FRP-CONCRETE DEBONDING: EXPERIMENTAL TESTS UNDER CYCLIC ACTIONS

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ABSTRACT
External bonding of fibre reinforced polymer (FRP) composites has become a popular technique used worldwide for strengthening existing reinforced concrete structures. A key factor for the effectiveness of such technique is the bond of FRP reinforcement to the concrete substrate; numerous experimental works have been carried out to investigate such aspect. In particular, different test set up layouts, namely single shear test, double shear test and beam test, respectively, have been used to determine the maximum force which can be carried out by external reinforcement, the bond stress–slip relationship and the fracture energy of the interface law.
However, experimental data concerning cyclic tests on both FRP sheets or plates applied on concrete specimens are still lacking. Thus a series of Single Shear Test (SST) under both monotonic and cyclic actions, without inversion of sign, have been performed on concrete prismatic specimens (characterized by a low compressive strength in order to simulate the application on existing structures to be strengthened) reinforced with CFRP sheets and plates. In order to evaluate and compare the influence of cyclic external actions on the bonding behaviour of both sheets and plates reinforcements, the monotonic and cyclic tests results have been reported and analyzed in the paper in terms of force-displacement curves, axial strains and shear stresses recorded during the tests along the FRP reinforcement; the influence of the load path on the FRP debonding behaviour has been also examined.

KEYWORDS: FRP, cyclic, reinforcement, bond, experimental test

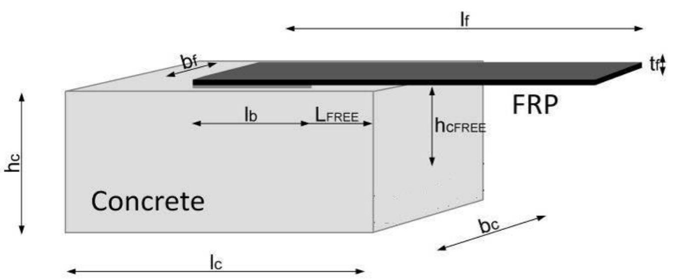
1. INTRODUCTION

The flexural strength of reinforced concrete (RC) members can be significantly increased by externally bonded FRP sheets and plates (referred in the following as "laminates" for brevity). Thus such strengthening method has become very popular around the world over the past decade, due to the well-known advantages of FRP composites over other materials such as their high strength/stiffness-to-weight ratio and excellent corrosion resistance.
Ideally, an RC beam strengthened with an FRP laminate (i.e. FRP-plated beam) should fail by either crushing of the compressive concrete or tensile rupture of the FRP. In reality, debonding of the FRP laminate from the concrete substrate controls the FRP failure in most cases, unless appropriate local measures are taken to prevent it. In order to avoid debonding failure, that is very brittle, it is essential a fundamental understanding of FRP bonding behavior: several theoretical scientific contributions have been proposed by researchers in the last years concerning both the behavior of FRP-to-concrete interface and the evaluation of the interface stresses ([1],[2],[3],[4],[5],[6],[7],[8]); moreover many experimental tests have been carried out for evaluating both bond strength and effective bonding length ([2],[9],[10],[12]), and the influence of different parameters on its value (FRP stiffness [11], FRP width [2],[10] and FRP bond length [1],[9],[10],[11], as well as concrete compressive strength [1],[10] and surface treatments [9],[4]). Both theoretical and experimental contributions allowed the development of design guidelines and codes ([13],[14],[15],[16]). Such guidelines are based mainly on the results of monotonic bonding tests, while many strengthened structures are subjected to fatigue loads (i.e. roads and railways bridges) or to shorter but more intense cyclic actions as seism: in this cases, the FRP-concrete interface is subject to cyclic stress regimes which can lead to premature debonding failure. In order to avoid that and to develop a more economical design for FRP-strengthened structures, the investigation on the influence of the cyclic external actions on the bond of the FRP reinforcements to the concrete substrate is essential. Thus

some researchers have recently began to investigate the fatigue performance of the FRP-concrete interface ([6],[17],[18]). Nevertheless, at present, the bonding tests under cyclic actions performed on CFRP sheets applied on concrete blocks are not so numerous as monotonic ones and particularly lacking are the cyclic tests performed on CFRP plates. Thus a series of SST tests under both monotonic and cyclic actions, without inversion of action sign, have been carried out and presented in the paper; the experimental outcomes allowed to compare the bonding behavior of sheets and plates at the FRP-to-concrete interface under monotonic and cyclic actions; the influence of different load paths are also herein analysed and discussed.

