FLEXURAL AND SHEAR STRENGTHENING OF RC BEAMS WITH COMPOSITES MATERIALS – THE INFLUENCE OF CUTTING STEEL STIRRUPS TO INSTALL CFRP STRIPS

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1 INTRODUCTION

Experimental [1], numerical and analytical [2] research reveals that as larger is the height of the cross section of Carbon Fiber Reinforced Polymer (CFRP) strip, as more effective is the Near Surface Mounted (NSM) technique for flexural strengthening of reinforced concrete (RC) beams. However, this height is, in general, limited to the concrete cover, since the application of strips of cross section height larger than the concrete cover requires that the bottom arm of the steel stirrups be cut [3]. This work aims to assess the influence, in terms of shear resistance, of cutting the bottom arm of steel stirrups to install NSM strips for the flexural strengthening of RC beams. In the present paper the experimental program is described, and the relevant obtained results are presented and discussed.

2 CHARACTERISTICS OF THE BEAMS AND REINFORCEMENT SYSTEMS

The experimental program is composed by beams of distinct heights, once it is admissible to assume that as larger is the height of the beam cross section as lesser important will be the influence of cutting the steel stirrups. For this experimental program three series of beams with distinct heights were tested, and each of these series was composed by four beams, as follows:

– VRi – RC reference beam
– VEi – RC beam (equal to VRi), with the bottom arm of the stirrups cut
– VLi – RC beam (equal to VEi), flexural strengthened with CFRP strips
– VLMi – RC beam (equal to VLi), shear strengthened with CFRP strips of sheet

The beams were designed according to the Portuguese design guideline for RC structures [4]. Figure 1 schematizes the geometry and loading conditions of the tested beams, and Table 1 includes the values of the variables indicated in Fig.1.

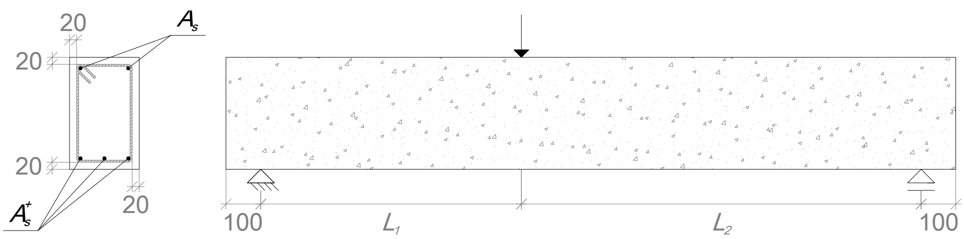

Fig. 1 Geometry and loading conditions of the tested beams – dimensions in millimetres.

Table 1 Dimensions and reinforcement characteristics of the different types of beams.

Series	L_1 [mm]	L_2 [mm]	b [mm]	h [mm]	A_s^+ (lower face)	A_s^- (upper face)
1	550	950	200	250	2ϕ10 + 1ϕ6	2ϕ10
2	750	1150	200	320	2ϕ10 + 1ϕ10	2ϕ10
3	900	1300	200	380	2ϕ12 + 1ϕ8	2ϕ12

The steel bars used for the reinforcement of the beams had a yield stress ranging between 546 MPa and 597 MPa and a tensile strength between 648 MPa and 738 MPa. At 28 days the concrete pesented an average compressive strength of 31.1 MPa and a Young's Modulus of 28.9 GPa. More details about the properties of the intervening materials can be found elsewhere [8]. In each series of beams the number of NSM CFRP laminates for the flexural strengthening was designed [5] to double the load carrying capacity of the respective reference beam. Additionally, the shear reinforcement configurations of the flexural strengthened beams (VLi) were designed to provide a shear failure for these beams. In both strengthened beams of each series (VLi and VLMi type) two S&P Laminates CFK 150/200, with 1.4 mm × 20 mm cross section, were applied (Young's Modulus of 165 GPa and tensile strength of 1850 MPa, according to the supplier) The shear strengthening systems applied in VLMi beams were designed according to the fib TG 9.3 [6] recommendations. These beams were reinforced with strips of one layer of S&P C-Sheet 240 (200 g/m^2), with 50 mm of width (w_f), and applied in U-shape (Young's Modulus of 240 GPa and tensile strength of 3800 MPa, according to the supplier). These shear strengthening systems were applied according to the externally bonded reinforcing (EBR) technique [6]. The flexural and shear strengthening configurations are represented in Figure 2.

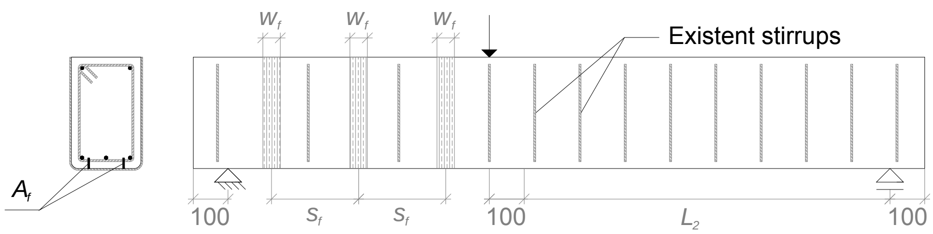

Fig. 2 Flexural and shear strengthening configurations – dimensions in millimetres.

