BOND AND FLEXURAL BEHAVIOUR OF A NSM CFRP STRENGTHENING SYSTEM UNDER FATIGUE LOADING

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ABSTRACT: The present paper aims to contribute to the knowledge of the long-term performance and durability of concrete structures strengthened with the Near-Surface Mounted (NSM) technique. The durability of strengthening systems is affected by environmental conditions, such as freeze-thaw and temperature cycling, exposure to aggressive chemical agents and ultraviolet light. Additionally, the long-term performance of the NSM system could be compromised by fatigue loading, which may result in deterioration and weakening of individual components (steel, FRP, concrete), or loss of bond performance and composite action. Thus, in order to assess the bond and flexural behavior of NSM CFRP strengthening system under fatigue loading, an experimental program was carried out, composing of direct pullout tests and loading of slab specimens. The main investigated parameters were the stress level (or fatigue stress) and the amplitude of cycle. This paper describes the conducted tests and presents and analysis the obtained results.

1. Introduction

In the context of strengthening of reinforced concrete (RC) structures, fiber reinforced polymers (FRP) have been emerging in the last decades, to extend the service life of existing transportation infrastructures, such as heavy traffic highways and, specially, bridges. This type of structures is submitted to fatigue loading caused by fluctuating cycles of vehicle loads with different intensities. Therefore, it is of paramount importance to study the performance of RC structures strengthened with FRP when subjected to millions of load cycles over their service lives. Although the typical loading levels associated with this type of structures are considerably less than their ultimate capacity, the repeated cyclic loading can cause failure by fatigue (Yun *et al.*, 2008). Moreover, fatigue loading presents a significant influence on the FRP-concrete interface properties, as described in a recent research work (Carloni and Subramaniam, 2013). Few publications were found to focus on the fatigue behavior of strengthened structures using the NSM technique, e.g. Sena-Cruz *et al*. (2012) and Badawi and Soudki (2009). Even though these studies pertained to a reduced number of testes, they revealed an excellent response of the overall NSM system under cyclic loading.

The present study has the main objective of improving the knowledge of the bond and flexural behavior of RC structures strengthened with NSM CFRP strips under fatigue loading conditions. This objective is pursued through an experimental program that comprises both direct pullout tests (bond behavior evaluation) and load tests on slab specimens (evaluation of overall structural behavior). The influence of stress level and cycle amplitude was investigated.

2. Experimental program

The experimental program was composed of nine direct pullout tests (DPT) and five load tests on slab specimens (SL). The pullout specimens were divided into three series, each one composed of three specimens, whereas the slabs specimens were grouped into two series, as shown in Table 1. The code names given to the specimens ID consist on alphanumeric characters separated by underscores. The first set of characters designates the specimen type (DPT and SL). The second set of characters specifies the specimen number for the case the pullout specimens (see also Fig. 2), while in the case of slabs it indicates whether it is strengthened (STR) or not (UN). The third set of characters defines the load configuration (M for the monotonic test and F for the fatigue test). Finally, for the fatigue tests the last character indicates the percentage of the maximum load (F_p) applied during the fatigue cycles when compared to the ultimate strength of the corresponding specimen type.

Table 1 – Experimental program (average values).

Specimen type	**Series**	**Specimen ID**	F_p [kN]	F_{min} [kN]	F_{max} [kN]	S_{min} [%]	S_{max} [%]
Direct pullout test	**S1**	DPT_M	30.36 (2.0%)	-	-	-	-
	S2	DPT_F50	28.67 (0.7%)	7.02	15.81	23	52
	S3	DPT_F60	-	7.77	17.70	26	58
Slabs	**S4**	SL_UN_M	12.03	-	-	-	-
		SL_STR_M	31.63	-	-	-	-
	S5	SL_UN_F75	-	5.1	9.0	42.4	74.8
		SL_STR_F50	-	8.3	15.1	26.2	47.8
		SL_STR_F70	-	16.2	22.5	51.2	71.0
		SL_STR_F80	-	19.6	26.3	62.0	83.1

Note: the values between parentheses are the coefficients of variation of the series.

