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ORIGINAL ARTICLE

Evaluation of the replacement of minimum shear reinforcement by steel fibers in reinforced concrete beams

Avaliação da substituição da armadura transversal mínima por fibras de aço em vigas de concreto armado

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Abstract: The shear strength of fiber reinforced elements is usually predicted through analytical models calibrated from experimental tests. Few results obtained from these tests consider the mechanical characterization of the material, allowing to evaluate the different performances of fiber reinforced concrete. This work evaluates the possibility of replacing the minimum shear reinforcement of reinforced concrete beams with steel fibers. For this, comparations were made evaluating the shear strength of 240 experimental tests of steel fiber reinforced concrete (SFRC) beams using formulations from the literature and international standards, to define which equations are in better agreement with the experimental data. Thus, once this expression was identified, SFRC beam design abacuses were developed to determine the amount of steel fibers needed to replace the minimum shear reinforcement, according to NBR 6118 [1]. The results showed that the model by Kwak et al. [2] presented results similar to those obtained in experimental tests of beams. Finally, it is concluded that the developed abacuses will facilitate decision-making in the design of SFRC beams.

Keywords: steel fiber, beams, reinforced concrete, shear.

Resumo: A resistência ao cisalhamento de elementos reforçados com fibras é geralmente prevista por meio de modelos analíticos, calibrados a partir de ensaios experimentais. Poucos resultados obtidos através desses ensaios levam em consideração a caracterização mecânica do material, permitindo avaliar os diferentes desempenhos do concreto reforçado com fibras. Este trabalho avalia a possibilidade de substituição da armadura mínima de cisalhamento de vigas de concreto armado por fibras de aço. Para isso, foram feitas comparações avaliando a resistência ao cisalhamento de 240 ensaios experimentais de vigas de concreto reforçado com fibras de aço (CRFA), utilizando formulações da literatura e normas internacionais para definir quais equações apresentam uma maior concordância com os dados experimentais. Assim, identificada essa expressão, foram desenvolvidos ábacos de dimensionamento de vigas em CRFA que determinam a quantidade de fibras de aço necessárias para substituir as armaduras mínimas de cisalhamento, conforme a NBR 6118 [1]. Os resultados mostraram que o modelo de Kwak et al. [2] apresentou resultados semelhantes aos obtidos em ensaios experimentais de vigas. Por fim, conclui-se que os ábacos desenvolvidos facilitarão a tomada de decisão no dimensionamento de vigas CRFA.

Palavras-chave: fibras de aço, vigas, concreto armado, cisalhamento.

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1 INTRODUCTION

The discovery of concrete was responsible for the growth of buildings in the world. Concrete is a widely used material in civil construction and one of the most consumed in the world, according to IBRACON [3]. Because it is widely used, concrete is one of the most researched building materials, so there is a constant search for innovation in its use. Thus, it is noted the importance of knowing concrete more deeply as structural material.

In recent decades, a material that has shown considerable growth is the steel fiber reinforced concrete (SFRC). This material has been gaining space and its use is concentrated in low fiber consumption applications, being used in works of great social demand, such as sanitation and transportation. Being used in several fields, such as airports, bridges, tunnels, earthquake-resistant structures, and with different types of concrete, such as pre-stressed concrete and pre-cast concrete, [4]-[7]. However, some barriers still need to be overcome, so that there is greater acceptance of this material in the field of civil construction.

In Brazil, some technical standards address the SFRC theme, most of which are recently published: NBR 15530 [8], NBR 8890 [9], NBR 16935 [10], NBR 16938 [11], NBR 16939 [12] and NBR 16940 [13]. However, in other countries the fibers are already widely used, so several international standards address this issue: ACI 318 [14], ACI 544.1R-96 [15], ACI 544.2R-89 [16], ACI 544.3R-93 [17], ACI 544.4R-18 [18], DAfStB [19], fib Model Code [20], JSCE [21] and RILEM [22].

In the past decades, research have shown that the inclusion of steel fibers is highly beneficial to enhance both the behavior of the structural members at Serviceability Limit State (SLS) [23]-[25] and the structural resistance at Ultimate Limit State (ULS) [26]-[32]. Steel Fiber Reinforced Concrete (SFRC) generally exhibits improved toughness, ductility, cracking resistance, and tensile strength relative to normal concrete, the possibility to replace partially or totally the conventional reinforcement (Trindade et al. [33]). According to Bentur and Mindess [34], the main contribution of the addition of fibers occurs in the post-cracking zone, in which the fibers bridge across the cracked matrix. The behavior of the composite can be influenced by several parameters: structure of the concrete matrix; material, shape and geometry of the fiber; fiber content; distribution of the fibers and fiber-matrix interface structure, which can justify the variability presented on the mechanical responses of this type of composite.

Recently, several authors have studied the post-cracking behavior of SFRC according to EN 14651 [35], investigating the influence of several parameters [36]-[42]. In the same way, several research have been developed for the application of steel fibers in structural elements to replace shear reinforcement. According to Lim et al. [43], the replacement of stirrups by the fibers in structural members is especially attractive in regions of high shear and bending moments.

Studies of shear strength in SFRC beams have been developed over the years [44]-[56], with the intention of understanding how the addition of steel fibers inside the concrete influence the increase of strength to shear force. Some authors report a considerable gain in the shear strength of SFRC beams compared to conventional concrete beams. Slater et al. [57] described a 258% increase, according to study by Adebar et al. [58]. However, the same authors cite a study by Shin et al. [59] where the strength gain of SFRC beams was below 9%. Nzambi et al. [60] observed that shear strength increased approximately 109% with the addition of 1% of steel fibers, comparing beams with the same longitudinal reinforcement ratio. Thus, variability in the experimental results of studies related to the gain of shear strength promoted by steel fibers has been observed.

Steel fibers are defined as a discontinuous element, presenting length much greater than the largest dimension of the cross section. They are manufactured with different shapes and geometries (hooked, crimped, straight smooth, mixed, fibers with a flat end, flat fibers, round fibers, mill-cut fibers, 4D/5D hooked-end ones, recycled fibers, and corrugated fibers, among others) [8], [61]-[63], presenting an important influence on the behavior of the composite [64].

Generally, steel fibers provide an increase in the shear strength of SFRC beams by their random distribution inside the concrete, promoting a small space between them, transferring the tensile stresses between the cracks, changing the post-cracking behavior of the concrete, and increasing the ductility of the material. The interest in studying the behavior of shear in beams is essential since this force can cause a fragile rupture, which can be altered with the addition of fibers. In previous studies, [65]-[70], the influences of several parameters: compressive strength of concrete (f_c), the relationship between the shear span and effective depth of the beam cross section (a/d), longitudinal reinforcement ratio (ρ), fiber volume (V_f), fiber format (ρ_f), and aspect ratio (l_f/d_f) on the shear strength behavior of SFRC were analyzed. Lantsoght [61], Vitor et al. [71], Kwak et al. [2], and Arslan et al. [56] reported a gain in the strength of steel fiber reinforced concrete beams, using longitudinal reinforcements and without stirrups.

