

This article describes recent research conducted at the University of Minho, the host institution of FRPRCS-11.

Flexural and Shear Strengthening of Reinforced Concrete Elements

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This work focuses on research carried out on the use of the near surface mounted (NSM) technique to increase the flexural capacity of statically indeterminate reinforced concrete (RC) slabs or shallow beams, and the use of embedded through-section (ETS) bars for shear strengthening of these structures.

NSM technique to increase the load carrying capacity of continuous RC slab strips

Experimental program

The potential of the NSM technique for increasing the load carrying capacity of two-span continuous RC slab strips was explored. Carbon fibre reinforced polymer (CFRP) laminates of rectangular cross section were used. The experimental program was composed of seventeen 5875 mm long RC slab strips having section dimensions 375 x 120 mm strengthened with NSM-CFRP laminates, grouped in two series that were different in terms of their strengthening configuration: the **H series**, were strengthened with NSM-CFRP applied in the hogging region only; and the **HS series** in which NSM CFRP is applied in both the hogging and sagging regions. Slab specimen configuration and identification is summarised in Table 1. Figure 1 shows the slab test configuration.

Table 1. Specimen identification.

Specimen	moment redistribution (η)	NSM-CFRP provided	target strength increase	strength increase observed
SL15	15%	none	-	-
SL30	30%	none	-	-
SL45-H & HS	45%	none	-	-
SL15s25-H	15%	H	25%	8.1%
SL15s25-HS	15%	H & S	25%	36.1%
SL15s50-H	15%	H	50%	19.8%
SL30s25-H	30%	H	25%	5.9%
SL30s25-HS	30%	H & S	25%	29.8%
SL30s50-H	30%	H	50%	9.2%
SL30s50-HS	30%	H & S	50%	49.4%
SL45s25-H	45%	H	25%	2.9%
SL45s25-HS	45%	H & S	25%	24.4%
SL45s50-H	45%	H	50%	8.5%
SL45s50-HS	45%	H & S	50%	37.2%

The amount and disposition of the steel bars were designed to assure moment redistribution percentages of 15%, 30% and 45%. The NSM-CFRP systems applied were designed for increases in load carrying capacity of 25% and 50% over the control slabs.

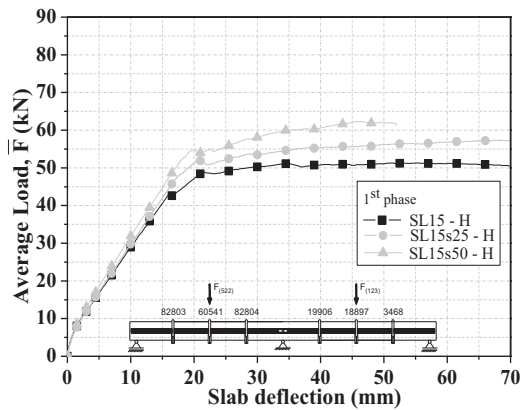


Figure 1. Test configuration.

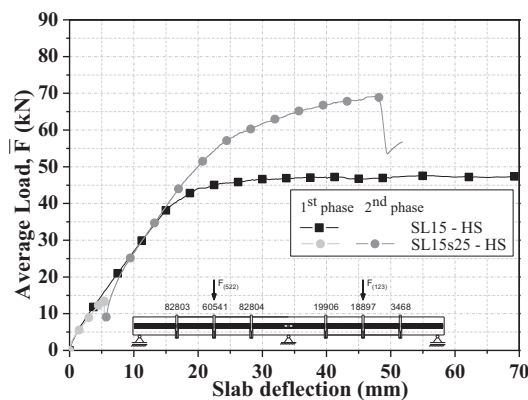
From the results obtained, shown in Table 1, it was verified that the strengthening configurations composed of NSM-CFRP applied only in the hogging region (H) did not attain the target increases of the load carrying capacity. In fact, when the CFRP laminates were applied in the hogging region, an increase of the load carrying capacity of between only 3 and 20% was achieved.

