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ORIGINAL ARTICLE

Shear in reinforced concrete beams with continuous internal transverse reinforcement

Cisalhamento em vigas de concreto armado com armadura transversal interna contínua

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Abstract: Reinforced concrete elements with a high longitudinal and transverse reinforcement ratio may present conflicts on both of them, resulting in reduced labor productivity and a poor job when assembling the transversal reinforcement, reducing its effectiveness. Thus, this research presents a type of internal transverse reinforcement as an alternative to mitigate this conflict between the transverse and longitudinal bars. A total of 5 reinforced concrete wide beams were made, one of them as a reference with closed stirrups, and the other ones with internal stirrups, varying the inclination of the internal transverse reinforcement in 60° and 90°, and the number of vertical legs of the internal transverse reinforcement used. Comparing the results of the beams with internal stirrups with the reference beam, it was observed that the internal stirrups provided increases of up to 14% in shear strength when compared with the closed stirrup.

Keywords: shear; internal transverse reinforcement; unconnected stirrups.

Resumo: Elementos de concreto armado com elevada taxa de armadura longitudinal e transversal podem apresentar conflitos das duas armaduras gerando redução em produtividade durante a armação do elemento e mal posicionamento da armadura transversal diminuindo a efetividade da armadura. Diante disso, essa pesquisa apresenta um tipo de armadura transversal interna como forma de mitigar esse conflito entre as barras transversais e longitudinais. Foram ensaiadas 5 vigas faixa de concreto armado, sendo uma de referência com estribos fechados e as outras 4 com estribos internos variando a inclinação das armaduras transversais internas em 60º e 90º e a quantidade de pernas verticais da armadura transversal interna utilizada. Comparando os resultados das vigas com estribos interno com a viga de referência, observou-se que os estribos internos garantiram ganhos de até 14% de capacidade de resistência ao cisalhamento em comparação com o estribo fechado.

Palavras-chave: cisalhamento; armadura transversal interna; estribos desconectados.

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1 INTRODUCTION

The need to overcome larger spans with reinforced concrete elements, without interfering in the architecture design and resist greater loads, generates greater shear stresses in beams and slabs. Elements with high shear and bending stresses (Figure 1) may present conflict between the types of reinforcement used, being necessary to rearrange the distribution of the shear reinforcement to solve the conflict between the bars. However, Freitas [1] highlights that the redistribution of the transverse reinforcement might reduce the structural performance.

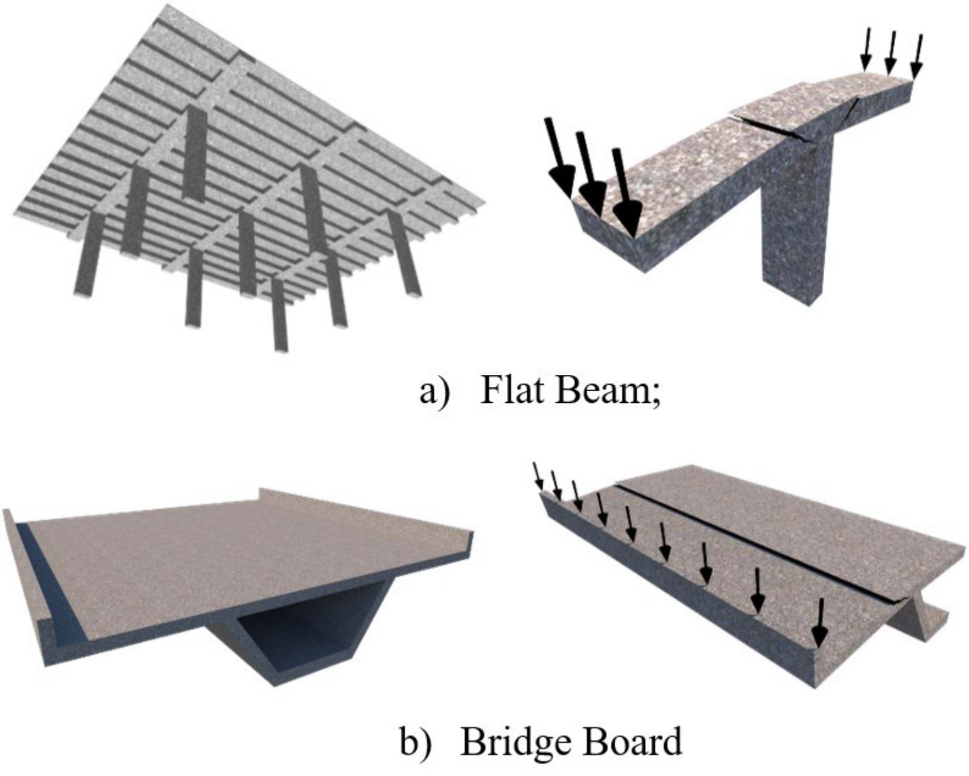


Figure 1 - Structures under one-way shear failure.

Today, there are many types of transverse reinforcement, such as the conventional stirrups, which can be open or closed, and the studs or dowels, which have flattened heads and are recommended for use on flat slabs to avoid punching failure, as an alternative to the conflict of reinforcement. However, there may still be a conflict between the transverse and longitudinal reinforcement, since both types of reinforcement are external, that is, the ends need to be on the longitudinal bars. One of the alternatives to avoid the conflict between reinforcement is the use of shear reinforcement with internal anchoring, positioned between the tensile and compression bars, as discussed by [2]–[4]. Figure 2 shows the types of transverse reinforcement.

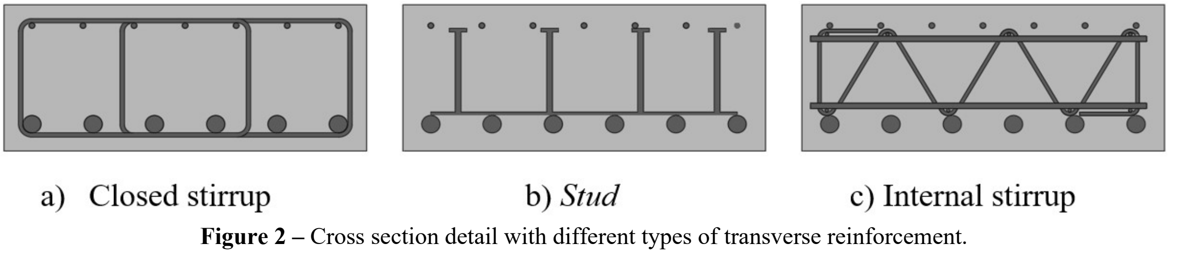


Figure 2 – Cross section detail with different types of transverse reinforcement.

The closed stirrup is a type of cross-sectional reinforcement widely used in Brazil, mainly in the most remote locations of large urban centers, due to the possibility of being manufactured *in loco*, not requiring specialized labor and presenting ease of manufacture, as well as meeting the recommendations of NBR 6118 [5], which recommends these stirrups to involve the flexural reinforcement to ensure better anchoring. However, the closed stirrup, in elements with a high ratio of transverse and longitudinal reinforcement, presents difficulties in assembling, which may reduce the efficiency of the service done.

In this context, the use of transverse reinforcement with internal anchoring has been highlighted, with several articles about it being published [2]–[4], [6]–[13]. As the shear reinforcement with internal anchoring are positioned between the upper and lower bars of the flexural reinforcement, their positions can be independent, avoiding the conflict of bars. This way, it is possible to industrially manufacture such reinforcement modules, speeding the construction process and generating greater savings with labor, contributing to the reduction of construction costs [14]–[16].

Despite the constructive advantages related to this type of reinforcement, [17], [18] found that the transverse bars that do not anchor to the longitudinal bars tend to show lower performance than those that have this anchoring guaranteed. In addition, some research have pointed out that premature failures and delamination cracks were related to shear reinforcement with internal anchoring [6]–[8]. However, it is worth noting that, in some cases, it was possible to control the cracking by delamination in structures with internal shear reinforcement, through a COMPLEMENTARY REINFORCEMENT, as observed in the results of Pinto [4], in which the complementary reinforcement works as well as the transverse reinforcement, allowing the flow of forces and the functioning of the Mörsh truss, resulting in strengths equal to or greater than that of elements with closed stirrups and studs [3], [4], [10].

