Concrete Slabs Strips Reinforced with Epoxy-bonded Carbon Laminates into Slits

E. Bonaldo, J. A. O. Barros, P. B. Lourenço
University of Minho, Portugal

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. Since both faces of the laminate are bonded to concrete by epoxy adhesive, the maximum attainable strain in the CFRP at the failure of the strengthened element is higher than when the CFRP is externally bonded. This strengthening technique is designated by Near Surface Mounted and has been successfully used to increase the flexural and the shear resistance of concrete and masonry structures. In the present work, the effectiveness of this technique to increase the service and ultimate load carrying capacity of reinforced concrete 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.

Keywords**:** Strengthening, Carbon fibre reinforced polymer, Slab strips, Cross section model.

Everaldo Bonaldo, PhD Student
University of Minho
Department of Civil Engineering
School of Engineering
P 4800 Guimarães
Portugal

Email: bona@civil.uminho.pt
Tel.: +351 253 510 200

1.0 Introduction

The use of carbon fibre reinforced polymer (CFRP) laminate strips installed into pre-cut slits opened in the concrete cover of structural elements has shown to be a remarkable strengthening technique to increase the flexural and the shear resistance of reinforced concrete elements [1-3]. This strengthening technique is designated as Near Surface Mounted (NSM). A laminate strip has a cross section of about 10 mm width and 1.4 mm thick, while a slit has a width of 4 to 5 mm and a depth of 12 to 15 mm. Barros et al. [1] showed that a CFRP cross sectional area, A_f, of 0.2% of the column cross sectional area, A_c, has provided an average increase of 92% and 34% on the load carrying capacity of columns reinforced with 4ϕ10 mm and 4ϕ12 mm longitudinal steel bars (cross sectional area, A_s, of 314 mm^2 and 452 mm^2, respectively, corresponding to a reinforcement ratio, $\rho_s = A_s / A_c$, of 0.79% and 1.13%). The premature debonding which generally occurs in the externally bonded reinforcing (EBR) technique was avoided and strain values close to the CFRP ultimate rupture strain were measured on this composite material. These results indicate that the NSM strengthening technique is very promising for increasing the load carrying capacity of concrete columns failing in bending. Barros and Fortes [2] have also used the NSM strengthening technique for doubling the load carrying capacity of concrete beams failing in bending. This purpose was practically attained since an average increase of 91% on the maximum load was obtained. In addition, high deformability at the failure of the strengthened beams was assured. Maximum strain values ranging from 62% to 91% of the CFRP ultimate rupture strain were registered, revealing that this technique can mobilize stress levels close to the tensile strength of this composite material. The performance of EBR and NSM techniques on increasing the shear resistance of concrete beams failing in shear was compared by Barros and Dias [3]. The NSM technique was based on bonding laminate strips of CFRP onto pre-cut slits opened in the concrete cover of the vertical beam faces, which proved to be the most effective. The maximum load and the corresponding deflection of the beam strengthened with this technique were 9% larger and 16% smaller than the comparable values registered in the beam reinforced with steel stirrups of the equivalent shear reinforcement ratio. Beyond these structural benefits, these authors verified that this technique was easier and faster to apply than the one based on embracing the beam with strips of CFRP sheet. The bond between the CFRP laminate strips and the concrete has been extensively investigated [4] to define a local bond stress-slip relationship to be used in design practice [5]. In the present work the efficiency of the NSM strengthening technique to increase the flexural resistance of RC slabs is assessed. For this purpose, an experimental and a numerical research were carried out. The experimental program was composed by four point bending tests with RC slab strips strengthened according to the NSM technique. These tests were simulated using a numerical strategy that combines a cross section layer model [6] with the matrix displacement method. In this paper, the experimental program is described and the results are presented and analyzed. The performance of the developed numerical model is also assessed.