2. EXPERIMENTAL CAMPAIGN

The experimental activity consisted in bonding tests on CFRP sheets and plates applied on concrete prisms. In particular 12 SST tests were performed on FRP laminates applied on two opposite longitudinal faces of six concrete prisms made up with the same nominal dimensions: width b_c = 150mm, height h_c = 200mm and length l_c = 500mm. Further geometrical dimensions of the specimens are reported in Figure 1: h_{cFREE} = 50mm is the height of the concrete free edge ($h_{cFREE} = h_c - h_b$ where h_c is the height of concrete prism and h_b is the height of the support block), l_b = 400mm is the bond length, L_{FREE} = 100mm is the length of FRP left un-bonded, b_f = 100 mm and b_f= 50mm are the FRP widths of sheets and plates respectively, t_f= 0.166 mm and t_f= 1.4 mm are the corresponding thicknesses.



h_c [mm]	200
b_c [mm]	150
l_c [mm]	500
l_f [mm]	650
l_b [mm]	400
l_{FREE} [mm]	100
$h_{c,FREE}$ [mm]	45

Figure 1. Concrete prisms and FRP reinforcements dimensions

The concrete prisms aggregate was characterized by a maximum diameter D_{max} = 31.5 mm and consistency class S3. Concrete mix design was specifically designed in order to obtain low compressive concrete strength to better simulate the FRP application on the existing structural members that need to be strengthened. Compressive tests were performed on 14 specimens at 28 days after the casting: the cylinder mean strength was f_{cm} = 23.82 MPa.
CFRP Young's moduli provided by the manufacturer were E_f = 230000 MPa and E_f = 170000 MPa for sheets and plates respectively and the ultimate strains was ε_u = 2% for both. Before the application of FRP reinforcement the concrete surface was preliminarily treated by both sand paper, in order to eliminate the mortar till the aggregate became clear, and primer to consolidate the concrete surface.
Tests were carried out under a servo-hydraulic testing machine (MTS810) at the laboratory of the Department of Structural Engineering (DIST) of the University of Naples Federico II.
Metallic tabs were installed at the end of FRP reinforcement in order to guarantee an adequate clamping in the test machine grip. To block the specimen in the machine a steel frame was designed; test setup scheme is reported in Figure 2. Several strain gauges were applied along the FRP laminates in order to measure axial strains during the bonding test.
Each test has been identified by a label "XY_n": X indicates the type of reinforcement (P=Plate; S=Sheet), Y indicates the type of action (M=Monotonic; C=Cyclic), n is the progressive test number.
Tests on concrete specimens reinforced by CFRP plates (PM_1, PM_2, PM_3) and sheets (SM_1, SM_2, SM_3) were performed under displacement control (0.001mm/s, and 0.003mm/s respectively - see Table 1). Once the mean debonding load value, $P_{max,M}$, was determined through monotonic tests on both types of reinforcement, different cyclic load paths have been adopted. In particular:

- One test (PC_4) was performed with 3 series of five cycles of load-unload starting from 15% of $P_{max,M}$

up to 30, 50 and 70% of $P_{max,M}$ respectively.

- Four tests (PC_5, PC_6, SC_4 and SC_5) were performed with 4 series of 10 cycles of load-unload starting from 15% of $P_{max,M}$ up to 30, 50, 70 and 90% of $P_{max,M}$ respectively.
- One test (SC_6) was performed with 300 cycles of load-unload between 70% and 90% of $P_{max,M}$.

Cyclic actions were provided in a force control; each cyclic test ended with a final monotonic reloading step starting from 15% of $P_{max,M}$ up to failure under displacement control. Cyclic load paths are summarized in Table 1.