In order to propose a new model of transverse reinforcement with internal anchoring, this work experimentally analyzes the behavior of reinforced concrete wide beams with internal stirrups with multiple legs, vertical and inclined ones, used as shear reinforcement. To evaluate the performance of these stirrups, the behavior of the beams with this type of reinforcement will be compared with that of a beam with closed stirrups, with the same transverse reinforcement ratio, as well as all the observed ultimate strengths will be compared with theoretical strengths, obtained by the recommendations of NBR 6118[5], ACI 318 [19] and Eurocode 2 [20].

2 CODE RECOMMENDATIONS

Several code recommendations guide that the possibility of shear failure in concrete elements be reduced through the design, due to its brittle behavior, which can occur without many warnings, making interventions impossible. According to several authors, the use of transverse reinforcement is the most viable way to guarantee the increase in strength and ductility in concrete structures [21]–[29].

Thus, it is common to find in the design codes recommendations on the use of a minimum shear reinforcement ratio, even when the tangential stress is not so high. When it is necessary to design a concrete element under shear forces, the Brazilian, American, and European codes provide recommendations regarding the calculation of the contribution portion of concrete and transverse reinforcement. These recommendations will be presented in this section. It is worth mentioning that the equations will be presented without weighting coefficients, allowing the reader to better compare the codes, thus obtaining characteristic strengths, and not design ones.

2.1 NBR 6118 (2014)

NBR 6118 [5] mentions two models for calculating one-way shear strength estimates in reinforced concrete elements. The models consider that the shear strength in elements with transverse reinforcement ($V_{R,cs}$) consists of concrete contribution ($V_{R,c}$) plus the contribution of steel ($V_{R,s}$), as shown in Equations 1 and 5.

Model I of the Brazilian code adopts the value of inclination of the strut equal to 45º, therefore it is recommended to use Equations 2 and 3 to calculate the contributions of concrete and steel, respectively, and it is limited by the maximum shear strength ($V_{R,max\ I}$) by Equation 4.

$$V_{R,cs\ I} = V_{R,c\ I} + V_{R,s\ I} \tag{1}$$

$$V_{R,c\ I} = 0.6 f_{ctk,inf}\ .bw.d \tag{2}$$

$$V_{R,s\ I} = \left(\frac{A_{sw}}{s}\right) \cdot 0.9 \cdot d \cdot f_{yw} \cdot (\sin\alpha + \cos\alpha) \tag{3}$$

$$V_{R,max\ I} = 0.27 \cdot \left(1 - \frac{f_{ck}}{250}\right) \cdot f_{cd} \cdot b_w \cdot d \cdot (\cot\alpha + 1) \quad (4)$$

Where:
$V_{R,csI}$ is the shear strength of reinforced concrete elements with transverse reinforcement estimated by model I;
$V_{R,cI}$ is the shear strength of reinforced concrete elements without transverse reinforcement estimated by model I;
$V_{R,sI}$ is the contribution of transverse reinforcement to the shear strength of reinforced concrete elements estimated by model I;
α is the angle of inclination of the transverse reinforcement in relation to the longitudinal one.
A_{sw} is the steel area of shear reinforcement per layer;
b_w is the width of the beam;
d is the depth;
s is the spacing between the shear reinforcement layers;
f_{ck} is the characteristic compressive strength of concrete;
f_{cd} is the design compressive strength of the concrete, where, as the safety factors were not used, the $f_{cd} = f_{ck}$;
$f_{ctk,\ inf} = 0.7.\ f_{ct}$, m - brittle tensile strength of concrete in 5% of cases;
$f_{ct,\ m}$ is the mean tensile strength of concrete, defined for concretes with a maximum strength of 50 MPa, calculated by $f_{ct,\ m} = 0.3.\ f_{ck}^{2/3}$;
f_{yw} is the yield strength of the shear reinforcement.

Model II of NBR 6118 [5] considers the effects caused by diagonal cracking, which impacts the reduction of the strut inclination and, consequently, the concrete contribution. In this model, the Brazilian code allows the variation of the inclination angle of the strut θ between 30° and 45°, only if the value of the concrete contribution ($V_{r,cII}$) is calculated by Equation 6. In this case, the concrete contribution is a function of the applied force (V_{sd}), calculated through an iterative process. The contribution of transverse reinforcement ($V_{R,sII}$) is calculated by Equation 7 and the maximum shear strength ($V_{R,\ max}$) by Equation 8.

$$V_{Rcs,\ II} = V_{R,c\ II} + V_{R,s\ II} \quad (5)$$

$$V_{R,c\ II} = V_{c0} \cdot \frac{V_{R,max\ II} - V_{sd}}{V_{R,max\ II} - V_{c0}} \leq V_{c0} \quad (6)$$

$$V_{R,s\ II} = \frac{A_{sw}}{s} \cdot 0.9 \cdot d \cdot f_{ywd} \cdot (cotg\,\theta + cotg\,\alpha) \cdot \sin\alpha \quad (7)$$

$$V_{R,max\ II} = 0.54 \cdot \left(1 - \frac{f_{cd}}{250}\right) f_{cd} \cdot b_w \cdot d \sin^2\theta \cdot (\cot\alpha + \cot\theta) \quad (8)$$

Being:
θ is the angle of inclination of the strut, varying from 30° to 45°;

2.2 ACI 318 (2014)

The American code considers one-way shear strength of reinforced concrete elements to be like the strength of a beam, so Equation 9 is used to estimate the shear strength of beams without transverse reinforcement ($V_{R,c}$). The code adopts, among the variables that impact shear strength, only concrete strength.

$$V_{R,c} = 0.17 \cdot \sqrt{f_c} \cdot b_w \cdot d \quad (9)$$

Where:
f_c is the concrete strength, obtained by tests with cylinder specimens;
b_w is the width of the beam;
d is the depth of the beam.

For beams with transverse reinforcement, ACI 318 [19] considers that the shear strength ($V_{R,cs}$) is given by the contributions of concrete and transverse reinforcement ($V_{R,s}$), calculated by Equation 10, emphasizing that the code estimates that the inclination of the strut is equal to 45°. The contribution of shear reinforcement is calculated by Equation 11. In addition, the American code limits the maximum shear strength of beams given by Equation 12, which refers to failure due to crushing of the strut ($V_{R,max}$).

$$V_{R,cs} = V_{R,c} + V_{R,s} \tag{10}$$

$$V_{R,s} = \left(\frac{d}{s}\right) \cdot A_{sw} \cdot f_{yw} \cdot (\sin\alpha + \cos\alpha) \tag{11}$$

$$V_{R,max} = 0.66 \cdot \sqrt{f_c} \cdot b_w \cdot d \tag{12}$$

Where:
s is the spacing between the transverse reinforcement layers;
A_{sw} is the steel area of one layer of transverse reinforcement;
f_{yw} is the yield strength of the transverse reinforcement, limited to 420 MPa;
α is the angle of inclination of transverse reinforcement in relation to the longitudinal one.

2.3 EUROCODE 2 (2004)

Eurocode 2 [20] gives Equation 13 to estimate the contribution of concrete to the shear strength of beams ($V_{R,c}$). In this equation, it is seen that the European code takes into account other factors, such as concrete strength, size effect and longitudinal reinforcement ratio, which impacts shear strength due to the dowel action.

$$V_{R,c} = max\begin{cases}(0.18 \cdot k \cdot (100 \cdot \rho_l \cdot f_c)^{1/3}) \cdot b_w \cdot d \\ 0.035 \cdot k^{\frac{3}{2}} \cdot \sqrt{f_c} \cdot b_w \cdot d\end{cases} \tag{13}$$

Where:
k considers the reduction in shear strength due to size effect, calculated by Equation 14.

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \tag{14}$$

ρ_l is the portion related to the longitudinal reinforcement ratio, calculated by $\rho_l = \frac{A_s}{b_w \cdot d} \leq 2$, A_s being the longitudinal steel area of the beam.

