spanish standard AENOR 83515 [8] is a possible alternative for bending tests and its use for the characterization of FRC is increasing widely [9–13]. In standard DPT, a double punch in cylindrical specimens with diameter/height ratio equal to 1 is performed. The deformation of the specimen is measured by means of a circumferential extensometer to provide the total circumferential opening displacement (TCOD).

In order to make the method more accessible to quality control laboratories, the axial displacement of the test machine may be used to measure the deformation of the specimen instead of TCOD [14]. By means of an analytical conversion, the crack opening corresponding to each measured load may be calculated. This procedure is simpler, since the only requirement is a conventional test machine equipped with an axial displacement control (not necessarily with a closed-loop control).

The performance of FRC tests with open-loop control systems is questioned by several studies [15–21]. Their concerns are mainly associated with the frequent occurrence of post-crack instability in flexural tests, which impairs the measurement of post-crack residual loads and may compromise reliability in the evaluation of FRC behavior. Instability may be observed when low volume of fibers is employed, leading to a significant difference between the strength of the matrix and the residual strength of the composite. Besides, the lack of rigidity of the equipment may also cause instability [16]. The influence of each variable on the post-peak instability has not been properly studied yet, probably due to di difficulties in isolating each variable. For flexural tests, instability is significantly reduced when closed-loop machines are employed to control the load application rate [5,6]. However, post-peak instability has not yet been studied for DPT.

In this context, the aim of this research is to evaluate the extension of instability in DPT performed in test machines with different control systems, focusing on its influence on the residual strength measured just after matrix cracking.

2. Methodology

This research was conducted Laboratory of Materials, Components and Construction Processes from the Polytechnic School of University of São Paulo (USP, Brazil). This paper contains two parts, as described in Fig. 1. The first part comprises a theoretical analysis of historical data of the DPT performed in open- and closed-loop equipment with varied composites, with the objective to evaluate the extent of their post-crack instability and if the determination of the residual load $F_{0.5}$ is compromised. The second part focuses on the experimental analysis of the influence of the equipment control system (either open- or closed-loop) on the post-crack response for a given composite. The descriptions of the DPT, the types of testing machine and the post-crack instability are presented subsequently.

2.1. Double punch test

The double punch test is a compression test normalized by AENOR 83515 [8]. This test is performed in cylindrical specimens, whose diameters are either 100 or 150 mm, with diameter/height ratio equal to 1. One metallic cylindrical punch, measuring ¼ of the diameter of the specimen, is positioned at the center of each circular face of the specimen, as shown in Fig. 2. Load is applied to obtain a constant displacement rate equal to 0.50 mm/min, until the vertical displacement of 7.0 mm is reached. This level of vertical displacement is adopted to reach the TCOD of 6 mm using the analytical conversion proposed in [14].

A typical load-displacement curve obtained in the DPT is presented in Fig. 3. The initial part of the curve (up to 0 mm) corresponds to the punch-specimen accommodation and elastic response of the matrix, and is not considered for any calculation. After that, the actual specimen loading starts, until the maximum load (F_{cr}) is reached. At this point, the matrix cracks and the load is transferred to the fibers and the residual behavior of the specimen may be characterized. The residual load $F_{0.5}$ is associated with the service limit state of the composite and is determined when the vertical displacement of 0.5 mm in the post-crack part of the curve is reached [22,23]. It is the most critical parameter to be obtained, because it is subjected to the post-crack instability. Besides, the residual load $F_{3.5}$ is determined when the vertical displacement of 3.5 mm is reached and is associated with the ultimate limit state of the composite.

2.2. Testing machines

In both parts, historical data and experimental program, the DPT tests were performed in two test machines with different control systems. One of them was an open-loop electromechanical universal test machine, from EMIC, model DL10000, with a capacity equal to 100 kN and toughness equal to 42 kN/mm (Fig. 4a). The other one was a closed-loop servo-hydraulic machine, from SHIMADZU, model UH-2000kNXR (Fig. 4b). It contains a feedback transducer, depicted in Fig. 4c, to control the load application rate in order to maintain the vertical displacement of the specimen constant.

