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Proposal for Verification of Reinforced Concrete Beams to Shear

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Abstract:
Background*: The behavior of reinforced concrete beams to shear is still the subject of much research, mainly because the standards estimate last resistances higher than those observed experimentally, since they consider gains of resistance proportional to the increase of transverse reinforcement, without any limitation and without considering the contribution of other parameters, such as longitudinal reinforcement, for example.*
Materials and Methods*: The Brazilian standard 2023 (2023) is no exception and also presents low accuracy and safety in its estimates.*
Results*: Aimed at these estimates, a database with 168 reinforced concrete beams with stirrups was assembled, all of which broke through shear by diagonal traction, and established parameters and relationships between them to improve the safety of the beams, rationalizing the sizing and stipulating the ultimate strength.*
Conclusion: *A formulation is presented to estimate this resistance based on the NBR 6118 (2023) standard and a statistical analysis of the safety parameters for the minimum armature calculation by the standard and the proposed formulation, comparing the performance and reliability of each model.*
Key Word*: Reinforced concrete; Beam; Shear; Database; Structural reinforcement.*

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I. Introduction

The sizing and verification of the ultimate and serviceability limit states in reinforced concrete beams subjected to bending are well understood and easily applicable in determining the longitudinal reinforcement. However, when it comes to calculating the transverse reinforcement to counteract shear forces, several factors complicate the simplified and consequently precise calculation. Therefore, it is essential to quantify and assess the key elements influencing shear resistance.

Various models have been proposed since the 1930s, as noted by Collins and other authors[1]. However, despite being developed over a hundred years ago, the truss analogy by Mörsch remains the most prominent in the Brazilian standard and several international codes due to its simplicity and practicality in calculations. More precise methods have been developed, considering factors such as the influence of friction between the cracks in the struts, which Reineck[2] demonstrated to contribute to increased resistance. Additionally, compression field models were developed by Mitchell and Collins[3], and the modified compression field theory was introduced by Vecchio and Collins[4] .

The shear failure mode in beams results from the combination of bending moment, shear force, and, in rare cases, axial forces, as shown in Figures 01 and 02. This combination determines the inclination of the cracks, which varies the angle of the strut according to the relationship between these factors and, most importantly, the loading conditions. However, it is important to highlight the complexity of the variables affecting the beam's resistance level, such as transverse dimensions, which do not exhibit a linear behavior concerning internal stresses, concrete compressive strength, longitudinal and transverse reinforcement ratios, and the mode of loading.

Figure 1: Stress components in the x-y plane (b) and principal plane (c).

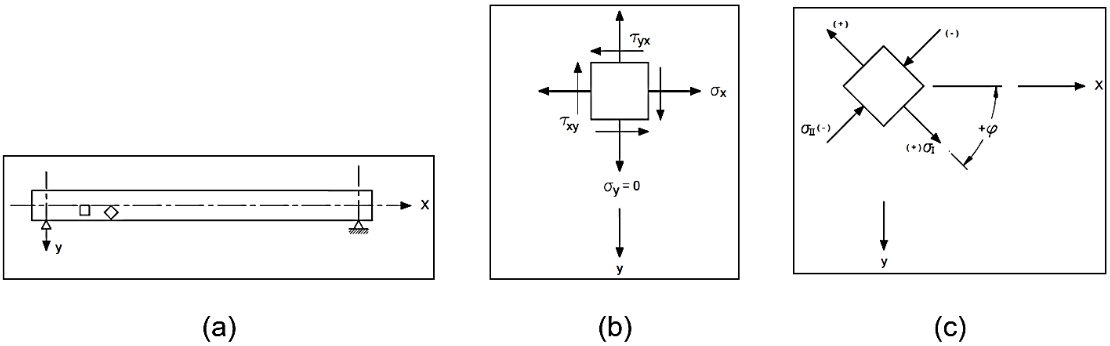
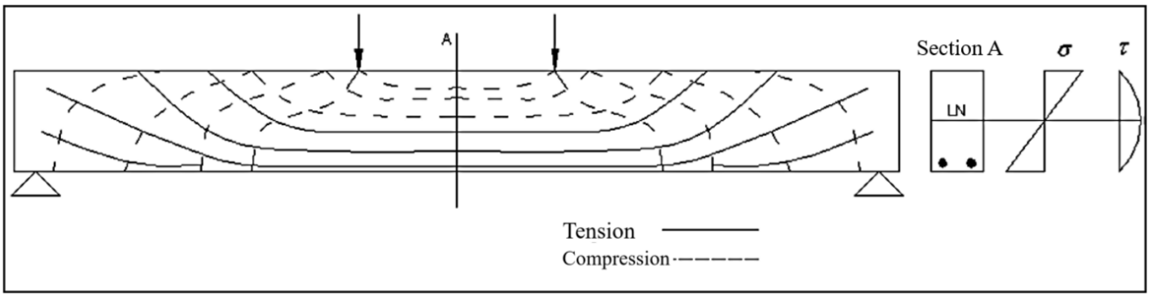