According to the results from this literature, it can be claimed that the development of this type of research brings significant benefits to the current scenario of civil construction. Once that the use of SFRC may dispense, in part or completely, the conventional (passive) reinforcements of the concrete elements, promoting an increase in productivity and minimization of construction errors. Furthermore, it may also provide a reduction in material consumption and optimization in construction processes.

Within this context, this research evaluates the possibility of replacing the minimum shear reinforcement by steel fibers in reinforced concrete beams. Through statistical methods, comparisons are made between 240 results of experimental tests with 3 international normative formulations and 10 sets of equations in the literature, evaluating the shear strength of reinforced concrete beams to choose the expression that was closest to the experimental data. Therefore, the formulation that best represented the experimental tests results was used to develop SFRC beam design abacuses, becoming a simple alternative to define the amount of steel fibers needed to replace the minimum shear reinforcement, according to the NBR 6118 [1]. The proposed design abacuses can be considered simple and easy to apply for SFRC beam design.

2 DATA BASE

The models for predicting shear strength in SFRC beams, presented in item 3, were applied to an experimental database. These tests measured the shear strength of concrete beams, reinforced longitudinally and without stirrups. The database developed for this study contains 240 experiments of SFRC beams, which was mainly collected from a public domain database compiled (488 experiments) by Lantsoght [61] and the 8 tests conducted by Vitor et al. [71]. The database covers a very large distribution of significative parameters, e.g., many different fiber types, several cross sections, the maximum beam width and height that has been tested are 610 mm and 1220 mm, respectively. More information about the public domain database, see in Lantsoght [61] and Lantsoght [72].

In this paper, only rectangular cross section beams were selected and whose concrete has a compressive strength up to 50 MPa. The rectangular cross section was chosen because it is the most commonly used in beam designs. The compressive strength of concrete belonging to Group 1 of NBR 6118 [1] was considered. The tests were conducted by [43], [46], [47], [51]-[54], [56], [58], [71], [73]-[90]. The database used in this work can be found at [91].

Table 1 shows the ranges and statistics of the parameters b_w (width of cross section), h (height of cross section), d (effective depth), L (length of the beam), a/d, ρ, d_a (maximum aggregate size), f_c, V_f, l_f, d_f and l_f/d_f in the database. It can be observed that wide ranges of selected parameters are considered.

Table 1. Ranges of parameters in database [91].

Parameter	Minimum	Maximum
b_w (mm)	100	310
h (mm)	152	1000
d (mm)	127	923
L (mm)	762	5538
a/d	0.58	5
ρ (%)	0.99	4.10
d_a (mm)	2	22
f_c (MPa)	9.77	49.9
V_f (%)	0.20	3.0
l_f (mm)	7.05	60
d_f (mm)	0.15	1.11
l_f/d_f	25	101.6

The frequency distribution of the main database parameters is shown in Figures 1 to 5. According to Figure 1, the geometric parameters of b_w and h have their values concentrated between $100 - 250$ mm ($< 97\%$) and up to 350 mm ($< 74\%$), respectively.

From Figure 2, it can be seen that the effective beam height (d) have their values concentrated between $100 - 400$ mm ($< 88\%$) and the span length (L) shows crowding in a small beam length range, up to 2250 mm ($< 74\%$).

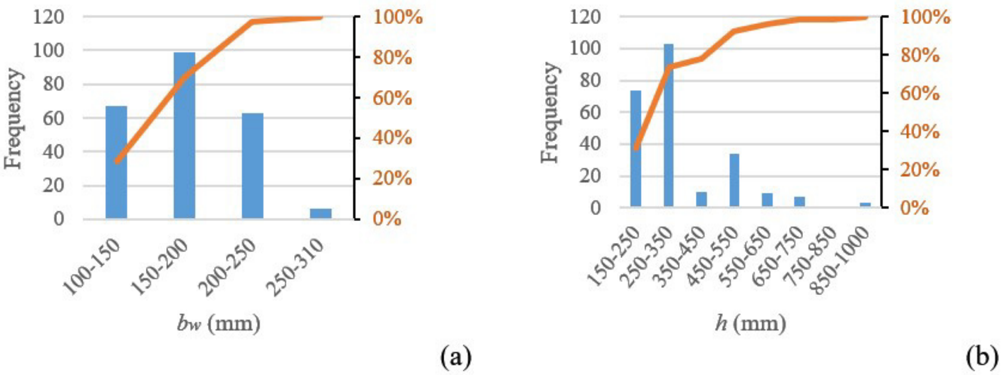

Figure 1. Distribution of parameters in database [91]: (a) beam width and (b) beam height.

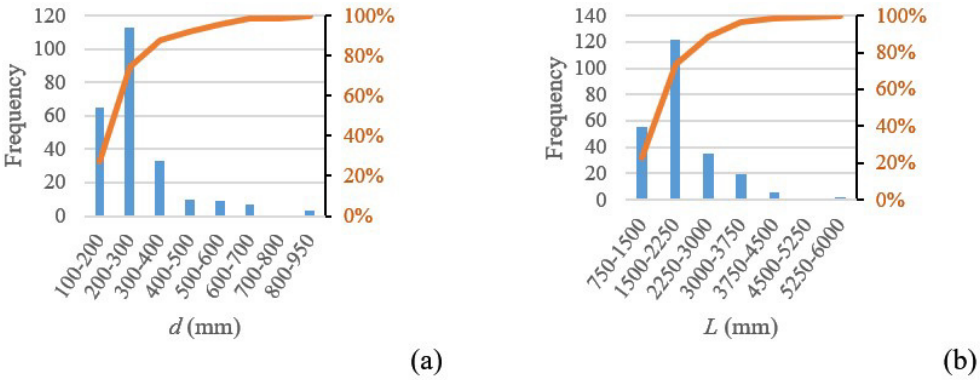

Figure 2. Distribution of parameters in database [91]: (a) effective height and (b) span length.

The specimens in the database are normally distributed in terms of shear span to depth ratio, see Figure 3a, with $a/d = 3.5$ as the most frequently used value. Typically, this value is widely used because smaller values increase the shear strength caused by the arching action [92]. Figure 3b shows the range of values of the reinforcement ratio from $1.0 - 3.5\%$ ($< 95\%$). The longitudinal reinforcement ratio was relatively well distributed, observing high values, which is common for this type of test, thus compelling beam failure in shear mode rather than flexure.

The maximum diameter of the aggregate has its values between 10 and 15 mm, as shown in Figure 4a. From Figure 4b, it can be seen that the concrete compressive strength was distributed between 20 and 50 MPa, and has its highest concentration between 30 and 45 MPa. The results lie withing the range of normal strength concrete.