3 DISCUSSION OF THE RESULTS

The beams were tested in a three point monotonic loading configuration, in a displacement controlled at a displacement rate of 2 μm/s, using a servo-hydraulic test machine. The force was measured by a load cell of 550 kN capacity, the beam deflection was recorded by 5 LVDTs, and strain gauges were applied in steel longitudinal and transversal steel bars, NSM laminates and CFRP strips for measuring the strains in these reinforcement elements.

The main obtained results are included in Table 2.

Table 2 Summary of the load carrying capacity increment in the different series of beams.

Beam	F_{max} [kN]	$\frac{F_{max}}{F_{VR1}}$
VR1	67	1.00
VE1	69	1.02
VL1	96	1.43
VLM1	121	1.80

Beam	F_{max} [kN]	$\frac{F_{max}}{F_{VR2}}$
VR2	88	1.00
VE2	89	1.00
VL2	137	1.55
VLM2	156	1.77

Beam	F_{max} [kN]	$\frac{F_{max}}{F_{VR3}}$
VR3	116.03	1.00
VE3	103.26	0.89
VL3	148.28	1.28
VLM3	157.96	1.36

The relationship between the applied force and the deflection at the beam loaded section for the beams of the three tested series is represented in Figs. 3 to 5. At the failure of all the tested beams, the longitudinal steel reinforcement was already yielded. The VRi and VEi beams of all the series failed in bending, while VLi beams, as expected, failed in shear. Therefore, the purpose of doubling the load carrying capacity of their corresponding reference beams was not attained. VLM1 and VLM3 beams also failed in shear, while VLM2 beam failed by the occurrence of concrete splitting in L_2 branch (Fig. 6). These failure models avoided the duplication of the load carrying capacity of the reference beams, which indicate that the fib formulation for the design of FRP shear strengthening U configurations still needs some improvements. Concrete splitting failure mode needs also to be avoided in order to increase the flexural strengthening effectiveness of NSM technique. The use of U FRP strips applied in the bottom part of the beam, according to the EBR technique, should be explored for this purpose.

The obtained results show that the effect of cutting the bottom arm of the steel stirrups was only visible in terms of the maximum load of the beams of largest cross section height, and this decrease was limited to 10%.

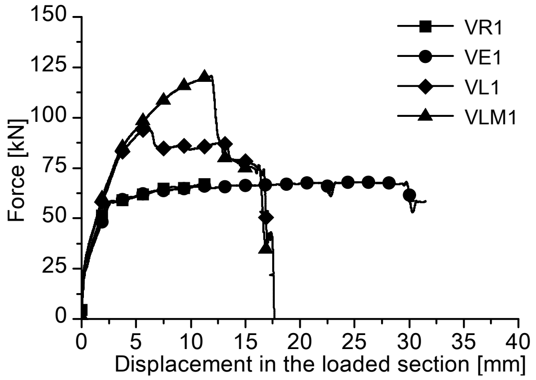

Fig. 3 Series 1.

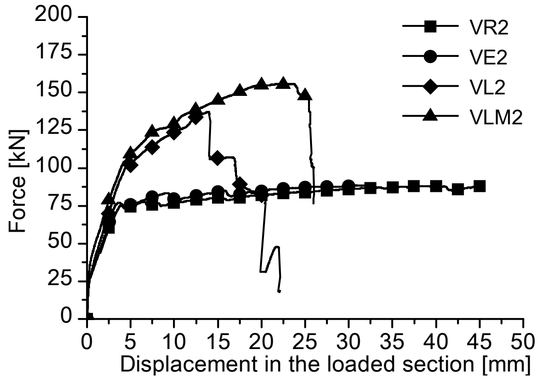

Fig. 4 Series 2.

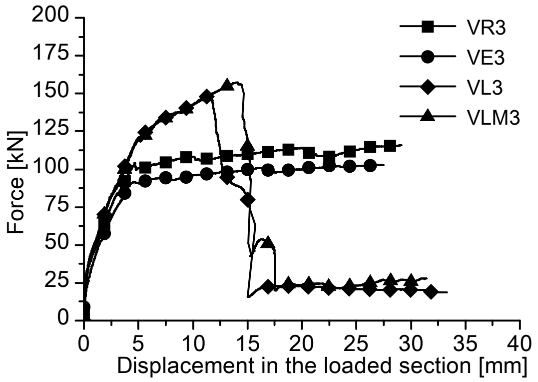

Fig. 5 Series 3.

