EMBEDDED THROUGH-SECTION BARS FOR THE SHEAR STRENGTHENING OF RC BEAMS

Gláucia DALFRÉ
PhD Student
ISISE, University of Minho
Campus of Azurém
*gmdalfre@civil.uminho.pt**

Joaquim BARROS
Full Professor
ISISE, University of Minho
Campus of Azurém
barros@civil.uminho.pt

Daniel MACHADO
MSc in Civil Engineering
ISISE, University of Minho
Campus of Azurém
a44227@alunos.uminho.pt

Abstract

Embedded Through-Section (ETS) technique is a relatively recent shear strengthening strategy for reinforced concrete (RC) beams, and consists on opening holes across the beam thickness, with the desired inclinations, where bars are introduced and are bonded to the concrete substrate with adhesive materials. To assess the effectiveness of this technique, a comprehensive experimental program composed of 14 RC beams was carried out and the obtained results confirm the feasibility of the ETS method and reveal that: (i) inclined ETS strengthening bars were more effective than vertical ETS bars and the shear capacity of the beams has increased with the decrease of the spacing between bars; (ii) brittle shear failure was converted in ductile flexural failure and (iii) the contribution of the ETS strengthening bars for the beam shear resistance was limited by the concrete crushing or due to the yielding of the longitudinal reinforcement.

Keywords: ETS technique, Reinforced concrete, Shear strengthening, Strengthening bars.

1. Introduction

This paper reports the relevant results obtained from an extensive experimental program to assess the effectiveness of the Embedded Through-Section (ETS) technique for the shear strengthening of RC beams. Since the strengthening bars are inserted into holes open through the cross section, they are much better protected from fire, environmental aggressive agents and vandalism acts than externally bonded reinforcement (EBR) and near surface mounted (NSM) techniques based on the use of fibre reinforced polymer (FRP) systems. This research program has started in 2007, where the use of FRP and steel bars, applied according to a technique that was originally designated by Core Drilled Mounted (CDM), was explored for the shear strengthening of concrete elements. In this context, direct shear tests were executed with the purpose of capturing the main features of the FRP/Steel CDM bars contribution for the shear resistance, and to provide data for a rational decision about the most effective bars and adhesives for this type of application [1, 2]. From the results, a significant increase in shear strength was obtained with a relatively low reinforcement ratio, and it was verified that steel bars were very effective. In a second phase of this project, a program of pullout tests with steel bars was carried out, where the influences of the type of adhesive, the thickness of the adhesive layer (2, 4, 5 and 6 mm), diameter of the steel bar and bond length (50 and 75 mm) on the bond phenomena were assessed [3, 4]. It was found that the overall behaviour of the adhesive/strengthening bar/concrete interfaces is dependent on the choice of adhesive. Additionally, the results show that the anchorage length and the thickness of the adhesive layer have marginal influence on the bond strength, but this last property has increased with the Young's modulus of the adhesive. The present paper resumes the research of the third part of this project, where the effectiveness of the ETS shear strengthening technique is assessed. For this purpose, an experimental program composed of two series RC beams of different cross section was carried out. The variables examined in the experimental program were (i) spacing of existing steel stirrups (225 and 300 mm), (ii) inclination of the strengthening steel bars with respect to the longitudinal axis of the beam (vertical and 45-degrees) and (iii) the interaction of existing steel stirrups and the strengthening bars. The experimental program is described and the obtained relevant results are presented and analysed.

2. Experimental program

2.1 Specimens

The experimental program is formed by two series, A and B, composed of beams with a cross section of 150x300 mm^2 and 300x300mm^2, respectively, with a total length of 2450 mm and a shear span length of 900 mm (Figures 1 and 2). The longitudinal tensile steel reinforcement of A and B series consists, respectively, of two and three steel bars of 25 mm diameter (∅ 25 mm). The longitudinal compressive steel reinforcement was composed of two and three steel bars of 12 mm diameter (∅ 12 mm) in the A and B series, respectively. Steel stirrups of two vertical arms and 6 mm diameter were used. The concrete clear cover for the top, bottom and lateral faces of the beams was 20 mm.

