INFLUENCE OF ADHESIVE TYPE ON THE FLEXURAL BEHAVIOUR OF RC SLABS STRENGTHENED WITH NSM-CFRP SYSTEMS

J. R. Cruz[1], J. Sena-Cruz [1], A. Borojevic[1], A. Kwiecień [2] and B. Zając[2]
[1] *ISISE, Dep. of Civil Engineering, University of Minho, Portugal*, *Email: jsena@civil.uminho.pt*
[2] *Department of Civil Engineering, Cracow University of Technology, Poland*

ABSTRACT

In the context of the strengthening of reinforced concrete (RC) structures, near surface mounted (NSM) technique can be used by applying carbon fibre reinforced polymer (CFRP) laminates on the concrete cover of the structural elements to be strengthened. An adhesive is used to fix the CFRP to concrete, which is responsible by the stress transfer between the concrete and the CFRP, assuming a key role for the success of the strengthening system. The influence of the adhesive type on the overall performance of these strengthened structures presents some research gaps in knowledge. In fact, only a reduced number of studies were found in the literature evaluating the influence of the mechanical characteristics of the adhesives on the performance of the strengthened elements. This paper presents the results of an investigation on the flexural behaviour of RC slabs strengthened with NSM CFRP systems using stiff (Adhesives 1 and 2) and flexible (Adhesive 3) adhesives. For this purpose, an experimental program was carried out, being considered two study variables: (i) the adhesive type and (ii) the existence or not of pre-cracking on the structural element. Flexural slab tests were used to characterize the differences on the slab's structural behaviour depending on the parameters tested. Regarding to the results obtained, it is clear the dependence of the response force *versus* mid-span vertical deflection and mid-span CFRP strains on the adhesive type as well as on the presence or absence of pre-cracking. However, it was verified that the maximum load attained is less dependent on the mention parameters. Thus, with the flexible adhesive, the maximum load attained is about 80% of the maximum load achieved in the tested slabs where stiff adhesives were used. The maximum load achieved is similar with presence or absence of pre-cracking. The failure of the CFRP laminate was observed with stiff adhesives while with the flexible one, CFRP debonding was observed. Finally, a higher ductility was observed by using flexible adhesive.

KEYWORDS

NSM, CFRP, slabs, flexural tests, adhesive.

INTRODUCTION

Repair and strengthening solutions are commonly adopted on existing reinforced concrete (RC) structures as a way of preserving them. The use of Fibre Reinforced Polymers (FRP) applied according to the Near Surface Mounted (NSM) technique is one of the possibilities for strengthening existing RC structures. NSM technique is based on the insertion of the reinforcing material in the concrete cover of the element to be strengthened. Typically, an epoxy adhesive is used to fix the CFRP laminate to concrete. This bonding agent plays a key role on the composite action of the system. Actually, there are very few studies developed to assess the influence of the adhesive characteristics on the flexural behaviour of RC elements strengthened using the CFRP systems. Derkowski *et al.* (2013) performed an investigation where the authors reported the advantage of using highly deformable (flexible) adhesives in external bonding (EB) of CFRP laminates to RC beams as strengthening, such as the higher load carrying capacity of these structural elements. Kwiecień (2012) studied the bond behaviour of EBR-CFRP masonry systems applying stiff and flexible adhesives through single-lap shear tests. The authors concluded that the flexible adhesive is more effective than the stiff one (epoxy resin). Using flexible adhesive higher level of ultimate force (of about 42%) and of ultimate displacement (of about 63%) were reached in comparison to epoxy adhesive. The loaded end slip attained with the flexible adhesive is about 40 times higher than for the case of stiff adhesive. Thus, the shear stress on the adhesive layer was reduced by the adhesive flexibility. Also, the author concluded that the flexible polymers protected the brittle substrate against the local peak stress caused by stiff adhesives, which are responsible for the activation of the rapid detachment process. Considering the advantages achieved by flexible adhesives described above, in the present investigation, the influence of (i) using two stiff (Adhesives 1 and 2) and one flexible adhesive (Adhesive 3) (ii) with and without pre-cracking, on the flexural behaviour of the RC slabs strengthened with the NSM CFRP, is assessed. In the following sections, the experimental program is detailed and the main results are presented and analysed.