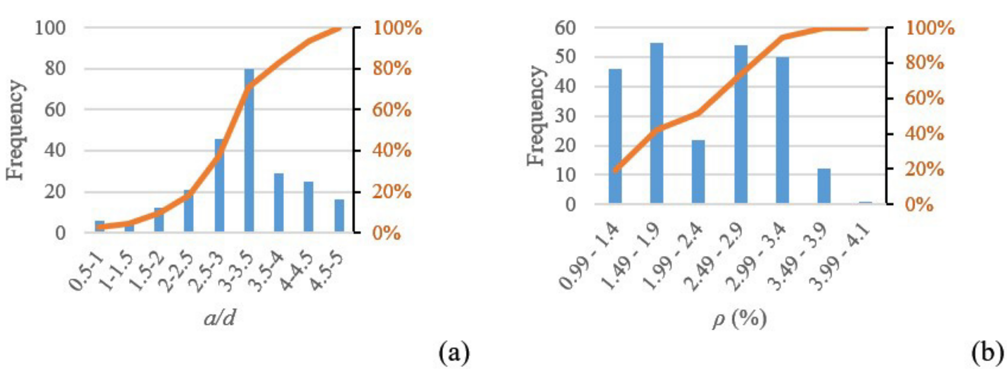

Figure 3. Distribution of parameters in database [91]: (a) shear span to depth ratio and (b) longitudinal reinforcement ratio.

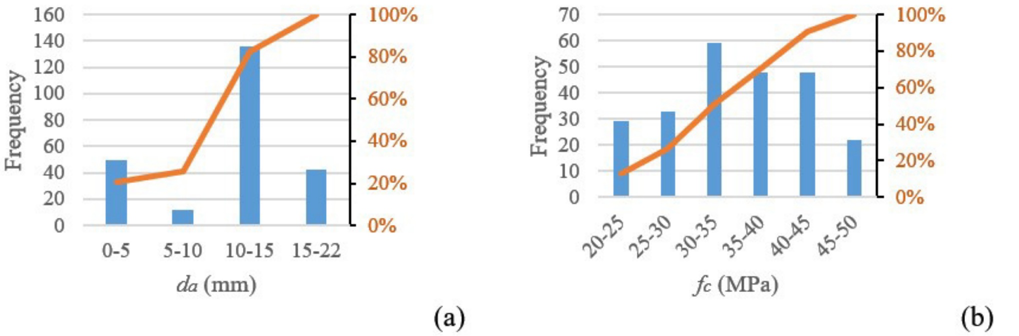

Figure 4. Distribution of parameters in database [91]: (a) maximum aggregate size and (b) compressive strength of concrete.

According to Figure 5a, the fiber volume fraction, shows crowding in the range of $0.5 - 1.5\%$ ($< 87\%$). Although tests with V_f up to 3% were considered, few tests have employed more than 1.5%, because above these fractions the material is less effective in terms of workability. Most of the steel fibers used in the tests have an aspect ratio between 50 and 75, as shown in Figure 5b. Various steel fiber types are available on the market today, however, the most frequently used fibers in the database are hooked (67%) and crimped (17%).

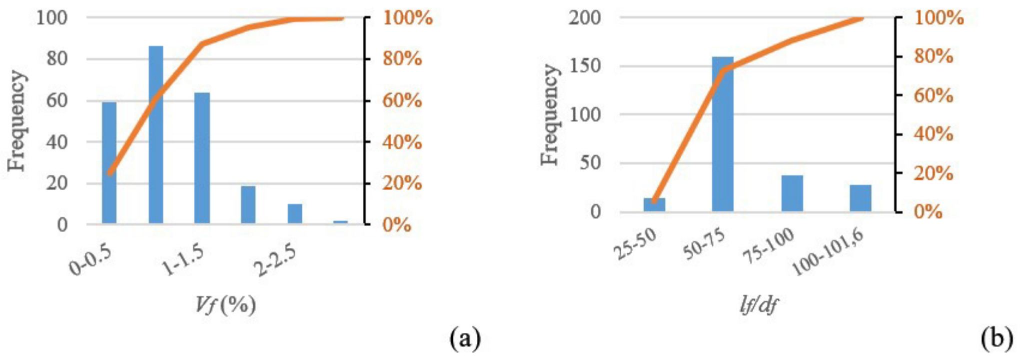

Figure 5. Distribution of parameters in database [91]: (a) fiber volume and (b) aspect factor.

3 MODELS OF PREDICTION OF THE SHEAR STRENGTH IN SFRC BEAMS

Over the past 60 years, several models for predicting shear strength in SFRC beams have been proposed. The vast majority of them are empirical models [2], [44], [53], [54], [93] and [94], developed from an experimental data set. Furthermore, some formulations are based on the mechanical properties of the composite material ([95], [96]). Generally, the models use as main parameters to predict shear strength in SFRC beams: the compressive and tensile strengths of concrete (f_c and f_{ct}), a/d ratio (shear span and effective height), longitudinal reinforcement ratio (ρ), fiber volume (V_f) and parameters related to the type of steel fiber used.

It is shown in the Table 2, the models for predicting shear strength in steel fiber reinforced concrete beams selected for this work: eight models proposed by several authors ([2], [44], [52]-[54], [93], [95], [96] - models 1 to 8), three models of international standards ([19], [20], [22] - models 9 to 11) and two models developed based on linear regression ([91] - models 12 and 13).

In the model 1 proposed by Singh and Jain [53], the value of fiber efficiency factor (D_f) was considered equal to 1 for hooked fibers and 0.75 for the others. Similarly, the value of bond strength between fibers and matrix (τ) was considered equal to $0.85\sqrt{f_c}$ for hooked fibers and $0.75\sqrt{f_c}$ for the other types of fibers. The value of height of compression zone (c) was obtained according to the established in the model of Dinh et al. [52].

In the model 4 from Kwak et al. [2], the value f_{cuf} was adopted as $f_c/0.85$, proposed by Lantsoght [61]. The value of adherence factor (β) was considered equal to the factor that takes into the type of steel fiber used (ρ_f). The factor ρ_f has the values 1.0, 0.75, and 0.5 for fibers with hooked, crimped and other types of fibers, respectively.

In the model 7 from Imam et al. [96], the maximum aggregate size (d_a) was considered equal to the weighted mean among the large aggregates used for the tests performed by Vitor et al. [71]. Additionally, Vitor et al. [71] used 25% of large aggregate with a maximum diameter of 12.5 mm and 75% with a maximum diameter of 19 mm, and this weighted mean was made, obtaining value of d_a equal to 17,375 mm.

Table 2. Models for predicting shear strength in SFRC beams.