Fig. 6 Crack pattern of the lower face of VLM2 along the L_2 span, at the end of the test

The relationship between the strains in the intermediate strip of shear strengthening configurations and the applied load is represented in Figs. 7 and 8, for the beams that failed in shear. The shear crack pattern is also schematized in these figures. It is visible that the strains only increased significantly after shear failure crack has formed. The measured maximum strains were about 0.75% and occurred in the strain gauges positioned between the beam bottom surface and the shear crack plan, due to the anchorage effect provided by the U configuration. The possibility of forming more than one shear crack, as occurred in VLM3 beam, put extra exigencies in terms of distance between shear strips. This distance should not exceeds *d*/2, where *d* is the internal arm of the beam cross section.

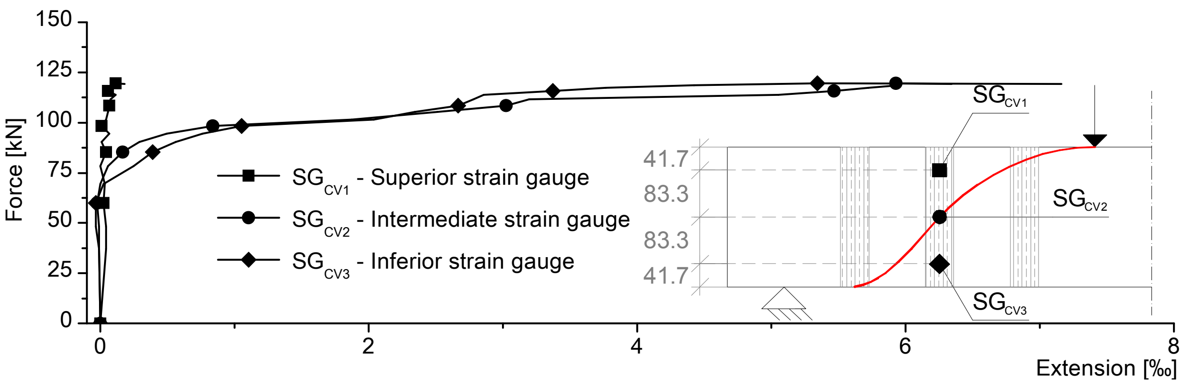

Fig. 7 Force versus extension in the strain gauges of VLM1 (SG_{CV1}, SG_{CV2} and SG_{CV3})

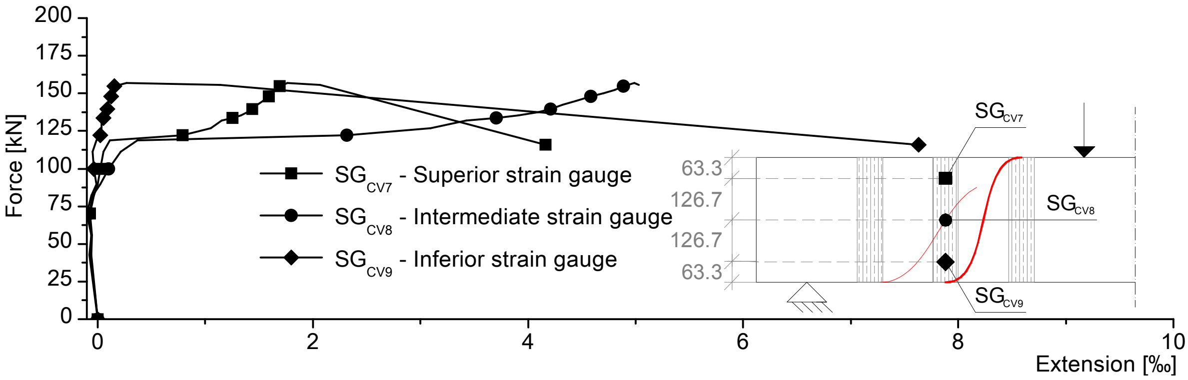

Fig. 8 Force versus extension in the strain gauges of VLM3 (SG_{CV7}, SG_{CV8} and SG_{CV9})

3 CONCLUSIONS

To assess the influence in terms of beam load carrying capacity that cutting steel stirrups has when installing NSM laminates for the flexural strengthening, an experimental program was carried out. From the obtained results the following remarks can be pointed out:

— For monotonic increasing loading in beams with a shear reinforcement ratio higher than the minimum and that exhibit flexural failure, the cut of the stirrups bottom arm induces a loss of load carrying capacity inferior to 10% (comparatively to the VRi reference beams);

— In RC beams with longitudinal reinforcement ratio up to approximately 0.4%, it is possible to guarantee an increase of load carrying capacity higher than 50% using the NSM technique (for a flexural strengthening ratio that varied from 0.076% up to 0.12%), even in beams with the bottom arm of the stirrups cut. However, it is necessary to avoid the occurrence of premature shear failure and the detachment of the CFRP reinforcement due to concrete splitting. The first situation (shear failure) can be prevented by using the EBR shear strengthening systems in a ratio/configuration that avoid the development of the shear crack. Apply CFRP strips of sheets in U-shape can avoid the premature detachment of the strips. The spacing between these strips of sheets may be greater than in shear strengthening, although the correct evaluation of this spacing requires specific investigation.

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