2.0 Experimental Work

2.1 Slab Specimens and Strengthening Technique

The geometry of the RC slab specimens, and the arrangement of both conventional reinforcement and CFRP laminate strips are represented in Figure 1(a). The loading and support conditions are sketched in Figure 1(b). Two unstrengthened RC slabs formed a control set (SL01 and SL06), and three slabs were strengthened with CFRP laminates according to NSM technique (SL03S, SL04S and SL08S). Tests on slabs SL02, SL05 and SL07 are not reported here since they include a top steel fibre reinforced concrete overlay for a research purpose that is outside the scope of this paper. The number of CFRP laminate strips applied in each RC slab was evaluated in order to increase

50% the service load (assumed equal to 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 point line loads at 0.6 m from the supports, see Figure 1(b). The loading was controlled by the LVDT placed at slab mid span, using a displacement velocity of 20 μm/s up to failure of the slab. Figure 1(c) outlines the disposition of the LVDTs. The LVDTs were supported in a suspension yoke bar in order to avoid the registration of extraneous displacements.

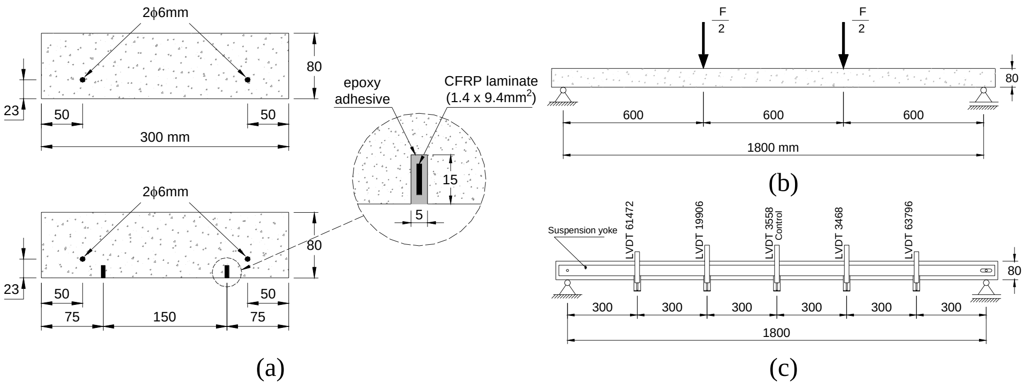


Figure 1. (a) Slab cross-section dimension and disposition of the steel bars and CFRP laminates, (b) load configuration, and (c) arrangement of the LVDTs (dimensions in mm).

The NSM strengthening technique consists of the following steps (see Figure 2): using a diamond cutter machine, slits of ~5 mm width and ~15 mm depth are opened in the concrete cover of the slabs; the slits are cleaned by compressed air; the CFRP laminates are cleaned by acetone; the slits are filled with an epoxy adhesive, manufactured according to the supplier recommendations; the CFRP laminate strips are introduced into the slits and the epoxy adhesive in excess is removed.

2.2 Characterization of the Materials

2.2.1 Concrete

The compression strength, f_c, of the used concrete was evaluated at the age of slab testing, from direct compression tests carried out with cylinders of 150 mm diameter and 300 mm height. The obtained results are included in Table 1 (three specimens were used for each concrete).

2.2.2 Reinforcing Steel

Two 6 mm diameter steel bars of deformed surface (ρ_{sl} = 0.24%), were positioned in the tension zone of the slab, see Figure 1(a). No shear reinforcement was used. Three uniaxial tensile tests carried out according to the recommendations of EN 10 002-1 [7] have indicated that the steel bars can be modelled by a bilinear stress-strain relationship with a yield stress and an ultimate strength of 494.1 MPa and 581.85 MPa, respectively.