Each series is made up of a beam without any shear reinforcement (Reference beam) and a beam for each of the following shear reinforcing systems: (i) steel stirrups of ∅6 mm at a spacing of 300 mm, (ii) ETS strengthening bars at 45º or at 90º in relation to the beam axis, with a spacing of 300 mm, (iii) steel stirrups of ∅6 mm at a spacing of 300 mm and ETS strengthening bars at 45º or at 90º, with a spacing of 300 mm. Additionally, for the A Series, two other shear reinforcing systems were also tested: (iv) steel stirrups of ∅6 mm at a spacing of 225 mm and (v) steel stirrups of ∅6 mm at a spacing of 225 mm and ETS strengthening bars at 90º, with a spacing of 225 mm. It should be noted that an ETS bar was designed as a stirrup of one arm, following the design recommendations of ACI Code [5] for the steel stirrups in the context of shear reinforcement or RC beams.

Table 1 includes general information of the beams composing the two series, where ρ_{sl} is the longitudinal steel reinforcement ratio [$\rho_{sl} = (A_{sl}/b_w \cdot d)\times 100$, where A_{sl} is the cross sectional area of the longitudinal steel bars, b_w is the web width and d is the distance from the extreme compression fibre of the cross section to the centroid of the longitudinal reinforcement]. In Table 1, the shear reinforcement ratio (ρ_{sw}) is given by $\rho_{sw} = (A_{sw}/b_w \cdot s_w)\times 100$, where A_{sw} is the cross sectional area of the two arms of the steel stirrups and s_w is the spacing between stirrups. Finally, the ρ_f indicated in Table 1 is the ETS strengthening ratio, $\rho_f = (A_f/b_w \cdot s_f \cdot sen\theta_f)\times 100$, where A_f is the cross sectional area of a ETS shear strengthening bar, s_f is the spacing between these bars and θ_f is the inclination of the strengthening bars with respect to the longitudinal axis of the beam. The number of days between the strengthening intervention and the test was indicated in this Table. Since the beams were not cast in the same batch, the corresponding batch is also indicated in this Table.

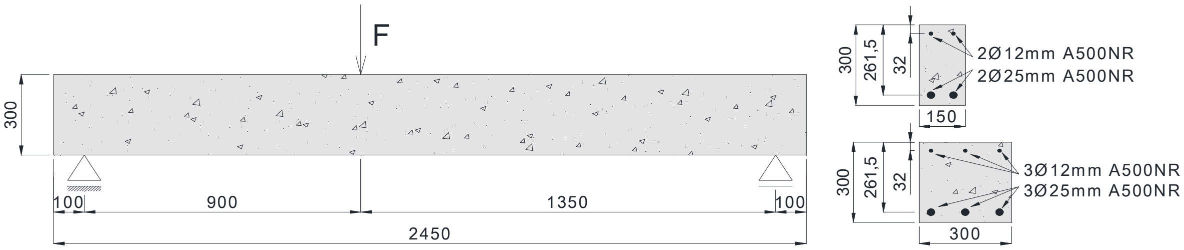


Figure 1. Test configuration. All dimensions are in mm

Table 1. General information of the beams.

Beams ID	150 x 300 mm^2					300 x 300 mm^2				
	Age of the strengthening when the beam was tested (days)	ρ_{sl} (%)	ρ_{sw} (%)	ρ_f (%)	Batch	Age of the strengthening when the beam was tested (days)	ρ_{sl} (%)	ρ_{sw} (%)	ρ_f (%)	Batch
Reference	------	2.50	0.00	0.00	1	------	1.88	0.00	0.00	1
S300.90	------	2.50	0.13	0.00	1	------	1.88	0.06	0.00	1
E300.90	34	2.50	0.00	0.17	1	65	1.88	0.00	0.11	1
E300.45	34	2.50	0.00	0.25	2	64	1.88	0.00	0.16	2
S300.90/ E300.90	33	2.50	0.13	0.17	1	69	1.88	0.06	0.11	1
S300.90/ E300.45	29	2.50	0.13	0.25	2	68	1.88	0.06	0.16	2
S225.90	------	2.50	0.17	0.00	2					
S225.90/ E225.90	35	2.50	0.17	0.23	2					