When NSM-CFRP was applied in both sagging and hogging regions (HS), an increase of the load carrying capacity was markedly greater and generally achieved the target capacity (Table 1). Therefore, to increase significantly the load carrying capacity of the RC slabs, the sagging zones need also to be strengthened. Figure 2 presents the load-midspan deflection of the slab strips SL15-H and SL15-HS. As seen in Figure 2, the NSM-CFRP strengthening configuration provided a significant increase of the load carrying during the second phase of the test loading process.

A lower-than-predicted moment redistribution (η) was observed in the slabs strengthened only in the hogging region. For this strengthening configuration, η decreases with an increase of the CFRP percentage. However, adopting a flexural strengthening strategy composed of NSM-CFRP applied in both hogging and sagging regions, resulted in the target values for η being attained; additionally, in this case, the influence of the percentage of CFRP was marginal on η . A detailed description of this experimental program is found in Dalfré (2013).



a) SL15-H



b) SL15-HS

Figure 2. Load-midspan deflection of the slab strips

Numerical simulations

For assessing the predictive performance of a FEM-based computer program for the simulation of the behaviour of these types of structures, the experimental tests were simulated by considering the nonlinear behaviour of the constituent materials. The numerical simulations have reproduced with high accuracy the behaviour of the tests (Dalfré 2013).

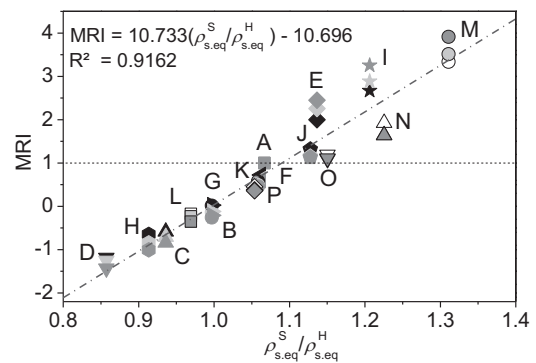
A parametric study composed of 144 numerical simulations was carried out to investigate the influence of the strengthening arrangement and CFRP reinforcing ratio in terms of load carrying capacity and moment redistribution capacity of continuous RC slab strips flexurally strengthened by the NSM technique. According to the results, shown in Figure 3, the load carrying and the moment redistribution capacities strongly depend on the flexural strengthening arrangement described by the equivalent reinforcing ratio:

$$\rho_{s,eq} = A_s/bd_s + (A_f E_f / E_s) / bd_f$$

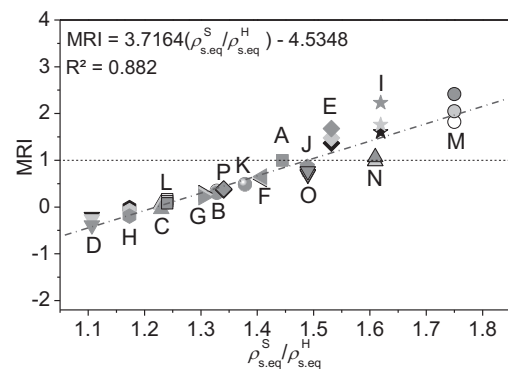
Where b is the width of the slab cross section; d_s and d_f are the effective depth of the longitudinal steel and

NSM-CFRP, respectively; and E_s and E_f are the Young's Modulus of the longitudinal steel bars and NSM-CFRP, respectively.

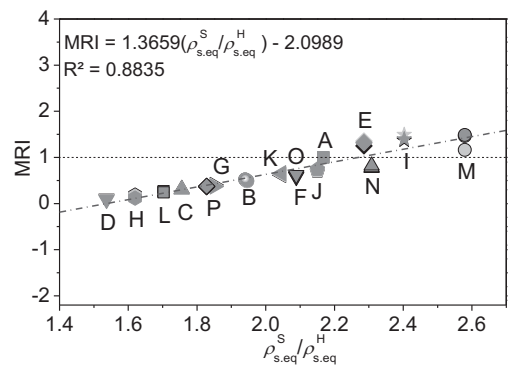
The load carrying capacity of the strengthened slabs increases with the equivalent reinforcement ratio applied in the sagging and hogging regions ($\rho_{s,eq}^S$ and $\rho_{s,eq}^H$, respectively), although the increase is more pronounced with $\rho_{s,eq}^S$, especially up to the formation of the plastic hinge in the hogging region.