Eurocode 2 [20] suggests Equation 15 to evaluate the shear strength of beams with transverse reinforcement ($V_{R,cs}$), where it is seen that this estimate considers only the contribution of reinforcement, and its strength cannot be lower than that of a beam without shear reinforcement. In addition, the code also recommends that the angle of inclination of the strut may vary from 21.8° to 45°. The maximum shear strength ($V_{R,max}$) is estimated by Equation 16.

$$V_{R,cs} = max\begin{cases}\frac{A_{sw}}{s} \cdot 0.9 \cdot d \cdot f_{yw} \cdot (\cot\theta + \cot\alpha) \cdot \sin\alpha \\ V_{R,c}\end{cases} \tag{15}$$

Being:
θ is the angle of inclination of the strut, varying from 21.8° to 45°;

$$V_{R,\max} = \frac{0.9 \cdot b_w \cdot d \cdot \nu_1 \cdot f_c \cdot (\cot\theta + \cot\alpha)}{1 + \cot^2\theta} \tag{16}$$

ν_1 being determined by Equation 17;

$$\nu_1 = 0.6 \cdot \left[1 - \frac{f_c}{250}\right] \tag{17}$$

As EC2 [20] admits the variation of the inclination angle of the strut θ for the design, it suggests that Equations 15 and 16 are equalized for checking the strength, to verify the smallest angle that can be used to evaluate the strength of a beam according to its characteristics. Equalizing these two equations, Equation 18 is obtained, which provides the smallest angle that may be used.

$$\cot \text{è} = \sqrt{\frac{b_w \cdot s \cdot \nu_1 \cdot f_c}{A_{sw} \cdot f_d \cdot \text{sen}\,\alpha}} \tag{18}$$

Where:
f_{yd} – is the yielding strength of steel, recommended by EC2 as $0.8.f_{ys}$, which is the yielding strength for the characterization test of the steel.

2.4 Flexural strength of reinforced concrete beams

Several code recommendations, such as EC 2 [20] and ABNT NBR 6118 [5], shows simplified theories to estimate the flexural strength of reinforced concrete elements assuming that: the Bernoulli hypothesis of plane sections is valid; perfect compatibility between the strains of concrete and steel; the tensile strength of concrete is ignored for the ultimate limit state; the stress distribution in concrete can be assumed as a parabola-rectangle diagram, which can be replaced by a rectangle. To estimate the flexural strength in this study, the recommendations of ABNT NBR 6118 [5] will be used, considering that the tensile and compression flexural reinforcement reach yielding, to obtain Equations 19 to 23.

$$C_c + C_{s\prime} - T_s = 0 \tag{19}$$

$$(\eta \cdot f_c \cdot b_w \cdot c) + (A_{s\prime} \cdot f_{ys\prime}) = A_s \cdot f_{ys} \tag{20}$$

$$c = \frac{(A_s \cdot f_{ys}) - (A_{s\prime} \cdot f_{ys\prime})}{\eta \cdot f_c \cdot b_w} \tag{21}$$

$$M_{flex} = A_s \cdot f_{ys} \cdot z \tag{22}$$

$$V_{flex} = \frac{M_{flex}}{a} \tag{23}$$

Being:
η is a constant, assumed to be 1 for constant sections and 0.9 for the other cases;
α_{cc} is assumed to be 0.85 for $f_c \leq 50$ MPa. In cases where the long-term effects of concrete can be neglected, such as short-time tests, 0.95 is assumed;
c is the height of the concrete compression block;
a is the shear span of the element.

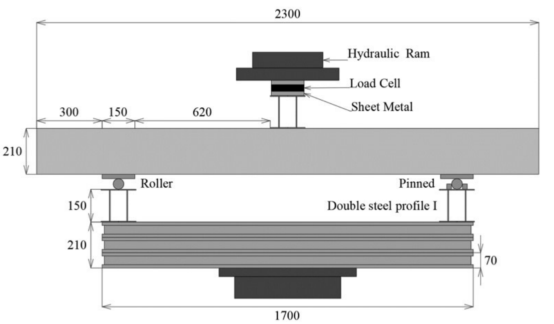
3 EXPERIMENTAL PROGRAM

This experimental program had a series of tests on five transverse reinforced concrete wide beams, with a cross section of 500 mm of width, 210 mm of height, and 2300 mm of length. In one of the beams, closed stirrups were used as shear reinforcement, being a reference for comparison with the other four beams, which had their transverse reinforcement composed by continuous stirrups with internal anchoring. The main variables analyzed were inclination of transverse reinforcement, diameter of the transverse steel bars and number of bars per layer, in such a way that these variations had the same transverse reinforcement ratio. In addition, reinforcement with internal anchoring had complementary reinforcement, to contribute to the anchoring and avoid delamination effect, with the same pieces used by [3], [4].

For the names of the beams, a system of three terms was adopted: *A-B-C*. The first term (*A*) represents the transverse reinforcement used, where, if indicated by letter *C*, it refers to the closed stirrups and, where indicated by letter *M*, it refers to the continuous internal stirrups. The second term (*B*) represents the number of vertical bars in each layer of shear reinforcement, which may be 4 or 8 legs, and the term *C* indicates the angle adopted for shear reinforcement (90º or 60º). Table 1 shows the main variables of the tested beams. Figure 3 shows the dimensions of the beams and how they were positioned in the press.

Table 1 - Characteristics of the tested beams

BEAM	$Ø_w$ (mm)	α (°)	No. $Ø_w$	A_{sw} (mm²)	S (mm)	$ρ_w$ (%)	f_{yw} (MPa)
C-4-90	6.3	90	4	113.10		0.23%	687.12
M-8-90	4.2	90	8	110.84		0.22%	612.56
M-4-90	6.3	90	4	113.10	100	0.23%	687.12
M-8-60	4.2	60	8	110.84		0.26%	612.56
M-4-60	6.3	60	4	113.10		0.26%	687.12
b_w (mm)	**h (mm)**	**a (mm)**	**d (mm)**	**L (mm)**	**$Ø_{f'}$(mm)**	**f_c (MPa)**	**f_{ys} (MPa)**
500	210	620	171.5	2300	8	25.01	531.95



a) Characteristics and dimensions of the beams;

b) Beam before test.

Figure 3 – Characteristics and dimensions of the tested beams.

3.1 Flexural reinforcement

The steel bars used as flexural and transverse reinforcement were CA-50 and CA-60 types, where CA stands for Reinforced Concrete and the values 50 and 60 correspond to the characteristic strength of steel, that is, the CA-50 steel bars must have a characteristic strength of 500MPa and the CA-60 steel bars must have a characteristic strength of 600MPa.

The longitudinal reinforcement was designed so that the beams presented greater flexural strength, allowing shear failure. In the tensile region, six CA-50 steel bars with a diameter of 25.0 mm were used, and in the compression region, seven CA-50 steel bars with a diameter of 8.0 mm.

To assess the mechanical properties of the steel used, three samples of the longitudinal bars were tested under tensile force according to NBR 6892 [30]. The samples of 8.0 mm bars showed an average of f_{ys}= 558.56 MPa, ε_{ys}= 2.72‰, E_s= 205.65 GPa and the samples of 25.0 mm bars showed an average of f_{ys}= 531.95 MPa, ε_{ys}= 2.71‰, E_s= 199.66 GPa. Table 2 presents the mechanical properties of tensile and compression bars.

Table 2 - Mechanical properties of the flexural bars

Ø (mm)	**E_s (GPa)**	**f_{ys} (MPa)**	**ε_{ys} (‰)**
8.0	205.65	558.56	2.72
STANDARD DEVIATION	14.05	19.55	0.09
25.0	196.66	531.95	2.71
STANDARD DEVIATION	5.68	8.94	0.06

3.2 Shear reinforcement

Beam C-4-90 was composed by 2 closed stirrups per layer, resulting in four CA-60 vertical bars with diameter of 6.0 mm in each stirrup layer. The recommendations from NBR 6118 [5] have been followed, where the stirrups involved tensile and compression reinforcement to guarantee their anchoring in the beam, as well as the bend diameter and development length were also based on the code recommendation.