2.3. Post-crack instability

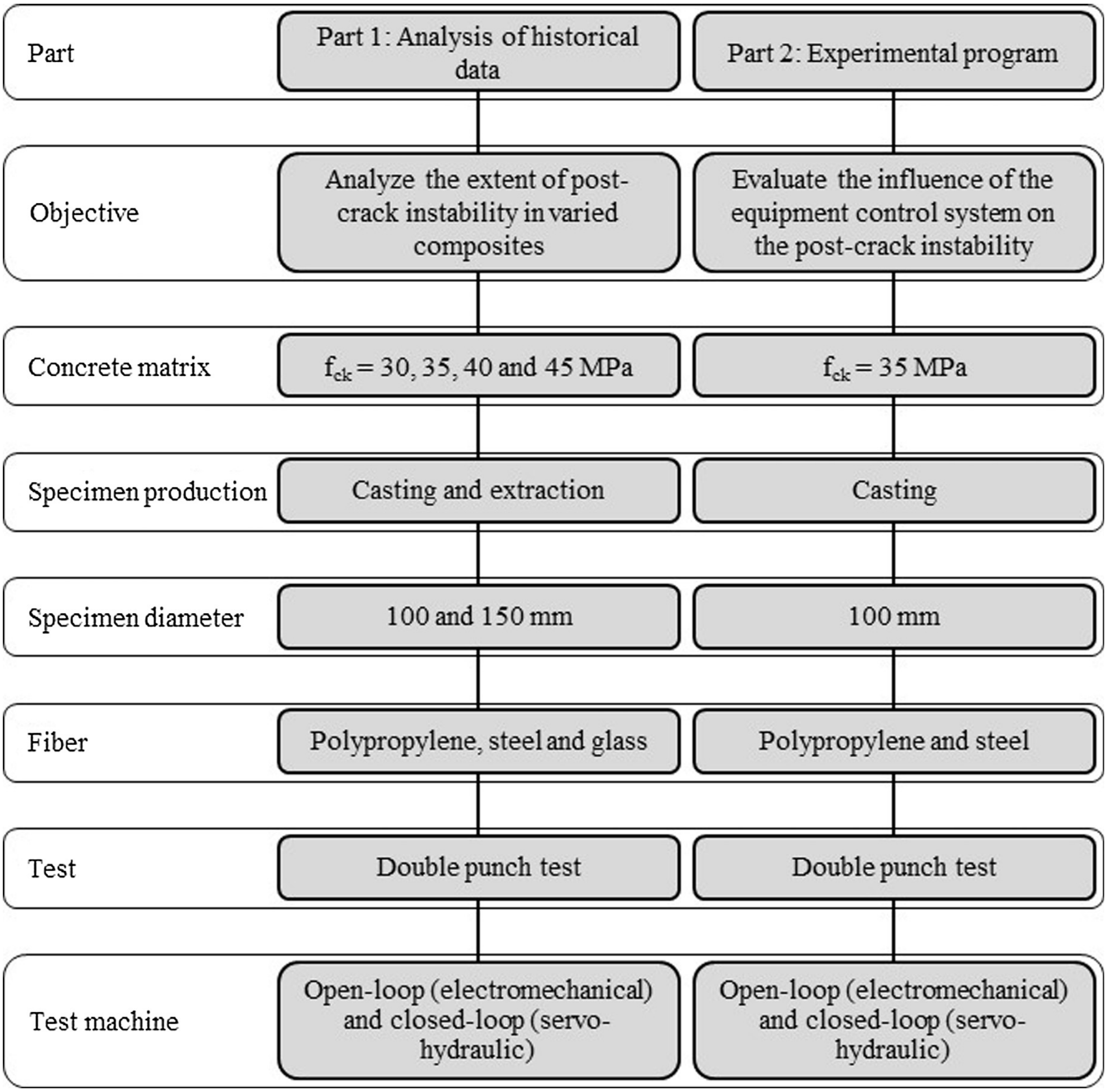
The post-crack instability can be identified by an abrupt drop in the load-bearing capacity of the specimen right after cracking and is represented in Fig. 5. When the matrix cracks and the load is transferred to the fibers, part of the energy stored in the equipment is released, causing an increase in the rate of deformation of the specimen. The failure mechanism of the DPT, a combination of fracture Mode I and Mode II, may partially affect the instability after cracking. Most of the elastic energy is released abruptly at the moment of cracking and a small part is released during the post cracking stage [24], and instabilities are more likely to occur in the precise moment that cracking occurs.