Ref.	Expression	
Model 1 – Singh and Jain [53]	$V_u = V_{CC} + V_{FRC}$	(1)
	$V_{CC} = 0.13\, A_s\, f_y$	(2)
	$V_{FRC} = 0.5\, \tau\, D_f\;\; l_f/d_f\;\; b_w\,(d-c)\;\cot\alpha$	(3)
	$\tau = \begin{cases} 0.85\sqrt{f_c} \rightarrow For\ hooked\ fibers \\ 0.75\sqrt{f_c} \rightarrow For\ crimped\ fibers \end{cases}$	(4)
Model 2 – Sahoo and Sharma [54]	$V_u = \left(0.251 + 0.173V_f + 0.069{V_f}^2\right)\sqrt{f_c}\, b_w\, d$ (d < 300 mm)	(5)
	$V_u = \left(0.202 + 0.377V_f - 0.113{V_f}^2\right)\sqrt{f_c}\, b_w\, d$ ($d \geq$ 300 mm)	(6)
Model 3 – Dinh et al. [52]	$V_u = V_{CC} + V_{FRC}$	(7)
	$V_{CC} = 0.13\, A_s\, f_y$	(8)
	$V_{FRC} = (\sigma_t)_{avg}\, b_w\,(d-c)\;\cot\alpha$	(9)
	$c = \dfrac{A_s\, f_y}{k_1\, k_3\, f_c\, b_w}$	(10)
	$k_1\, k_3 = 0.85\,\beta_1$	(11)
	$\beta_1 = \begin{cases} 0.85 \rightarrow\ f_c \leq 27.6\,MPa \\ 0.65 \rightarrow\ f_c \geq 55.1\,MPa \\ Interpolation \rightarrow\ 27.6\,MPa < f_c < 55.1\,MPa \end{cases}$	(12)
Model 4 – Kwak et al. [2]	$V_u = \left[3.7\, e\, f_{spfc}^{2/3}\left(\rho\dfrac{d}{a}\right)^{1/3} + 0.8\, \upsilon_b\right] b_w\, d$	(13)
	$f_{spfc} = \dfrac{f_{cuf}}{\left(20-\sqrt{F}\right)} + 0.7 + \sqrt{F}$	(14)
	$e = \begin{cases} 1 \rightarrow \dfrac{a}{d} > 3.4 \\ 3.4\,\dfrac{d}{a} \rightarrow \dfrac{a}{d} \leq 3.4 \end{cases}$	(15)
	$\upsilon_b = 0.41\,\tau\, F$	(16)
	$F = \left(l_f/d_f\right) V_f\, \beta$	(17)
Model 5 – Sharma [44]	$V_u = \left[\dfrac{2}{3}\, f_{ct}\left(\dfrac{d}{a}\right)^{0.25}\right] b_w\, d$	(18)
Model 6 – Sarveghadi et al. [95]	$V_u = \left[\rho + \dfrac{\rho}{\upsilon_b} + \dfrac{1}{\frac{a}{d}}\left(\dfrac{\rho\, f_t\,(\rho+2)\left(f_t\,\frac{a}{d} - \frac{3}{\upsilon_b}\right)}{\frac{a}{d}} + f_t\right) + \upsilon_b\right] b_w\, d$	(19)
	$f_t = 0.79\sqrt{f_c}$	(20)
Model 7 – Imam et al. [96]	$V_u = \left[0.6\,\psi\,\sqrt[3]{\omega}\left((f_c)^{0.44} + 275\sqrt{\omega/\left(\frac{a}{d}\right)^5}\right)\right] b_w\, d$	(21)
	$\psi = \left(1 + \sqrt{5.08/d_a}\right)/\sqrt{1 + (d/25d_a)}$	(22)
	$\omega = \rho(1+4F)$	(23)
Model 8 – Arslan [93]	$V_u = \left[\left(0.2\,(f_c)^{2/3}\,\dfrac{c}{d} + \sqrt{\rho\,(1+4F)\,f_c}\right)\sqrt[3]{\dfrac{3}{\frac{a}{d}}}\right] b_w\, d$	(24)
	$\left(\dfrac{c}{d}\right)^2 + \left(\dfrac{600\,\rho}{f_c}\right)\left(\dfrac{c}{d}\right) - \dfrac{600\,\rho}{f_c} = 0$	(25)
Model 9 – DafStB [19]	$V_{Rd,ct}^{f} = V_{Rd,ct} + V_{Rd,cf}$	(26)
	$V_{Rd,ct} = \dfrac{C_{Rd,c}}{\gamma_c}\, k(100\,\rho\, f_{ck})^{1/3}\, b_w\, d$	(27)

Table 2. Continued...

Ref.	Expression	
	$V_{Rd,cf} = \dfrac{\alpha_c^f\, f_{ctR,u}^f\, b_w\, h}{\gamma_{ct}^f}$	(28)
	$f_{ctR,u}^f = k_F^f\, k_G^f\, 0.37\, f_{cfIk,L2}^f$	(29)
	$k_G^f = 1.0 + 0.5\, A_{ct}^f \leq 1.7$	(30)
	$A_{ct}^f = b_w\, min.(d; 1.5m)$	(31)
	$k = 1 + \sqrt{200mm/d}$	(32)
Model 10 – fib model code [20]	$V_{Rd,f} = \dfrac{C_{Rd,c}}{\gamma_c}\, k \left(100\, \rho \left(1 + 7.5\, \dfrac{f_{Ftuk}}{f_{ctk}}\right) f_{ck}\right)^{1/3} b_w\, d$	(33)
	$f_{Ftuk} = 0.06\, f_{R1} + 0.3\, f_{R3}$	(34)
	$f_{ctk} = 0.3\, (f_{ck})^{2/3}, for\ f_{ck} \leq 50MPa$	(35)
Model 11 – RILEM [22]	$V_{Rd} = V_{cd} + V_{fd}$	(36)
	$V_{cd} = 0.12\, k(100\, \rho\, f_{ck})^{1/3}\, b_w\, d$	(37)
	$V_{fd} = 0.7\, k_f\, k\, \tau_{fd}\, b_w\, h$	(38)
	$k_f = 1.0 + n\left(\dfrac{h_f}{b_w}\right)\left(\dfrac{h_f}{d}\right) \leq 1.5$	(39)
	$n = \dfrac{b_f - b_w}{h_f} \leq 3\ and\ n \leq \dfrac{3b_w}{h_f}$	(40)
	$\tau_{fd} = 0.12\, f_{Rk,4}$	(41)
Model 12 – Linear Regression [91]	$V_u = \left(1.001 + 14.551\, \rho - 0.208\, \dfrac{a}{d} - 0.233\, \rho_f - 0.051\, V_f - 0.093\, d_f + 0.219\, F\right) \sqrt{f_c}\, b_w\, d$	(42)
Model 13 – Weighted Linear Regression (WLR) [91]	$V_u = 474.41 + 2157.81\, \rho - 83.49\, \dfrac{a}{d} + 1.61\, f_c + 2.073\, l_f - 70.72\, V_f - 32.46\, d_f - 1.94\, \dfrac{l_f}{d_f} - 0.162\, f_f + 106.07\, F$ (For hooked fibers end and $a/d < 3.0$)	(43)
	$V_u = -245.20 - 59.79\, \dfrac{a}{d} + 3.90\, f_c + 33.17\, V_f + 0.218\, f_f$ (For crimped fibers and $a/d < 3.0$)	(44)
	$V_u = 59.97 - 3769.81\, \rho - 6.36\, \dfrac{a}{d} + 8.99\, f_c + 1.44\, l_f - 6.89\, V_f - 162.24\, d_f - 1.48\, \dfrac{l_f}{d_f} - 0.024\, f_f + 147.81\, F$ (For other types of fibers and $a/d < 3.0$)	(45)
	$V_u = 907.90 - 6032.88\, \rho - 154.46\, \dfrac{a}{d} + 4.26\, f_c + 2.13\, l_f - 91.87\, V_f - 199.69\, d_f - 1.43\, \dfrac{l_f}{d_f} - 0.074\, f_f + 143.22\, F$ (For hooked fibers and $a/d \geq 3.0$)	(46)
	$V_u = 694.72 - 7.79\, \dfrac{a}{d} + 1.54\, f_c + 2.07\, l_f - 12.97\, V_f - 1.13\, \dfrac{l_f}{d_f} - 0.605\, f_f$ (For crimped fibers and $a/d \geq 3.0$)	(47)
	$V_u = -2344.49 + 37569.49\, \rho - 3.96\, \dfrac{a}{d} - 3.82\, f_c - 83.88\, l_f - 92.22\, V_f + 5043.99\, d_f + 20.78\, \dfrac{l_f}{d_f} + 0.081\, f_f + 432.59\, F$ (For other types of fibers and $a/d \geq 3.0$)	(48)