Beams M-8-90 and M-8-60 were assembled with an internal transverse reinforcement, i.e., the stirrups were positioned between the flexural reinforcement of the beam. The internal stirrups, called stirrups *M*, were manufactured with CA-60 steel of 4.2 mm in diameter, with 8 vertical bars. In addition, 6.3 mm longitudinal bars with CA-50 steel were inserted inside the bending points of the internal stirrups, contributing to anchoring, as recommended by NBR 6118 [5] and Eurocode 2 [20], in addition to assist in the manufacture of shear reinforcement in modules.

Beams M-4-90 and M-4-60 were also reinforced with internal shear reinforcement, M stirrup. The stirrups were made of CA-60 steel with a diameter of 6.0 mm, composed of 4 vertical legs. To assist in anchoring, CA-50 steel longitudinal steel bars with a diameter of 10 mm were used. All beams with stirrups M were added with complementary reinforcement.

The stirrup layers of M-8-90 and M-4-90 beams were positioned at 90º in relation to the longitudinal axis of the beams, while the stirrup layers of M-8-60 and M-4-60 beams were inclined at 60º in relation to the longitudinal axis of the beams. The stirrups of all tested beams were spaced every 100.0 mm, keeping the reinforcement ratio close to that of the reference beam. Figure 4 shows the cross section, the spacing and inclination of the reinforcement of the tested beams, and Figure 5 shows the stirrups used in the beams and the assembled module.

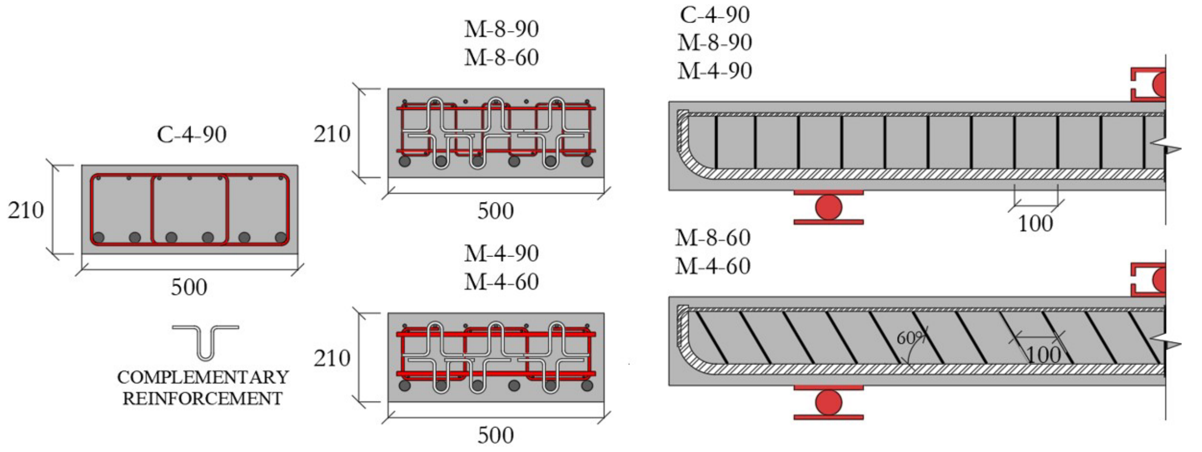


Figure 4 - Cross section and reinforcement layout of the tested beams.

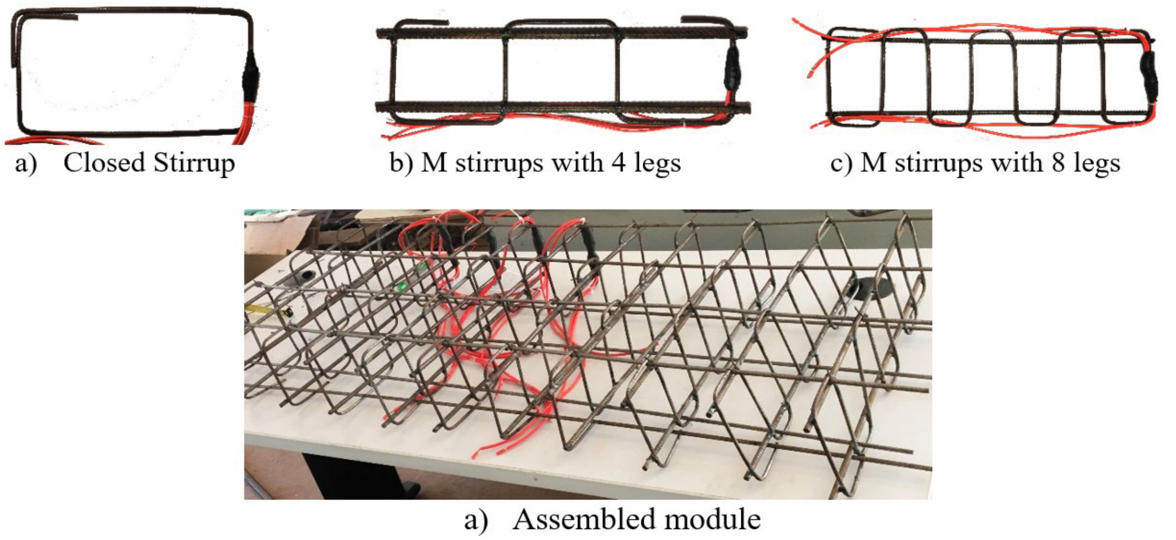


Figure 5 – Stirrups used in the beams.

In the studies by Ferreira et al. [2] and Tapajós [3], the beams studied with internal transverse reinforcement showed a delamination effect due to an anchoring failure of the internal stirrups. To reduce these effects, Tapajós [3] used a complementary reinforcement to mitigate delamination effect and allow the flow of internal forces. In this study, this complementary reinforcement was adopted in the four beams with internal stirrups. The complementary reinforcement was manufactured with CA-50 steel with a diameter of 6.3 mm. Six complementary reinforcements were used per stirrup layer, they were positioned in the flexural reinforcement, being 3 of them located in the compression region and the other 3 in the tensile region, totaling a complementary reinforcement ratio ρ_{wc} of 0.75% for beams with transverse reinforcement at 90º and 0.86% for beams with transverse reinforcement at 60º. Figure 6 shows the dimensions and the manufactured complementary reinforcement.

a) Dimensions of the complementary reinforcement.   b) Complementary reinforcement used.

Figure 6 – Complementary reinforcement.

Three samples of each diameter used were separated from the steel used in the shear reinforcement and subjected to tensile tests following the recommendations from NBR 6892 [30]. Samples of CA-60 steel of 4.2 mm presented means of f_{ys} = 612.56 MPa, ε_{ys} = 3.07‰, E_s = 200.16 GPa, samples of CA-60 bars of 6.0 mm showed means of f_{ys} = 687.12 MPa, ε_{ys} = 3.60‰, E_s = 192.28 GPa and samples of CA-50 bars of 6.3 mm presented means of f_{ys}= 585.83MPa, ε_{ys}= 3.08‰, E_s= 190.61GPa. Table 3 presents the mechanical properties of the steel bars used as transverse reinforcement of the beams.

Table 3 - Mechanical properties of the transverse reinforcement

Ø (mm)	E_s (GPa)	f_{ys} (MPa)	ε_{ys} (‰)
4.2	200.16	612.56	3.07
STANDARD DEVIATION	10.63	15.07	0.17
6.0	192.28	687.12	3.60
STANDARD DEVIATION	17.62	31.28	0.49
6.3	190.61	585.83	3.08
STANDARD DEVIATION	11.46	13.81	0.18

3.3 Concrete

Concrete was produced with CP-II-E Portland cement (Portland cement composed with slag), medium sand as fine aggregate, gravel 01 with a maximum diameter of 19 mm as coarse aggregate and, to improve the workability of concrete, a multifunctional plasticizer and setting retarder admixture was used.