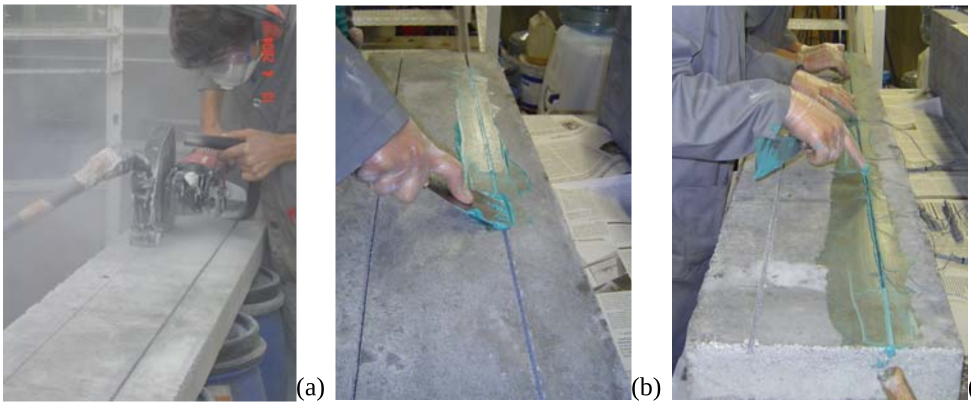
2.2.3 CFRP Laminate

The CFRP laminate strip was provided in rolls, produced by S&P® and distributed by Bettor MBT® Portugal, and have a cross section of 9.37 mm width and 1.41 mm thickness. To determine the corresponding tensile strength and modulus of elasticity, uniaxial tensile tests were carried on coupons in a servo controlled test machine, according to the recommendations of ISO 527-5 [9]. From these tests a modulus of elasticity of 156.10 GPa and a tensile strength of 2880 MPa were obtained.

Table 1: Characteristics of the concrete

Property	Control Slabs		Strengthened Slabs		
	SL01	SL06	SL03S	SL04S	SL08S
fc (MPa)	45.65	49.39	43.13	32.41	49.35
Ec(*) (GPa)	35.67	36.61	35.00	31.82	36.60

(*) *Derived from model code CEB FIP 1993* [8]



(a) (b) (c)

Figure 2. Strengthening steps: (a) opening the slits, (b) applying the epoxy adhesive, and (c) introducing the CFRP laminate into a slit.

2.2.4 Epoxy Paste

An epoxy adhesive with a Trademark of Resin 220, supplied by Bettor MBT® Portugal, was used to bond the CFRP laminate to the concrete into the slits. From uniaxial tensile tests carried out according to the recommendations of ISO 527-2 [10], a modulus of elasticity of 5 GPa was evaluated and the tensile strength ranged from 16 up to 22 MPa.

2.3 Test Set-up and Equipment

Figure 3 outlines the arrangement of the strain gauges (SG) applied to measure the strains in the CFRP laminates, steel bars and concrete. Figure 4 shows the full arrangement of the four point bending test. A servo-controlled test machine was used in the experimental program.

2.4 Results of the Experimental Program and Comments

Table 2 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 that 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, one slab has failed in a shear/flexure combined mode, but the remaining have failed in flexural failure mode. The appearance of the slabs after having been tested is shown in Figure 5.