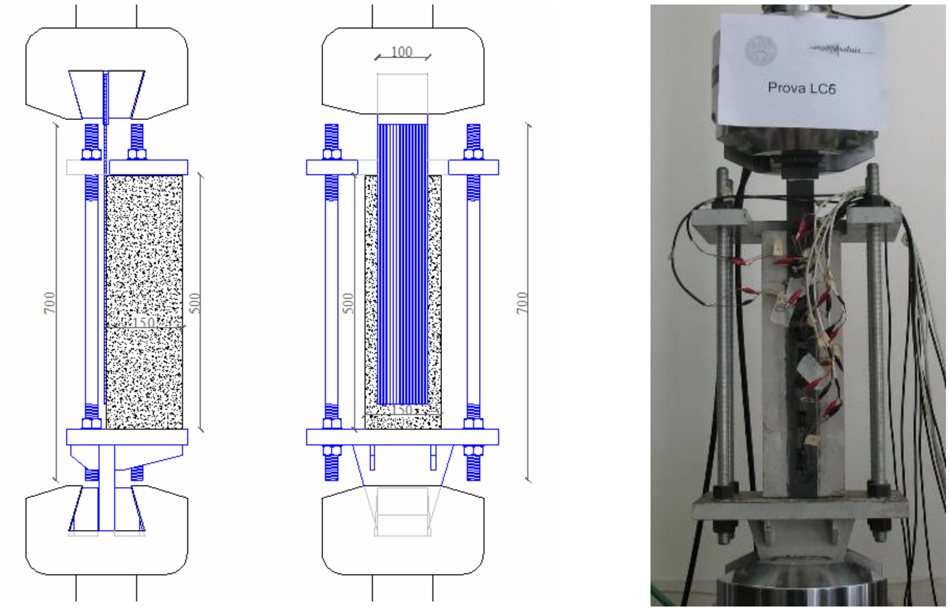


Figure 2. Test setup layout.

Table 1 – Tests load paths

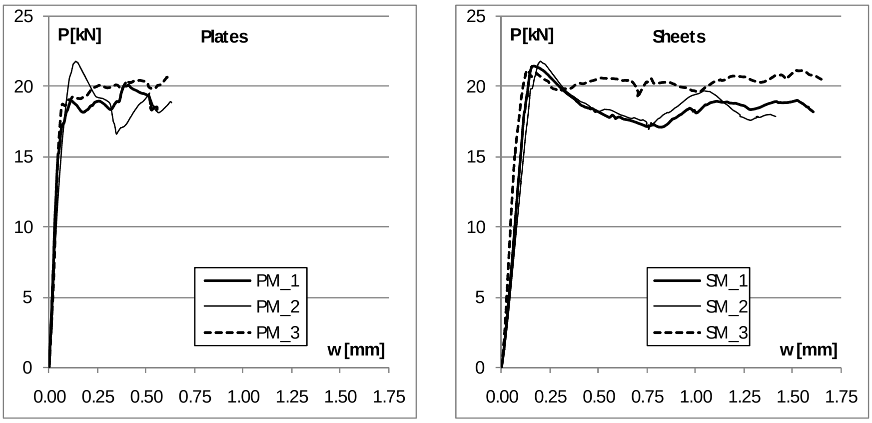
	Test	Actions	Cycles details
PLATES	**PM_1** **PM_2** **PM_3**	**Monotonic** up to failure	-
	PC_4	**15** cycles up to **70% $P_{max,M}$** + monotonic reloading	**5** cycles: **15 - 30**% of $P_{max,M}$ **5** cycles: **15 - 50**% of $P_{max,M}$ **5** cycles: **15 - 70**% of $P_{max,M}$ + **15**% of $P_{max,M}$ - **failure**
	PC_5 **PC_6**	**40** cycles up to **90% $P_{max,M}$** + monotonic reloading	**10** cycles: **15 - 30**% of $P_{max,M}$ **10** cycles: **15 - 50**% of $P_{max,M}$ **10** cycles: **15 - 70**% of $P_{max,M}$ **10** cycles: **15 - 90**% of $P_{max,M}$ + **15**% of $P_{max,M}$ - **failure**
SHEETS	**SM_1** **SM_2** **SM_3**	**Monotonic** up to failure	-
	SC_4 **SC_5**	**40** cycles up to **90% $P_{max,M}$** + monotonic reloading	**10** cycles: **15 - 30**% of $P_{max,M}$ **10** cycles: **15 - 50**% of $P_{max,M}$ **10** cycles: **15 - 70**% of $P_{max,M}$ **10** cycles: **15 - 90**% of $P_{max,M}$ + **15**% of $P_{max,M}$ - **failure**
	SC_6	**300** cycles up to **90% $P_{max,M}$** + monotonic reloading	**300** cycles: **70 - 90**% of $P_{max,M}$ + **15**% of $P_{max,M}$ - **failure**