2.1. Specimens and test configuration

The geometry and test configuration adopted both for monotonic and fatigue experiments in DPT and SL specimens are shown in Fig. 1. The pullout tests were performed in concrete cubic blocks (edge=200 mm), into which a NSM CFRP laminate strip was embedded (see Fig. 1a and b). To avoid premature failure due to the formation of a concrete fracture cone at the loaded end, the bond length started 100 mm from the top of the cube. The cross-section of the slab is 300 mm wide and 80 mm thick, whereas its free span is 1800 mm (see Fig. 1c and d). The longitudinal reinforcement is composed of 4Ø6, which corresponds to a longitudinal reinforcement ratio, ρ_l, equal to 0.47%. The flexural strengthening solution is composed of 3 NSM CFRP (10×1.4 mm^2) laminate strips, which corresponds to an equivalent longitudinal reinforcement ratio, $\rho_{s,eq}$, of 0.68%.

The fatigue tests were conducted in three main steps: (i) specimens were initially pre-loaded under force control up to mean value between the maximum, F_{max}, and minimum, F_{min}, load of a fatigue cycle; (ii) then, 3 and 2 million cycles were imposed at 3 and 2 Hz of frequency between $S_{min} \times F_p$ and $S_{max} \times F_p$ for the DPT and SL tests, respectively; (iii) finally, the specimens that did not fail by fatigue action were submitted to a monotonic loading up to failure. The monotonic tests were performed under displacement control, at a rate of 2 μm/s and 20 μm/s for the DPT and SL, respectively. The maximum and minimum fatigue levels applied in the present work are presented in Table 1. The fatigue tests were performed under force control.

Additional information related to the preparation/configuration of specimens, as well as the adopted instrumentation can be found elsewhere (Sena-Cruz *et al*., 2013).

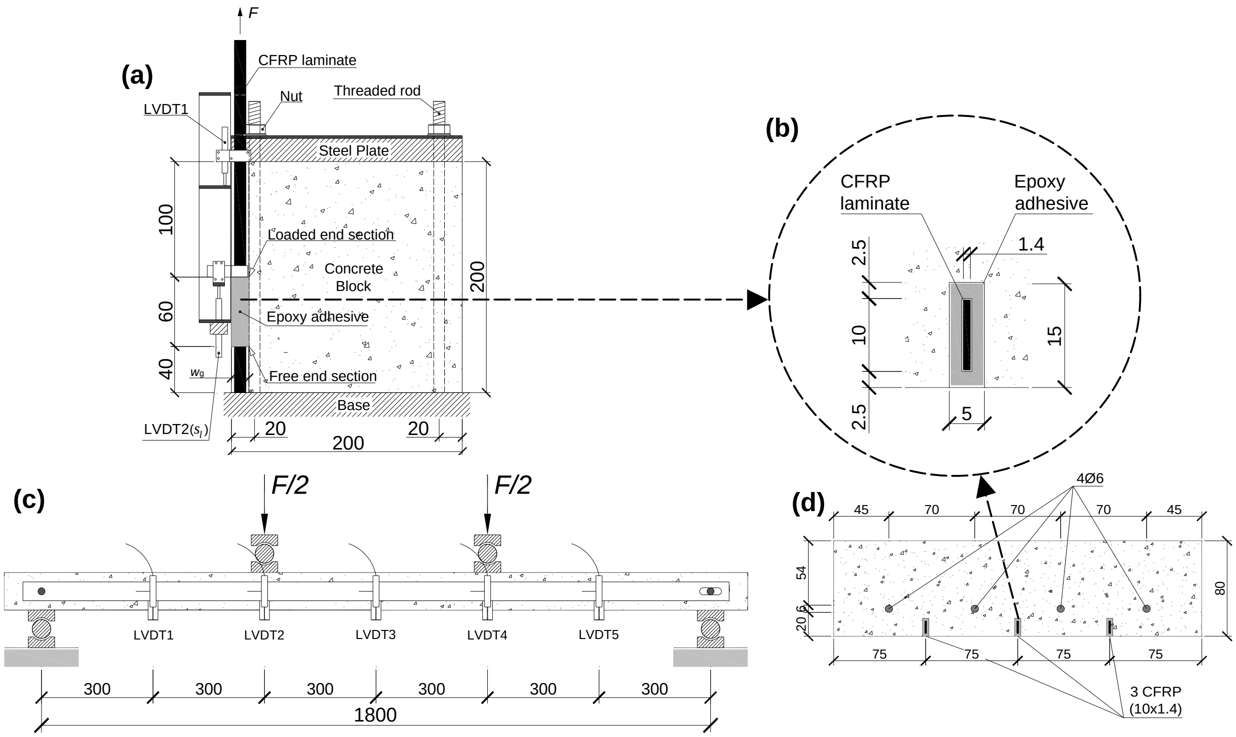

Fig. 1 – Tests configuration: (a) direct pullout specimen; (b) geometry details of the strengthening; (c) longitudinal view of slab specimen; (d) cross-section of slab specimen (dimensions in mm).