In addition to the models from the literature, the models of three international standards were adopted: German standard DAfStB [19], fib Model Code [20] and the model code of RILEM [22]. These standards enable to perform prism tests to determine the portion of steel fibers in obtaining shear strength.

Therefore, to be able to apply the formulations, some parameters were adopted, according to Lantsoght [61]. For applications of the international standards, it should be adopted that the values of γ_c and γ_{ct}^f equal to 1, to compare the shear strength prediction models in SFRC beams. In turn the value of $f_{cfIk,L2}^f$ of the German standard DAfStB [19] should be equal to the value of f_{spfc}, according to the expression proposed by Thomas and Ramaswamy [97] (Equation 49).

$$f_{spfc} = 0.63\sqrt{f_{cuf}} + 0.288\,F\sqrt{f_{cuf}} + 0.052\,F \tag{49}$$

being f_{cuf} igual to $f_c/0.85$, as adopted for the model of Kwak et al. [2].

For the model code of RILEM [22], Lantsoght [61] recommended to adopt the value of $f_{Rk,4}$ equal to f_{spfc}, calculated according to Thomas and Ramaswamy [97]. In the fib model code [20], the value f_{Ftuk} is adopted equal to $f_{ctR,u}^{f}$, according to the German standard [19].

The first linear regression model proposed in this research (model 12) was developed from the database (item 2), taking into account all parameters: width of the cross section of the beam (b), height of the beam cross section (h), effective height of the beam cross section (d), beam test span (L), shear span (a), longitudinal reinforcement ratio (ρ), relationship between shear span and the effective height of the cross section of the beam (a/d), maximum aggregate size (d_a), compressive strength of concrete (f_c), fiber shape (ρ_c), fiber length (l_f), fiber volume (V_f), fiber diameter (d_f), aspect ratio (l_f/d_f), tensile strength of the fibers (f_f), and fiber factor (F), and considering the normalized shear stress $\nu_u/\sqrt{f_c}$.

After a preliminary study, it was verified that some parameters (b, h, d, L, a, d_a, f_c, l_f, l_f/d_f and f_f) had a little influence on the value of normalized shear stress. Thus, such parameters were disregarded and the formulation associated with linear regression is shown in Table 2.

For developing equations related to the weighted linear regression (model 13) the database was divided into six groups. These groups varied according to the type of steel fiber used and a/d ratio. Similar methodology was adopted by Slater et al. [57] and Islam and Alam [98].

The characteristics of the groups adopted for the application of the weighted linear regression model are shown in Table 3. This table shows that most of the data are in the groups of steel fibers hooked (G1 and G4), because this type of fiber is the most used in experimental tests. After classifying the data into groups, linear regression was applied to each group and the equations obtained are presented in Table 2. It can be observed that some equations do not present all parameters, due to the reduced influence it has on the shear strength of SFRC beams.

Table 3. Characteristics of the groups according to the type of steel fiber used and the a/d [91].

Groups	a/d	Types of Fibers	Number of beams
G1	< 3.0	hooked	68 (28.33%)
G2		crimped	10 (4.17%)
G3		other	12 (5.0%)
G4	≥ 3.0	hooked	93 (38.75%)
G5		crimped	31 (12.92%)
G6		other	26 (10.83%)

3.1 Comparison between the prediction models

All models used for predicting shear strength in steel fiber reinforced concrete beams, presented in Table 2 were compared with the experimental results. For the comparison between the prediction models, some statistical tests were used.

Initially, the relationship between experimental shear strength and strength obtained in the prediction models $(\frac{V_{u-exp}}{V_{u-teo}})$ was calculated, with their mean, maximum and minimum values. Then, the standard deviation (S.D.) and coefficient of variation (C.V.) tests were applied for the ratio $(\frac{V_{u-exp}}{V_{u-teo}})$. Also, the absolute mean error (E_{mean}), the correlation coefficient (R) and the coefficient of determination (R^2) between the values of V_{u-teo} and V_{u-exp} were considered.

Finally, the maximum and minimum values of shear strength were calculated for each model (V_{u-teo}). The shear strength in SFRC beams obtained using the analyzed models, see item 5, is compared with experimental data through point cloud graphs.

4 DESIGN ABACUSES

To analyze the possibility of replacing the minimum shear reinforcement by steel fibers in reinforced concrete beams, initially it was necessary to define the minimum limit for shear force, following the Calculation Model I based on NBR 6118 [1], according to Equation 50.

$$V_{Rd,min} = 0.0137\, b_w\, d\, \sqrt[3]{{f_{ck}}^2} \tag{50}$$

The design value of the external shear force (V_{Sd}) should be compared with the minimum resistant shear force ($V_{Rd,min}$), so that:

- If $V_{Sd} \leq V_{Rd,min} \rightarrow$ minimum shear reinforcement used;
- If $V_{Sd} > V_{Rd,min} \rightarrow$ the shear reinforcement calculated for V_{Sd}.

Analyzing Equation 50, it is observed that the factors that influence the definition of minimum shear reinforcement values for beams are the effective width (b_w and d) of the cross section and the concrete compressive strength (f_{ck}). From this formulation, it was possible to define the shear force limit for each analyzed beam and to determine the minimum resistant shear force value that would need to be adopted in SFRC beams. This equation was compared with the formulation of Kwak et al. [2] (Equations 13 to 17), which was developed to obtain the ultimate shear force in concrete beams without stirrups, with steel fibers, longitudinally reinforced, as can be seen in Equation 51.

$$V_d = \frac{1}{\gamma_{cf}} \left[3.7\, e\, f_{spfc}^{2/3} \left(\rho \frac{d}{a}\right)^{1/3} + 0.8\, v_b\right] b_w\, d \tag{51}$$

being, V_d the design shear force for the formulation of Kwak et al. [2].

In the development of structural designs, the use of characteristic strength values represents a safety margin in relation to the average values of this variable. In this context, in normative procedures safety coefficients are used, applied to the characteristic values of strength and actions.