EXPERIMENTAL PROGRAM

Test program

The experimental program was composed of seven slab specimens (see Table 1). For application of NSM CFRP strengthening system, three adhesive types were used: Adhesive 1 (ADH1), Adhesive 2 (ADH2) and Adhesive 3 (ADH3). Each adhesive type complains two slabs: (i) one without pre-cracking and (ii) other one with pre-cracking. The cross-section of CFRP laminate adopted was 20×1.4 mm^2. It was also included a reference slab without any strengthening. The generic denomination adopted for which slab is SL_ADHX_Y where X represents the adhesive type (1, 2 or 3) and Y represents the absence or presence of pre-cracking (U - Uncracked and C - Cracked). SL_REF is the adopted denomination for the reference slab.

Table 1: Experimental program.

Type of adhesive	Pre-cracking	CFRP cross-section geometry, $w_f \times t_f$ [mm^2]	Slab's denomination
--	--	--	SL_REF
Adhesive 1 (ADH1)	No	20×1.4	SL_ADH1_U
	Yes		SL_ADH1_C
Adhesive 2 (ADH2)	No		SL_ADH2_U
	Yes		SL_ADH2_C
Adhesive 3 (ADH3)	No		SL_ADH3_U
	Yes		SL_ADH3_C

Notes: No – absence of pre-cracking (U-Uncracked); Yes – presence of pre-cracking (C-Cracked).

Slab's geometry and test configuration

Figure 1 presents the test configuration adopted, the geometry of the slab specimens and the details of the strengthening system. The slabs have a total length of 2600 mm with a rectangular cross-section of 600×120 mm^2. The bottom steel reinforcement was composed of 4 steel bars of 8 mm diameter (4∅8) and the top steel reinforcement was composed of 3∅6. Steel stirrups of 6 mm diameter spaced of 300 mm were adopted (∅6@300). A concrete cover of 20 mm was adopted. The strengthening solution is composed of 2 CFRP laminates of 20×1.4 mm^2 installed on the concrete cover according NSM technique. The corresponding equivalent longitudinal reinforcement ratio ($\rho_{s,eq}$) is, according to Sena-Cruz *et al.* (2012), equal to 0.39%. It should be noted that the main propose of the designed strengthening solution is to duplicate the load carrying capacity of SL_REF. The grooves used for the introduction of the CFRP laminates have a constant cross-section of 5×25 mm^2. The CFRP laminate has a total length of 2200 mm, existing on both extremities of the groove, 200 mm where the CFRP laminate does not exist. This option was taken to assure the absence of the confinement effect of the NSM CFRP system in the extremities provide by the concrete compression on the supports during the test. A four-point bending test configuration is adopted to test the slabs. The distance between lower supports (span length) is 2400 mm, being the shear span of 900 mm (i.e. 7.5 times the slab thickness). The slabs instrumentation included the measurement of the applied load (F) through a load cell with the maximum capacity of 200 kN and a linear error of ±0.05%. For measuring the deflection along the longitudinal axis of the slab, 5 linear variable displacement transducers (LVDT1 to LVDT5) were used: 3 in the pure bending zone (range of ±75 mm and linearity error of ±10%) and 2 (range of ±25 mm and linearity error of ±10%), one in each side, between the bottom supports and the point loads. The strains in the materials of the slab were also assessed: (i) bottom steel bars at mid-span; (ii) concrete under compression stress state, at the top fibre of mid-span; and, (iii) CFRP laminates - 5 strain gauges were placed at mid-span and along the CFRP. Two different types of strain gauges were used for measurement of the strains: (i) TML BFLA-5-3-3L for steel bars and CFRP laminate and (ii) TML PFL-30-11-3L for concrete. The tests were conducted using a servo-controlled equipment under displacement control at LVDT3 at a rate of 20 μm/s.

