# EFFICIENT STRENGTHENING TECHNIQUE FOR REINFORCED CONCRETE SLABS

*SFRC and CFRP laminate strips*

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**Abstract:** A promising strengthening strategy, using carbon fiber reinforced polymer (CFRP) materials, consists in applying CFRP laminate strips into pre-cut slits opened in the concrete cover of the elements to strengthen. This strengthening technique is designated by Near Surface Mounted (NSM) and has been successfully used to increase the flexural and the shear resistance of concrete and masonry structures. The present work describes an efficient strategy, using steel fiber reinforced concrete (SFRC) and NSM CFRP laminates, for the strengthening of existing reinforced concrete (RC) slabs. The use of a SFRC compression overlay can provide the necessary ductility for attaining high level of tensile stress in the CFRP strengthening system and therefore preventing the concrete crushing failure mode. In the present work, the effectiveness of this technique to increase the service and ultimate load carrying capacity of RC slabs is assessed by an experimental program. A numerical strategy was developed to predict the load-deflection relationship of this type of elements. The results are presented and analyzed, and the performance of the numerical model is appraised.

**Key words:** flexural strengthening; reinforced concrete slabs; CFRP laminate; thin bonded overlay; steel fibre reinforced concrete; epoxy adhesive.

## 1. INTRODUCTION

The Near-Surface Mounted (NSM) strengthening technique has been used in the recent years, with remarkable efficiency, to increase the flexural strength[1-4] and the shear resistance[1,5] of reinforced concrete elements. The NSM technique involves the embedment of CFRP bars - of circular, square or rectangular cross-section - into grooves opened on the concrete surface. When compared to the Externally Bonded Reinforcing (EBR) technique, the

NSM technique assures a higher anchoring capacity to the FRP. As a consequence, a high tensile stress can be mobilized in the CFRP, as long as the member load carrying capacity is not limited by a premature failure mode. For RC slabs of low or medium concrete strength, the increment of the flexural resistance that NSM can provide might be limited by the maximum allowable compression strain in the most compressed concrete fibre. This drawback can be overcome by adding a concrete layer in the compression zone of the existent slab[6]. To attain the desired structural performance (e.g. full composite action), the new concrete overlay and the existent concrete slab should behave monolithically. A sound bond between the new layer and the existing concrete slab can be guaranteed if a proper epoxy compound is used[7,8].

# 2. EXPERIMENTAL WORK

## 2.1 Slab specimens, test set-up and materials

To assess the efficiency of the hybrid strengthening technique for the increase of flexural load carrying capacity of RC slabs, the slab strip specimens represented in Figure 1 were used. The cross section dimensions and the test set up of the tested slab strip specimens are also illustrated in Figure 1. Two unstrengthened RC slabs formed a control set (SL01 and SL06), three slabs were strengthened with CFRP laminates according to NSM technique (SL03S, SL04S and SL08S), and three were strengthened with NSM laminates and a compression SFRC overlay (SL02SO1, SL05SO1 and SL07SO2). The number of CFRP laminate strips applied in each RC slab was evaluated in order to obtain an increase of 50% in the service load, which was assumed as the load producing a mid-span displacement of $\ell/250 = 1800$ mm/250 = 7.2 mm. Each slab specimen was tested in simply supported conditions, with a clear span of 1.8 m, and under line loads at 0.6 m from the supports, see Figure 1(b). The monotonic loading was controlled by the LVDT placed at slab mid span (see Figure 1(b)), using a displacement velocity of 20 μm/s up to failure of the slab. Figure 2 outlines the arrangement of the strain gauges (SG) applied to measure the strains in the CFRP laminates, steel bars and concrete. Tables 1 and 2 include the main mechanical properties of the materials used in the present work. In Table 1 $f_{cm}$ is the compressive strength and $E_c$ the elastic modulus, $f_{ctm,fl}$ and $f_{ctm,ax}$ the flexural and axial tensile strength, respectively, of plain concrete. In Table 2, E is the elastic modulus, $\sigma_u$ and $\varepsilon_u$ the ultimate strength and strain, respectively; $\sigma_{sy}$ and $\varepsilon_{sy}$ the steel yield stress and strain in tension; $f_{cm}$ the compressive strength, $f_{eqm,2}$ and $f_{eqm,3}$ the equivalent flexural tensile strength parameters of SFRC overlays; $t_f$ and $W_f$ the thickness and width of the CFRP.