3. TEST RESULTS

In the following paragraphs the main experimental results are reported with reference to both monotonic and cyclic tests: in particular, for each test the first debonding load, P_{fd}, that identified the beginning of debonding phenomenon, the maximum load recorded during the test, P_{max}, and the mean load value P_{dm} obtained as the mean of local pick load values recorded after P_{fd} are reported. Furthermore the ultimate displacement w_u, and the experimental axial strains ε recorded throughout the FRP reinforcement are also examined.

3.1. Monotonic tests on Plates (PM_1, PM_2, PM_3) and Sheets (SM_1, SM_2, SM_3)

The experimental load-displacement relationships related to FRP plates and sheets reinforced specimens are shown in Figure 3(a) and Figure 3(b); the displacements, w, were computed with reference to the loaded extremity of the CFRP laminate (by integrating the strain recorded along the reinforcement). As concerns the behavior of plates reinforced specimens, it is possible to observe a substantially equal slope of the load-displacement curves in the first loading phase to a value of about 6kN; once such load value was achieved, a different slope of curve related to specimen PM_2 was observed. Proper on such specimen, it was recorded the maximum first debonding load equal to P_{fd} = 21.78 kN, slightly larger than those recorded on the other two specimens, P_{fd} = 18.99 kN and P_{fd} = 19.18 kN for PM_1 and PM_3, respectively. The displacement corresponding to the debonding load, w_{fd}, was equal to about 0.14 mm for PM_2 and 0.11 mm and 0.12 mm for PM_1 and PM_3, respectively. With reference to sheets reinforced specimens, it is possible to observe a substantially equal slope of the load displacement curves up to the first debonding load values P_{fd} that is equal to about 21.5 kN. The displacements corresponding to the debonding load, w_{fd}, achieved a mean value equal to about 0.14mm.



(a) (b)

Figure 3 – Experimental load-displacement relationships: Plates (a), Sheets (b).

On both plates and sheets tests, once P_{fd} was achieved the P-w relationships showed a pseudo-constant trend, up to the ultimate displacement w_u rather different for plates and sheets (the mean values were w_u=0.60mm and w_u=1.56mm respectively). In the range w_{fd}-w_u the load value achieved different peak values due to the transfer of the effective bond length along the wide bonded zone of FRP with a mean load P_{dm}, equal to 19.76 kN and 19.84 kN on average for plates and sheets respectively, and a maximum peak, P_{max}, equal to 20.86 kN and 21.49 kN. The main experimental results are summarized in Table 2.

Table 2 – Monotonic tests results

Test		P_{fd} [kN]	$P_{fd,M}$ [kN]	P_{max} [kN]	$P_{max,M}$ [kN]	P_{dm} [kN]	$P_{dm,M}$ [kN]	w_{fd} [mm]	$w_{fd,M}$ [mm]	w_u [mm]	$w_{u,M}$ [mm]
Plates	**PM_1**	18.99	19.98	20.10	20.86	19.40	19.76	0.11	0.12	0.56	0.60
	PM_2	21.78		21.78		19.79		0.14		0.63	
	PM_3	19.18		20.71		20.09		0.12		0.61	
Sheets	**SM_1**	19.18	21.49	21.41	21.49	19.30	19.84	0.10	0.14	1.61	1.56
	SM_2	21.81		21.81		19.45		0.20		1.42	
	SM_3	21.24		21.24		20.78		0.13		1.65	