a) SL15



b) SL30



c) SL45

Figure 3. Relationship between the moment redistribution index and $\rho_{s,eq}^S / \rho_{s,eq}^H$

The moment redistribution index (*MRI*) is the ratio of moment redistribution factors of the strengthened and reference slabs: $MRI = \eta_{streng}/\eta_{ref}$; where η is the moment redistribution ratio at the formation of the second hinge (in the sagging region). According to the results, the *MRI* increases with $\rho_{s,eq}^S/\rho_{s,eq}^H$ and positive values (indicating that the moment redistribution of the strengthened slab is greater than its corresponding reference slab) are obtained when $\rho_{s,eq}^S/\rho_{s,eq}^H > 1.09$, $\rho_{s,eq}^S/\rho_{s,eq}^H > 1.49$, and $\rho_{s,eq}^S/\rho_{s,eq}^H > 2.27$ for η equal to 15%, 30% and 45%, respectively. Thus, the moment redistribution percentage can be estimated if $\rho_{s,eq}^S/\rho_{s,eq}^H$ is known. Figure 3 presents the relationship between *MRI* and $\rho_{s,eq}^S/\rho_{s,eq}^H$ for series SL15, SL30 and SL45. The results demonstrate that the use of efficient strengthening strategies can provide an adequate level of ductility and moment redistribution in statically indeterminate structures, with a considerable increase in the load carrying capacity. A flexural strengthening strategy composed of NSM-CFRP applied in both hogging and sagging regions has a deflection ductility performance similar to the corresponding RC slab. Finally, the rotational capacity of the strengthened slab strips decreases with the increase of $\rho_{s,eq}^H$, and increases with $\rho_{s,eq}^S$. In the slab strips strengthened in both hogging and sagging regions, a rotational capacity lower than the reference slabs was obtained.

Analytical formulation

To predict the load-deflection response up to the collapse of statically indeterminate RC structures, an analytical model was developed and its predictive performance was appraised using the data obtained in experimental programs (Dalfré 2013).

The proposed approach is based on the force method of establishing a number of displacement compatibility equations that can provide the unknown variables. To determine the tangential flexural stiffness in these equations, moment-curvature relationships are determined for the cross sections representative of the structure. This model can be easily implemented in a design environment, and is applicable to statically determinate or indeterminate RC structures strengthened with the NSM or externally bonded (EB) reinforcement techniques. The predictive performance of the model was appraised by simulating the slab strips tested in the experimental program. The results, shown in Figure 4, showed that the developed numerical strategy is capable of capturing with enough accuracy the relevant features observed experimentally.

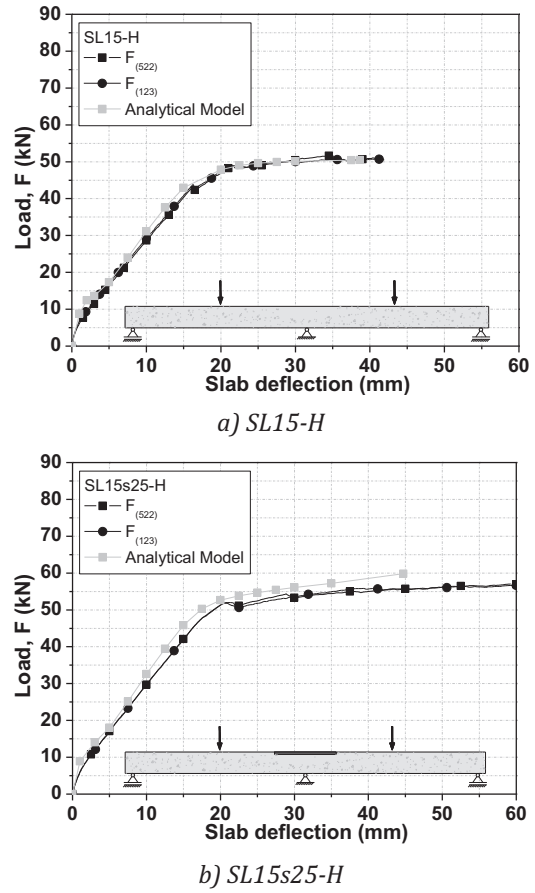
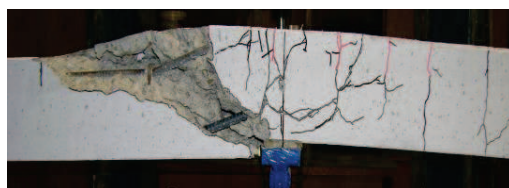


