# INFLUENCE OF THE PERCENTAGE OF STEEL STIRRUPS IN THE EFFECTIVENESS OF THE NSM LAMINATES SHEAR STRENGTHENING TECHNIQUE

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**Keywords**: NSM, CFRP, Laminate, Shear, Steel stirrups, Beams, Reinforced concrete.

## 1 INTRODUCTION

A new strengthening technique for concrete structures failing in shear was developed based on introducing laminates of Carbon Fiber Reinforced Polymer (CFRP) into slits made on the concrete cover of the lateral faces of the beams to be strengthened (Figure 1). The designation of this strengthening technique is Near Surface Mounted (NSM) with CFRP laminates. Existing Reinforced Concrete (RC) beams requiring shear strengthening intervention often have a certain percentage of steel stirrups. This paper presents an experimental program carried out with aim of estimating the influence of the percentage of existing steel stirrups in the effectiveness of the NSM shear strengthening technique using CFRP laminates. For this purpose, six CFRP shear strengthening configurations were applied in T cross section RC beams with a percentage of steel stirrups ($\rho_{sw}$) equal 0.10% and 0.17%. The main results of this experimental research are presented and analyzed.

## 2 EXPERIMENTAL STUDY

### 2.1 Test series and materials

Figure 1 presents the T cross section beam prototype used in the experimental program, which was composed by fourteen beams. The reinforcement systems were designed to assure shear failure mode for all the tested beams. To avoid shear failure in the $L_r$ beam span, steel stirrups $\phi$6@75mm were applied in this span. The differences between the tested beams are restricted to the shear reinforcement systems applied in $L_i$ beam span. The experimental program was made up of seven beams with steel stirrups $\phi$6@300mm ($\rho_{sw}$ = 0.10%) and seven beams with steel stirrups $\phi$6@180mm ($\rho_{sw}$ = 0.17%). According to Table 1, six NSM CFRP shear strengthening configurations were applied in beams with $\rho_{sw}$ = 0.10% and beams with $\rho_{sw}$ = 0.17%. Two distinct levels of percentage of CFRP laminates were studied and, for each CFRP percentage ($\rho_f$), three inclinations for the laminates, 90º, 60º and 45º, were analysed (Table 1 and Figure 2). For both percentages of CFRP, the spacing of laminates for each inclination was obtained with the purpose that the contribution of the CFRP would be similar [1]. The laminates had a cross section area of 9.5×1.4 mm$^2$.

The average compressive strength at the date of beam testing was evaluated from uniaxial compression tests with cylinders (150 mm diameter and 300 mm height) according to EN 206-1 [2] and the value obtained was 39.7 MPa. The properties of the steel bars were obtained from uniaxial tensile tests, carried out according to EN 10 002-1 [3] (Table 2). For the laminates (S&P Laminates CFK 150/2000), six tests were also carried out according to the ISO 527-5 [4] recommendations, from which the following average values were obtained: maximum tensile strength = 2741.7 MPa, Young's modulus = 170900 MPa, ultimate tensile strain = 1.6%. The MBrace Resin 220 [5] epoxy adhesive was used to bond the laminates to the concrete.

**Table 1** CFRP shear reinforcement configurations of the tested beams.

| CFRP quantity | CFRP percentage (%) | CFRP spacing (mm) | Angle [a] (º) | Beams [b] ($\rho_{sw}$ = 0.10%) | Beams [c] ($\rho_{sw}$ = 0.17%) |
|---|---|---|---|---|---|
| 2×4 laminates | 0.08 | 180 | 90 | 2S-4LV | 4S-4LV |
| 2×4 laminates | 0.08 | 275 | 45 | 2S-4LI45 | 4S-4LI45 |
| 2×4 laminates | 0.07 | 243 | 60 | 2S-4LI60 | 4S-4LI60 |
| 2×7 laminates | 0.13 | 114 | 90 | 2S-7LV | 4S-7LV |
| 2×7 laminates | 0.13 | 157 | 45 | 2S-7LI45 | 4S-7LI45 |
| 2×6 laminates | 0.11 | 162 | 60 | 2S-6LI60 | 4S-6LI60 |

a Angle between the CFRP fiber direction and the beam axis; b 2S-R is the reference beam without CFRP (Figure 2);
c 4S-R is the reference beam without CFRP (Figure 2).