Since data acquisition occurs at a constant rate, instability is observed in the load-displacement curve by a region with larger distances between points (Fig. 5).

In order to determine the post-crack instability graphically, axial displacement needs to be converted into crack opening (TCOD). For this conversion, Eqs. (1)–(3) proposed by Pujadas et al. [14] may be used. Those formulations were proposed and validated for conventional and ultra-high performance FRC, using polypropylene and steel fibers.

$$TCOD = 0 \quad \delta \le \delta_{cr} \tag{1}$$

$$\mathrm{TCOD} = \mathrm{n} \times \frac{\mathrm{a} \times \delta_{\mathrm{R},0}}{2 \times \mathrm{l}} \times \mathrm{sen}\frac{\pi}{\mathrm{n}} \times \left(1 - \frac{\mathrm{F}}{\mathrm{F_{cr}}}\right) \quad \delta_{cr} < \delta < \delta_{\mathrm{R},0} \tag{2}$$



Part	Part 1: Analysis of historical data	Part 2: Experimental program
Objective	Analyze the extent of post-crack instability in varied composites	Evaluate the influence of the equipment control system on the post-crack instability
Concrete matrix	f_{ck} = 30, 35, 40 and 45 MPa	f_{ck} = 35 MPa
Specimen production	Casting and extraction	Casting
Specimen diameter	100 and 150 mm	100 mm
Fiber	Polypropylene, steel and glass	Polypropylene and steel
Test	Double punch test	Double punch test
Test machine	Open-loop (electromechanical) and closed-loop (servo-hydraulic)	Open-loop (electromechanical) and closed-loop (servo-hydraulic)

Fig. 1. Scheme of the research conducted in this study.

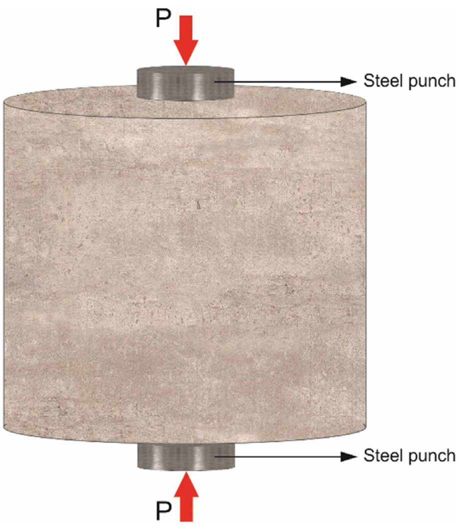


Fig. 2. Double punch test setup.

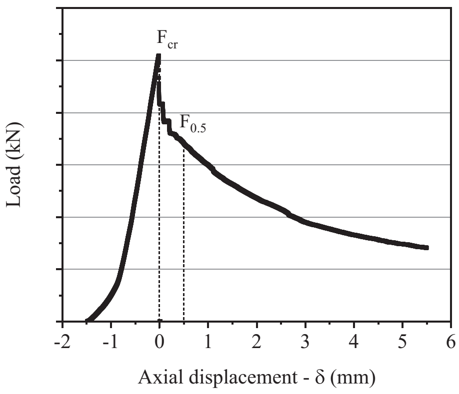


Fig. 3. Typical curve of load by axial displacement.