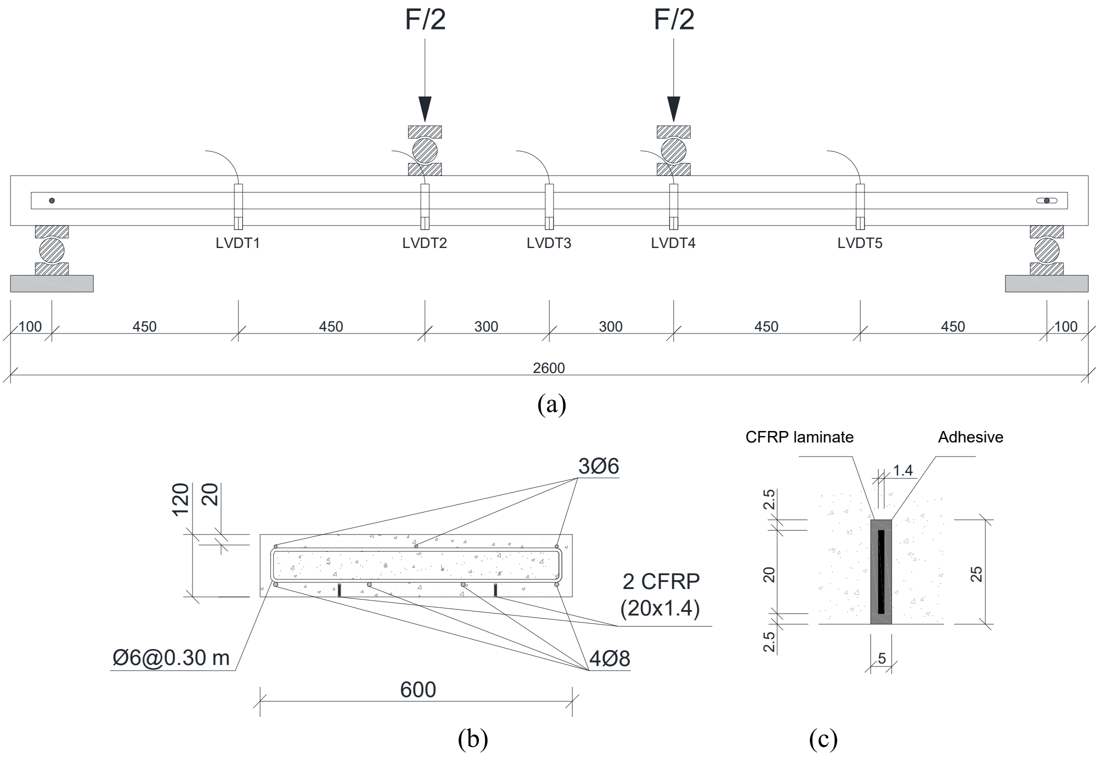


Figure 1: Slab specimens: (a) test configuration; (b) cross-section geometry; (c) detail of the strengthening solution. Note: all dimensions are in millimeters.

Material characterization

The concrete compressive strength was assessed using cylinders with 150 mm of diameter and 300 mm of height, at 28 and 110 days after casting (the latter date coincides with the date of slab's testing). The modulus of elasticity and the compressive strength were assessed according to LNEC E-397-1993:1993 and NP EN 12390-3:2009 recommendations, respectively. An average modulus of elasticity (E_{cm}) of 27.0 GPa, with a coefficient of variation, CoV, of 0.5% and an average compressive strength (f_{cm}) of 35.4 MPa (CoV = 4.8 %) were obtained at 28 days. At 110 days, E_{cm} = 28.3 GPa (CoV = 2.5%) and f_{cm} = 38.5 MPa (CoV = 2.1%) were obtained. The steel bars (A400 NR SD) used for this experimental program presented the following values for the yield (f_y) and ultimate (f_u) strength: ∅6 - f_y = 631.61 MPa (CoV = 3.4 %) and f_u = 781.03 MPa (CoV = 2.4 %); and ∅8 - f_y = 546.76 MPa (CoV = 5.3 %) and f_u = 669.06 MPa (CoV = 5.6 %). The mechanical properties of the adhesives were assessed according to ISO 527-2:2012. The following average values were obtained for the elastic modulus (E_a) and tensile strength (f_a): ADH1 - E_a = 11.67 GPa (CoV = 0.51%) and f_a = 25.59 MPa (CoV = 7.40%); (ii) ADH2 - E_a = 7.57 GPa (CoV = 6.15%) and f_a = 17.19 MPa (CoV = 5.43%); (iii) ADH3 - E_a = 0.012 GPa (CoV = 9.09%) and f_a = 2.67 MPa (CoV = 12.49%). The mechanical properties of CFRP laminates were assessed by Sena-Cruz *et al.* (2013), being the elastic modulus equal to 161.8 GPa (CoV = 0.9%) and the tensile strength equal to 2784 MPa (CoV = 3.9%).

Strengthening Procedures

The preparation of the strengthened specimens included several steps: (i) casting, (ii) groove's opening, (iii) pre-cracking (only on 3 slabs), (iv) cleaning of the grooves and CFRP laminates, (v) application of a primer on the groove surface (only on ADH3 specimens - SL_ADH3_U and SL_ADH3_C) and (vi) application of the strengthening system: adhesives ADH1 and ADH2 were applied with the assistance of a spatula while the ADH3, due to its low viscosity, was applied by gravity. The specimens were cured and kept in laboratory environment for approximately one month and half before being tested.