2.2 Test setup and monitoring system

Figure 3 depicts the positioning of the sensors for data acquisition. To measure the deflection of a beam, four linear voltage differential transducers (LVDTs) were supported in a suspension yoke (see Figure 3(a)). The LVDT 3558 was also used to control the test at a displacement rate of 20 µm/s up to the failure of the beams. The beams were loaded under three-point bending with a shear span of 900 mm. This corresponded to an a/d ratio equal to 3.44, where a is the shear span and d the depth of the longitudinal reinforcement. The applied load (F) was measured using a load cell of ±500 kN and accuracy of ±0.05%. Two or three electrical resistance strain gauges (S1 to S3), depending on the shear reinforcing arrangement, were installed in the steel stirrups to measure the strains. Additionally, six or eight SGs (1 to 8) were bonded on the ETS strengthening bars according to the strengthening arrangement represented in Figure 3(b).

2.3 Material properties

Table 2 includes the values obtained from the experimental tests for the characterization of the main properties of the materials used in the present work. The average compressive strength (f_{cm}) was determined according to NP-E397 [6]. To characterize the tensile behaviour of the steel bars, uniaxial tensile tests were conducted according to the standard procedures of ASTM 370 [7]. Sikadur 32N structural epoxy bonding agent was used to bond the ETS steel bars to the concrete. For the characterization of the tensile behaviour of the epoxy adhesive, uniaxial tensile tests were performed according to the procedures outlined in ISO 527-2 [8].

2.4 Strengthening technique steps

Before drilling the holes, a rebar detector was used to verify the position of the existing longitudinal bars and stirrups. Afterward, the positions of the strengthening bars were marked on the RC beams and holes were made with the desired inclinations through the core of the cross-section of the RC beams. These holes had 16 mm or 18 mm of diameter, where bars of 8 mm or 10 mm diameter were introduced, respectively, resulting in an adhesive layer of about 4 mm thickness. The holes were cleaned with compressed air, and one extremity of the holes was blocked before bonding the strengthening bars to the concrete. The bars were cleaned with acetone to remove any possible dirt. The adhesive was prepared according to the supplier recommendations and the bars were introduced into the holes, that were filled with the adhesive (care was taken to prevent air bubble formation in the adhesive layer during the application of strengthening system). Finally, the adhesive in excess was removed. A period of 15 days was dedicated to cure of the adhesive (in laboratory environmental conditions) prior to testing the beams.