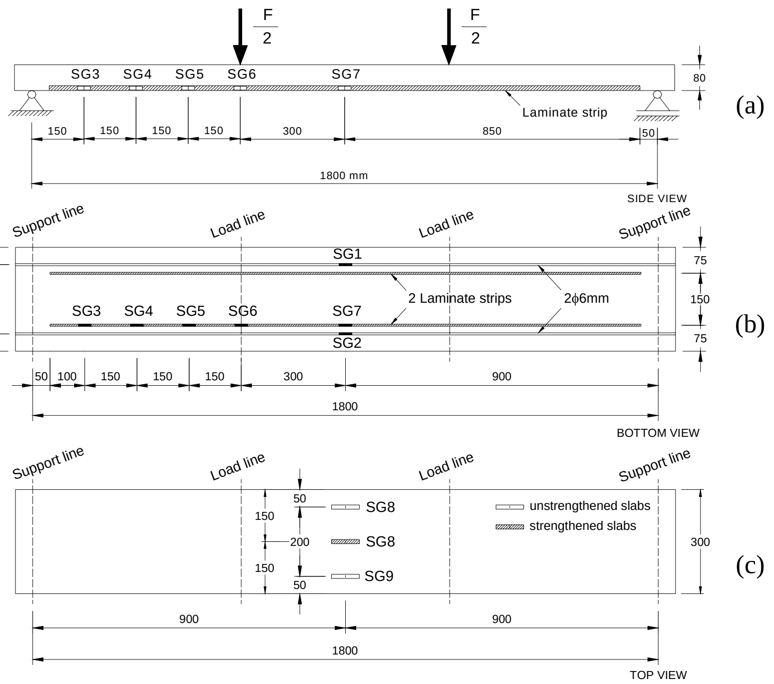


Figure 3. Disposition of the strain gauges: (a) side, (b) bottom, and (c) top views.

Table 2: Summary of the slab test results

Slab	Maximum Load (kN)	Average of the Maximum Load (kN)	$\frac{F_{ML}^{STR} - F_{ML}^{UNS}}{F_{ML}^{UNS}}$ (%)	Concrete Compression Strain[(1)] (‰)	CFRP Laminate Strain[(2)] (‰)	Mode of Failure
SL01	5.35	5.03	-	3.32	NA	Flexure
SL06	4.71			2.27	NA	Flexure
SL03S	24.38	24.48	386.7	3.40	14.10 [20.80]	Shear/Flexure
SL04S	24.91			NE	NE	Flexure
SL08S	24.15			2.90	12.70 [18.70]	Flexure

F_{ML}^{STR} - Average maximum load of strengthened slabs; F_{ML}^{UNS} - Average maximum load of unstrengthened slabs; NA: not applicable; NE: not possible to evaluate; [(1)] average of SG8 and SG9 for unstrengthened slabs, and SG8 for strengthened slabs; [(2)] maximum values recorded in SG7 and corresponding load in brackets.

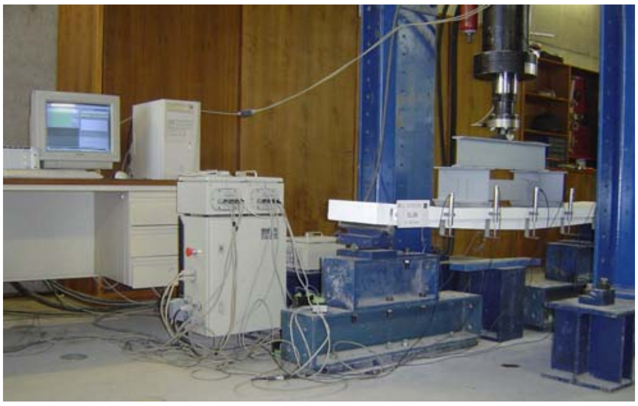
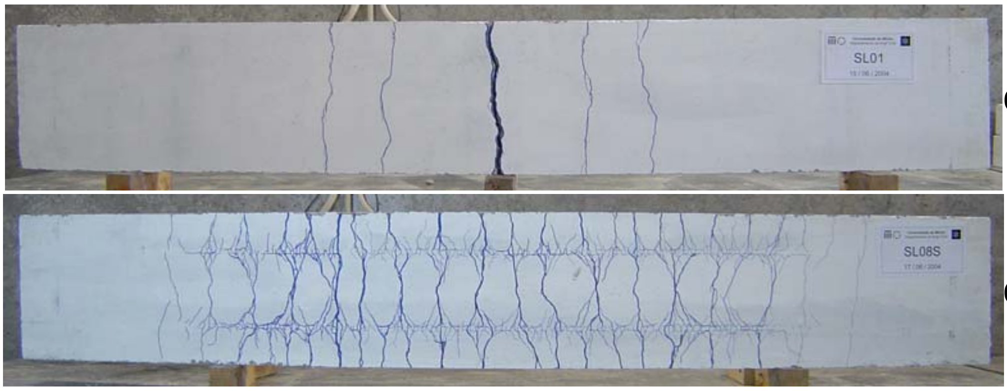


Figure 4. Layout of the four-point bending test.