The pre-cracking process was performed using the same test configuration used for the tests up to failure previous described. The main difference is that the pre-cracking process was performed under force control at a rate of 0.05 kN/s up to a force of 15 kN, which corresponds approximately to 2/3 of the load carrying of the slab SL_REF. When this load level was achieved, this value of force was kept constant for 10 minutes to mark the crack pattern and measure the cracks width. It can be noted that during the time while the force remained constant, there was an increase on mid-span displacement due to creep. After this period, the mid-span deflection was about 13 mm. Finished this task, the load was removed. During the removal of the force, it could be observed the recovery of the elastic deformation, remaining a residual mid-span deflection of about 6 mm and a residual steel stain of about 0.1%.

RESULTS AND DISCUSSION

Main results

Table 2 presents the main results obtained from the slab tests. In this table, K_I, K_{II} and K_{III} represent the flexural stiffness in each one of the three main phases, respectively: (i) elastic phase; (ii) cracked phase; and, (iii) phase after steel yielding. This parameter was determined by computing the slope of the respective branch, using two representative points. On the cracked phase, these two points were selected in a zone after the cracking opening. F_{cr}, F_y and F_{max} correspond to the force at the cracking initiation, steel yielding and maximum force, respectively and δ_{cr}, δ_y and δ_{max} correspond to the relative mid-span displacements, respectively. ε_{fmax} is the maximum strain attained in the CFRP laminate at F_{max}. The values between parentheses represent the increase of load carrying capacity compared to SL_REF. The ductility of each slab was also assessed through the parameter δ_{max}/δ_y. Finally, last column includes the observed failure modes.

Table 2: Main results obtained from the flexural slab tests.

Slab's denomination	Flexural stiffness			Crack initiation		Yielding		Maximum			Ductility parameter	Residual force ratio	FM
	K_I	K_{II}	K_{III}	δ_{cr}	F_{cr}	δ_y	F_y	δ_{max}	F_{max}	ε_{fmax}	δ_{max}/δ_y	F_{max}/F_y	--
	[kN/mm]			[mm]	[kN]	[mm]	[kN]	[mm]	[kN]	[x10^{-3}]	-	[%]	
SL_REF	7.75	0.78	0.01	0.71	7.57	20.17	21.47	158.43[a]	23.56[a]	-	-	50.26	-
SL_ADH1_U	9.57	1.10	0.40	1.25	10.86 (43%)	21.85	31.93 (49%)	74.04	52.87 (124%)	12.06	3.39	47.77	F
SL_ADH2_U	8.95	1.07	0.41	1.35	10.52 (39%)	22.47	31.11 (45%)	74.95	52.08 (121%)	12.49	3.34	78.45	F
SL_ADH3_U	7.94	1.28	0.34	1.58	10.86 (43%)	20.79	27.35 (27%)	72.24	42.71 (81%)	8.46	3.47	47.56	D
SL_ADH1_C	6.30[b]	1.92	0.41	1.32[b]	7.16[b]	18.95	31.58 (47%)	68.87	51.53 (119%)	12.46	3.63	50.08	F
SL_ADH2_C	6.03[b]	1.91	0.40	0.99[b]	7.78[b]	17.36	30.47 (42%)	69.33	51.06 (117%)	12.02	3.99	78.98	F
SL_ADH3_C	5.38[b]	1.81	0.34	1.06[b]	6.18[b]	13.97	24.61 (15%)	69.54	41.82 (78%)	8.33	4.98	50.26	D

Notes: FM = Failure modes; F = CFRP failure; D = Debonding failure of the CFRP laminate due to cohesive failure of the adhesive; on the ratio F_r/F_{max}, the value used for F_r corresponds to a 90 mm of mid-span vertical deflection for slabs SL_ADH1 and SL_ADH2 and 120 mm for slabs SL_ADH3; the values between parentheses represent the increase in load carrying capacity in each phase compared to SL_REF. [a] Maximum value reached during the test without failure of the slab (by concrete crushing or failure of the longitudinal tensile steel bars). [b] Values obtained from the pre-cracking phase (see Cruz (2016)).

Force *versus* mid-span displacement relationships

Figure 2 presents the applied force *versus* mid-span displacement relationships obtained for the tested slabs. These relationships present the typical observed flexural behaviour in strengthened RC flexural elements with NSM-CFRP systems. It is notorious an increase in load carrying capacity due to the strengthening application. Except pre-cracked slabs, three main phases can be observed: (i) the elastic phase (I), from the beginning of the test up to the crack initiation without significant change in stiffness (when compared with SL_REF), due to the amount of the CFRP reinforcement used; (ii) the cracked phase (II), from the cracked initiation up to the steel yielding, where the contribution of the CFRP reinforcement starts playing an important role; and, (iii) the post-yielding phase (III), from the steel yielding up to the maximum load carrying capacity, where the contribution of the CFRP reinforcement is responsible for carrying the additional increments of load. As expected, the elastic phase doesn't exist in the pre-cracked slabs since they have been already cracked before testing up to the failure (see Figure 2b). It is also observed the decrease of the flexural stiffness along the test as result of the loss of the mechanical properties of the materials, the loss of bond properties between them and the cracking.