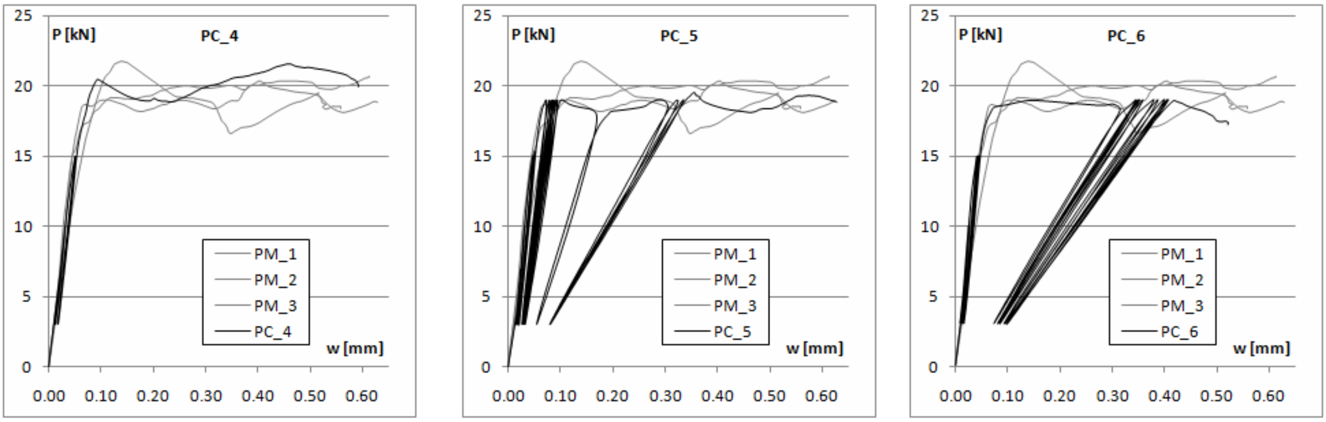
Finally, it is noted that all tested specimens failed due to debonding in concrete (DB-C) referring to failure type classification reported in Teng et al. [10]. This failure type clearly assessed the quality of bond between FRP and concrete substrate obtained through the installation procedure adopted during the FRP application.

3.2. Cyclic tests on plates (PC_4, PC_5, PC_6)

The first test in presence of cyclic action PC_4 was performed with an initial series of 5 cycles between 3kN and 7kN (respectively about 15% and 30% of $P_{max,M}$). Observing the P-w diagram reported in Figure 4 (a) (in which P-w curve of PC_4 test is reported in bold and compared with those related to monotonic tests PM_1, PM_2 and PM_3) it is clear that between 15% and 30% of $P_{max,M}$ load levels the FRP-concrete interface behavior was still elastic even if negligible residual displacements, Δ, were recorded after each load cycle. A second series of 5 load cycles between 3kN and 10kN (i.e. 50% of $P_{max,M}$) and between 3kN and 15 kN (i.e. 70% of $P_{max,M}$) were then performed. For these cycles, residual displacements Δ larger than first ones were recorded; in particular they ranged between 0.3‰ and 0.4 ‰ of the mean ultimate displacement $w_{u,M}$ achieved during monotonic tests. The test ended with a monotonic load path starting from a load value of 3kN (i.e. 15% of $P_{max,M}$) up to the failure load. During such step the bonding behavior observed was very similar to that observed during the monotonic tests: the first debonding load was not influenced by cyclic actions; its value P_{fd} = 20.01 kN was very similar to the mean $P_{fd,M}$ = 19.98 kN value recorded during monotonic tests. The maximum load value, P_{max}, and the ultimate displacement, w_u, were also slightly affected by cycles (see Table 3).