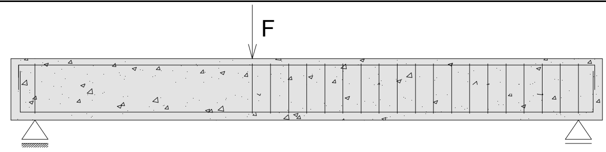
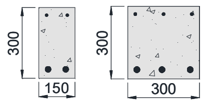
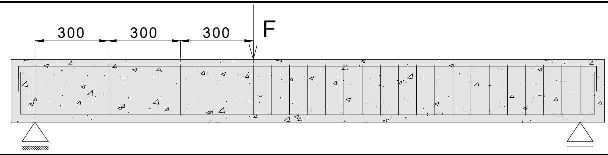
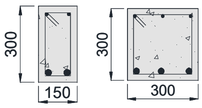
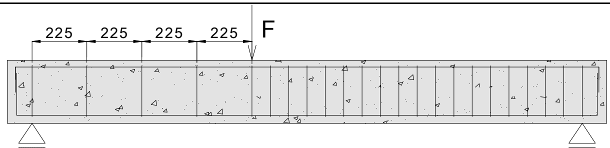
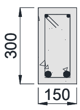
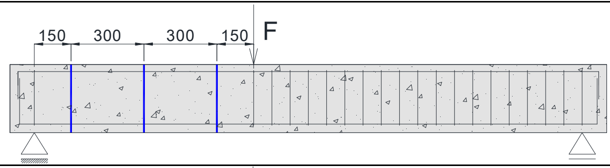
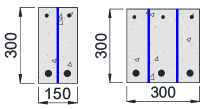
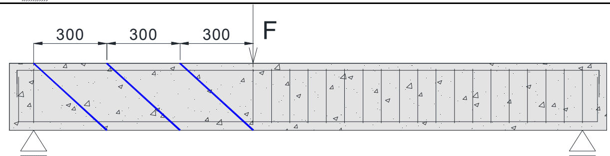
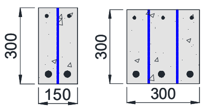
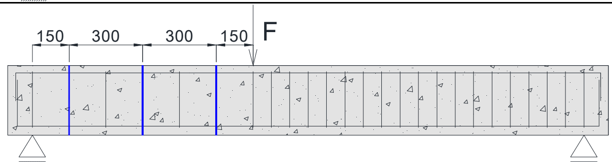
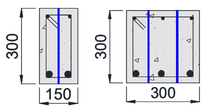
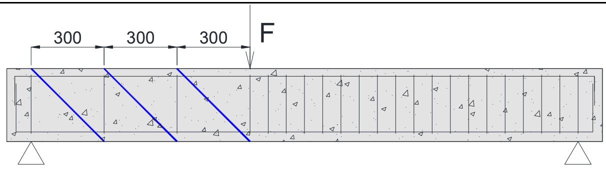
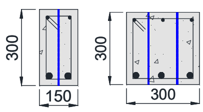
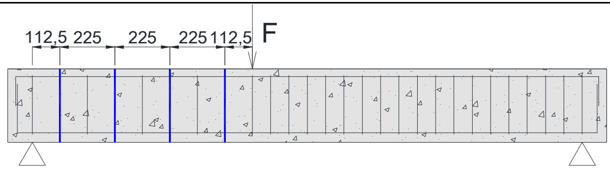
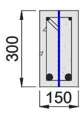
SHEAR STRENGTHENING SYSTEM		SHEAR STRENGTHENING ARRANGEMENTS	SHEAR SPAN REINFORCEMENT/ STRENGTHENING
Reference	-----------		
S300.90	Stirrups at 90° (2∅6 mm of 2 arms, 300 mm spacing)		
S225.90	Stirrups at 90° (3∅6 mm of 2 arms, 225 mm spacing)		
E300.90	ETS strengthening bars at 90° (3∅10 mm, 300 mm spacing)		
E300.45	ETS strengthening bars at 45° (3∅10 mm, 300 mm spacing)		
S300.90/ E300.90	Stirrups at 90° (2∅6 mm of 2 arms, 300 mm spacing) ETS strengthening bars at 90° (3∅10 mm, 300 mm spacing)		
S300.90/ E300.45	Stirrups at 90° (2∅6 mm of 2 arms, 300 mm spacing) ETS strengthening bars at 45° (3∅10 mm, 300 mm spacing)		
S225.90/ E225.90	Stirrups at 90° (3∅6 mm of 2 arms, 225 mm spacing) ETS strengthening bars at 90° (4∅10 mm, 225 mm spacing)		