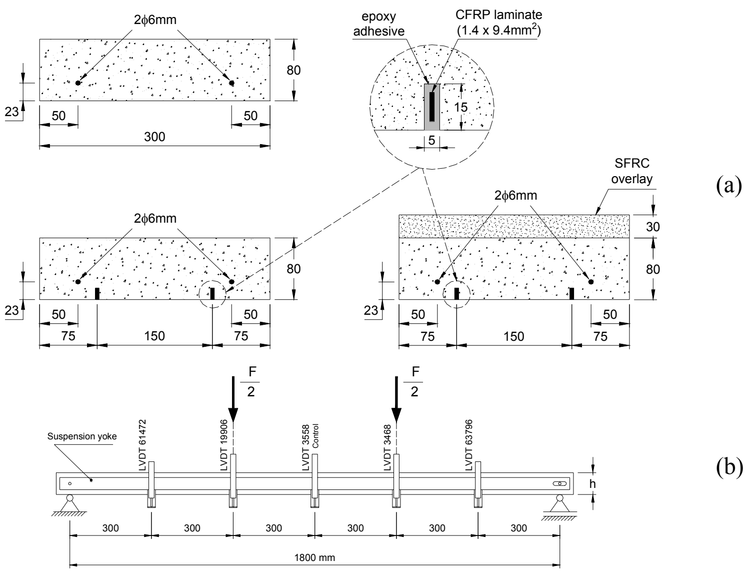



*Figure 1.* (a) Slab cross-section dimension and disposition of the steel bars and CFRP laminates and (b) load configuration and arrangement of the LVDTs (dimensions in mm).

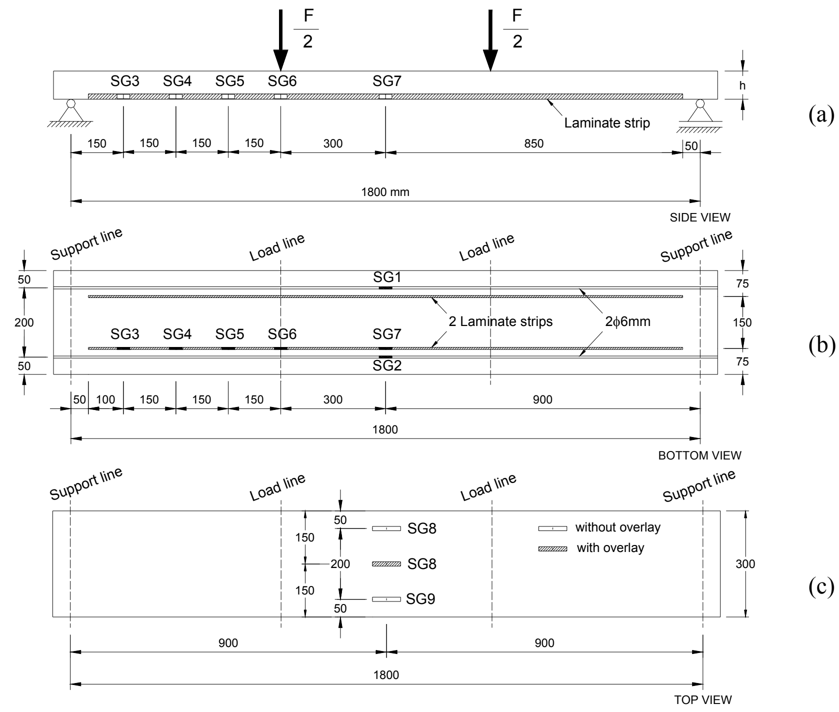



*Figure 2.* Disposition of the strain gauges: (a) side, (b) bottom and (c) top views.