Figure 02: Principal stresses in uncracked beams under bending.



II. Material And Methods

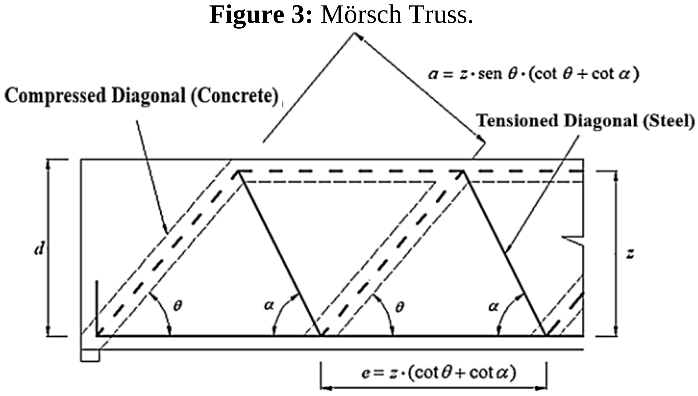
Normative Prescription (NBR 6118)

Design

NBR 6118[5] maintained the significant changes introduced in previous versions for the design of reinforced and prestressed concrete beams under shear forces, incorporating the contributing values of the transverse reinforcement (V_{sw}) and concrete (V_c) Additionally, the standard adopted certain similarities with Eurocode[6] by implementing a generalized truss model and modifying the contributing values for concrete.

The analogy used to determine the required loads or reinforcement to resist shear is based on a parallel-chord truss model, utilizing diagonal compressed struts with angles varying between 30° and 45°. In this model, the stirrup resists the failure of the diagonally tensioned members of the truss, which corresponds to the sliding of cracked interfaces, as illustrated in Figure 3.

Figure 3: Mörsch Truss.



Model I (θ=45º)

The Model I presented by NBR 6118[5] is based on the Ritter-Mörsch truss with a fixed strut angle (θ=45º) and a constant contribution value from concrete (V_c), regardless of the applied shear force on the stirrup (V_{sw}).

Verification of the Compressed Diagonal

For the design of reinforcements or verification of the structure, it is desirable to check the integrity conditions of the struts. In other words, it is undesirable for the beam to fail due to sudden rupture in these struts; the goal is to ensure failure occurs due to tension in the diagonal.

First, the following safety condition is observed:

$$\tau_{Sd} > \tau_{Rd2} \quad \text{Equation (1)}$$

$$\tau_{Sd} < \tau_{Rd3} = \tau_c + \tau_{sw} \quad \text{Equation (2)}$$

Where:
τ_{Sd} – Shear stress demand for calculation;
τ_{Rd2} – Shear stress related to the failure of compressed diagonals;
τ_{Rd3} - Shear stress related to tension failure in the diagonal;
τ_c – Contribution of the concrete's resistant stress to the truss model;
τ_{sw} - Contribution of the stirrup's resistant stress to the truss model.