The ABNT NBR 16935 [10] standard recommends values of 1.4 and 1.5 for the safety factors associated with compressive and tensile strength of fiber reinforced concrete. In this work, for the definition of the safety coefficients, the normative recommendations of NBR 6118 [1] were considered and the safety factor $\gamma_{cf} = 1.4$ was adopted.

To facilitate the determination of the amount of steel fibers (fiber volume - V_f) needed to promote the replacement of the minimum shear reinforcement by steel fibers in reinforced concrete beams were developed design abacuses. Given a reinforced concrete beam and considering that it can be reinforced transversely with minimum reinforcement ratio [1], the abacus determines the volume of steel fiber that could be used to dispense the minimum shear reinforcement.

The abacuses connect the a/d ratio and the longitudinal reinforcement ratio (ρ), providing the steel fiber volume ratio for values between 0.25%, 0.50%, 0.75%, 1.0%, 1.25% and 1.50%. These percentages of fibers were chosen because they are volumes normally used in practice. The limit of $V_f = 1.50\%$ was defined because above this value, the workability of the concrete is compromised. If a large amount of steel fibers (above 1.50%) for avoid of the minimum shear reinforcement is required, it would be convenient to seek another solution, such as maintaining the shear reinforcement or changing the dimensions of the beam.

The abacuses were developed for the following value ranges: $3.5 \leq a/d \leq 12.0$, $0 \leq \rho \leq 4\%$ and 20 MPa $\leq f_c \leq$ 50 MPa with increments of 5 MPa. The limits were defined to reproduce cases that approach practical situations, meeting the restrictions of NBR 6118 [1].

5 RESULTS AND DISCUSSIONS

A summary of the statistical tests applied to the entire set of beams in the database (240 tests) is presented with the models for predicting the shear strength of steel fiber reinforced concrete beams in Table 4. Some studies used different criteria to define the best model for predicting shear strength in SFRC beams. The results were evaluated in terms of the mean/maximum(Max)/minimum(Min) of the relationship between the experimental (V_{u-exp}) and theoretical (V_{u-teo}) values of the shear force of rupture, standard deviation ($S.D.$), coefficient of variation ($C.V.$), absolute mean error (E_{mean}) and coefficient of determination (R^2). In this work, the $C.V.$ will be prioritized in the choice of the model that most closely approximates the experimental values of shear strength of the tested beams.

It is observed that the model by Kwak et al. [2] has the smallest coefficient of variation ($C.V. = 24.9\%$), as shown in Table 4. However, when evaluating the means of the relationship $\left(\frac{V_{u-exp}}{V_{u-teo}}\right)$, being verified that the models of Imam et al. [96]

and the weighted linear regression (WLR), developed in this work, present the best values (closer to the unit), although the model of Kwak et al. [2] also has a higher mean (1.04). The Imam model ([49], [96]) presents a minimum value for the relationship $\frac{V_{u-exp}}{V_{u-teo}} = 0.09$, reflection of the maximum value of the ultimate shear force (V_{u-teo} =4592.48 kN). This value occurred for the beams of the tests performed by Narayanan and Darwish [45], since it has a very low a/d ratio, which impacts the value of V_{u-teo} for this model. Lantsoght [61] determined that the model of Kwak et al. [2] presented the best approximations for the values of shear strength in SFRC beams, analyzed a total of 488 tests. When only rectangular cross section beams were analyzed, the author determined that the Arslan [93] was more efficient.

Table 4. Statistical analysis of shear strength prediction models in SFRC beams.

Model	$\frac{V_{u-exp}}{V_{u-teo}}$			$S.D.$	$C.V.$	E_{mean}	R^2	V_{u-teo}	
	Mean	Max	Min		(%)	(%)		Max (kN)	Min (kN)
Singh and Jain [53]	1.26	4.41	0.37	0.59	46.7	27.2	0,659	783.87	16.51
Sahoo and Sharma [54]	2.06	8.23	0.95	1.13	54.7	43.8	0,626	364.82	14.60
Dinh et al. [94]	1.46	5.38	0.65	0.63	43.4	27.7	0,687	543.70	21.30
Kwak et al. [2]	1.04	1.87	0.33	0.26	24.9	23.0	0,801	840.35	16.62
Sharma [44]	1.17	3.52	0.54	0.42	36.4	21.7	0,691	718.51	20.81
Sarveghadi et al. [95]	1.05	1.80	0.34	0.28	26.7	23.1	0,837	809.09	16.66
Imam et al. [96]	1.01	1.91	0.09	0.32	31.3	43.2	0,257	4592.48	18.68
Arslan [93]	1.14	2.43	0.63	0.29	25.9	17.5	0,805	722.18	18.85
DAfStB [19]	1.35	4.42	0.65	0.62	45.9	23.4	0,684	559.96	21.12
Fib [20]	1.37	4.49	0.66	0.63	46.0	25.1	0,686	479.62	22.87
Linear regression [91]	1.05	6.46	0.46	0.45	43.5	22.6	0,801	806.69	6.57
WLR [91]	1.01	2.44	-3.63	0.47	46.6	33.4	0,642	375.75	-9.64

The models of Arslan [93] and Sarveghadi et al. [95] present the second and third best $C.V.$, respectively, in addition to very good values of $\frac{V_{u-exp}}{V_{u-teo}}$ means. When observing the value of R^2, it was verified that, after the model of Sarveghadi et al. [95], the model of Arslan [93] reflects 80.5% of the experimental data, very close to the third place that is the Kwak et al. [2] (80.1%). The model Imam et al. [96], despite having the best mean ratio $\frac{V_{u-exp}}{V_{u-teo}}$, as discussed above, has the lowest value for $R^2 = 0.257$.

The model of Sahoo and Sharma [54] has the highest $C.V.$ and also the highest value of the mean ratio $\frac{V_{u-exp}}{V_{u-teo}}$, followed by the models of international standards, Dinh et al. [94] as well as Singh and Jain [53]. The models with the highest values of the mean ratio $\frac{V_{u-exp}}{V_{u-teo}}$ are the most conservative, which is desirable by the standards.

The linear regression models developed in this study showed very good values for the relationship $\frac{V_{u-exp}}{V_{u-teo}}$. The linear regression model (model 12) also presented excellent values of E_{mean} and R^2. The negative value of V_{u-teo} in the WLR model (model 13) result from the application of the regression equations.

The absolute mean error (E_{mean}) is another measure that can be used to analyze the model with less disparity in relation to experimental data. When analyzing this measure, it can be seen that the model of Arslan [93] had the smallest E_{mean}, followed by Sharma model [44], Linear regression [91] and Kwak et al. [2], respectively.