(a)

(b)

Figure 5. Typical crack pattern in (a) reference slabs (SL01), and (b) strengthened slabs (SL08S).

3.0 Numerical Analysis

3.1 Numerical Modeling Technique

Previous works [6,11] 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 Figure 6. 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). To simulate the concrete compression behavior, the stress-strain relationship recommended by model code CEB-FIP 1993 [8] was used, see Figure 7(a). Up to concrete tensile strength, f_{ct}, the concrete was assumed behaving linearly. Here f_{ct} was taken equal to the $f_{ctk,min}$, derived from model code CEB-FIP 1993 [8]. After peak load, the behavior of the concrete layers in softening was simulated by the trilinear diagram represented in Figure 7(b). The trilinear tension-stiffening diagram depicted in Figure 7(b) was also used to model the post-cracking behavior of the concrete layers under the influence of the steel bars, in the case of the reference slabs, and under the influence of the CFRP laminate strips, for the strengthened slabs, where the ultimate strain is equal to the CFRP maximum strain registered in the tensile tests (subsection 2.2.3). The concrete data used in the numerical simulation are indicated in Table 3. Figure 8 shows the stress-strain relationship used to model the tension and the compression behavior of the steel bars. The data defining this relationship are indicated in Table 4. A linear elastic stress-strain diagram was taken to model the tensile behavior of the CFRP laminates. Figure 9 shows that the developed numerical strategy is able of fitting with enough accuracy the registered experimental load-central deflection curves of the tested slabs. This simple model can be useful to evaluate the stress and the strain levels of each intervening material during the slab loading process. The experimental and numerical load-displacement curves coincide in a typical trilinear diagram, defined by the singular points of concrete cracking and yielding of the reinforcement. In consequence of the increase of the post-cracking stiffness provided by CFRP laminates the service load has increased 54% (see inset of Figure 9). The load at yielding of the reinforcement and its corresponding deflection has also increased significantly. The cracking load is also augmented. The strengthened slabs had a typical strain variation tendency registered on the SG installed on the CFRP laminate strips. A representative graph of the strain variation is shown in Figure 10(a). The average bond stress (τ_{bm}) in the CFRP laminate strips, derived from strain variation, is shown in Figure 10(b). It can be noticed that the maximum bond stress along the strips is very low when compared to the bond stress limit value recorded in pullout-bending tests [4,5] using the NSM strengthening technique.