Table 3 – Cyclic tests results

Test		P_{fd}	P_{max}	P_{dm}	w_{fd}	w_u
		[kN]	[kN]	[kN]	[mm]	[mm]
Plates	**PC_4**	20.01	21.55	20.50	0.06	0.56
	PC_5	19.00	19.49	19.00	0.35	0.63
	PC_6	18.47	19.01	18.68	0.39	0.52
Sheets	**SC_4**	20.96	21.69	20.64	0.21	1.86
	SC_5	20.45	20.74	20.16	0.20	1.75
	SC_6	20.14	22.11	20.72	0.42	1.81

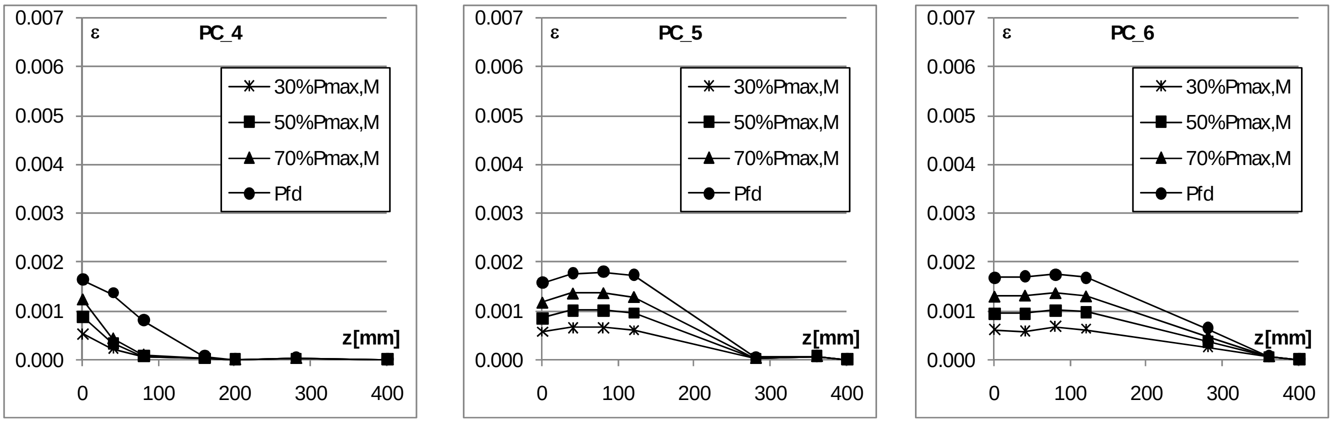


(a) (b) (c)

Figure 4 - Experimental load-displacement relationships: a) Test PC_4; b) Test PC_5; c) Test PC_6

Based on such results, two further tests, PC_5 and PC_6 (see Figure 4 (b) and Figure 4(c)) characterized by the same load path (see Table 1), were performed: ten instead of five was the number of cycles for each series and 90% $P_{max,M}$ instead of 70% $P_{max,M}$ the maximum load value achieved during the cyclic phase of the test. The first series of 10 load-unload cycles was between 3kN e 7kN, approximately equal respectively to the 15% and the 30% of $P_{max,M}$: for these levels of load the FRP-concrete interface behavior was elastic and the residual displacements were negligible. No visible cracks were observed during cyclic series between 15 and 50% of $P_{max,M}$ and between 15 and 70% of $P_{max,M}$ but residual displacements, Δ, were recorded after each cycle. During the last series of 10 load-unload cycles between 3 and 19kN (i.e. 90% of $P_{max,M}$) the large displacements at FRP-concrete interface denoted the beginning of the debonding phenomenon with the formation of cracks, visible to the naked eye, along the lateral edges of FRP plates. It is important to remark that the clear debonding phenomenon recorded during the last series of cycles happened after the fifth cycle between 15% and 90% of $P_{max,M}$ during the PC_5 test and the first cycle between 15% and 90% of $P_{max,M}$ during the PC_6 test. By a comparison with the counterpart monotonic values (Table 2) resulted that the cyclic action did not affect significantly the ultimate displacement, but reduced the debonding load value of about 10%.