Figure 6 shows for each model the comparison between tested V_{u-exp} and predicted V_{u-teo} results. As can be seen in Figure 6d-f-h, Kwak et al. [2], Sarveghadi et al. [95] and Arslan [93] presented the points cloud close to the identity function (line) as they are the models with the best values for $S.D.$, $C.V.$, E_{mean} and R^2. Despite some discrepancies with the experimental results, the model of Kwak et al. [2] is adopted because it presents the smallest $C.V.$ value. In addition, this model was chosen for the elaboration of the design abacuses because it is more easily used, since the analysis parameters (f_c, a/d, ρ, ρ_f, L_f/d_f and V_f) are directly related to the ultimate shear force (V_u), as presented in the Equations 13 to 17.

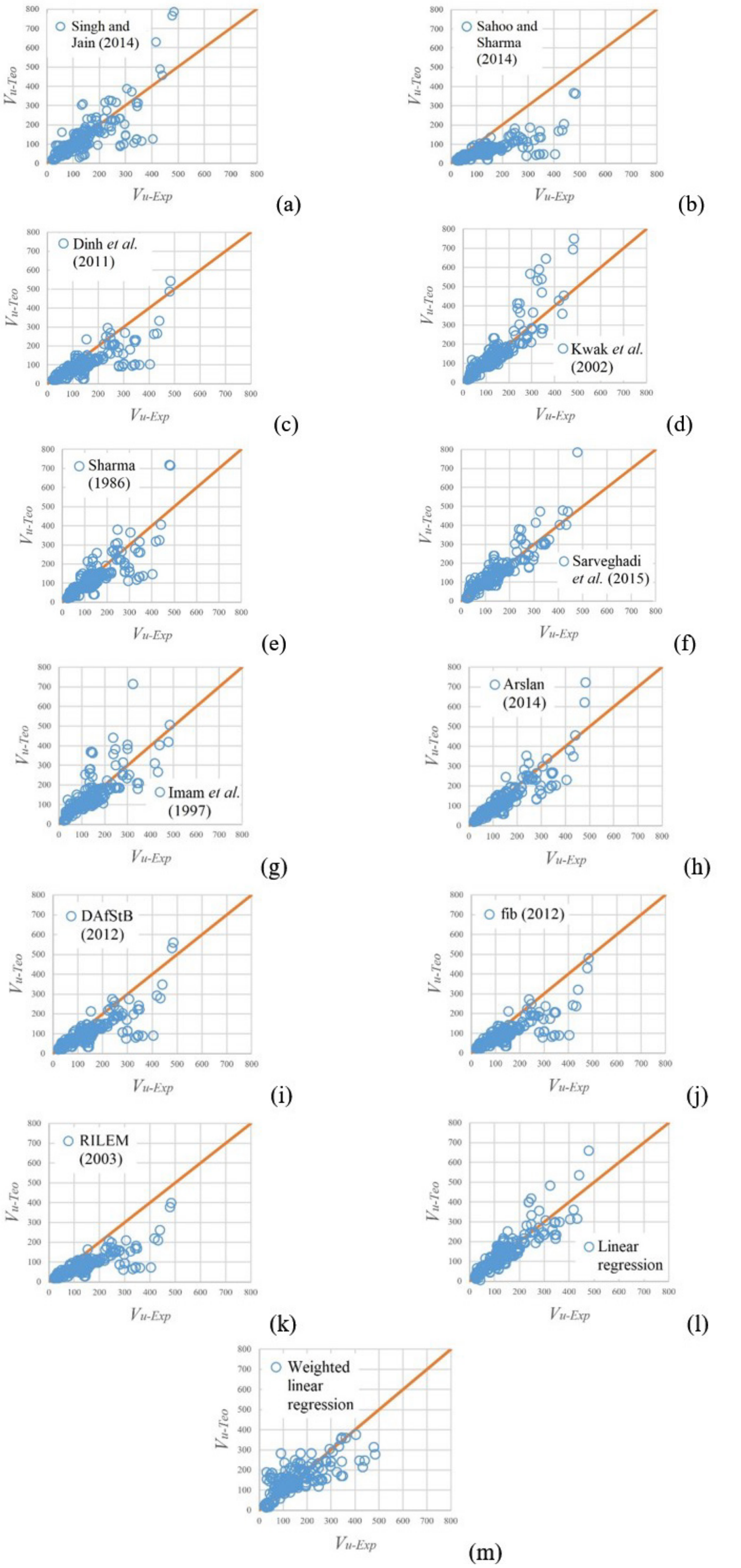

Figure 6. Relationship between experimental and theoretical values of the ultimate shear force: (a) Singh and Jain [53], (b) Sahoo and Sharma [54], (c) Dinh et al. [94], (d) Kwak et al. [2], (e) Sharma [44], (f) Sarveghadi et al. [95], (g) Imam et al. [96], (h) Arslan [93], (i) DAfStB [19], (j) fib Model Code [20], (k) RILEM [22], (l) Linear regression [91] and (m) Weighted linear regression [91].

It is observed that many authors ([53], [54], [61], [71], [94]) converge to the opinion that more research needs to be carried out to better understand the behavior of shear in SFRC beams.

Finally, to make more practical the process of using steel fibers in place of the minimum shear reinforcement in reinforced concrete beams, when these reinforcements are dimensioned according to the NBR 6118 [1], design abacuses have been developed. In order to estimate the V_f in a straightforward manner, abacuses can be derived from the Equations 13 to 17 of Kwak et al. [2], in which steel fiber volume, values from 0.25% to 1.50% with increments of 0.25%, can be immediately derived as a function of the parameters: longitudinal reinforcement ratio (ρ) and a/d ratio.

Abacuses were elaborated for f_c from 20 MPa to 50 MPa with increments of 5 MPa and taking into account the parameters related to the type of steel fiber used, $\rho_f = 1{,}0$ (fiber hooked), 0,75 (fiber crimped), 1,0 (other type) and $l_f/d_f = 35$, 60 and 80. The 42 abacuses developed can be found at [91]. In this work, it is shown only an abacus for the development of an application example.

5.1 Design abacus application – Case study

The present example illustrates the calculation of steel fiber volume for SFRC beam without stirrups. The rectangular section illustrated in Figure 7 is defined by the following geometric parameters: $b_w = 0.15$ m, $h = 0.30$ m, effective height $d = 0.25$ m and $L = 3.50$ m. The material used is concrete with $f_c = 30\ MPa$. Longitudinally reinforced with 3 reinforcements of 16.0 mm at the bottom (tension) and 2 reinforcements of 5.0 mm at the top (compressed). Considering a shear span equal to $a = L/2 = 175\ cm$, ratio $a/d = 7.0$, longitudinal tensile reinforcement equal to $(3\emptyset\ 16.0\ mm)$, longitudinal reinforcement ratio $\rho = 1.61\%$ and shear reinforcement equal to minimum reinforcement ($A_{sw,min}$).

For example, let's consider the abacus B2.3 (Figure 8) from Santos [91] with the following parameters: $\rho_f = 1.0$ (fiber hooked), $l_f/d_f = 60$ ratio and $f_c = 30\ MPa$. Using the abacus in Figure 8, the point of intersection of the parameters $a/d = 7.0$ and $\rho = 1.61\%$ is immediately identified. This point represents the steel fiber volume, and fall between the iso-limit curves $V_f = 0.75\%$ and $V_f = 1.0\%$; linear interpolation between 0.75% and 1.0% provides the value of the searched steel fiber volume.