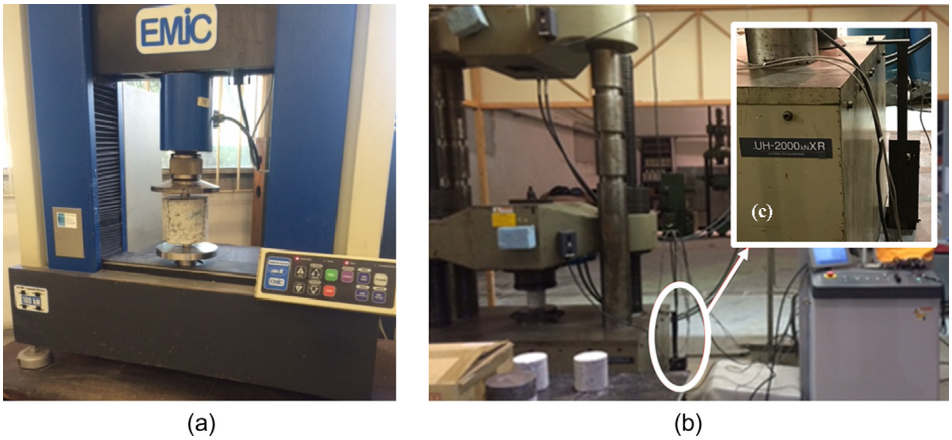


Fig. 4. a) Open-loop control testing machine - EMIC DL10000; (b) Closed-loop control Testing Machine - SHIMADZU UH-2000kNXR; c) detail of the feedback transducer.

$$TCOD = n \times \frac{a}{2 \times l} \times \mathrm{sen}\frac{\pi}{n} \times \left[\delta - \delta_{cr} + \delta_{R,0} \times \left(1 - \frac{F_{R,0}}{F_{cr}}\right)\right] \quad \delta \geq \delta_{R,0} \tag{3}$$

where:

- n $f_{ctRx}$is the number of radial cracks formed in the test (n equal to 3 for the analysis of historical data, due to the lack of registration reports)
- a is the diameter of the cylindrical punches used in the test (a equal to 25 and 37.5 mm for specimen diameter equal to 100 and 150 mm, respectively)
- l is the length of the wedge formed under the cylindrical punches (l equal to 26.81 and 40.21 mm for specimen diameter equal to 100 and 150 mm, respectively)

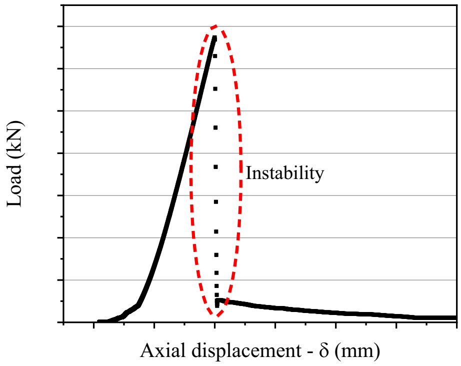


Fig. 5. Instability in the curve of load by axial displacement.

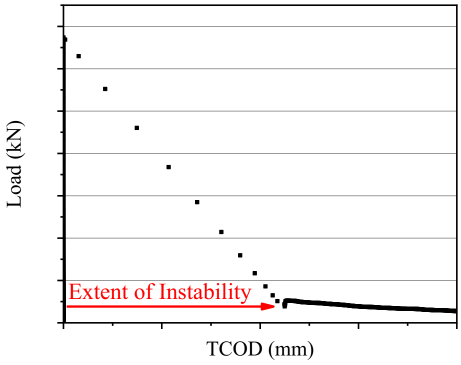


Fig. 6. The extent of instability in the curve of load by TCOD.

- F is the load at the calculated point
- F_{cr}, δ_{cr} are the load and the displacement at the point of maximum load
- $F_{R,0}$, $\delta_{R,0}$ are the load and the displacement at the starting point of residual strength.

Calculating the TCOD of the data presented in Fig. 5 results the curve presented in Fig. 6. The load-TCOD curve after the analytical conversion shows clearly the extent of instability, where the spacing of the points becomes more evident. Consequently, the extent of instability may be defined as the distance, in terms of TCOD, between the peak load and the end of instability (Fig. 6).

The use of low fiber content in FRC turns the test response more susceptible to instabilities. The use of a closed-loop control system may mitigate the problem, but may also be considered a barrier for spreading the test in routine quality control laboratories because of higher cost of the equipment. Tests performed with open-loop control systems, such as MDPT [25] and DEWS [26,27], can also show post peak instabilities and should be carefully evaluated. The instability can also compromise the determination of constitutive models that provide the σ–ε relation valid for both the linear-elastic and post-cracking stages. In the case of DPT, a simplified constitutive model was proposed by Blanco et al. [24], in which stresses were expressed as function of the load associated to a certain displacement. The authors [24] indicate some difficulties for the model to predict the beginning of the curve, just after the cracking occurs, and a better adherence for higher displacements. It can be associated to uncertainties caused by the instabilities. In this sense, these open-loop tests must be associated to others closed-loop tests in order to not compromise the evaluation of structural behavior of the composite. However, the DPT test could be considered suitable to perform regular quality control of FRC taking in consideration the correlation with closed-loop test parameters [23].