To determine the mechanical properties of concrete, 15 cylinder specimens (three for each beam) were made, with a diameter of 100 mm and height of 200 mm, following the recommendations of NBR 5738 [31]. They were used in compression tests based on NBR 5739 [32], 28 days after concreting the specimens, and tensile tests following the recommendations of NBR 7222 [33]. As the beams were tested in the same week and cast with the same batch of ready-mix concrete, their compressive strength as the mean of all tests performed, to avoid the influence of the variation of results in different tests from those samples. The concrete showed an average compressive strength of f_c = 25 MPa and tensile strength of f_{ct} = 3.57 MPa. Table 4 presents the mechanical properties of the concrete used in the tested beams.

Table 4 - Concrete compressive strength and concrete splitting strength at 28 days

Sample	f_{ck} (MPa)	f_{ct} (MPa)
CP1	23.85	3.80
CP2	25.78	3.49
CP3	25.54	3.68
CP4	25.27	3.59
CP5	27.12	3.42
CP6	23.79	3.51
CP7	23.69	3.50
Mean	**25.01**	**3.57**
SD	**1.19**	**0.12**
COV	**5%**	**3%**

3.4 Instrumentation

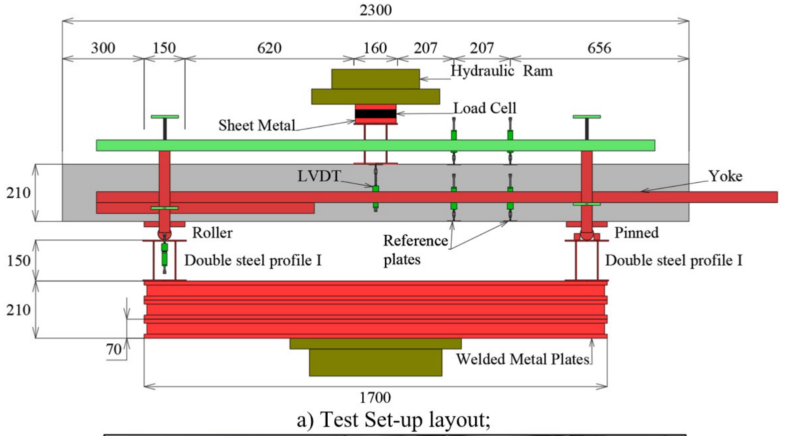
The Mid-span Deflection of the beams was measured with the aid of a LVDT, positioned in the mid-span of the beams, then measuring the maximum deflections of the beams. The potentiometer was fixed on the Yoke (device that helps in the positioning of the equipment), to avoid that the accommodation of the beams compromises the reading of the deflections.

The monitoring of concrete strains took place from an electric strain gauge (SG), positioned on the side face of each of the beams, in the mid-span. To measure the strain of the flexural reinforcement of each beam, two SG were used in one of the central bars of the flexural reinforcement in the tensile region, adopting the mean of the two obtained readings.

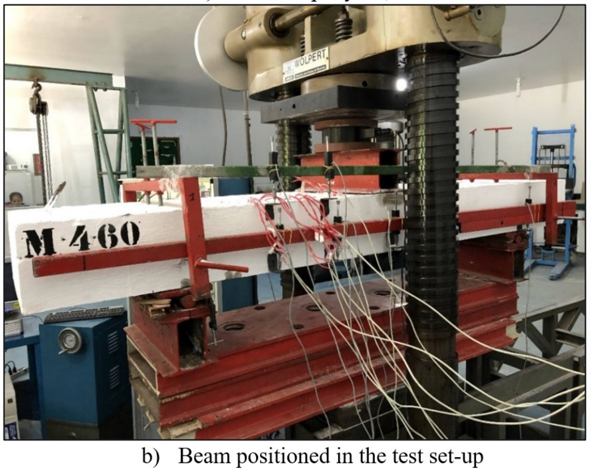
The choice of the positioning of the SG in the stirrups was based on the studies by [3], who instrumented all the stirrups positioned in the shear span to, thus, evaluate different levels of transverse reinforcement strain. Thus, as the studied beams had the same spacing between the stirrups, four stirrups located in the middle of the shear span of each beam were instrumented, obtaining the reading, and observing the behavior of all layers of the transverse reinforcement in the shear span.

3.5 Test Set-up

The beams were tested through a three-point test, using a hydraulic ram with a capacity of up to 3000 kN, where two points represent a roller and a pinned support, and the third point represents the load application in a simply supported beam. Due to limitations in the hydraulic ram dimensions, three hollow metal plates with a length of 1700 mm, a height of 70 mm and a thickness of 15 mm were used over the center of the hydraulic ram table, so that the beams were positioned correctly. Figure 7 shows the Test Set-up used.



a) Test Set-up layout;



b) Beam positioned in the test set-up

Figure 7 – Test Set-up.

For load application, a double steel I-profile with a width of 160 mm was used in the mid-span, at the top of the beam. Two double metal I-profiles, 150 mm wide, were used for the supports. Both supports had steel rollers, on top of metal plates, one being free and the other with horizontal movement restrictions that simulated conditions of roller and pinned supports, respectively. A load cell with a loading capacity of up to 3000 kN was used on the central double steel I-profile, for monitoring the loading level throughout the tests. All instruments used to monitor the tests were connected to a data acquisition module.

4 RESULTS AND DISCUSSIONS

4.1 Mid-span Deflection and Strain on the Flexural Reinforcement

Figure 8 shows the behavior of the shear force (V) versus deflection (δ) in the mid-span of the tested beams. Due to the setting used in the test, the value of the shear force used in the graphs is half of the value obtained in the load cell.

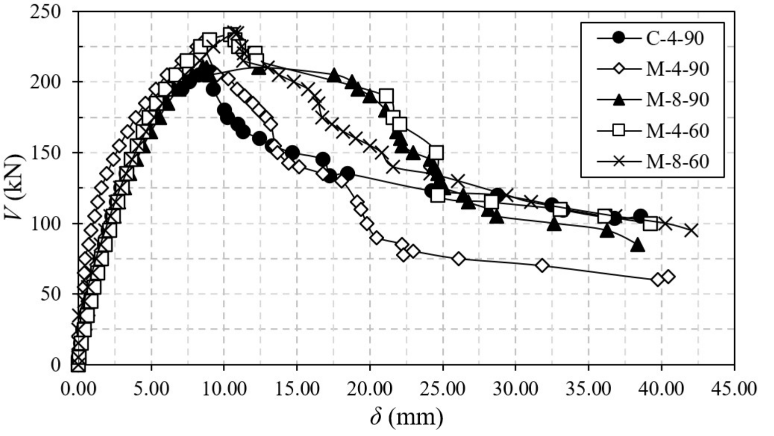


Figure 8 – Shear force versus Deflection of the beams.

The five tested beams, in general, presented a similar behavior for the same load until they reached the failure load and shear failure, where it was observed that the beams with internal transverse reinforcement presented greater strength and ductility than that of the beam with the closed stirrup (C-4-90), as also observed in the results of [3].

The M-4-90 beam showed a stiffer behavior for the same loading level than the other beams until the failure load, and after reaching it, presented greater strains when compared with the reference beam. This occurred due to the appearance of delamination cracks close to the failure load, reducing the post-peak performance of the beam.

Beam M-8-90 presented behavior and strength similar to that of the reference beam until the failure load, however, after failing, it presented a ductile behavior, with low load reduction for a high strain, in relation to beams C-4-90 and M-4-90, which after the failure load presented high strains for a lower loading level.

The beams with stirrups inclined to 60º, M-8-60 and M-4-60, presented greater strength capacity in comparison with the other tested beams, as observed by [4] in the tested beam with prefabricated truss stirrups inclined at 60º and with complementary reinforcement on both sides. The performance is due to the capacity of the inclined stirrups to allow a larger steel area in the cracks, ensuring greater strength to the beam. Beams M-8-60 and M-4-60, as well as beam M-8-90, presented a ductile post-peak behavior with high strain in relation to load reduction.