2.2. Materials characterization

The fatigue tests on slab specimens began when concrete had approximately 1 year of age (19 months in the case of pullout bond specimens), and its compressive strength in cylinders of 150mm/300mm was assessed by means of compression tests. A compressive strength of 48.2 MPa with a coefficient of variation (CoV) of 3.2% was obtained. The tensile properties of the CFRP laminate strips were assessed according to ISO 527-5:1997. A tensile strength of 2648.3 MPa (CoV=1.8%) and a Young's modulus of 169.5 GPa (CoV=2.5%) were obtained for the CFRP laminates. The uniaxial tensile properties of hardened epoxy adhesive used to bond the CFRP laminate strips to the concrete were assessed according to ISO 527-2:1993. From these tests, the following average values were obtained: 22 MPa (CoV=4.5%) for tensile strength, 7.2 GPa (CoV=3.7%) for Young's modulus and 0.36% (CoV=15.2%) for the strain at the peak stress. The main mechanical properties of the steel reinforcement used are available elsewhere (Sena-Cruz *et al*., 2013).

3. Results and discussion

3.1. Pullout specimens

As previously mentioned, six pullout specimens were tested under two different fatigue load ranges: (i) 23%-52% (series S2), and (ii) 26%-58% (series S3) of the average maximum pullout force, F_p, obtained from the three specimens tested under monotonic loading (see also Table 1).

Fig. 2a depicts the envelope of pullout force *versus* loaded end slip (F_l-s_l) relationship for all three specimens tested monotonically up to the failure (DPT_M). The obtained F_l-s_l responses are coherent with the results observed in monotonic tests performed by Sena-Cruz *et al*. (2013).

Regarding the fatigue tests, the variation of loaded end slip (s_l) with respect to number of cycles are plotted in Fig. 2b for both minimum and maximum loads applied during the fatigue tests of series S2 and S3. For the three fatigue tests of series S3, the number of cycles at the failure (N_f) were 95,000, 561,000 and 376,000 cycles for the specimens DPT1_F60, DPT2_F60 and DPT3_F60, respectively. Even though these specimens were submitted to the same fatigue and amplitude load, they present a significantly scattered behavior in terms of their number of cycles at failure. Nevertheless, the failure mode observed in these three specimens was identical and corresponded to progressive debonding of the CFRP at the adhesive/laminate interface up to a complete separation between both materials. For the three specimens of series S3, three regions can be identified: a region of fast increase of the slip in the first cycles, followed by a progressive slip growth zone, and finally a region where the slip increased faster again until the specimen reached the failure. The magnitude of values of the slip at the failure is in agreement with the ones obtained in monotonic tests, i.e. approximately 0.6 mm (see Fig. 2a). In series S2, after a similar initial behavior (when compared with S3 series), the slip-rate increase was much lower in the second stage. In this series the specimens did not fail after being submitted to a 3 million of cycles.

As shown in Table 1, the stress levels adopted for both series S2 and S3 were quite close. In spite of that, fatigue failure was only observed in the S3 series. In order to clarify this different behavior, the local bond stress-slip relationship $\tau - s$ was assessed by applying an analytical-numerical strategy, based on the experimental results obtained in series S1 (Sena-Cruz and Barros, 2004). The F_l-s_l analytical-numerical response calibrated from S1 average experimental F_l-s_l curve is plotted in Fig. 2a. It is possible to observe that the implemented numerical strategy was able to predict the F_l-s_l response with good accuracy. Based on this simulation, it can be concluded that for an applied load of 50% (S2) and 60% (S3) of F_p, 74.3% and 84.4% of the total bond length is effective, respectively. During the fatigue test, as the effective bond length (closer to the loaded end) is becoming damaged by the fatigue cycles, the stresses shift to the undamaged zone of the total bonded length (closer to the free end). Although the stress transfer process occurred in an identical way for both series (S2 and S3), since the applied stress level in series S3 was higher than in S2, it probably led to a faster bond degradation and, consequently, to the corresponding failure.