Figure 2. General information about the A and B Series. All dimensions are in mm

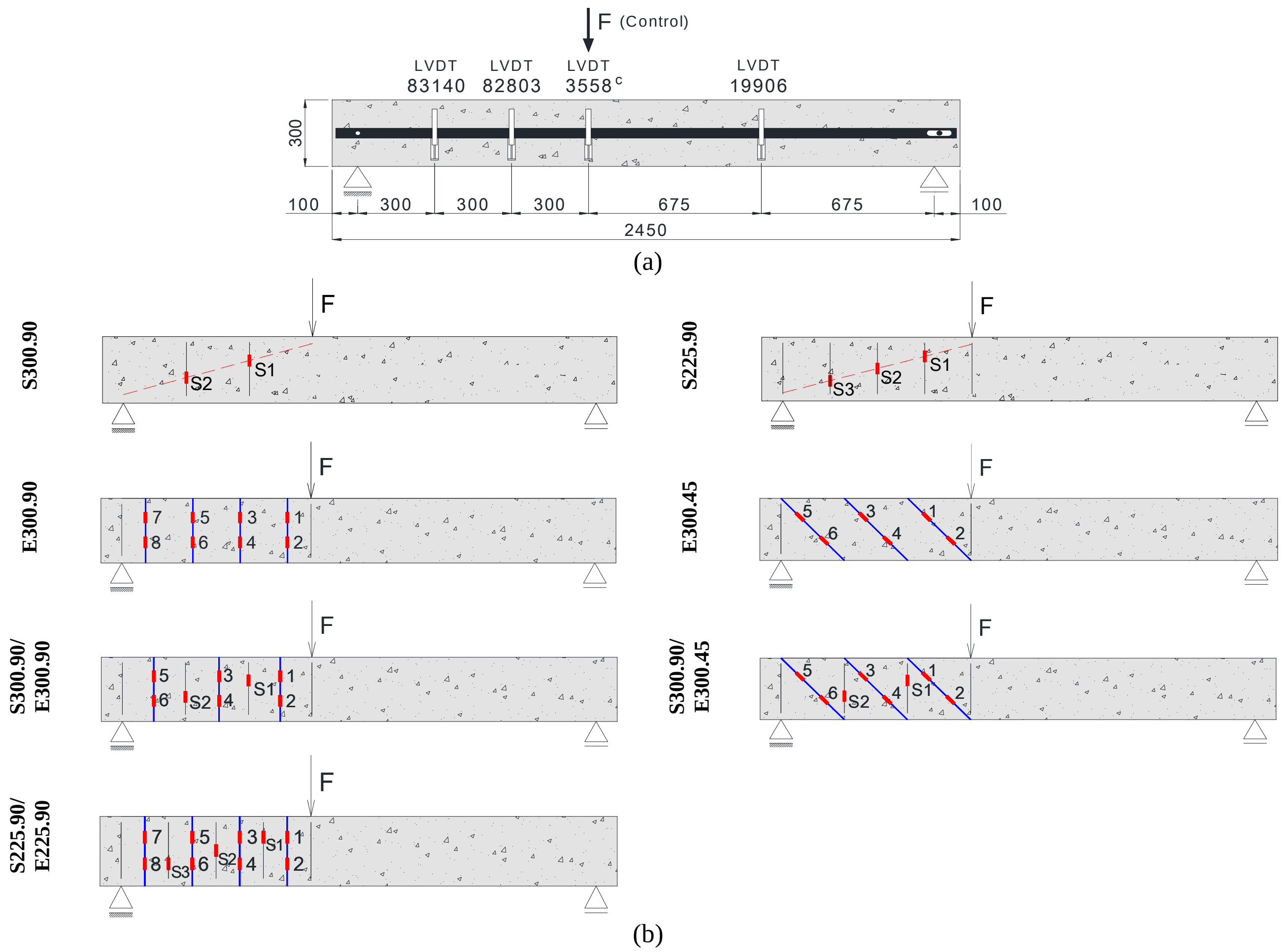


Figure 3. Monitoring system: (a) arrangement of the displacement transducers and (b) strain gages in stirrups and ETS strengthening bars. All dimensions are in mm

Table 2. Materials properties

STEEL REINFORCEMENT						CONCRETE	
Steel bar diameter (∅s)	Modulus of elasticity (GPa)	Yield stress (MPa)	Strain at yield stress (‰)	Tensile strength (MPa)	Bars ID	Batch ID	f_{cm} (MPa)
12 mm	206.62 (1.84)	484.68 (1.26)	2.35 (3.21)	655.53 (0.91)	Longitudinal reinforcement	1	30.78 (4.90)
25 mm	216.19 (9.83)	507.68 (0.96)	2.27 (4.76)	743.41 (1.31)	Longitudinal reinforcement	2	28.81 (4.55)
6 mm	206.07 (6.72)	559.14 (1.00)	2.75 (6.54)	708.93 (1.44)	Stirrups	ADHESIVE	
8 mm	212.36 (4.29)	566.50 (4.17)	2.66 (6.97)	675.73 (2.03)	ETS strengthening bar	Modulus of elasticity (GPa)	3.94 (9.82)
10 mm	205.16 (3.25)	541.60 (0.91)	2.66 (3.98)	643.23 (0.39)	ETS strengthening bar	Tensile strength (MPa)	26.29 (10.62)
(value) Coefficient of Variation (COV) = (Standard deviation/Average) x 100; f_{cm} = mean cylinder concrete compressive strength							