Figure 4. Relationship between applied load and deflections at spans of the slab strips.

ETS technique for shear strengthening RC elements

The effectiveness of the NSM technique can be compromised by the detachment of the concrete cover that includes the NSM-CFRP laminates and by formation of shear cracks in the hogging region of the flexurally strengthened elements (Figure 5). Moreover, in some cases, the failure mode shifts from ductile flexural failure to brittle shear failure following flexural strengthening. Shear failure of the retrofitted system must be avoided, since this failure is often brittle and occurs with little or no visible warnings. In this context the Embedded Through-Section (ETS) was applied for the shear strengthening of RC beams.



a) SL45s25-HS



b) SL45s50-HS

Figure 5. Failure mode of strengthened slab strips.

To assess the contribution of the bond mechanism of the ETS bars in the context of shear strengthening, and to better select the type of strengthening bars and adhesive materials, a comprehensive pull-out program was firstly executed (Dalfré 2013). Based on the results of this, steel bars and epoxy-based adhesive were selected for an ETS shear strengthening program with RC beams. The influence of the following parameters on the ETS shear strengthening effectiveness was investigated: spacing of the existing steel stirrups (225 and 300 mm), spacing (225 and 300 mm) and inclination (vertical and 45-degree) of the strengthening bars, and width of the cross section of the beam. The results obtained showed that, for the same shear strengthening ratio, the ETS technique provides increased levels of load carrying and deflection capacities, higher than those attained by FRP-based shear strengthening techniques (Dalfré 2013). An example of crack patterns and failure loads of ETS-strengthened slab strips is shown in Figure 6. According to the results, the ETS technique can be used to avoid the occurrence of shear failure in RC beams. Furthermore, the ETS technique uses low cost steel bars bonded to concrete with a 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.

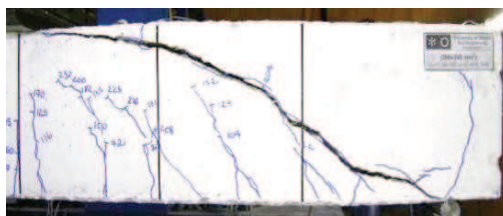
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Reference

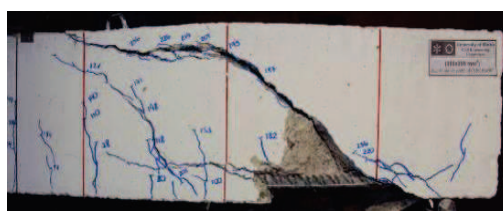
G. M. Dalfré, Flexural and shear strengthening of RC elements, PhD Thesis, University of Minho, Portugal (2013).



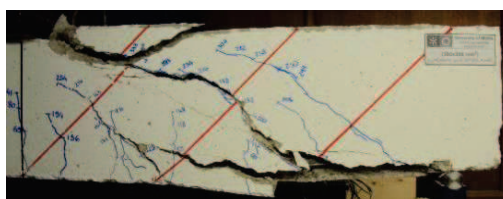
a) reference slab; $F = 203.4 \text{ kN}$



b) steel stirrups at 90° and spacing of 300mm; $F = 232.3 \text{ kN}$



c) ETS bars at 90° and spacing of 300mm; $F = 238.9 \text{ kN}$



d) ETS bars at 45° and spacing of 300mm; $F = 336.2 \text{ kN}$

Figure 6. Crack pattern and failure load.

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