*Table 1.* Characteristics of the plain concrete (obtained experimentally[9])

| Property | Control Slabs | | NSM Strengthened Slabs | | | NSM & SFRC Strengthened Slabs | | |
|---|---|---|---|---|---|---|---|---|
| | SL01 | SL06 | SL03S | SL04S | SL08S | SL02SO1 | SL05SO1 | SL07SO2 |
| $f_{cm}$ (MPa) | 45.65 | 49.39 | 43.13 | 32.41 | 49.35 | 47.76 | 49.56 | 47.80 |
| $f_{ctm,fl}$ (MPa) | 4.98 | 6.10 | 5.92 | 4.73 | 5.80 | 5.86 | 5.59 | 6.04 |
| $f_{ctm,ax}$ [a] (MPa) | 2.75 | 3.37 | 3.27 | 2.61 | 3.21 | 3.24 | 3.10 | 3.32 |
| $E_c$ [a] (GPa) | 35.67 | 36.61 | 35.00 | 31.82 | 36.60 | 36.21 | 36.66 | 36.22 |

[a] Derived from CEB FIP model code 1990

*Table 2.* Summary of the characteristics of the steel reinforcement, CFRP and its adhesive, and SFRC and its adhesive (obtained experimentally[9])

| Steel reinforcement | CFRP laminate | Laminate adhesive | SFRC overlay[a] | | Overlay adhesive |
|---|---|---|---|---|---|
| $\phi_s$ = 6mm<br>$E_s$ = 217.3GPa<br>$\sigma_{sy}$ = 548.8MPa<br>$\varepsilon_{sy}$ = 2.70‰ | $t_f$ = 1.41mm<br>$W_f$ = 9.37mm<br>$E_f$ = 156.1GPa<br>$\sigma_{fu}$= 2879.1MPa<br>$\varepsilon_{fu}$= 18.45‰ | $E_a$ = 7.47GPa<br>$\sigma_{au}$= 33.0MPa<br>$\varepsilon_{au}$= 4.83‰ | O1 | $f_{cm}$ = 38.93MPa<br>$f_{eqm,2}$ = 5.00MPa<br>$f_{eqm,3}$ = 4.12MPa | $E_e$ = 3.62GPa<br>$\sigma_{eu}$= 26.56MPa<br>$\varepsilon_{eu}$= 10.74‰ |
| | | | O2 | $f_{cm}$ = 53.10MPa<br>$f_{eqm,2}$ = 4.83MPa<br>$f_{eqm,3}$ = 3.86MPa | |

[a] Evaluated according to RILEM TC 162 TDF recommendations as reported in Barros et al.[10]

## 2.2 Results and comments

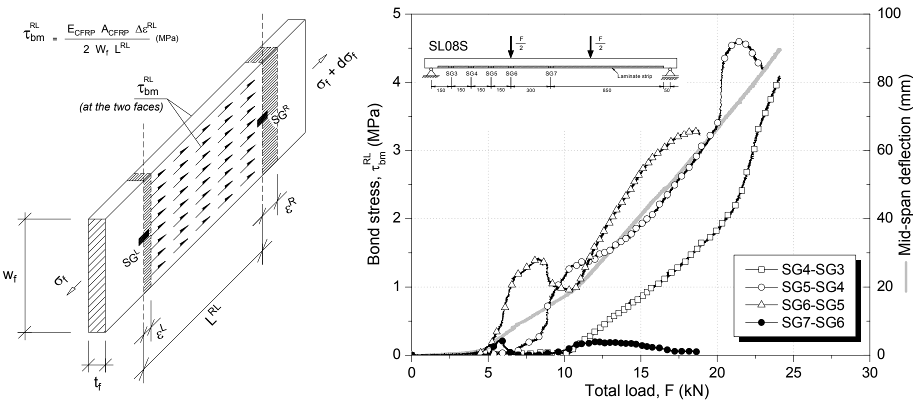
Table 3 includes the maximum load, the maximum concrete compression strain, the maximum strain in the CFRP laminates and the failure modes of the tested slab strips. Due to problems with the data acquisition system, the strains in the SL04S were not measured. The maximum load of the strengthened slabs was about five times higher than the maximum load of the corresponding unstrengthened slabs. The maximum concrete compression strain has exceeded the strain corresponding to the concrete strength. The maximum strains recorded in the CFRP laminates are about 80% of its ultimate strain, but these values do not correspond to the maximum load since the strain gage data acquisition was interrupted for the load values included in brackets. Due to the significant increase of the slab load carrying capacity, provided by the NSM strengthening technique and the hybrid system, some slabs have failed in a flexure/shear combined mode, but for a deflection that was several times the deflection at the yielding of the reinforcement.