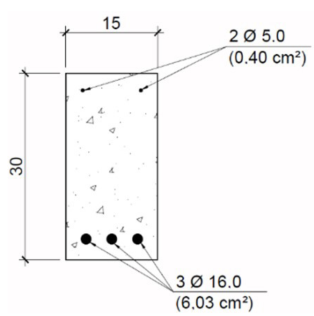

Figure 7. Details of the cross section of the beam.

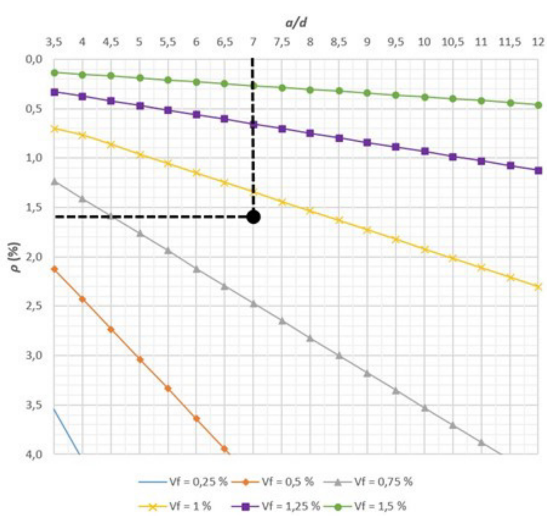

Figure 8. Abacus B2.3 [91] for steel fiber volume in beam.

If the point was above the limit curve ($V_f = 1.50\%$) it would be necessary to use a steel fiber content higher than 1.50%, thus, it would be better to seek for other alternatives. It is not recommended to use large quantities of steel fibers to avoid problems with the workability of concrete.

Figure 9 shows the influence of f_c, ρ, V_f in V_d and the amount of steel fibers required to replace the minimum shear reinforcement in SFRC beams. It can be concluded that the required amount of steel fiber was reduced with the increase of the longitudinal reinforcement ratio (ρ) and with the reduction of the a/d ratio. This reduction occurs due to increased shear strength (Equation 51).

Through the abacuses [91], it is observed that the growth in shear strength in SFRC beams (V_d) occurs with the growth of the parameters f_c, ρ and V_f. It is noticed that the increase in these values causes an increase in shear strength in SFRC beams (V_d). It is also observed that by increasing the compressive strength of concrete (f_c), there was a need for a greater amount of steel fibers to replace the minimum shear reinforcement. Thus, a possible increase of f_c, is not an economical solution, since in addition to increasing the cost for a more resistant concrete as well as the cost of fibers. It should be noted that the analyses shown in the Figure 9 consider a single type of steel fiber. For other types of fibers, see Santos [91].

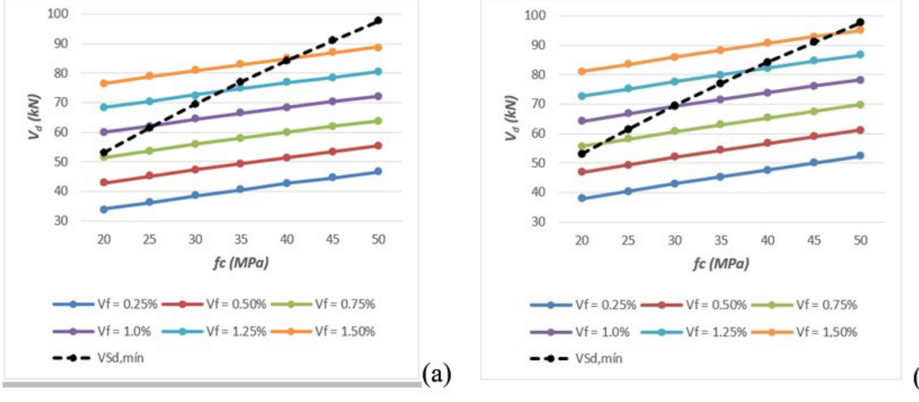

Figure 9. Influence of f_c, ρ, V_f in V_d and the amount of steel fibers required to replace the minimum shear reinforcement in SFRC beams: (a) $\rho = 1.0\%$, (b) $\rho = 1.50\%$.

The increase in V_d with the growth of the parameters f_c, ρ and V_f is not always observed in experimental tests. Vitor et al. [71] found a reduction of up to 11.25% in the shear strength of SFRC beams, with $f_c = 40$ MPa, $\rho = 1.32\%$ and V_f from 0.67% to 0.77%, when the measurement of normalized shear stress ($v_u/\sqrt{f_c}$) was used. In [69] it was observed that the higher the parameter that takes into account the type of steel fiber (ρ_f) and the form factor (L_f/d_f), the higher the beam shear strength and the fewer steel fibers will be required to replace the minimum shear sectional reinforcement.

Therefore, with the beam data and considering that minimum shear reinforcement was obtained, according to the normative procedures of NBR 6118 [1], the procedure for defining the amount of steel fibers required to replace the minimum shear-reinforcement become very simple with the use of abacuses.

6 CONCLUSIONS

This study aimed to evaluate the possibility of replacing the minimum shear-reinforcement in steel fiber reinforced concrete beams, being designed as recommended by the NBR 6118 [1]. In this context, the authors analyzed and compared some models of prediction of the shear strength of SFRC beams, proposed in the literature and in international standards.

Statistical analysis selected the model that presented the highest agreement with the experimental tests. Subsequently, abacuses were developed to define, in a simple and more straightforward, the content of steel fibers necessary to replace the minimum shear reinforcement in SFRC beams.

With the results obtained, the following conclusions can be stated:

- A great variability was observed in the results of experimental tests related to shear strength in SFRC beams, when analyzing the database with 240 beams.
- Most of the steel fibers in the database were type hooked. The volume of fibers used in the database ranges from 0.5% to 1.50%. These values are normally used in practice to contribute to the shear strength of SFRC beams.
- The model of Kwak et al. [2] presented the best coefficient of variation. But the models of Sarveghadi et al. [95] and Arslan [93] were also very efficient in this analysis. The models of international standards were quite

conservative. The linear regression models developed in this research showed a good mean of the relationship $\frac{V_{u-exp}}{V_{u-teo}}$, but very high values in the coefficient of variation.

- The definition of the amount of steel fibers required to replace the minimum shear reinforcement in SFRC beams, when these beams are sized according to NBR 6118 [1], using abacuses can be considered simple and practical, which can facilitate its use in SFRC beams of conventional structures.
- It was observed through abacuses that the growth of the longitudinal reinforcement ratio (ρ) and the reduction of the a/d ratio results in a smaller amount of steel fibers required to replace the minimum shear reinforcements in reinforced concrete beams. The increase of the parameters f_c, ρ, ρ_f and L_f/d_f causes growth in shear strength in SFRC beams (V_u) and fewer steel fibers (V_f) will be necessary to replace the minimum shear reinforcement.

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