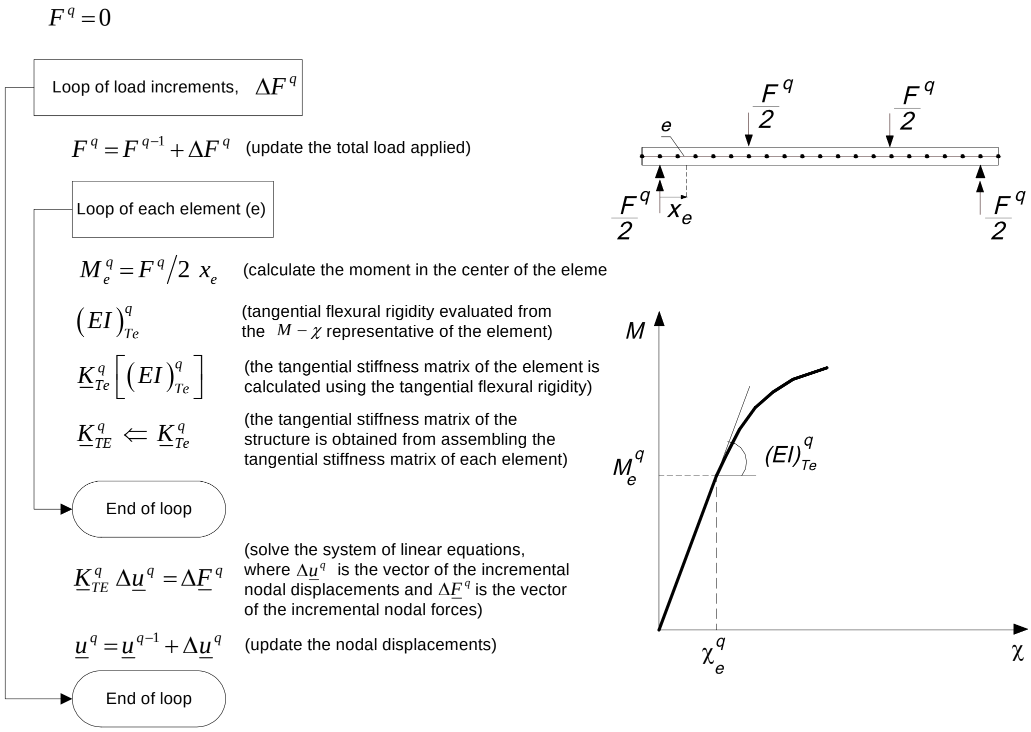


Figure 6. Algorithm to simulate the deformational behavior of structural elements failing in bending.

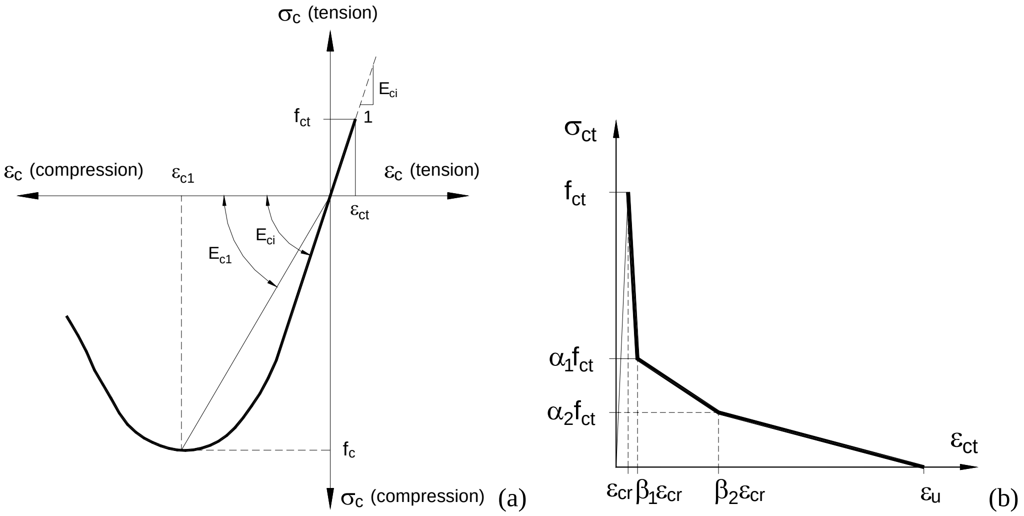


Figure 7. Concrete laws: (a) compression and tension up to crack initiation, and (b) tension post-crack initiation (tension softening and tension-stiffening).

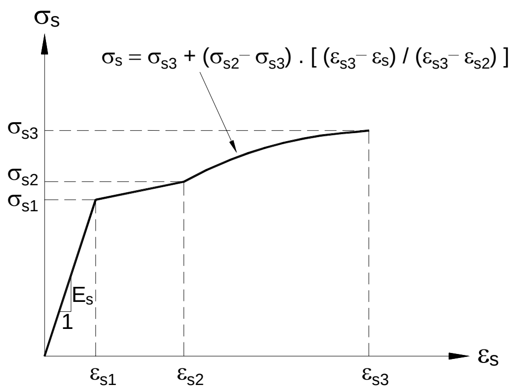


Figure 8. Stress-strain relationship for the steel bars.