**Table 2** Properties of the steel bars.

| Property | ϕ6 | ϕ12 | ϕ16 | ϕ32 |
|---|---|---|---|---|
| Yield stress | 542 MPa | 453 MPa | 447 MPa | 759 MPa |
| Maximum strength | 594 MPa | 591 MPa | 566 MPa | 902 MPa |

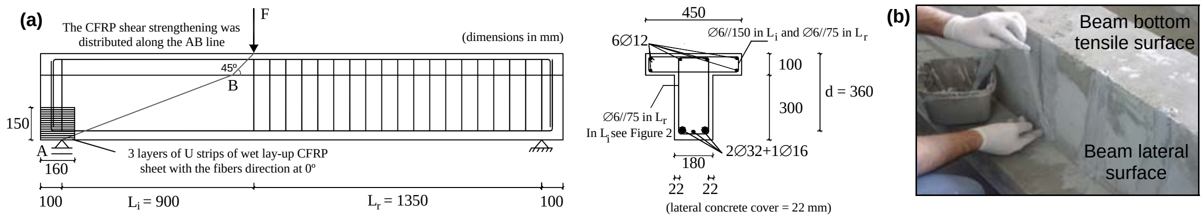


**Fig 1** (a) Tested beams: geometry, steel reinforcements applied in all beams and CFRP strengthening of the most loaded beam support (to avoid concrete spalling); (b) Shear strengthening by NSM with CFRP laminates.