NBR 6118[5] utilizes several factors that limit the compressive strength of concrete, such as the value of α_{v2} to represent the fragility index of concrete, given by $\left(1 - \frac{f_{ck}}{250}\right)$ and the lever arm limited to $0{,}9 \cdot$ d (where "d" is the effective depth) as shown in Equation 3:

$$\tau_{Rd2} = 0{,}27 \cdot \alpha_{v2} \cdot f_{cd} \quad \text{Equation 3}$$

For the purposes of verifying the integrity of the structural element, we have $\tau_{Sd} = \tau_{Rd3}$, consequently:

$$\tau_{Sd} = \tau_c + \tau_{sw} \quad \text{Equation 4}$$

Being:

$$\tau_c = 0{,}09 \cdot f_{ck}^{\,2/3} \quad \text{Equation 5}$$

$$\tau_{sw} = 0{,}9 \cdot \rho_w \cdot f_{ywd} \cdot (cotg\alpha + cotg\theta) \cdot sen\alpha \quad \text{Equation 6}$$

Model II (30º≤θ<45º)

The calculation model II allows for the variation of the strut angle between 30° and 45°, and the contribution from (V_c) ecreases linearly with the increase of (V_{sd}) by adopting the generalized truss model and utilizing the same principles as the Ritter-Mörsch truss, we achieve greater rationalization of the ultimate and serviceability limit state values.

Verification of the Compressed Diagonal

The Model II is represented analogously to Model I regarding the verification of struts, but with a more comprehensive formula, where all the trigonometric relationships hidden in the substitutions for Model I appear.

$$\tau_{Rd2} = 0{,}54 \cdot \alpha_{v2} \cdot f_{cd} \cdot sen^2\theta \cdot (cotg\alpha + cotg\theta) \quad \text{Equation 07}$$

The entire calculation process is similar to the previous model; however, the resistance relative to concrete decreases linearly with the increase of the collaborative portion from the stirrups. Therefore, interpolation between the values is performed.

Thus, we have:

$$\tau_{c1} = \tau_{c0} \cdot \left(\frac{\tau_{Rd2} - \tau_{Sd}}{\tau_{Rd2} - \tau_{c0}}\right) \quad \text{Equation 8}$$

Where:
τ_{c0} – Reference value for τ_c, when $\theta = 45°$
τ_{c1} - Reference value for τ_c, when $30 \leq \theta < 45°$

Database

The Brazilian standard utilizes few parameters for the design of transverse reinforcement; thus, the inclusion of new variables for the design and verification of the ultimate limit state of reinforced concrete beams is essential for greater accuracy and rationalization of the calculation, ensuring safety and cost-effectiveness.

In this study, the behavior of 168 reinforced concrete beams, strengthened by stirrups taken to failure, was analyzed. The characteristics of these elements are summarized in Table 1.

Table 1: Summary Database

Researcher	Elements	bw (cm)	d (cm)	f'c (KN/ cm²)	pl (%)	pwfy (KN/cm²)	tEXP
[1]	**2**	15,2	29,8	5,97 - 8,29	3,36	0,034	0,22 - 0,25
[2]	**7**	30,48 - 30,5	53,87	3,64 - 7,23	2,41	0,034 - 0,069	0,135 - 0,23
[3]	**6**	35,53 - 45,72	55,88 - 76,2	7,24 - 12,53	1,59 - 2,75	0,034 - 0,104	0,15 - 0,34
[4]	**4**	5	28	6,11 - 7,14	4,39 - 6,62	0,214 - 0,321	0,6 - 0,9
[5]	**9**	37,5	65,5	3,6 - 8,7	2,8	0,035 - 0,102	0,15 - 0,29
[6]	**2**	30	92,5	6,5 - 8	1,01	0,04	0,14 - 0,16
[7]	**36**	25	19,8 - 29,9	6,36 - 8,94	1,66 - 2,8	0,06 - 0,149	0,24 - 0,42
[8]	**12**	20	35,1 - 35,3	4,99 - 8,7	2,28 - 2,99	0,058 - 0,129	0,25 - 0,44
[9]	**3**	15	65,65	8,86 - 9,99	2,99	0,044 - 0,064	0,26 - 0,31
[10]	**38**	15,24	25,4	2,02 - 5,7	0,98 - 4,16	0,038 - 0,225	0,19 - 0,62
[11]	**10**	17,78	38,1	2,41 - 4,49	1,89 - 5,68	0,068 - 0,191	0,256 - 0,491
[12]	**2**	15,2	55,88	3,24 - 3,62	1,68	0,138 - 0,149	0,3 - 0,33
[13]	**6**	29	27,8	4,93 - 4,98	1,95	0,059 - 0,193	0,22 - 0,39
[14]	**1**	30	92,5	4,7	0,76	0,04	0,123
[15]	**3**	15	32,5	2,23 - 2,61	1,24	0,14	0,25 - 0,31

Table 1: Summary Database (Cont.)