3. PART 1: analysis of historical data

3.1. Methodology of analysis

Part 1 consisted in determining the extent of post-cracking instability in the DPT in order to verify if it compromises the determination of the residual load $F_{0.5}$, determined when the axial displacement is 0.5 mm after the critical load. A total of 135 load-displacement curves collected from reports of previous studies performed in the laboratory of the Polytechnic School of the University of São Paulo were analyzed. Tests were performed in open- and closed-loop machines, allowing to compare the effect of this variable. The axial displacement obtained in the curves was converted analytically to TCOD to determine crack opening for $F_{0.5}$.

Table 1 presents the specimens used in the first part of the study. Unpublished results refer to experimental programs performed by undergraduate students. Specimens measuring 100 mm in diameter were extracted from prismatic beams measuring 150 mm × 150 mm × 550 mm (height × width × length) that were previously used in flexural tests. Two cores were extracted from one beam, each core 100 mm distant from the crack formed during the flexural test. Extraction was performed in the casting direction of the beam. Specimens whose diameters were 150 mm were obtained from cutting cylinders measuring 150 mm × 300 mm (diameter × height) in half. Both specimen types were tested in open- and closed-loop machines.

3.2. Analysis of results

3.2.1. Results obtained from the open-loop machine

In order to analyze the influence of the extent of instability on the residual load $F_{0.5}$, the crack opening at the end of instability and the crack opening for the residual load $F_{0.5}$ were compared. Fig. 7 shows the correlations obtained between the results of TCOD (mm) versus $F_{0.5}/F_{cr}$ (kN/kN). The dashed curve represents the extent of instability and the continuous curve represents the crack opening for $F_{0.5}$. Each experimental point represents one specimen.

The crack opening values for the determination of $F_{0.5}$ are higher than the values corresponding to the extent of instability for all the cases analyzed. This indicates that $F_{0.5}$ is determined from crack opening values that fall outside the instability region of the test. When the $F_{0.5}/F_{cr}$ ratio approaches 0.1 and 1, the crack opening values were above 2.0 mm and below 0.5 mm, respectively. However, when the $F_{0.5}/F_{cr}$ ratio is greater than 0.6, the crack opening is less influenced (crack opening values between 0.7 and 0.9 mm), that is, the instability level is very low. This analysis confirms that instability is directly proportional to the difference between the strength of the matrix and the residual strength of the composite [16,18].

3.2.2. Results obtained from the closed-loop machine

This analysis was done similarly to the previous one. Fig. 8 shows the correlations obtained between the results of TCOD (mm) versus $F_{0.5}/F_{cr}$ (kN/kN), where the dashed curve represents the extent of instability and the continuous curve represents the crack opening for $F_{0.5}$.

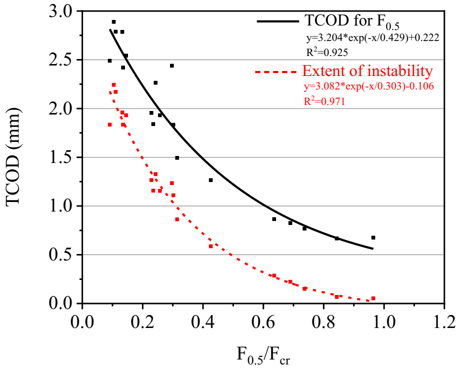


Fig. 7. TCOD versus $F_{0.5}/F_{cr}$ for open loop control.

The extent of instability is significantly reduced when the closed-loop machine is employed. Comparing Figs. 7 and 8, it is possible to observe that $F_{0.5}$ and the extent of instability are associated with smaller crack openings (TCOD) for the closed-loop test because the energy transfer from the equipment to the specimen is less abrupt. This difference occurs due to the higher level of control after concrete cracks, provided by the closed-loop system. Although the magnitude of the instability is smaller, it is not completely eliminated when axial displacement feedback occurs. A possible solution would be to use the deformation of the specimen as a feedback parameter for the load application.