3. Main results

Figure 4 shows the relationship between the total applied load versus the deflection of the loaded section, *F-u*, for A and B Series, respectively. Each figure provides the *F-u* for the reference beam (Ref.) and for the beams strengthened with the different shear strengthening arrangements. The *F-u* responses clearly shows that the shear strengthening/reinforcement systems are only active for deflection levels above the one corresponding to the formation of the shear failure crack of the reference beam. For similar ρ_{sw} and ρ_f the behaviour of RC beams reinforced with steel stirrups or strengthened with ETS bars have identical behaviour (S300.90 and E300.90 beams). For the same volume of ETS bars, but applied with different inclination (which means different shear strengthening ratio, ρ_f), the results show a significant increase of load carrying capacity and deflection at peak load with ρ_f (E300.90 and E300.45 beams in both series). In series B the stiffness of the beams up to their peak load is almost the same, which indicate a prevalent influence of the concrete aggregate interlock for the stiffness due to the larger width of the cross section of the beams of this series. Due to the significant increase provided by the ETS bars for the shear resistance, the beams reinforced with steel stirrups and strengthened with ETS bars collapsed by the yielding of the longitudinal steel bars, followed by concrete crushing. In the design phase of the ETS strengthening systems it was not expected a so high shear strengthening effectiveness for these systems. This means that if abnormally high ρ_{sl} ratios have not been adopted (to force the occurrence of shear failure), the ETS shear strengthening arrangements would have converted brittle shear failure into a ductile flexural failure with the yielding of the longitudinal steel bars, and the level of increase of the ultimate load would have been even higher that the ones registered in the present experimental program.

Table 3 presents the main results obtained experimentally. In this Table, $F_{\max}$ is the maximum value of the load registered in the load cell during the test, $\Delta F_{\max} / F_{\max}^{REF}$ is the increase in terms of load carrying capacity, $\delta_{F\max}$ is the deflection of the loaded section at $F_{\max}$ and $\Delta\delta_{F\max} / \delta_{F\max}^{REF}$ is the increase in terms of deflection capacity provided by the strengthening technique. Additionally, $V_n = 0.6F_{\max}$ is the shear resistance of the beam and V_c, V_s and V_f are the shear resistance attributable to the concrete, steel stirrups and ETS strengthening bars, respectively ($V_n = V_c + V_s + V_f$). Finally, $\varepsilon_{s,F\max}$ and $\varepsilon_{f,F\max}$ are the maximum strains in the steel stirrups and in the ETS strengthening bars at $F_{\max}$.

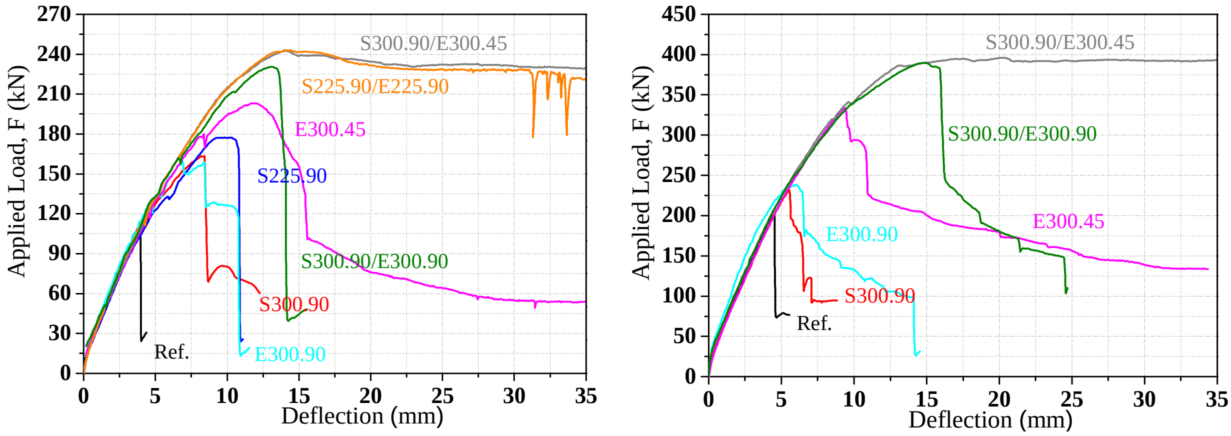
Note that the values indicated in Table 3 were obtained based on the following assumptions: a) the shear resistance due to concrete is the same regardless the beam is reinforced with steel stirrups or/and strengthened with ETS bars; and b) the contribution of steel stirrups for the shear resistance is the same in strengthened and unstrengthened beams. From the obtained results it can be pointed out the following main observations:

(i) The use of steel ETS bars for the shear strengthening allowed significant increase of the load carrying capacity of RC beams for the both bar orientations considered. The effectiveness is not only in terms of the beam load carrying capacity, but also in terms of the deflection performance.

(ii) Based on the results of the unstrengthened beams (Reference), it was found that the beams reinforced with steel stirrups (S300.90) and the beams strengthened according to the ETS technique (E300.90) presented an increase in the load carrying capacity of 51 % and 48 % (A Series) and of 14 % and 17% (B Series), respectively. In terms of deflection capacity, an increase of 110 % and 74 % (A Series) and of 25 % and 36 % (B Series), respectively, was obtained.

(iii) The shear reinforcing system composed by inclined ETS strengthening bars was more effective than vertical ETS bars, assuring a better performance in terms of load and deflection capacities than vertical bars. This is justified by the orientation of the shear failure cracks that had a tendency to be almost orthogonal to inclined ETS bars. Furthermore, for vertical ETS bars, the total resisting bond length is lower than that of inclined ETS bars. Based on the results of the E300.90 beams, it was found that the E300.45 beams presented an increase in the load carrying capacity of 27 % and 41% for A and B Series, respectively. The deflection capacity has also increased in 72 % and 55 % for A and B Series, respectively.

(iv) Since the strains recorded by strain gauges (SGs) are quite dependent of the relative position between the SGs and the shear failure crack, remarks based on these values should not be regarded as conclusions. However, since ETS has increased significantly the load carrying capacity of the shear RC beams, the increase of the maximum strains in both stirrups and ETS bars was expected, and the obtained values were around the yield strain (ε_{sy}) of the corresponding bars and some of them have even exceeded ε_{sy}, such was the case of the beams with ETS bars at 45°.



(a) (b)

Figure 4. Relationship between the applied load versus the loaded section deflection for A (a) and B (b) Series

Table 3. Experimental results.

SPECIMEN		F_{max} (kN)	$\frac{\Delta F_{max}}{F_{max}^{REF}}$ (%)	$\delta_{F\max}$ (mm)	$\frac{\Delta\delta_{F\max}}{\delta_{F\max}^{REF}}$ (%)	V_n (kN)	V_c (kN)	V_s (kN)	V_f (kN)	$\varepsilon_{s,F\max}$ (‰)	$\varepsilon_{f,F\max}$ (‰)
A Series	Ref.	108.86	------	4.01	------	65.32		--------	--------	------	------
	S300.90	164.67	51.27	8.40	109.58	98.80		33.48	--------	2.73 (S2)	--------
	S225.90	180.31	65.63	9.92	147.32	108.19		42.87	--------	4.27 (S2)	--------
	E300.90	160.78	47.69	6.97	73.96	96.47		--------	31.15	--------	2.15 (1)
	E300.45	203.98	87.38	12.04	200.25	122.39	65.32	--------	57.07	--------	2.07 (4)
	S300.90/ E300.90	231.83	112.96	13.12	227.18	139.10		33.48	40.30	2.44 (S2)	2.57 (1)
	S300.90/ E300.45	244.41	124.52	14.00	249.21	146.65		33.48	47.85	2.41 (S1)	15.64 (4)
	S225.90/ E225.90	244.17	124.30	14.44	260.10	146.50		42.87	38.31	2.08 (S3)	2.60 (1)
B Series	Ref.	203.36	------	4.45	------	122.02		--------	--------	------	------
	S300.90	232.31	14.24	5.56	24.94	139.39		17.37	--------	1.66 (S2)	--------
	E300.90	238.88	17.47	6.06	36.18	143.33		--------	21.31	--------	0.53 (1)
	E300.45	336.19	65.32	9.42	111.68	201.71	122.02	--------	79.69	--------	1.97 (4)
	S300.90/ E300.90	390.11	91.83	15.01	237.30	234.07		17.37	94.68	2.91 (S1)	2.54 (3)
	S300.90/ E300.45	396.51	94.97	20.18	353.48	237.91		17.37	98.52	14.63 (S1)	4.77 (1)