Researcher	Elements	bw (cm)	d (cm)	f'c (KN/ cm²)	pl (%)	pwfy (KN/cm²)	tEXP
[16]	**3**	20	30,3	4,19	2,99	0,063 - 0,115	0,29 - 0,35
[17]	**12**	19,5 - 20,1	30,5 - 31,2	3,77 - 4,52	2,86 - 2,99	0,06 - 0,105	0,21 - 0,38
[18]	**9**	20	36,25 - 36,36	2,42 - 5	1,35 - 2,03	0,135 - 0,208	0,26 - 0,38
[19]	**3**	10	15	3,4	2,68	0,255 - 0,506	0,54 - 0,7

[1] MPHONDE APUD CASTRO[7]; [2] JONHSON & RAMIREZ[8]; [3] ROLLER & RUSSELL[9]; [4] FERNANDES[10]; [5] YOON et al [11]; [6] ANGELAKOS[12]; [7] KONG & RANGAN[13]; [8] CLADERA[14]; [9] TEOH et al[15]; [10] PLACAS & REGAN[16]; [11] HADDADIN et al[17]; [12] BELARBI & HSU[18]; [13] ADEBAR & COLLINS[19]; [14] COLLINS & KUCHUMA[20]; [15] CARELLI[21]; [16] ETXEBERRIA APUD CLADERA[22]; [17] GONZÁLEZ APUD CLADERA[23]; [18] WANG et al[24]; [19] LIM & OH[25] .

The database was compiled using the following methodologies:

- Compressive strength of concrete ($f'c > 2\ KN/cm^2$);
- Beams with stirrups and failure due to tension in the diagonal;
- All beams have transverse and longitudinal reinforcement perpendicular to each other;
- Ratio of shear span to effective depth (a/d) greater than 2.4;
- Beams with a steel yield strength of less than 900 MPa were considered.

III. Result and Discussion

Formula

Correlation of Parameters

First, all the main parameters that influence the shear strength in beams were correlated, and the parameters absent from the NBR 6118[5] standard will be discussed by comparing the values of these variables with the ultimate strength of the elements in the database.