Table 3: Concrete properties used in the numerical simulation (refer to Figure 7)

Slab	Compression		Tension	Softening					Stiffening				
	f_c (†) (MPa)	E_c (†) (GPa)	f_{ct} (MPa)	α_1	α_2	β_1	β_2	ε_u (‰)	α_1	α_2	β_1	β_2	ε_u (‰)
SL01 SL06	47.52	36.14	2.38	0.4	0.2	2.0	10.0	3.0	0.40	0.20	2.0	10	3.0
SL03S SL04S SL08S	41.63	34.47	2.12					3.2	0.46	0.40	28	242	18.0

(†) *Average values of Table 1*

Table 4: Properties of the steel bars used in the numerical simulation (refer to Figure 8)

Bar diameter (mm)	E_s (GPa)	ε_{s1} (mm/mm)	σ_{s1} (MPa)	ε_{s2} (mm/mm)	σ_{s2} (MPa)	ε_{s3} (mm/mm)	σ_{s3} (MPa)	P
6	200.0	0.00247	494.1	0.00247	494.1	0.0515	581.85	3.127

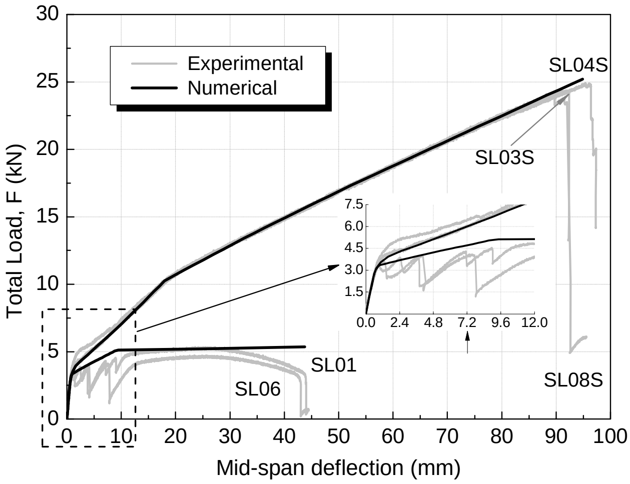
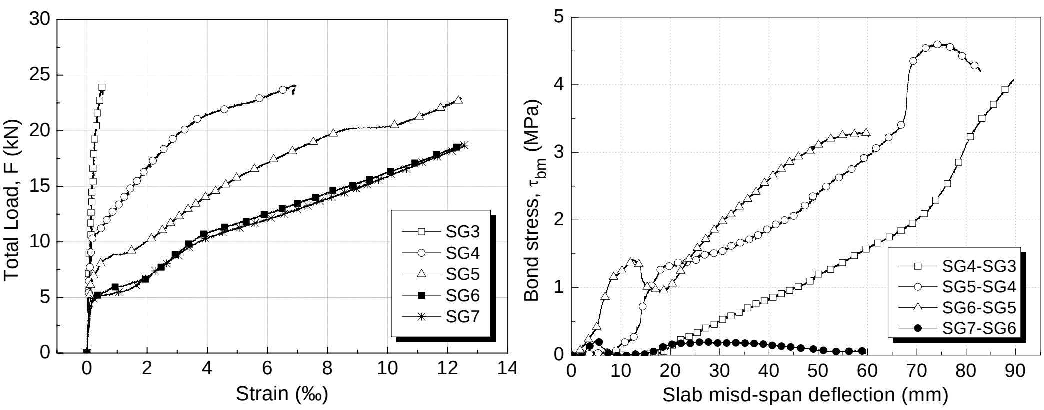


Figure 9. Experimental versus numerical load-central deflection curves.