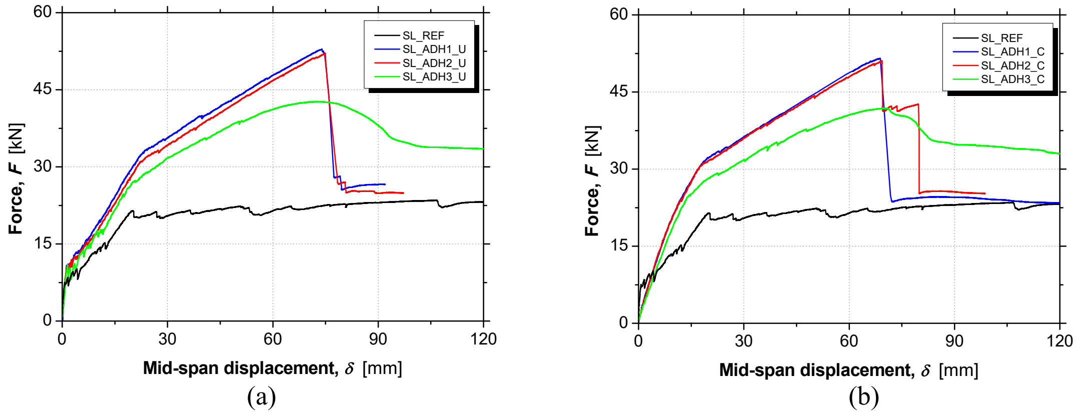


Figure 2: Force vs. mid-span displacement obtained on the (a) uncracked and (b) cracked series.

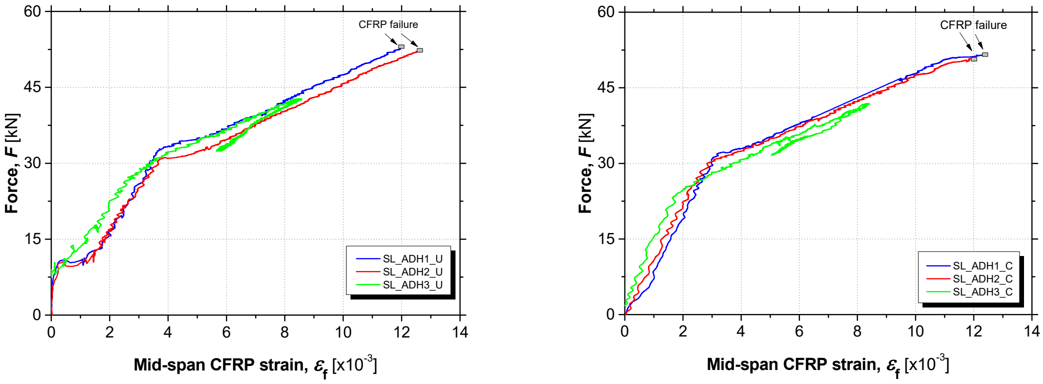
Similar responses were obtained during the elastic phase for all slabs, including SL_REF. In the cracked phase, all the strengthened slabs exhibited very similar behaviour. However, at the yielding point important differences can be observed for the different types of adhesive used: SL_ADH1 and SL_ADH2 present a higher yielding point than the SL_ADH3 (independently if the slab is pre-cracked or not). This behaviour is due to the level of slip between the CFRP and concrete occurred at this load level, directly dependent on the flexibility of the adhesive. After yielding, slabs SL_ADH1 and SL_ADH2 exhibited an almost linear elastic behaviour. Since ADH1 and ADH2 provided higher level of bond between the CFRP and concrete linked with low levels of slip, the tensile failure CFRP was achieved. As expected, after failure of the CFRP of these slabs (SL_ADH1 and SL_ADH2) the flexural response is close to the one observed on the SL_REF. It should be noted that on slabs SL_ADH3, the third branch is different of the one observed on SL_ADH1 and SL_ADH2, with a pronounced non-linear relationship between the applied force and the deflection at mid-span. This behaviour is mainly governed by the significant amount of slip between the CFRP laminates and the concrete. Due to that, the CFRP failure did not occurred. After the maximum load, those deformability coincides with the one observed in the slabs SL_ADH1 and SL_ADH2, a "softening" branch with a gradual decrease of strength is observed, with a significant residual strength (for 120 mm of deflection was about 77% of F_{max}). This response can be explained by the loss on bond between the CFRP laminate and the adhesive and by the increasing cohesive failure at the adhesive, which decreases the contribution of the CFRP laminates for flexural capacity of these slabs.