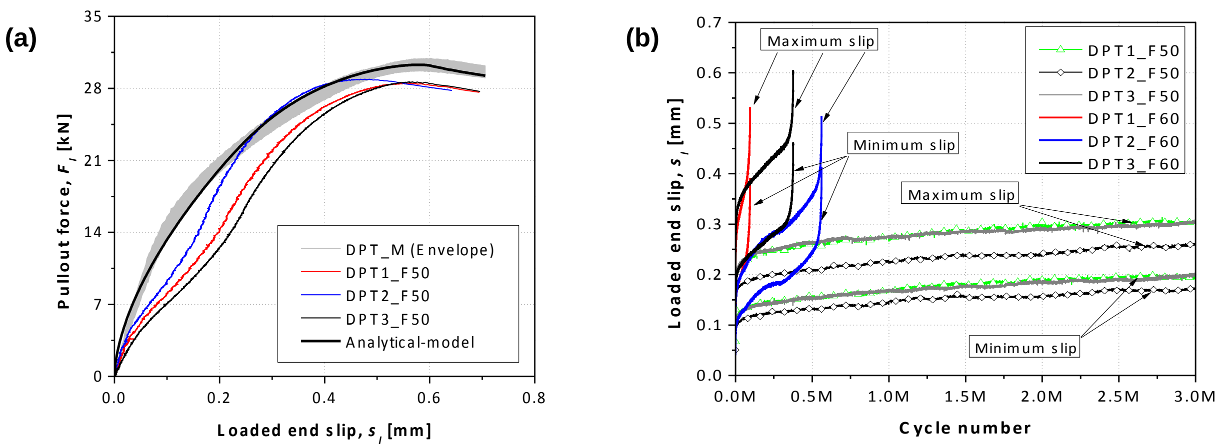

Fig. 2 – (a) F_l-s_l responses under monotonic loading and numerical inverse analysis; (b) Loaded end slip *versus* number of cycles.

As mentioned above, after the fatigue tests, all the pullout specimens that did not fail by fatigue (S2 series) were loaded monotonically up to failure. The post-fatigue F_l-s_l monotonic responses are presented in Fig. 2a. Table 1 also includes the average F_p obtained in the post-fatigue monotonic tests. In terms of bond performance, as expected, the fatigue loading caused a significant reduction in the initial bond stiffness, which leads to the conclusion that the fatigue loading damaged the system (Fig. 2a). It can be observed that, in comparison to series S1, the maximum pullout force had a slight decrease of about 6% (in terms of average values), and the loaded end slip was not influenced by the fatigue load. In general, with exception of the reduction in terms of initial bond stiffness, the overall bond behavior was not much affected by the stress level applied in the S2 series.

3.2. Slab specimens

Fig. 3a presents the evolution of the midspan deflection of SL specimens according to the number of load cycles. During the fatigue tests some technical problems occurred (overheating of the servo-controlled system), which induced deflection discontinuities for the slabs SL_STR_F70 and SL_STR_80. During the fatigue tests, the slab SL_UN_F75 (unstrengthened slab) recorded an increase of midspan deflection between the first and last cycle of approximately 8%, while for the strengthened slabs, the increment was about 6%, in spite of SL_STR_F80 has been submitted to a higher fatigue level. The deflection increase may be attributed to the bond degradation between steel and concrete, as well as between CFRP and concrete.