Fig. 9 illustrates the difference between crack openings for $F_{0.5}$ determined in open- or closed-loop machines, which varies according to the $F_{0.5}/F_{cr}$ ratio. The difference exceeds 1 mm when $F_{0.5}/F_{cr}$ ratio approaches 0.1. Therefore, the greater the distance between the cracking load and the residual load at 0.5 mm the higher the TCOD associated with the $F_{0.5}$ load. This can be considered a limitation of the test method, especially for the parametrization of the post-crack behavior and for the establishment of constitutive equations. However, the use of DPT as a control test may be feasible if the post-crack response is established as a function of axial displacement and if they are correlated with 3-point bending tests. In this regard, it is necessary to verify the reliability of the determination of $F_{0.5}$ as a function of the equipment control system, which was the objective of the experimental program (part 2) conducted in this study.

Table 1
Specimens used in the first part of the study.

Specimen	Matrix	Fiber				Reference
Diameter (mm)	f_{ck} (MPa)	Material	Length (mm)	Aspect ratio	Dosage (kg/m^3)	
150	45	Polypropylene	–	–	5; 7; 10	Unpublished
150	45	Steel	60	80	20; 30; 45	Unpublished
150	35	Steel	60	80	15; 30; 55	[28]
150	35	Steel	60	80	15	[29]
150	40	Steel	33	40	15; 30	Unpublished
150	45	Polypropylene	48	–	3.5	Unpublished
150	45	Glass	43	59	3.8; 7.6; 11.5	[11]
100	35	Polypropylene	54	115	2.5	Unpublished
100	35	Polypropylene	48	61	2.5	Unpublished
100	30	Steel	60	80	20; 35; 55	Unpublished
100	30	Steel	60	80	20; 35; 55	Unpublished
100	30	Steel	30	45	30; 47	Unpublished
100	30	Polypropylene	54	180	5.5	Unpublished
100	30	Steel	30	45	30	Unpublished
		Polypropylene	54	180	1.8	
100	30	Steel	30	45	30	Unpublished
		Polypropylene	54	180	9.1	

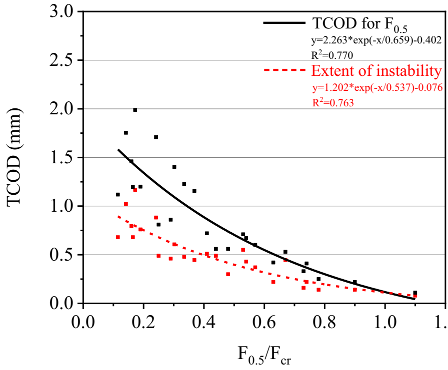


Fig. 8. TCOD versus $F_{0.5}/F_{cr}$ for closed loop control.

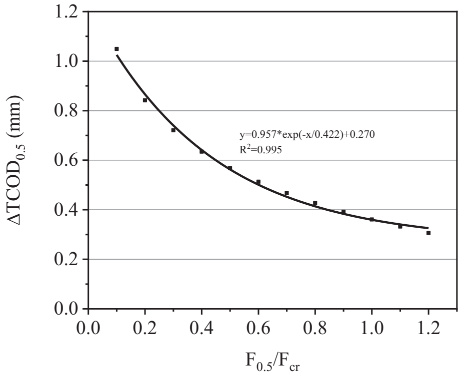


Fig. 9. Difference between the TCOD determined in open or closed loop tests as function of the $F_{0.5}/F_{cr}$ ratio.

4. PART 2: experimental program

4.1. Methodology of analysis

Part 2 consisted in evaluating the mechanical behavior of cylindrical FRC specimens by the DPT performed in open- and closed-loop machines. One concrete matrix (f_{ck} = 35 MPa) was produced with type II Portland cement (containing up to 35% of blast furnace slag), quartz river sand, artificial sand (crushed rock), crushed granite (d_{max} = 19 mm) and potable water, whose respective weight proportions were 1.00:1.18:0.63:2.79:0.51. The mix design adopted was based on FRC conventional applications.

A hooked end steel fiber was used at 10 kg/m^3, 30 kg/m^3 and 50 kg/m^3 and a polypropylene macrofiber was employed at 2 kg/m^3, 4 kg/m^3 and 6 kg/m^3. The properties and characteristics of fibers are described in Table 2. For each fiber type and content, sixteen specimens measuring 100 mm in diameter were produced. Eight of them were tested in the open-loop machine and the other eight in the closed-loop machine.