Figure 9 shows the behavior of the shear force versus specific strain of the flexural reinforcement (ε_l) of the tested beams.

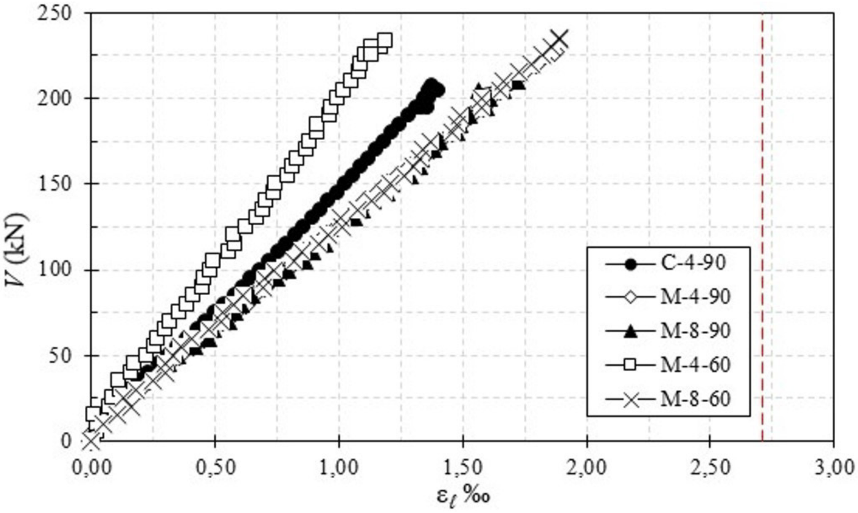


Figure 9 – Shear force versus Strains of the flexural reinforcement of the beams.

The beams showed similar behaviors and no flexural reinforcement reached the yielding strain, ruling out the hypothesis of a possible flexural failure. The reinforcement of beams M-4-90, M-8-60 and M-8-90 showed greater strain of the longitudinal reinforcement, for the same loading level, when compared with beams C-4-90 and M-4-60. This behavior was probably due to M stirrups presenting initial strains with a low loading level of the beams when compared with the other beams.

4.2 Concrete strain

Figure 10 shows the behavior with the shear force curve versus concrete strain (ε_c) of the tested beams.

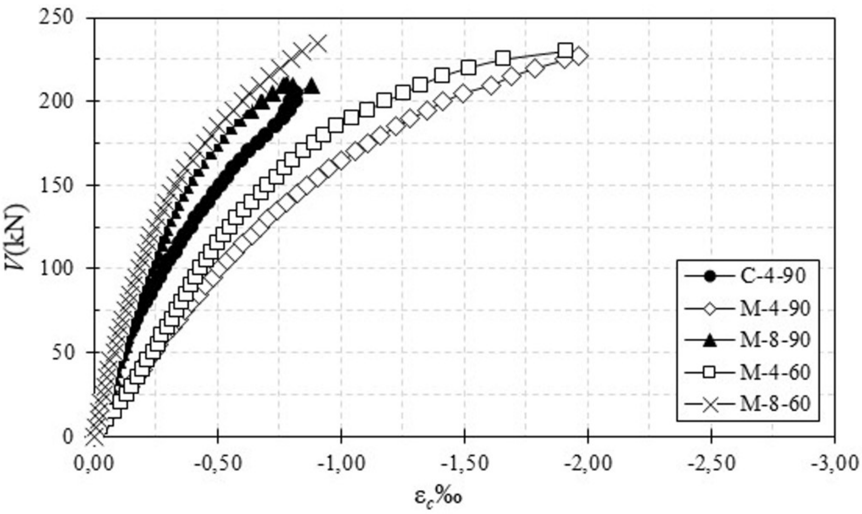


Figure 10 – Shear force versus Concrete Strain.

The beams showed similar behavior, and in all specimens, it was observed that the maximum strain concrete was less than 2‰, discarding any hypothesis of failure due to flexural compression. Beams M-8-90 and M-8-60, with 8 vertical legs in the transverse reinforcement, presented smaller concrete strains for the same loading level in relation to the other beams. This behavior, as observed by [2]–[4], may have happened due to a larger steel area in the compression region of the beams, given that the constructive reinforcement of the modules added 78.5 mm^2 of steel in the transverse reinforcement ratio, and by the greater number of legs in the stirrups of beams M-8-90 and M-8-60, as observed in the beams tested by [3], where beams with the same reinforcement ratio and less spacing presented greater stiffness in comparison with the other beams tested by the author.

Beams M-4-90 and M-4-60 showed greater concrete strain in relation to the other tested beams, probably due to the M stirrup, used in the two beams, having only 4 vertical legs per layer, thus allowing greater strains of concrete, for the same loading level, in relation to the other beams, as observed in the beams tested by [3], [4], where beams with the same reinforcement ratio, but with a greater number of stirrups, showed a stiffer behavior for the concrete strain. However, beam M-4-60 presented a difference in behavior when related to the strain of the flexural reinforcement with the concrete strain, and this difference may have occurred due to a possible failure in the instrumentation; it is necessary to carry out tests with more specimens to validate this behavior.

4.3 Shear reinforcement strain

Figure 11 shows the behaviors with the shear force curve versus strain of the transverse reinforcement (ε_w) of the tested beams.

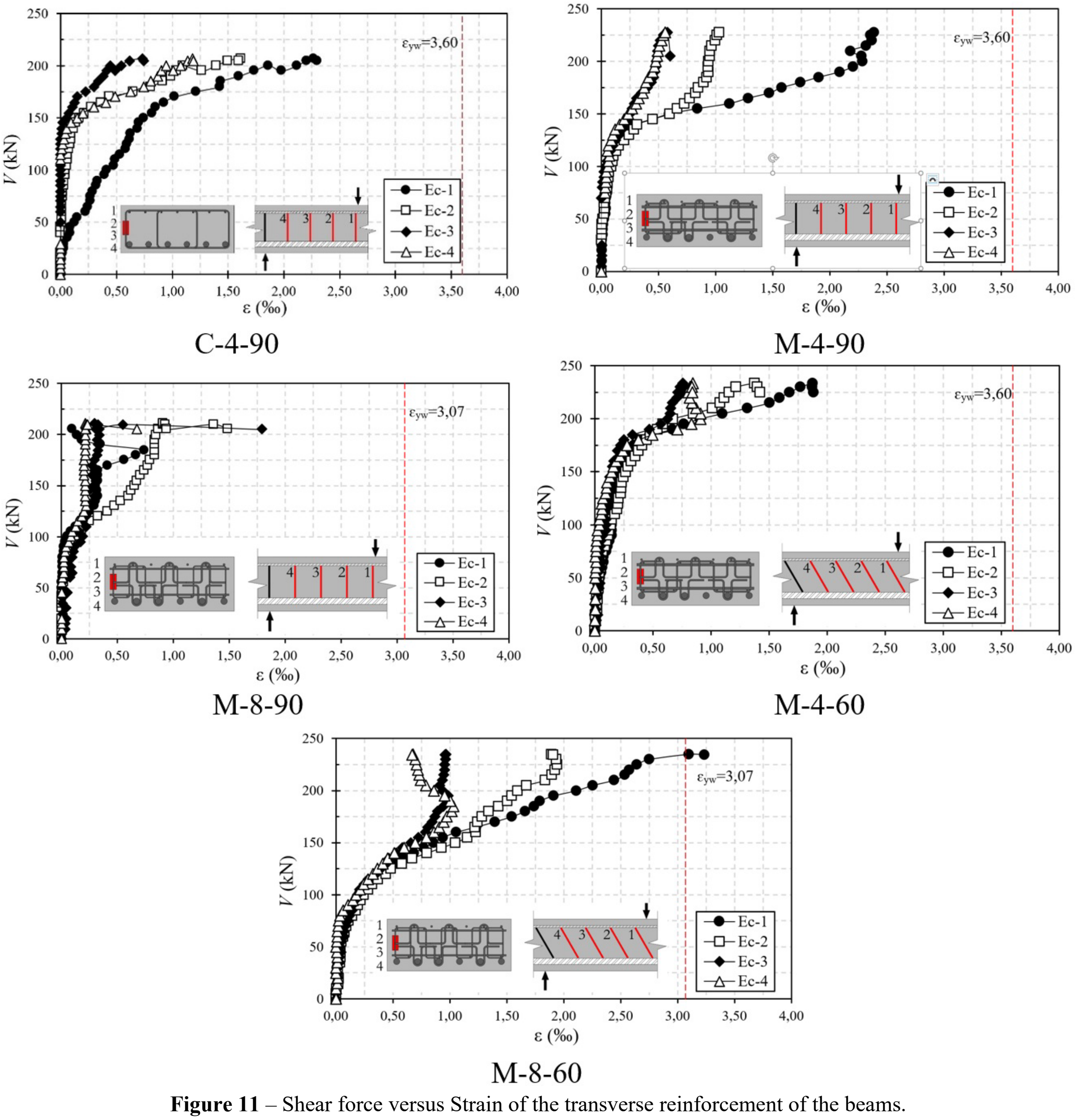


Figure 11 – Shear force versus Strain of the transverse reinforcement of the beams.