(value) = SG that registered the maximum strain at F_{max}.

4. Conclusions

This study presents the relevant results of an experimental program for the assessment of the effectiveness of the Embedded Through-Section (ETS) technique for the shear strengthening of reinforced concrete beams. The influence of the following parameters was investigated: spacing of the existing steel stirrups (225 and 300 mm), spacing (225 and 300 mm) and inclination of the strengthening bars (vertical and 45-degree), width of the cross section of the beam. The obtained results evidenced that ETS provides increase levels of load carrying and deflection capacities higher than shear strengthening techniques based on the use of FRP systems, like EBR and NSM. Furthermore, in the ETS technique it can be used low cost steel bars bonded to concrete with cement based matrix that incorporates a small percentage of resin based-component. Since ETS steel bars have a relatively thick concrete cover, corrosion and injuries due to vandalism acts are not a concern.

5. Acknowledgements

The study reported in this paper forms a part of the research program "DURCOST - Innovation in reinforcing systems for sustainable pre-fabricated structures of higher durability and enhanced structural performance" supported by FCT, PTDC/ECM/105700/2008. The authors wish to acknowledge the support provided by the "Empreiteiros Casais", Sika Portugal and Secil (Unibetão, Braga) Companies. The first author would like to acknowledge the National Council for Scientific and Technological Development (CNPq) – Brazil for financial support for scholarship (GDE 200953/2007-9).

6. References

[1] BARROS, J.A.O., DALFRÉ, G.M., TROMBINI, E., APRILE, A., "Exploring the possibilities of a new technique for the shear strengthening of RC elements", *Proceedings of the International Conference Challenges for Civil Construction*, University of Porto, Portugal, 2008.

[2] DALFRÉ, G., BARROS, J., Trombini, E., "Análise do desempenho de uma nova técnica de reforço ao corte para elementos estruturais de betão armado", *Proceedings of BE2008 – Encontro Nacional de Betão Estrutural*, 2008, Guimarães, Portugal, 2008 (in Portuguese).

[3] MACHADO, D., "Desenvolvimento de uma técnica de reforço ao corte de vigas de betão armado por intermédio de varões embebidos", *Master Thesis*, University of Minho, July, 2011 (in Portuguese).

[4] DALFRÉ, G., BARROS, J., MACHADO, D., "Comportamento da ligação varões de aço-betão no contexto de reforço ao corte segundo a técnica ETS para vigas de betão armado", *53º Congresso Brasileiro do Concreto (Ibracon 2011)*, Florianópolis, Brazil, November, 2011 (accepted for publication, in Portuguese).

[5] ACI Committee 318, "Building code requirements for structural concrete and Commentary (ACI 318-08)", *Reported by committee 318*, American Concrete Institute, Detroit, 2008.

[6] LNEC NP-E397, "Concrete - Assessment of the elasticity modulus under uniaxial compression", *Laboratório Nacional de Engenharia Civil*, 1993 (in Portuguese).

[7] ASTM 370, "Standard test methods and definitions for mechanical testing of steel products", *American Society for Testing and Materials*, 2002.

[8] ISO 527-2, "Plastics - Determination of Tensile Properties - Part 2: Test Conditions for Moulding and Extrusion Plastics", *International Organization for Standardization (ISO)*, Geneva, Switzerland, 2002.