Figure 4: Transverse Reinforcement Ratio

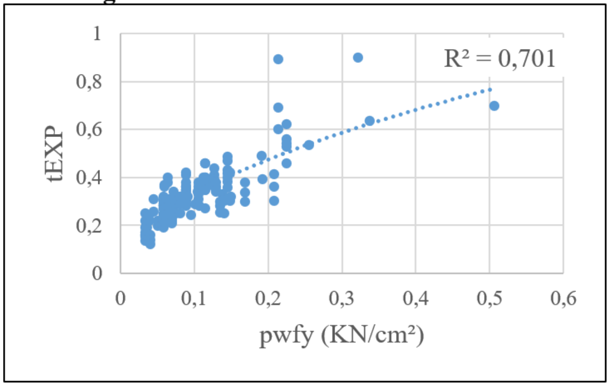


Figure 5: Beam Width

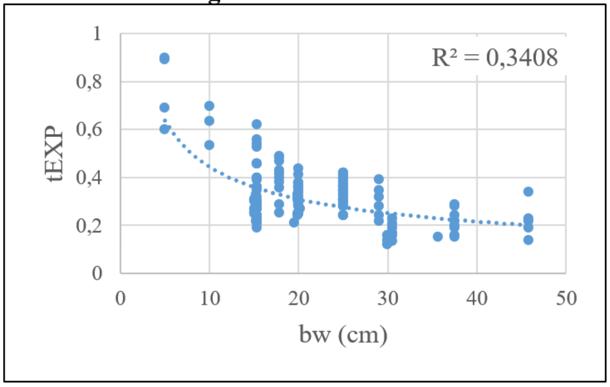


Figure 6: Effective Beam Height

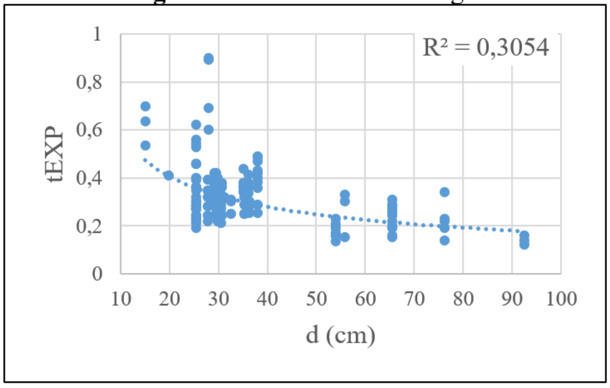


Figure 7: Longitudinal Reinforcement Ratio

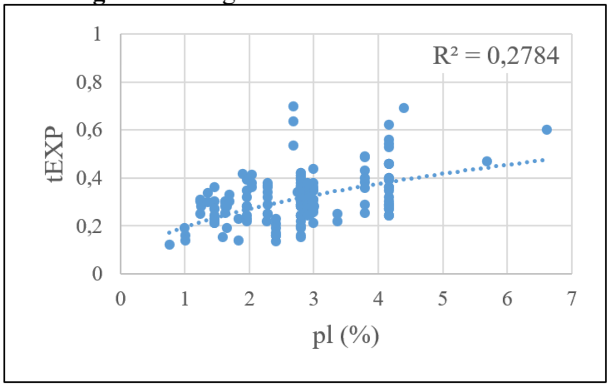
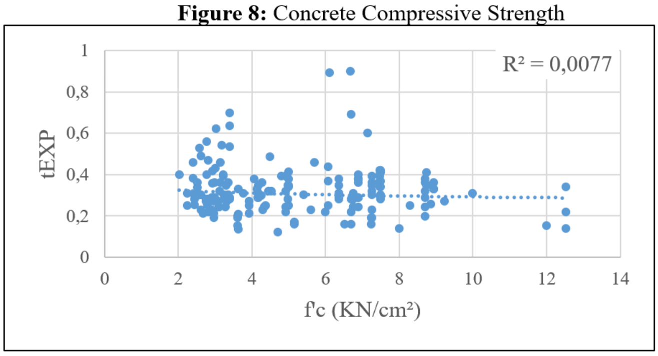


Figure 8: Concrete Compressive Strength



Size effect

The dowel effect in longitudinal reinforcement has been known since the 1930s. Several experimental studies, such as those by Placas and Regan[16] and Vecchio e Collins [4], Kani[26], have been conducted. This phenomenon can occur due to an increase in reinforcement diameter, stirrup spacing guiding the shear crack path, concrete cover, and the compressive strength of the concrete, which dictates the interaction between reinforcement and concrete.

Longitudinal reinforcement

The dowel effect in longitudinal reinforcement has been known since the 1930s. Several experimental studies have been conducted, such as those by Fenwick and Paulay[27] and Taylor[28]. This phenomenon can occur due to an increase in reinforcement diameter, stirrup spacing that guides the shear crack path, concrete cover, and the compressive strength of the concrete, which will dictate the interaction between reinforcement and concrete.

Parameter Analysis

From the graphs above, it is possible to observe the degree of correlation between the factors influencing shear stress in beams. Therefore, it is concluded that:

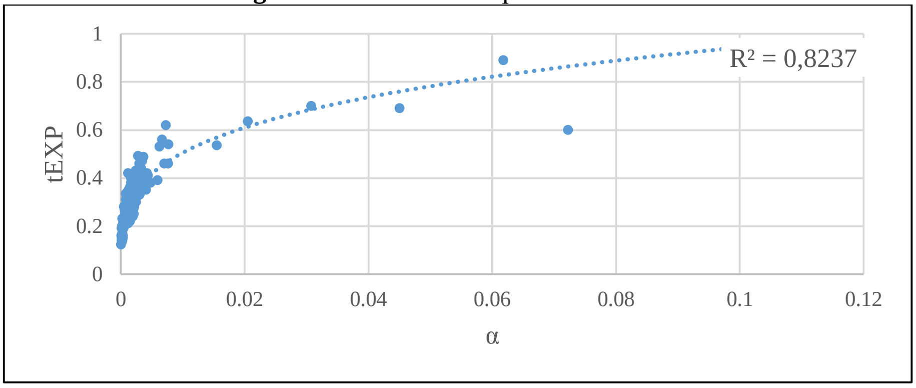
$\tau EXP \sim f'c$ $\quad$ $\tau EXP \sim \rho_l$ $\quad$ $\tau EXP \sim \rho_w f_y$ $\quad$ $\tau EXP \sim \frac{1}{d}$ $\quad$ $\tau EXP \sim \frac{1}{b_w}$