Force *versus* mid-span CFRP strain

Figure 3 presents the force *versus* mid-span CFRP strain relationships obtained for the strengthened slabs. Like in force *versus* mid-span displacement relationships, three phases can be observed on uncracked series and two phases can be observed on cracked series. In general, the level of mobilization of the CFRP is higher with stiff adhesives than with flexible one, which prove the higher capacity on stress transfer of the stiff adhesives. On the contrary to SL_ADH1 and SL_ADH2, on SL_ADH3 the CFRP did not fail and after F_{max}, a decrease on CFRP strain can be observed. Probably, this happens due to the CFRP slippage observed because of loss of bond at laminate adhesive interface. Finally, it should be noted a smaller level of CFRP strain on initial phase of the test on the uncracked series due to the contribution of the uncracked concrete under tension, contrary to cracked series. After the crack initiation, the process of stress transferring from the concrete under tension to the CFRP laminate results on a suddenly increase on the CFRP strain with the stiff adhesive, contrary to the slab with the flexible adhesive where this increase was not observed (an almost monotonic strain increase). This finding can be result of reduction of stress concentration and stress redistribution along the CFRP laminate (in the place of the crack) by the flexible adhesive, causing lower mobilization of the mechanical properties of the CFRP laminate. Flexible adhesive (SL_ADH3) protected the CFRP laminate against a notch effect in the place of the crack, which was responsible for the CFRP laminate failure when stiff adhesives were used (SL_ADH1 and SL_ADH2).

Failure modes

Figure 4 shows the failure modes obtained. Two types of failure modes were observed in this study: (i) slabs SL_ADH1 and SL_ADH2 failed by rupture of the CFRP laminate at mid-span (see Figure 4a) and (ii) slabs SL_ADH3 failed by debonding of the CFRP laminate at laminate-adhesive interface, mainly at mid-span (see Figure 4b), and by cohesive failure of the adhesive, mainly at the ends (see Figure 4c).



(a) (b)

Figure 3: Force vs. mid-span CFRP strain obtained on the (a) uncracked and (b) cracked series.

(a) (b) (c)

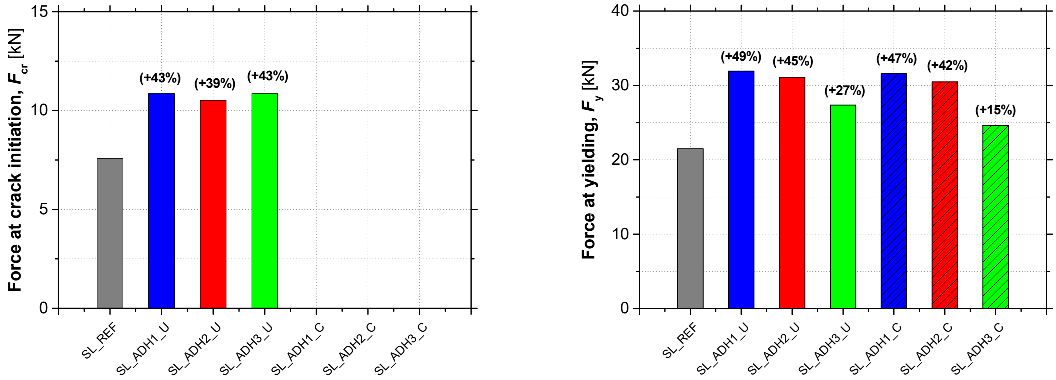
Figure 4: Failure modes: (a) CFRP laminate failure (SL_ADH1 and SL_ADH2); (b) debonding at laminate-adhesive interface (SL_ADH3); (c) cohesive failure of ADH3 at the ends of the strengthening system (SL_ADH3).

Influence of adhesive type and pre-cracking on the flexural behaviour of the slabs

As shown in Figure 5a, the presence of the strengthening leads to an increase in force at crack initiation in comparison to SL_REF, being observed an average increase of 42% comparing to SL_REF (see Table 2 and Figure 5). Thus, it can be concluded that at this stage, the flexural behaviour probably is not dependent of the adhesive type since they may have similar mechanical behaviour.