4.2. Analysis of results

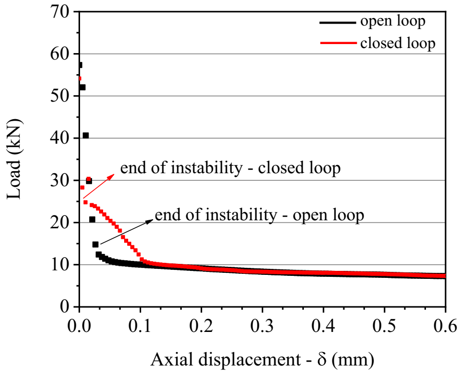


Fig. 10. Load versus axial displacement average curves for PFRC with 2 kg/m^{3}.

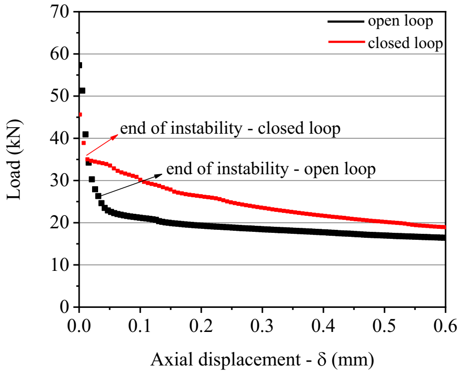


Fig. 11. Load versus axial displacement average curves for PFRC with 6 kg/m^{3}.

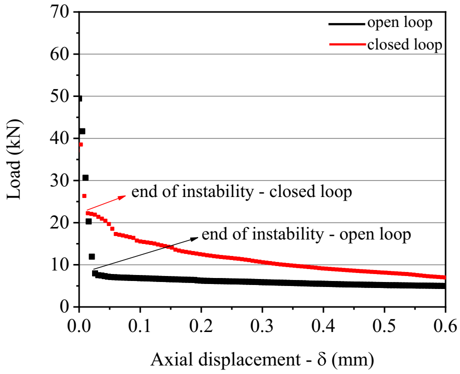


Fig. 12. Load versus axial displacement average curves for SFRC with 10 kg/m^{3}.

Figs. 10 and 11 show the average load-displacement curves obtained with concretes containing 2 and 6 kg/m^3 of polypropylene fibers (PFRC), respectively. Figs. 12 and 13 present the results obtained with concretes containing 10 and 50 kg/m^3 of steel fibers (SFRC), respectively. In both cases, curves obtained in open- and

Table 2
Properties and characteristics of fibers (provided by manufacturers).

Material	Tensile strength (MPa)	Dosage(kg/m^3)	Volume of fibers (%)	Diameter (mm)	Length (mm)	Geometry
Steel	1100	10; 30; 50	0.13; 0.39; 0.65	0.75	33	Hooked-end
Polypropylene	700	2; 4; 6	0.22; 0.44; 0.66	0.34	54	Twisted monofilament

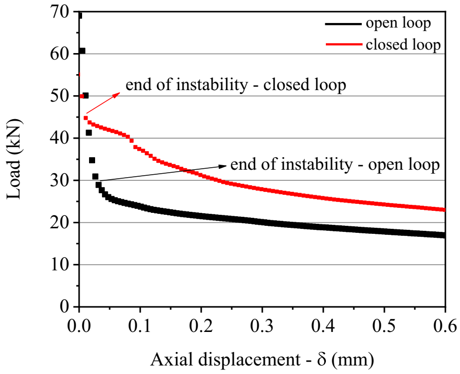


Fig. 13. Load versus axial displacement average curves for SFRC with 50 kg/m^3.

closed-loop machines are presented, with the axial displacement up to 0.6 mm in order to evidence the differences in the post-crack behavior in SLS.

Instability is identified by an abrupt fall in the load bearing capacity of the specimen right after cracking, which is more evident when the open-loop machine is used. Clearly, residual loads determined with the open loop system were inferior to the ones obtained with closed loop systems. Therefore, residual loads are underestimated when open loop tests are performed. The same tendency was previously demonstrated in previous studies performed with flexural tests [15–17,19].