Consequently, it is possible to define a factor **α** that encompasses these variables:

$$\alpha = \frac{f'c \cdot \rho_l \cdot \rho_w f_y}{b_w \cdot d}$$ Equation 9

By comparing the value of **α** with the experimental shear stress, we obtain:

Figure 9: Factor α vs. Experimental Stress



The factor **α** had a determination coefficient (r²) greater than the isolated values of the other parameters. Therefore, it provides a higher correlation for developing a formula that incorporates this value.

However, when we simplify the formula to shear strength according to the NBR 6118[5] standard, without the safety coefficients:

$$\tau_{NBRk} = 0{,}126 \cdot f'c^{\frac{2}{3}} + 1{,}26 \cdot \rho_w f_y$$ Equation 10

$$\tau_{sw1} = 1{,}26 \cdot \rho w f y$$ Equation 11

When the equation is simplified for the minimum reinforcement, we have:

$$\rho_w f_y = 0{,}06 \cdot f'c^{\frac{2}{3}}$$ Equation 12

By substituting Equation 12 into Equation 10:

$$\tau_{NBR\,MINk} = 0{,}126 \cdot f'c^{\frac{2}{3}} + 0{,}0756 \cdot f'c^{\frac{2}{3}} = 0{,}2016 \cdot f'c^{\frac{2}{3}}$$ Equation 13

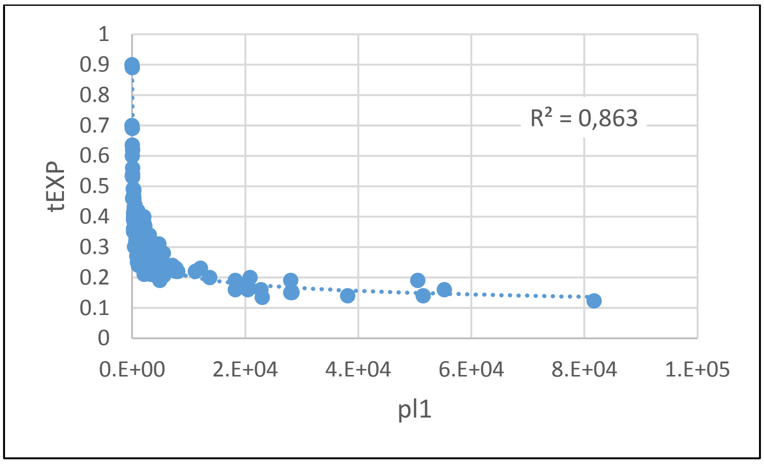
$$\tau_{sw2} = 0{,}0756 \cdot f'c^{\frac{2}{3}}$$ Equation 14

From the values of τ_{sw1} e τ_{sw2}, a factor with a higher determination coefficient is created:

$$\rho l1 = \frac{\tau_{sw2}}{\tau_{sw1} \cdot \alpha}$$ Equation 15

By correlating the variable $\rho l1$, we obtain:

Figure 9: Factor $\rho l1$ vs. Experimental Stress



Through a univariate exponential regression, it is determined that:

$$\tau_{TEO\ \rho l1} = 1{,}2202 \cdot \rho l1^{\ -0{,}194}$$ Equation 16 Equação 15

To evaluate the performance of the formula, Collins criterion[29] is adopted, where the ratio of experimental to theoretical data is penalized according to the degree of safety. For this purpose, several graphs were plotted to assess the values of the minimum reinforcement formula according to the Brazilian standard (NBR MIN) and the proposed formula ($\rho l1$).

Table 2: Adaptation of Collins criterion[29].