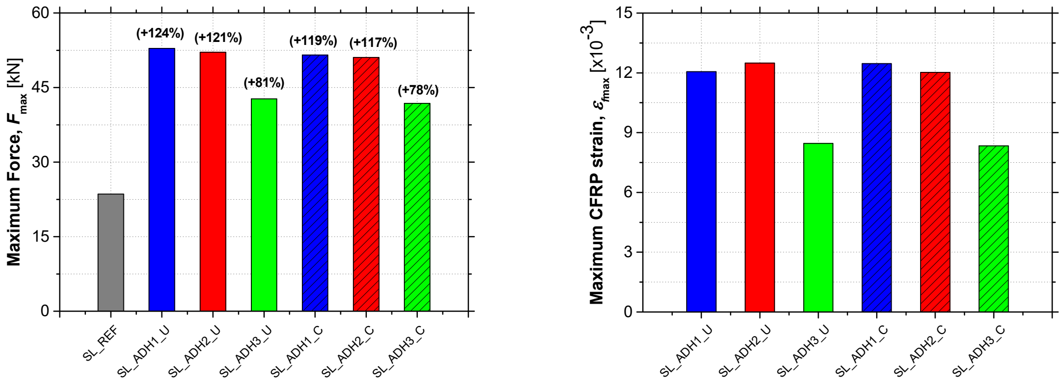
Figure 5b presents the force achieved at yielding phase for each slab and its respective increase compared to SL_REF. According to the results, the corresponding force was very similar on the slabs SL_ADH1 and SL_ADH2 (cracked or not), as expected. However, the slab SL_ADH1 presented a slightly higher value maybe due to the slightly higher mechanical properties of this adhesive. On SL_ADH3, the increase of the load at this phase was smaller than with the application of the stiff adhesives. According to the values shown in Table 2 and Figure 5b, the presence of pre-cracking resulted in a decrease of 1.1%, 2.1% and 10.0% of yielding force respect to uncracked slabs, respectively for SL_ADH1, SL_ADH2 and SL_ADH3. From this data, it can be concluded that, with the stiff adhesives, the presence of pre-cracking had a little influence on the level of force reached at the yielding phase, however, with the flexible one, this decrease is more significant. The little decrease on the force observed with the stiff adhesives maybe result of a residual deflection related with internal residual strains on the bottom steel reinforcement (not recovered of the pre-cracking process), which leads to a little efficiency of this constitutive material. Regarding to the slabs SL_ADH3, the deformability of the adhesive, maybe, is the main responsible of the obtained response. On the contrary to cracking phase, it can be concluded that at yielding phase the adhesive type has already some influence as well as the pre-cracking process, mainly on slabs SL_ADH3.

Figure 6a presents the maximum force achieved during the tests by each slab and its respective increase compared to SL_REF. Thus, similar values of load increase were obtained on the slabs strengthened using stiff adhesives, while on the slabs where the flexible adhesive was used, the load carrying capacity was 18% smaller (on both uncracked and cracked series) than the average value reached on the slabs strengthened using stiff adhesives. Thus, a better performance was obtained with stiff adhesives, which can explore the CFRP tensile strength. On the contrary, the tensile strength was not achieved with the flexible adhesive and it was observe the CFRP slippage instead of CFRP failure (see Figure 4). Comparing both series, a slightly decrease on maximum force was observed between slabs of the same adhesive.



(a) (b)

Figure 5: Force at: (a) crack initiation; (b) bottom steel yielding. Notes: the values between parentheses are the percentage increase to SL_REF at this phase of the test.



(a) (b)

Figure 6: Maximum force (a) and maximum CFRP strain (b). Note: the values between parentheses are the percentage increase to SL_REF at this phase of the test.

Regarding to the maximum CFRP strain (shown in Figure 6b), it is higher on slabs SL_ADH1 and SL_ADH2 than on slabs SL_ADH3 (in average, 32% lower). Regarding to the influence of the pre-cracking, no significant changes in strain were observed, with decreases on SL_ADH1, SL_ADH2 and SL_ADH3 of 5.7%, 4.3% and 3.8%, respectively. Similar values of maximum strain on CFRP laminate were observed, independent of the initial presence or absence of pre-cracking. This finding can be explained by the issue that the action of the concrete under compression, of the yield steel and the CFRP laminate only exists at the moment of the failure of the slab. This finding also can explain the similar values obtained for the maximum force. It is common on the literature studies where the lower influence of pre-cracking was observed (e.g. Dias *et. al* (2004)).