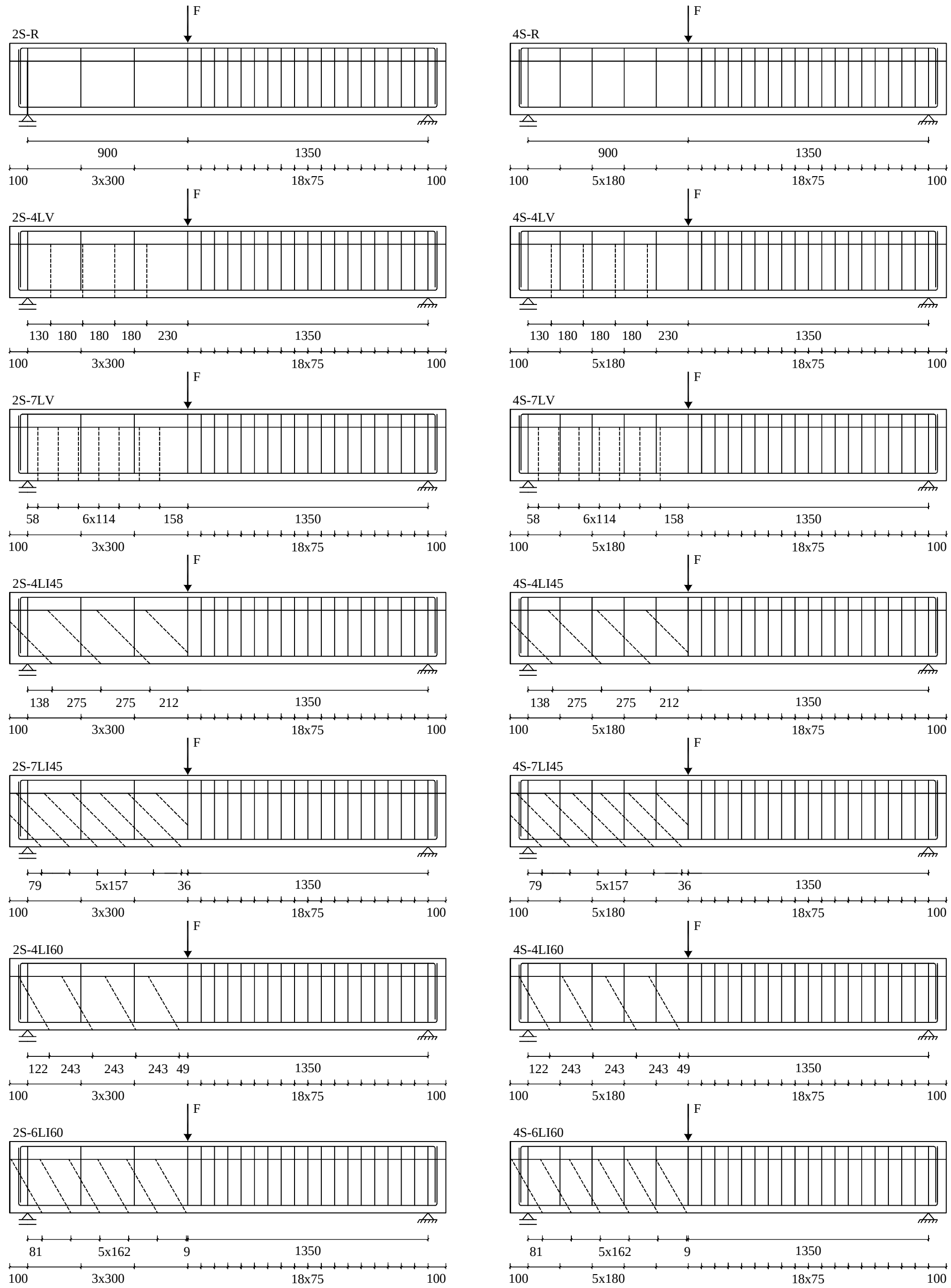


**Fig 2** Localization of the steel stirrups (continuous line) and CFRP laminates (dashed line) (dimensions in mm).

### 2.2 Discussion of test results

The recorded force-displacement diagrams (*F-u*) in the loaded section obtained for the tested beams are reported in Figure 3. Up to critical diagonal crack (CDC) initiation the strengthened and its corresponding reference beam had similar *F-u*, regardless of $\rho_{sw}$ and $\rho_f$. At CDC initiation the load decay observed in the reference beams did not occur in the CFRP shear strengthened beams, revealing that the presence of the CFRP delayed the propagation of the shear crack. This results in an increase of beam stiffness, maximum load ($F_{max}$) and corresponding deflection at loaded-section ($u_{Fmax}$). The $F_{max}$ and $u_{Fmax}$ values for all the tested beams are included in Table 3.

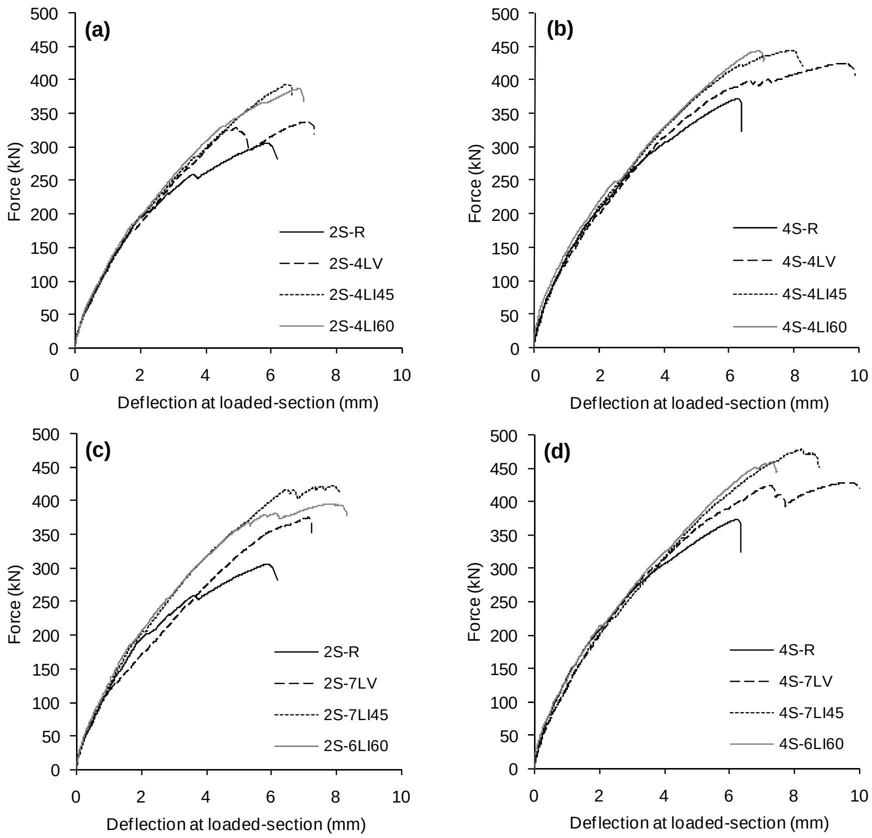


**Fig 3** Force *vs* deflection at the loaded-section for: (a) beams with $\rho_{sw}$ = 0.10% and the lower percentage of CFRP; (b) beams with $\rho_{sw}$ = 0.17% and the lower percentage of CFRP; (c) beams with $\rho_{sw}$ = 0.10% and the higher percentage of CFRP; (d) beams with $\rho_{sw}$ = 0.17% and the higher percentage of CFRP.