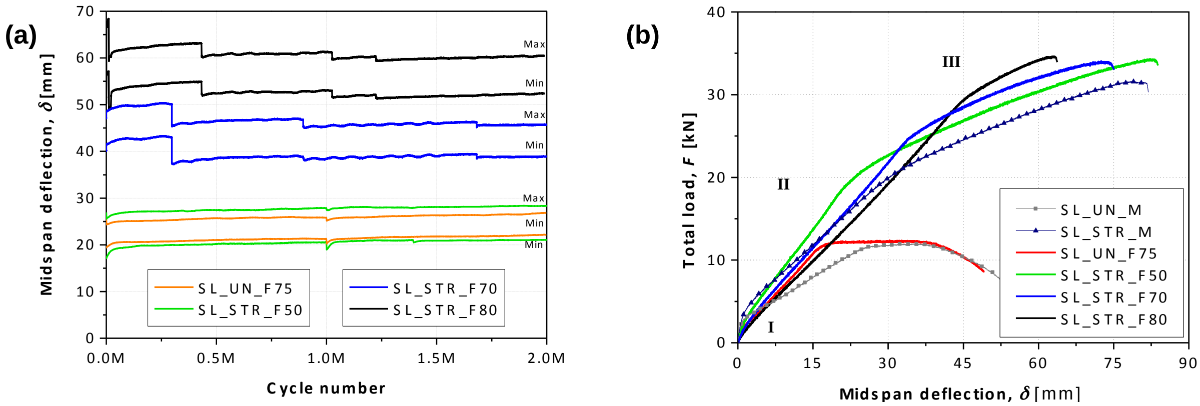

Fig. 3 – (a) Midspan deflection *versus* cycle number; (b) Total load *versus* deflection relationship of the tested slabs under monotonic loading.

During the fatigue cycles the evolution of the stiffness of the slabs was also evaluated. This stiffness was calculated as the slope of the line defined between the lower and the upper points of the load–deflection curve of a complete cycle. Based on the results forwarded in the 2nd column of Table 2, it is possible to observe a slight reduction of the stiffness between the first and the last cycle of the fatigue tests. It is clear that the unstrengthened slab experience the highest stiffness degradation (at about 14%). As expected, when the fatigue limits increase, the stiffness degradation also increases. The slabs did not fail after have been submitted to 2 million fatigue cycles. In the pullout tests that failed by fatigue, the CFRP laminate strips were submitted to a strain level of about 0.79% (DPT_F60 series), while for the slab SL_STR_F80 (worst case) the measured CFRP strain has ranged between 0.84% at midspan and 0.04% at the extremity. This very low CFRP strain level at the extremities can justify why the slabs did not fail by fatigue.

Table 2 – Results of the slabs submitted to the fatigue loading.

	Fatigue test		**Post-fatigue monotonic test**	
Slab ID	**(δ_f - δ_i)/δ_i** [%]	**(K_f-K_1)/K_1** [%]	**F_{max}** [kN]	**K_{II} / K_M**
SL_UN_F75	7.93	13.7%	12.41 (3.1%)	1.74
SL_STR_F50	6.58	2.0%	34.32 (8.5%)	1.42
SL_STR_F70	6.37	3.6%	34.06 (7.7%)	1.22
SL_STR_F80	6.05	7.2%	34.64 (9.5%)	1.11

Notes: δ_i = deflection registered at the first fatigue cycle; δ_f = deflection registered at the last fatigue cycle; K_1 = stiffness at the first fatigue cycle; K_f = stiffness at the last fatigue cycle; K_{II} = stiffness at stage II in the post-fatigue test; K_M = stiffness at stage II of a specimen without being submitted to the fatigue test.

Fig. 3b presents the relationship between the applied load and deflection at midspan for all the slabs obtained from the post-fatigue tests. Comparing these slabs (F series) with the corresponding control ones (SL_UN_M and SL_STR_M), an increase in terms of maximum force (F_{max}), as well as stiffness (K_{II})

at the stabilized cracked stage is observed. This better behavior was observed in previous research works, such as those reported by Yost *et al.* (2007) and Sena-Cruz *et al*. (2012). The increase of the K_{II} may be justified by the hardening behavior of the steel reinforcement during the fatigue cycles.

Finally, it is remarked that the main failure mode observed in the slabs submitted to the post-fatigue monotonic tests (as well as in the SL_UN_M and SL_STR_M slabs) was concrete crushing.

4. Conclusions

This paper presented an experimental study on bond and flexural behavior of concrete elements strengthened with NSM CFRP laminate strips under fatigue loading, through direct pullout tests (DPT) and load tests on slab specimens (SL).

From the bond pullout tests, it was observed that debonding failure at adhesive/laminate interface occurred for a maximum fatigue stress level of about 60%. For a maximum fatigue stress level of about 50% the specimens did not fail after had been submitted to 3 million of cycles. Progressive and continuous loss degradation in terms of bond stiffness was observed, for both fatigue load levels studied.

Regardless the stress level of fatigue loading, the strengthened slabs presented a lower decrease in terms of midspan deflections and stiffness than the unstrengthened slab at the end of 2 million of cycles. After fatigue loading, the slabs were submitted to the monotonic tests, and an increase of about 8% of ultimate load and stiffness was observed. Therefore it can be concluded that the damage accumulation due the fatigue cycles did not affect the ultimate capacity of the strengthened NSM CFRP slabs.

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