The extent of post-crack instability and the $F_{0.5}$ obtained with both machines were compared statistically to verify if the equipment control systems influences the results derived from the load-displacement curves. 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, and it is rejected for p-values below 0.05. Tables 3 and 4 summarize the results obtained for the extent of instability and $F_{0.5}$, respectively.

Analyzing Table 3, it can be observed that the extent of instability is significantly higher when the open-loop machine is employed. However, it is not possible to reject the hypothesis that the average differences in $F_{0.5}$ are equal to zero, as presented in Table 4. Consequently, it may be inferred that $F_{0.5}$ is not significantly influenced by the equipment control system, that is, residual loads may be considered equivalent no matter which machine is employed and whatever instability occurs. The types of fibers, polypropylene or steel, do not significantly affect the extent of instability (p-value equal to 0.526). On the other hand, the extent of instability increases when the fiber content decreases (p-value equal to 0.000).

This finding shows that DPT is robust and capable of producing comparable results even when different machines are used. This condition favors its application in technological control of FRC, in which $F_{0.5}$ is the critical parameter evaluated.

5. Conclusions

This work has brought a first-time analysis of a critical problem of the DPT which is the evaluation of the risk of post-peak instability to impair the determination of residual strength of the FRC. The extent of instability in DPT performed in open- and closed-loop machines was evaluated focusing their influence on the residual load $F_{0.5}$. The following conclusions may be derived from the results obtained:

- DPT presents instability, whose magnitude varies according to the type of displacement control used during the test. In FRC with high matrix strength and low post-crack residual strength, the extent of instability is higher.
- The $F_{0.5}/F_{cr}$ ratio proved to be a parameter capable of covering the influences of different composite characteristics in a congruent analysis of the post-peak instability
- The extent of the post-crack instability does not exceed the TCOD values corresponding to the determination of the residual load $F_{0.5}$ for all specimens evaluated in open- and closed-loop systems. Therefore, $F_{0.5}$ is not subjected to the uncertainty of the instability region whichever equipment is used.
- Although the closed-loop system is able to reduce the extent of instability in the post-crack region, differences if $F_{0.5}$ values were not statistically different from the ones obtained in the open-loop machine.
- The extent of instability is inversely proportional to the $F_{0.5}/F_{cr}$ ratio. For a given $F_{0.5}/F_{cr}$ ratio the instability obtained in the open loop system is greater. However, the DPT performed in open loop system may be considered as reliable alternative test

Table 3
T-test for average results of extent of instability for open- and closed-loop machines.

Fiber	Content (kg/m^3)	Extent of instability (mm)		p-value	Null hypothesis
		Open-loop	Closed-loop		
Polypropylene	2	2.0 ± 0.4	1.0 ± 0.4	0.000	rejected
	4	1.3 ± 0.3	0.9 ± 0.4	0.016	rejected
	6	1.2 ± 0.6	0.6 ± 0.3	0.030	rejected
Steel	10	2.2 ± 0.5	1.2 ± 0.5	0.001	rejected
	30	1.1 ± 0.6	0.5 ± 0.2	0.027	rejected
	50	1.2 ± 0.5	0.5 ± 0.3	0.004	rejected

Table 4
T-test for average results of $F_{0.5}$ for open-and closed-loop machines.

Fiber	Content (kg/m^3)	$F_{0.5}$ (kN)		p-value	Null hypothesis
		Open-loop	Closed-loop		
Polypropylene	2	7.6 ± 1.0	8.2 ± 2.0	0.666	no rejection
	4	13.6 ± 2.6	13.9 ± 2.4	0.815	no rejection
	6	17.0 ± 4.2	20.2 ± 4.6	0.165	no rejection
Steel	10	5.2 ± 2.1	8.1 ± 4.6	0.134	no rejection
	30	15.3 ± 4.7	18.4 ± 4.6	0.203	no rejection
	50	17.9 ± 5.7	24.3 ± 8.1	0.092	no rejection

for the technological control of FRC. On the other hand, the determination of the constitutive equations from the results obtained in this test method can compromise the accuracy in the determination of the strength associated with the service limit state for composites that present lower values of $F_{0.5}/F_{cr}$ ratio.

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The authors declare that there is no conflict of interest at all.

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