**Table 3** Relevant results in terms of the load capacity up to beam's failure.

| CFRP | | Beams | $F_{max}$ | Gain due to | $u_{Fmax}$ | Beams | $F_{max}$ | Gain due to | $u_{Fmax}$ |
|---|---|---|---|---|---|---|---|---|---|
| Percentage (%) | Angle (º) | ($\rho_{sw}$ = 0.10%) | (kN) | CFRP (%) | (mm) | ($\rho_{sw}$ = 0.17%) | (kN) | CFRP (%) | (mm) |
| - | - | 2S-R | 303.8 | - | 5.88 | 4S-R | 371.4 | - | 6.25 |
| 0.08 | 90 | 2S-4LV | 337.4 | 11.1 | 7.14 | 4S-4LV | 424.5 | 14.3 | 9.32 |
| 0.08 | 45 | 2S-4LI45 | 392.8 | 29.3 | 6.45 | 4S-4LI45 | 442.5 | 19.1 | 7.93 |
| 0.07 | 60 | 2S-4LI60 | 386.4 | 27.2 | 6.90 | 4S-4LI60 | 443.8 | 19.5 | 6.91 |
| 0.13 | 90 | 2S-7LV | 374.1 | 23.1 | 7.17 | 4S-7LV | 427.4 | 15.1 | 9.75 |
| 0.13 | 45 | 2S-7LI45 | 421.7 | 38.8 | 7.93 | 4S-7LI45 | 478.1 | 28.7 | 8.26 |
| 0.11 | 60 | 2S-6LI60 | 394.4 | 29.8 | 7.87 | 4S-6LI60 | 457.6 | 23.2 | 7.31 |

The CFRP shear strengthening configurations provided an increase in maximum load between 11% and 39% of the maximum load of the reference beams (see Table 3 and Figure 4). Independently of the percentage of CFRP and the percentage of existing steel stirrups, the inclined laminates were more effective than vertical laminates. An increase of the percentage of CFRP produced an increase of the shear strengthening contribution. The contribution of the NSM CFRP laminates for the beam shear resistance was limited by the concrete tensile strength, since at failure, a certain concrete volume was attached to the laminates. The failure modes of the beams with NSM laminates are influenced by the percentage of the CFRP. In some beams with the higher percentage of CFRP occurred a group effect between neighbouring laminates that originated a separation of parts of the concrete cover, which had already been observed in previous experimental programs [1,6].

Figures 3 and 4 shows that the amount of existing steel stirrups plays a very important role on the effectiveness of the NSM shear strengthening technique with CFRP laminates. In fact, the effectiveness of the CFRP was higher in the beams with the lower percentage of steel stirrups analysed ($\rho_{sw}$ = 0.10%). According to Figure 4, for an increase from 0.1% to 0.17% in the percentage of steel stirrups in the $L_i$ beam span (about 70%), the NSM strengthening effectiveness decreased in about 70% (the value regarding the lower percentage of vertical laminates was excluded for this evaluation). It emerges that a formulation for the prediction of the NSM shear strengthening contribution cannot neglect the percentage of existing steel stirrups.

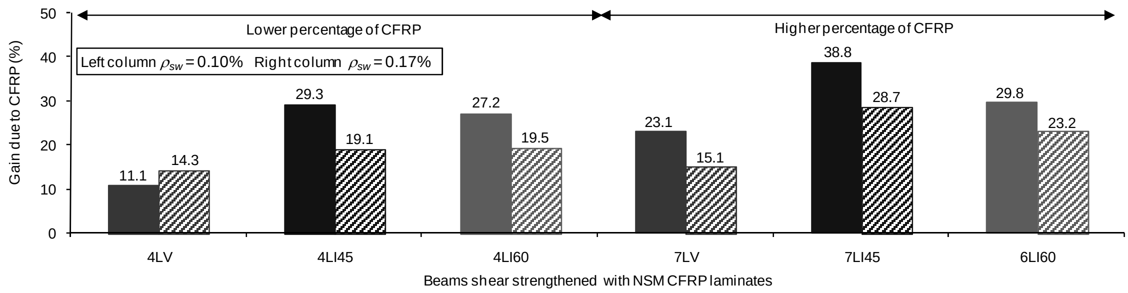


**Fig 4** Influence of the percentage of existing steel stirrups in the effectiveness of the NSM shear strengthening technique using CFRP laminates.

## 3 CONCLUSIONS

The following conclusions can be obtained from the experimental results:

- NSM technique with CFRP laminates provided a significant contribution for the shear resistance of T section RC beams. Inclined laminates were more effective than vertical laminates. An increase of the percentage of laminates produced an increase of the shear capacity of the beams.
- The contribution of the NSM CFRP laminates for the beam shear resistance is limited by the concrete tensile strength. The failure modes of the beams with NSM laminates are influenced by the percentage of the CFRP.
- An interaction between the percentage of steel stirrups and the CFRP laminates was observed, resulting a detrimental effect in terms of the effectiveness of the NSM technique for the shear resistance of RC beams.
- An analytical formulation for the prediction of the NSM shear strengthening contribution should take into account the concrete mechanical properties, the percentage and orientation of the CFRP and the percentage of the existing steel stirrups.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the support provided by the “Empreiteiros Casais”, Degussa, S&P® and Secil (Unibetão, Braga). The study reported in this paper forms a part of the research program “SmartReinforcement - Carbon fibre laminates for the strengthening and monitoring of reinforced concrete structures” supported by ADI-IDEIA, Project nº 13-05-04-FDR-00031.

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