$\lambda = \frac{\tau EXP}{\tau TEO}$	Classification	Penalty
$< 0{,}5$	Extremely dangerous	10
$[0{,}5 - 0{,}85[$	Dangerous	5
$[0{,}85 - 1{,}15[$	Appropriate safety	0
$[1{,}15 - 2{,}00[$	Conservative	1
$\geq 2{,}00$	Extremely conservative	2

Applying COLLINS' Criterion[29]:

Table 3: NBR MIN Formula Without Safety Coefficient

$\lambda = \frac{\tau EXP}{\tau TEO}$	NBR	
	Number of beams	Penalty
<0,5	72	10
[0,5–0,85[	69	5
[0,85–1,15[	14	0
[1,15–2,00[	13	1
≥2,00	0	2
Total	1078	
Average	0,596	
DP	0,288	
CV	48,3 %	

Figure 10: Ratio $\tau EXP/\tau TEOmin$ of Elements Without Safety Coefficient According to NBR 6118[5]

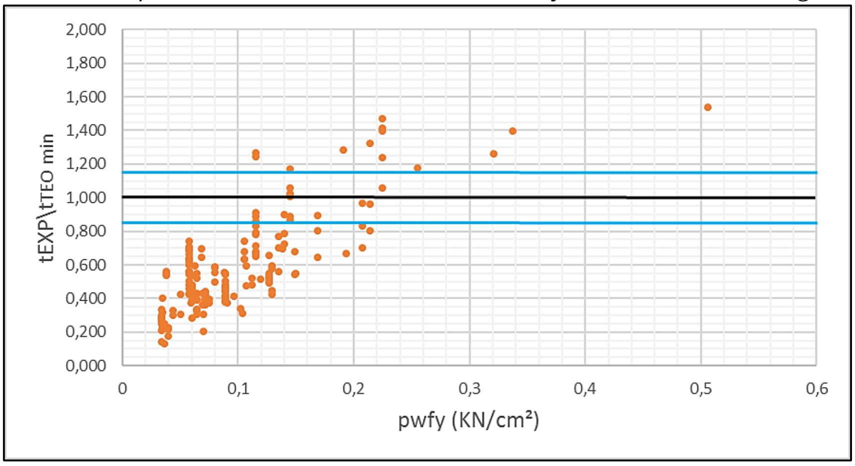


Table 4: NBR MIN Formula With Safety Coefficient

$\lambda = \frac{\tau EXP}{\tau TEO}$	NBR	
	Number of beams	**Penalty**
<0,5	15	10
[0,5–0,85[	56	5
[0,85–1,15[	44	0
[1,15–2,00[	40	1
≥2,00	13	2
Total	496	
Average	1,045	
DP	0,505	
CV	48,3 %	

Figure 11: Ratio $\tau EXP/\tau TEOmin$ of Elements With Safety Coefficient According to NBR 6118

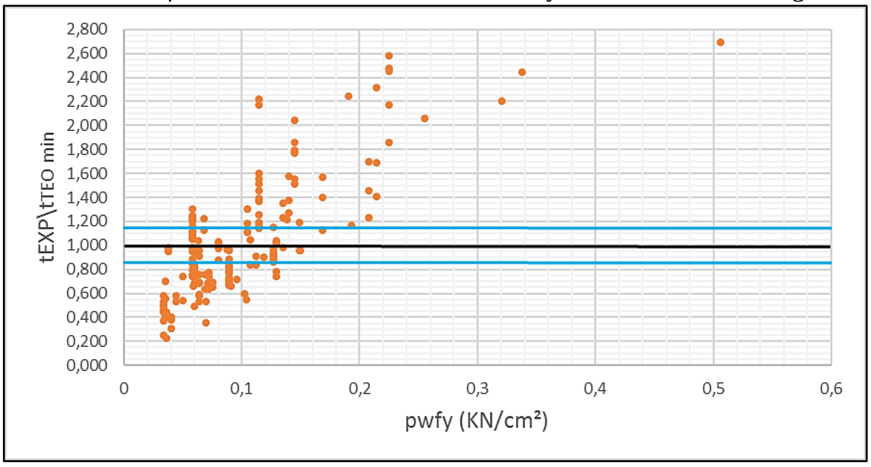


Table 5: $\rho l1$ Formula

$\lambda = \frac{\tau EXP}{\tau TEO}$	NBR	
	Number of beams	**Penalty**
<0,5	0	10
[0,5–0,85[	5	5
[0,85–1,15[	134	0
[1,15–2,00[	29	1
≥2,00	0	2
Total	54	
Average	1,054	
DP	0,125	
CV	11,9%	