*Table 3.* Summary of the slab test results

| Strengthening | Slab I.D. | Average ultimate load (kN) | Strength increasing ratio (%) | Concrete compression strain[c] (‰) | CFRP laminate strain[d] (‰) | Type of Failure |
|---|---|---|---|---|---|---|
| Reference | SL01 | 5.03 (*9.00%*) | NA | 2.26[5.35] | NA | Flexure |
| | SL06 | | | 1.96[4.71] | | Flexure |
| CFRP laminate strengthening | SL03S | 24.48 (*1.59%*) | 386.68 | 3.40[24.24] | 14.10[23.13] | Flexo-shear |
| | SL04S | | | NE | NE | Flexure |
| | SL08S | | | 2.90[24.00] | 12.70[18.70] | Flexure |
| CFRP + SFRC strengthening | SL02SO1 | 33.79 (*5.56%*) | 571.77[a] 38.03[b] | 2.66[35.42] | 12.95[34.42] | Flexo-shear |
| | SL05SO1 | | | 2.53[31.66] | 13.50[31.50] | Flexo-shear |
| | SL07SO2 | | | NE | 12.58[26.84] | Flexure |

(*value*) Coefficient of Variation (COV) = (Standard deviation/Average) x 100
[a] With respect to the reference; [b] With respect to the CFRP laminate strengthening; [c] Value in square brackets is the maximum load; [d] Maximum value recorded in SG7 and corresponding load in square brackets; NA: not applicable; NE: not evaluated

Using the strains recorded in the strain gauges installed on the laminates, the average laminate-concrete bond stresses ( $\tau_{bm}^{RL}$ ) developed along the CFRP laminate strips was evaluated (refer to Figure 3(a)). A typical bond stress variation in the CFRP laminate strips is shown in Figure 3(b).




(a) (b)

*Figure 3.* (a) average bond stress calculation and (b) typical bond stress variation in monitored CFRP laminate strip for the slab SL08S.

Figure 3(b) shows that up to crack initiation, the CFRP laminates were not yet mobilized. In general, at service load, corresponding to a deflection of 7.2 mm at mid-span, the bond stress did not exceed 1.0 MPa. Despite the fact that in some strengthened slabs it was not possible to evaluate the average bond stress variation up to the ultimate load, it can be noticed, however, that the bond stress did not surpass 5.0 MPa. This maximum value is much lower than the bond stress limit value (12 MPa), registered in pullout-bending tests[11].

## 3. NUMERICAL ANALYSIS

Previous works[3] have shown that, using a cross-section layered model that takes into account the constitutive laws of the intervening materials and the kinematic and the equilibrium conditions, the deformational behavior of structural elements failing in bending can be predicted from the moment-curvature relation, $M - \chi$, of the representative sections of these elements, using the algorithm described in a former paper[12]. To evaluate the $M - \chi$ relationship, the slab cross section was discretized in layers of 0.5 mm thickness. The slab tangential stiffness matrix was determined evaluating the tangential stiffness matrix of the two nodes Euler-Bernoulli beam elements discretizing the slab (a mesh of 60 elements). The values of the parameters for the models defining the behavior of plain concrete, SFRC, steel bars and CFRP laminates are given elsewhere[12]. Figure 4 shows that the developed numerical strategy is able of fitting with enough accuracy the registered experimental load-central deflection curves of the tested slabs.