It was observed that the transverse reinforcement bars did not reach yielding, except for M-8-60 beam, where only one layer reached the steel yielding strain value. This behavior was also observed in the second series tested by [3] and occurred due to the high transverse reinforcement ratio, which allows a greater distribution of forces between the shear reinforcement layers.

The closed stirrups, used in beam C-4-90, showed lower strains, in the initial loading stages, however for loading close to the failure load, the reinforcement presented greater strains, except for stirrup 1, which presented strains since the initial loading due to an accumulation of cracks near the stirrup.

The beams tested with M stirrup showed greater shear strength when compared with the C-4-90 reference beam, where it was seen that stirrups 1 and 2 developed more than stirrups 3 and 4 in all tested beams, due to the inclination of the cracks, where the diagonal concrete struts that rest on the longitudinal tensile bar lose anchoring. This delamination effect was seen in all beams with M stirrup, as observed by [2]–[4]. However, the efficiency of the complementary reinforcement stands out, as evidenced by [3], [4], since even with the appearance of cracks due to the delamination effect, beams with M stirrup showed greater strength when compared with C-4-90 beam.

Regarding the number of legs of the transverse reinforcement, beams M-4-90 and M-4-60 showed lower initial strains for stirrups, however they presented a ductile behavior in relation to beam M-8-90, which presented initial strain higher than the beams with 4 vertical legs, however, when approaching the failure load, stirrups presented greater stiffness, probably due to the complementary reinforcement. Again, there was an accumulation of cracks close to stirrups 1 and 2.

4.4 Failure Surface

Figure 12 shows the failure surfaces of the beams after the tests. All of them presented shear failure, with inclination of the main crack varying between 24º and 34º. In beams with internal shear reinforcement, even with complementary reinforcement, there was a delamination effect, however, as observed by [4], the effect was controlled by the complementary reinforcement and occurred close to the failure load, confirming the efficiency of the hooks in controlling and reducing the delamination effect.

4.5 Failure shear force

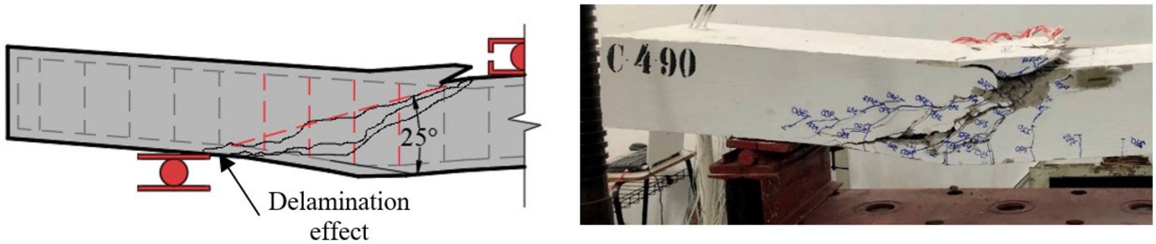
Regarding the failure load of the beams, they showed shear strength between 207 kN and 235 kN, in which the beams with the internal stirrups showed an increase in strength up to 10% when compared with the beam with closed stirrups (C-4-90), as observed in the results of [3], specifically in relation to the beam with prefabricated truss stirrups and complementary reinforcement. The beam with M stirrup, which presented lower performance in relation to the other beams, was M-8-90 beam, when compared with the reference beam, which showed a strength gain of only 2%. It is believed that this performance may have occurred due to the delamination cracks that appeared in the beam, thus reducing its shear strength.

The beams M-4-60 and M-8-60, with transverse reinforcement inclined at 60º, as expected, showed greater strength in comparison with the beams M-4-90 and M-8-90, with the stirrups at 90º, as observed in the study by [4], since the inclined transverse reinforcement manages to intercept a greater number of cracks, ensuring greater load capacity for the beam.

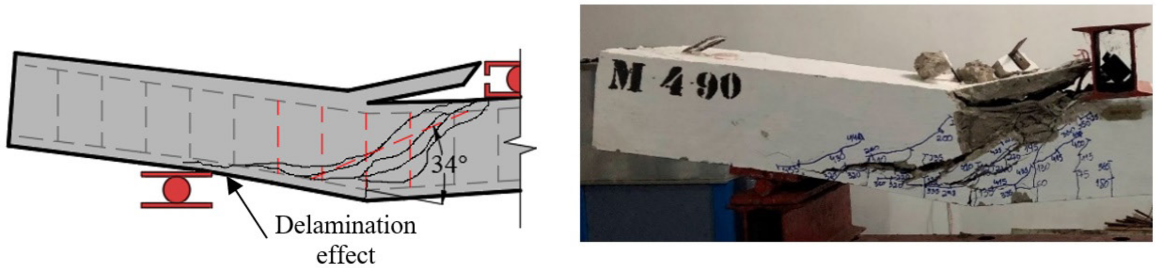
It was also observed that, when the stirrups with 4 vertical legs are compared with the stirrups with 8 legs, M-4-90 beam showed greater shear strength when compared with M-8-90 beam, however, the delamination effect may have limited the real strength of the beam.

The beams with M stirrup inclined at 60º, M-4-60 and M-8-60, presented an approximately equal strength, thus it is observed that the variation of the number of legs does not present increase in shear strength.

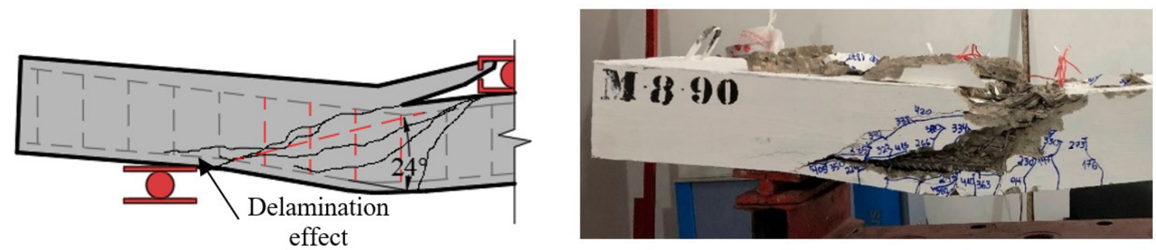
As for the flexural strength, it was observed that all beams had shear failure. And in relation to the reference beam, beams M-4-60 and M-8-60 showed the greatest strength increase, around 14%, followed by M-4-90 beam, which showed an increase of 10%, and finally M-8-90 beam, with a 2% strength gain, in comparison with the reference beam.