(a) (b)

Figure 10. Experimental strain variation (a), and average bond stress (b) in the monitored CFRP laminate strip for the slab SL08S.

4.0 Conclusions

The test program has clearly demonstrated that NSM strengthening technique has high potential to increase the flexural resistance of RC slabs. A percentage of 0.12% of CFRP laminates has increased in about 54% the service load of the 1.8 m concrete slabs of 0.24% steel reinforcing ratio. This strengthening system has also provided an increase of about 390% in the RC slab maximum load carrying capacity. The stiffness has increased significantly and the strengthened slabs failed for a deflection of about 5% of the slab span. A numerical model was developed to simulate the load-deflection relationship of concrete elements reinforced with conventional steel bars and strengthened by CFRP laminate strips. This model has reproduced with high accuracy the force-mid span deflection of the carried out tests.

5.0 Acknowledgements

The first author acknowledges the financial support of the Portuguese Science and Technology Foundation (FCT), PhD grant number *SFRH / BD / 11232 / 2002*. Thanks also for the companies S&P® Reinforcement, "Degussa Construction Chemicals Portugal S.A.", "Companhia Geral de Cal e Cimento S.A. (SECIL)", "Pedreiras Bezerras" which generously have supplied CFRP laminates, epoxy adhesive and superplasticizer, cement, and aggregates, respectively.

6.0 References

1. Barros, J.A.O., Sena-Cruz, J.M., Dias, S.J.E., Ferreira, D.R.S.M., Fortes, A.S., "Near surface mounted CFRP-based technique for the strengthening of concrete structures", *Workshop on R+D+I in Technology of Concrete Structures - a tribute to Dr. Ravindra Gettu, Barcelona, October 5, 2004*, pp. 205-217.
2. Barros, J.A.O., Fortes, A.S. 2004. "Flexural strengthening of concrete beams with CFRP laminates bonded into slits", *Journal Cement and Concrete Composites*, in press.
3. Barros, J.A.O., Dias, S.J.E., "Shear strengthening of reinforced concrete beams with laminate strips of CFRP", *International Conference Composites in Constructions - CCC2003, Cosenza, Italy, 16-19 September 2003*, pp. 289-294.
4. Sena-Cruz, J.M., Barros, J.A.O. 2004. "Bond between near-surface mounted CFRP laminate strips and concrete in structural strengthening", *Journal of Composites for Construction*, Vol. 8, No. 6, pp. 519-527.
5. Sena-Cruz, J.M., Barros, J.A.O. 2004. "Modeling of bond between near-surface mounted CFRP laminate strips and concrete", *Computers and Structures Journal*, Vo. 82/17-19, pp. 1513-1521.
6. Barros, J.A.O., Cunha, V.M.C.F., Ribeiro, A.F., Antunes, J.A.B. 2004. "Post-Cracking Behaviour of Steel Fibre Reinforced Concrete", *Materials and Structures Journal*, in press.
7. EN 10 002-1. 1990. "Metallic materials - Tensile testing. Part1: Method of test (at ambient temperature)", CEN, Bruxelas, 35 pp.
8. CEB-FIP Model Code. Comite Euro-International du Beton, Bulletin d'Information No. 213/214, 1993.
9. ISO 527-5. 1997. "Plastics - Determination of tensile properties - Part 5: Test conditions for unidirectional fibre-reinforced plastic composites". International Organization for Standardization, Genève, Switzerland, 9 pp.
10. ISO 527-2. 1997. "Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics". International Organization for Standardization, Genève, Switzerland, 5 pp.
11. Barros, J.A.O., Oliveira, J.T., Bonaldo, E., Lourenço, P.B. 2004. "Flexural behavior of reinforced masonry panels", *ACI Structural Journal*, in appreciation.