The ductility was assessed on this study by the ratio δ_{max}/δ_y (see Table 2). On the uncracked series, the values were quite similar, showing the irrelevant influence of the adhesive type. Comparing two series, the ductility increases was observed on cracked series for slabs SL_ADH1, SL_ADH2 and SL_ADH3 of 7.1%, 19.5% and 43.5%, respectively, being more pronounced on slabs SL_ADH3. Thus, there was observed a trend of the ductility level increase with pre-cracking. Using the ratio F_r/F_{max} it is possible to show the significantly higher residual force developed by the SL_ADH3 slabs after the maximum load, comparing with SL_ADH1 and SL_ADH2 slabs.

Analytical predictions based of ACI 440

The ACI 440.2R-08 only includes design procedures for flexural strengthening with the NSM technique and does not explicitly include the flexural failures modes at ultimate limit state. Additionally, this standard does not consider the influence of the adhesive type. To prevent such an intermediate crack-induced debonding failure mode, the effective strain in FRP reinforcement should be limited to the strain level at which debonding may occur, ε_{fd}. For the case of NSM technique, ACI recommends the use of: $\varepsilon_{fd} = 0.7\varepsilon_{fu}$, where ε_{fu} is the ultimate CFRP strain. Thus, applying this recommendation to the slabs of the present investigation, a maximum load, F_{max}, of

47.19 kN was obtained. According this result and considering the results obtained from the experimental program developed, this value underestimate F_{max} in the case of SL_ADH1 and SL_ADH2 but overestimate in the case of SL_ADH3.

CONCLUSIONS

This paper presents an experimental research on the flexural behaviour of strengthened slabs using the NSM CFRP system and considering the following variables: (i) type of adhesive to fix the CFRP to concrete (stiff and flexible adhesives) and (ii) presence or absence of pre-cracking. From this study, the following conclusions can be pointed out:

- The application of the strengthening increases the load carrying capacity of the slabs;
- On the uncracked series, the cracking load is almost independent of the adhesive type;
- On the yielding, the load is dependent of the adhesive type, being higher for stiff adhesives;
- The two stiff adhesives provided similar load carrying capacity, which it was higher than the one obtained using the flexible adhesive;
- The response obtained in both uncracked and cracked series is similar, except the elastic phase once on the cracked series the elastic phase does not exist;
- Two distinct failure modes were observed depending on the adhesive type. Using stiff adhesives, the slabs failed by the CFRP rupture while using the flexible adhesive, the slabs failed by debonding of the CFRP;
- Using the flexible adhesive, after the maximum load, the CFRP continues to contribute to the load carrying capacity once it does not failed and the adhesive continues to provide resistance (additional post failure safety).

ACKNOWLEDGMENTS

This work was supported by FEDER funds through the Operational Program for Competitiveness Factors – COMPETE and National Funds through FCT (Portuguese Foundation for Science and Technology) under the project FRPLongDur POCI-01-0145-FEDER-016900 (FCT PTDC/ECM-EST/1282/2014) and partly financed by the project POCI-01-0145-FEDER-007633. Finally, the authors also like to thank the S&P Clever Reinforcement Ibérica Lda. company for providing the materials.

REFERENCES

A. Kwiecień (2012). "Stiff and flexible adhesives bonding CFRP to masonry substrates - Investigated in pull-off test and Single-Lap test". *Archives of Civil and Mechanical Engineering*, 12(2), 228-239.

ACI (2008). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures", 440.2R-08, Farmington hills. Report by ACI Committee 440, *American Concrete Institute*, MI, USA, 26.

P. M. G. Fernandes, P. Silva, J. M. Sena-Cruz, (2015). "Bond and flexural behavior of concrete elements strengthened with NSM CFRP laminate strips under fatigue loading", *Engineering Structures*, 84, 350-361.

J. M. Sena-Cruz, J. A. O. Barros, M. R. F. Coelho, L. F. F. T. Silva (2012). "Efficiency of different techniques in flexural strengthening of RC beams under monotonic and fatigue loading", *Construction and Building* Materials, 29,175-182.

J. Sena-Cruz, M. Jorge, J. M. Branco, V. M. C. F. Cunha (2013). "Bond between glulam and NSM CFRP laminates", *Construction and Building Materials*, 40, 260-269.

J. R. Cruz (2016). "Influence of the adhesive type on the behavior of concrete elements strengthened with NSM-CFRP systems", *MSc thesis, University of Minho*. [in Portuguese]

W. Derkowski, A. Kwiecień, B. Zając (2013). "CFRP strengthening of bent RC elements using stiff and flexible adhesives", *Technical Transactions 1-B/2013*, 37-52.

S. J. E. Dias, L. F. P. Juvandes, J. A. Figueiras (2004). "Effect of the concrete pre-cracking on the flexural behaviour of the slabs strengthened with CFRP composites. *REC Number 19*, pp. 41-54. [in Portuguese]