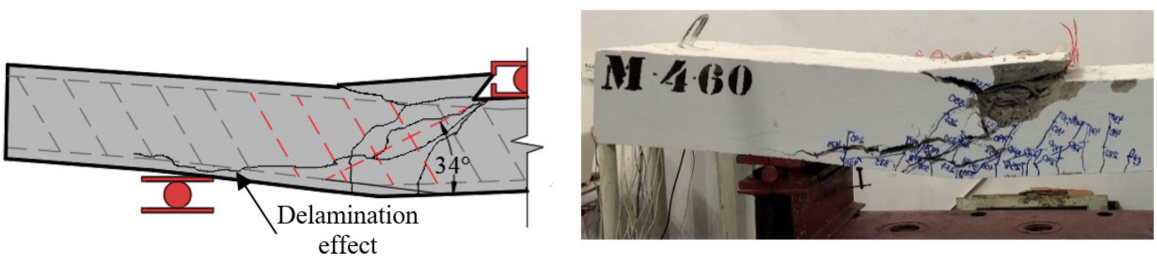
a) Cracks of beam C-4-90 and beam after the test



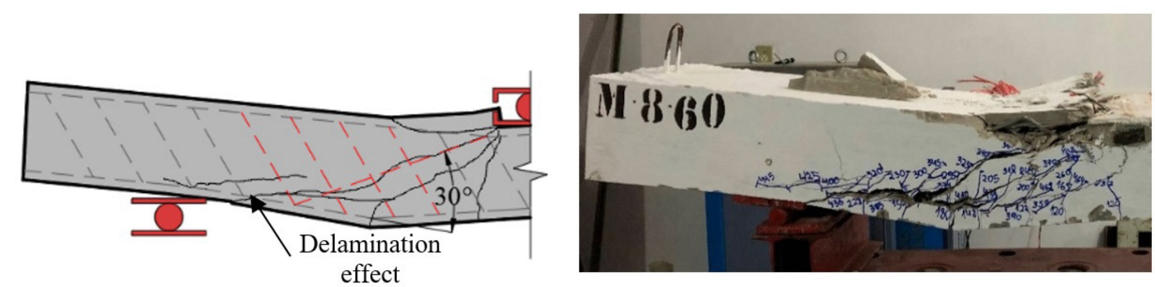
b) Cracks of beam M-4-90 and beam after the test



c) Cracks of beam M-8-90 and beam after the test



d) Cracks of beam M-4-60 and beam after the test



e) Cracks of beam M-8-60 and beam after the test

Figure 12 – Failure surface of the tested beams

4.6 Code comparison

Table 5 shows the failure load of the beams, compared with the flexural shear and the values expected by theoretical prediction. Figure 13 shows the graph comparing the failure load with the theoretical prediction.

Table 5 - Failure load of the beams and comparison with theoretical estimates.

Beams	V_u (kN)	V_u/V_{flex}	V_u/V_{ref}	V_u/V_{NBR-I}	V_u/V_{NBR-II}	V_u / V_{ACI}	V_u / V_{EC2}
C-4-90	207.00	0.71	1.00	1.15	0.97	1.28	0.95
M-4-90	227.50	0.78	1.10	1.27	1.07	1.41	1.04
M-8-90	210.50	0.72	1.02	1.18	1.00	1.32	0.98
M-4-60	233.50	0.80	1.13	1.10	0.97	1.22	1.00
M-8-60	235.00	0.81	1.14	1.12	0.99	1.24	1.03
Mean				1.17	1.00	1.30	1.00
Standard deviation				0.06	0.04	0.07	0.04
COV (%)				5%	4%	6%	4%

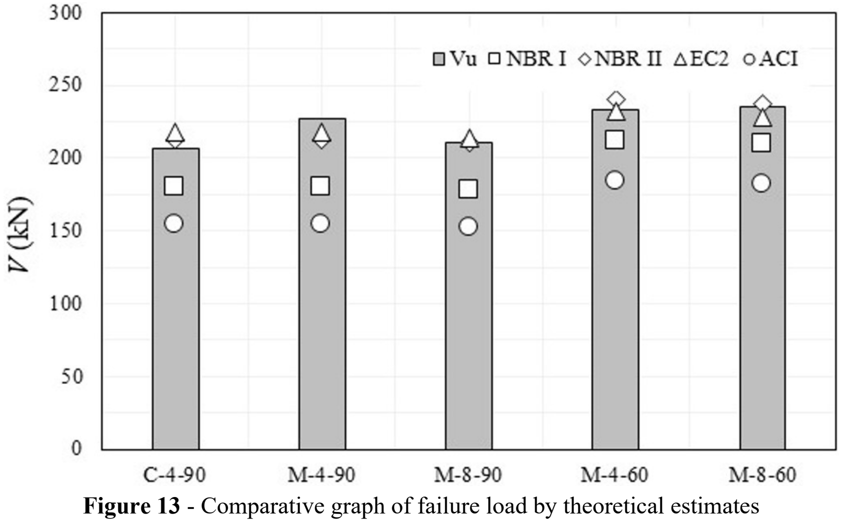


Figure 13 - Comparative graph of failure load by theoretical estimates

In general, it is possible to observe that the level of dispersion of the results was relatively low, as well as the level of safety of the analyzed codes, for this sample universe, proves to be adequate.

Regarding the comparison with the analyzed codes, the most conservative was the American one [19], which was already expected, since it has this conservative profile in relation to safety, where all beams presented strength greater than 30% of what was estimated by it.

NBR 6118 [5] was conservative in its model I, however, model II presented all its values closer to the experimental ones, with theoretical estimates against security with the worst scenario 3% below what was predicted by the code. This approximation to the experimental values may have occurred due to model I considering only the 45º angle for the inclination of the strut in its design, while model II considers values between 30º and 45º, with this, a greater amount of transverse reinforcement layers is estimated, making the model II approach the tested values.

Eurocode 2 [20] approaches model II of NBR 6118 [5], where the mean of the comparisons of the two codes was equal to 1, and the standard deviation and variation of the code is equal to that of [5], confirming this proximity in the estimates, and this is justified since the recommendations for estimating the shear strength of the two codes are similar.

5 CONCLUSIONS

The main objective of this study was to evaluate the behavior of a new type of transverse reinforcement with internal anchoring, comparing it with closed stirrups, as they are a type of shear reinforcement widely used. It is worth mentioning that the objective of the study was not to compare the consumption of steel to produce the beams, as the possible benefits of this type of reinforcement would not bring savings in material consumption, but in productivity, since this type of reinforcement allows for industrialization and prefabrication, as the position of the transverse reinforcement does not depend on the position of the longitudinal reinforcement.

The test set-up adopted to carry out this experimental study proved to be efficient, presented good behavior and all the parameters that were planned could be collected without major difficulties. In general, all beams had shear failure and the beams with M stirrups also showed delamination effects, however, the efficiency of the complementary reinforcement to control and reduce the delamination cracks stands out, due to the better anchoring of the internal transverse reinforcement, allowing the stirrups to show greater shear strength.

The beams tested with M stirrup showed mid-span strains similar to those of the reference beam and shear strength, on average, 10% higher than that of the beam with closed stirrups, the C-4-90 beam. Regarding the variation in the number of legs used in M stirrups, there was no increase in strength for stirrups with 4 vertical legs or stirrups with 8 vertical legs, but it was observed that beams with M stirrups with 4 legs showed greater ductility in relation to beams with stirrups with 8 legs.

Beams M-4-60 and M-8-60, with internal transverse reinforcement inclined at 60º, presented greater shear strength in relation to beams with M stirrups inclined at 90º. This gain in load capacity was also justified in the tests of [4] and can even be attributed to the fact that the inclined transverse reinforcement intercepts a greater number of cracks, thus allowing a better flow of internal forces.

The results of the two types of internal transverse reinforcement show the M stirrup as a promising alternative, since it can be industrially manufactured, presents ease of execution and gains in productivity, since it is only positioned between the flexural bars, thus reducing the cost with labor to manufacture the M stirrups.

Through the comparisons made with the test results of the beams with the theoretical prediction of the analyzed standards, it is possible to design efficiently and with adequate shear safety for beams with the M stirrups, as there were no large dispersions of the results of the beams strength when compared with the predicted strengths. However, it is worth mentioning that, as only one specimen of each beam was tested, more tests must be performed to observe and confirm whether this behavior is maintained in a larger sample universe, with more variables involved.

6 ACKNOWLEDGEMENTS

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