Figure 12: Ratio $\tau EXP/\tau TEOmin$ of Elements Using the Proposed Formula

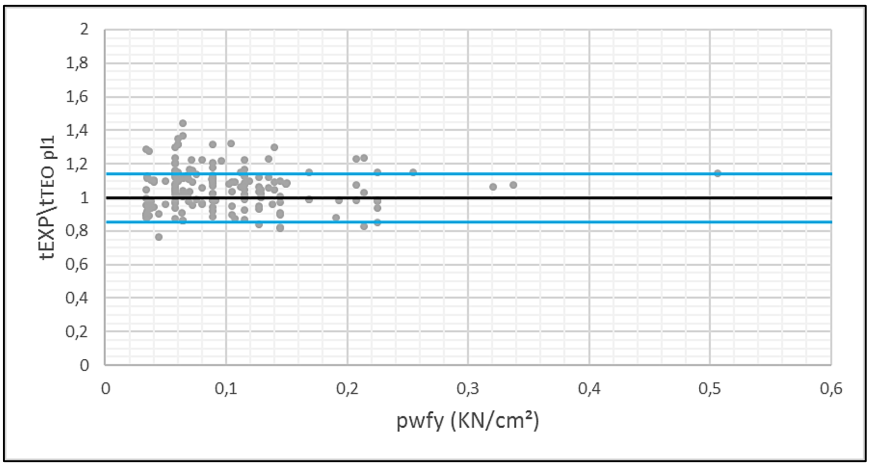
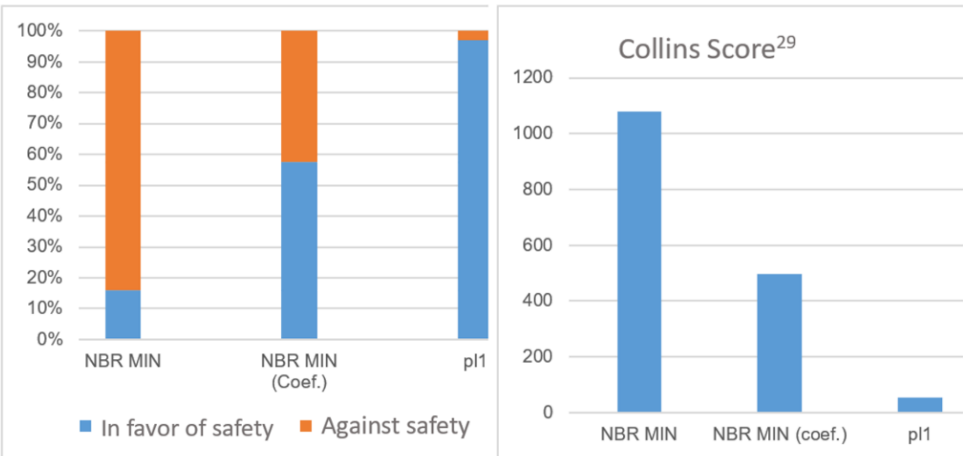


Figure 13: Safety and Dispersion Analysis



IV. Conclusion

Based on the results of this study, it is concluded that the formula for minimum reinforcement in NBR 6118 is extremely scattered and impractical for estimating values at the ultimate limit state of reinforced concrete members under shear. This is evident from the results obtained without safety coefficients, making the structural calculation routine for beam reinforcement imprecise. This can be justified by the fact that the formula evaluates the limit state of the elements using a single factor—the compressive strength of concrete. As observed in the database collection, $f'c$ is the parameter with the lowest correlation to shear strength, making it the least suitable factor to be considered in isolation in this study.

When the safety coefficients from NBR 6118 are applied, they merely increase the average ratio between theoretical and experimental values while maintaining the same level of dispersion. However, the values obtained using Collins', criterion demonstrate a higher degree of safety. Nevertheless, the minimum reinforcement formula does not provide greater rationalization of the values, as 31.5% of the elements are overdesigned, while 48.2% are underdesigned.

By incorporating all the predominant factors influencing shear in beams, as identified in the literature presented in this study, the proposed formula offers greater coherence in the final values. It achieves 97% of its results in favor of safety, thereby optimizing the accurate calculation of elements at the ultimate limit state and consequently improving the precision of reinforcement design.

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