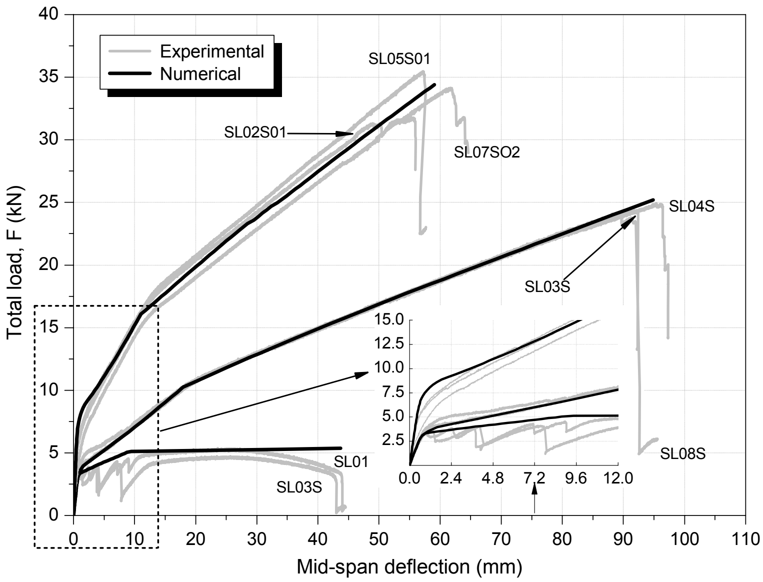



*Figure 4.* Experimental versus numerical load-central deflection curves.

As a consequence of the increase of the post-cracking stiffness, provided by CFRP laminates, the service load has increased 54% for the slabs strengthened with NSM (see inset of Figure 4). The hybrid strengthening lead to an increase of about 212% in the service load with respect to the reference (see inset of Figure 4).

## 4. CONCLUSIONS

The testing program carried out demonstrated that the hybrid strengthening technique has great potential application towards flexural strengthening of RC slabs. A percentage of 0.12% of CFRP laminates (CFRP reinforcement to the conventional steel reinforcement ratio close to 50%) has increased about 54% the service load of the 1.8 m RC slabs with a steel reinforcement ratio of 0.24%. However, the slabs strengthened with NSM technique and SFRC showed an increase of approximately 212% in the service load, with respect to the reference slabs. Comparatively to the NSM technique, the hybrid strengthening strategy has lead to an increase of about 103% in load at the service load level. The hybrid strengthening system has also lead to an increase of about 570% in the RC slab maximum load carrying capacity with respect to the reference slabs and an increase of about 40% in comparison with the slabs strengthened only with NSM technique. When compared to the reference case, about 390% of increase in the load carrying capacity was attained by the strengthening with NSM technique. The cracking spacing calculations and crack features observations, at the bottom of the slabs, indicate that a significant improvement in the crack behavior of RC slabs can be achieved with the NSM technique. When compared with the bond stress limit recorded in pullout-bending tests, a very low bond stress profile was observed through the interfaces CFRP laminate-epoxy adhesive-concrete, along the laminate strips in slabs where NSM strengthening was applied. The NSM strengthening system has also provided a significant increase in the stiffness and deformation at failure, which are consistent with the high stress redistribution owing to prominent composite action between the CFRP reinforcement and concrete. Since the hybrid strengthening system has lead to substantial increase in flexural load, the shear capacity of the composite slabs has limited their deformability; however, the stiffness of the slabs has strongly increased and high ductility was maintained. The numerical model developed to simulate the load-deflection relationship of RC elements reinforced strengthened with CFRP laminate strips has reproduced with high accuracy the force-mid span deflection of the carried out tests.

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