Local behavior of FRP-to-concrete interface was analyzed by plotting the profiles of the experimental axial strains measured during the test along the FRP reinforcement; in particular Figure 5 shows the experimental strains recorded at four different load values (at 30%, 50% and 70% of $P_{max,M}$, and at P_{fd}) in the monotonic final reloading phase of cyclic tests performed on plates (PC_4, PC_5, PC_6). Consistently with what observed by analyzing the P-w relationships, the cyclic action imposed up to 70% of $P_{max,M}$ value did not affect particularly the interface behavior as shown in Figure 5 (a). On the contrary, by observing the strains profiles of Figure 5 (b) and (c), referred to the cyclic tests PC_5 and PC_6, it is clear that the cyclic action imposed up to 90% of $P_{max,M}$ caused a premature debonding: in the wide zone of debonded FRP reinforcement the strains profiles assumed a constant trend. Moreover, during the cyclic phases of the test, the FRP wide bond length (L_b = 400mm), larger than effective one (about 240mm according to CNR-DT200/2004 [15]), allowed a transfer of the interface stresses from initially loaded zones to unloaded ones and thus to sustain the cyclic nature of the imposed action.



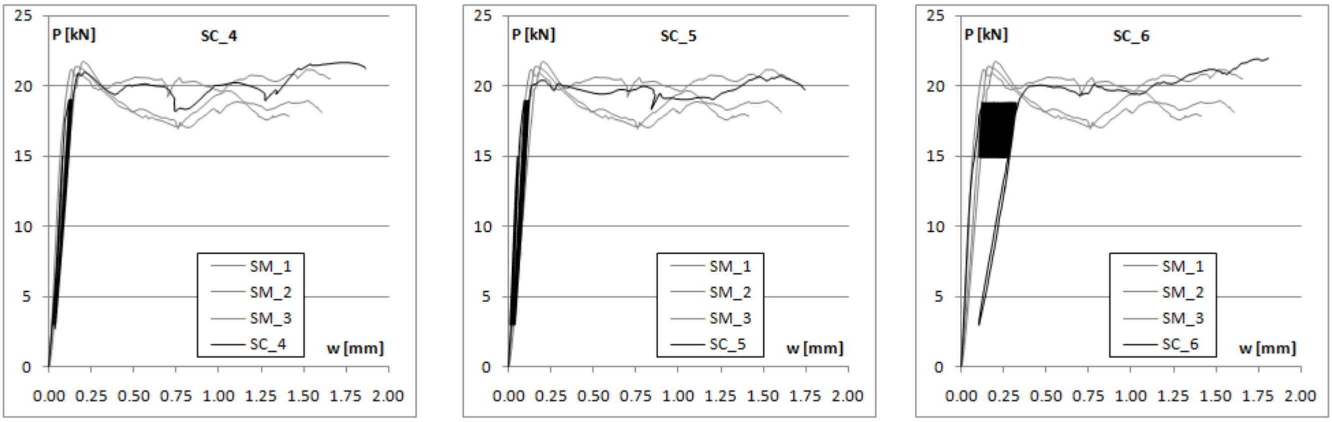
(a) (b) (c)

Figure 5 - Experimental strains: a) Test PC_4; b) Test PC_5; c) Test PC_6

3.3. Cyclic tests on sheets (SC_4, SC_5, SC_6)

In order to compare the experimental results between plates and sheets, two tests on sheets (SC_4 and SC_5) were performed adopting the same load path followed during tests PC_5 and PC_6 (see *Table* 1). The P-w relationships are reported in bold and compared to the counterparts monotonic SM_1, SM_2 and SM_3 in Figure 6(a) and in Figure 6(b): negligible residual displacements at the FRP-to-concrete interface were recorded after each cycle up to 70% of $P_{max,M}$. On the other hand, residual displacements recorded during the last series of cycles were more meaningful (the mean value of the two tests was about 0.0095mm – 0.60‰ of $w_{u,M}$) and comparable with those recorded on plates. Tests ended with a monotonic reloading path from 3kN up to failure. The first debonding was observed during such phase and the P_{fd} load value was slightly lower than those recorded during monotonic tests (SM_1, SM_2 and SM_3). As opposed to the experimental outcomes of tests on plates (PC_5 and PC_6) neither values of P_{dm} and P_{max} nor ultimate displacements, w_u, were significantly affected by cyclic actions on sheet reinforced specimens (see Table 3).

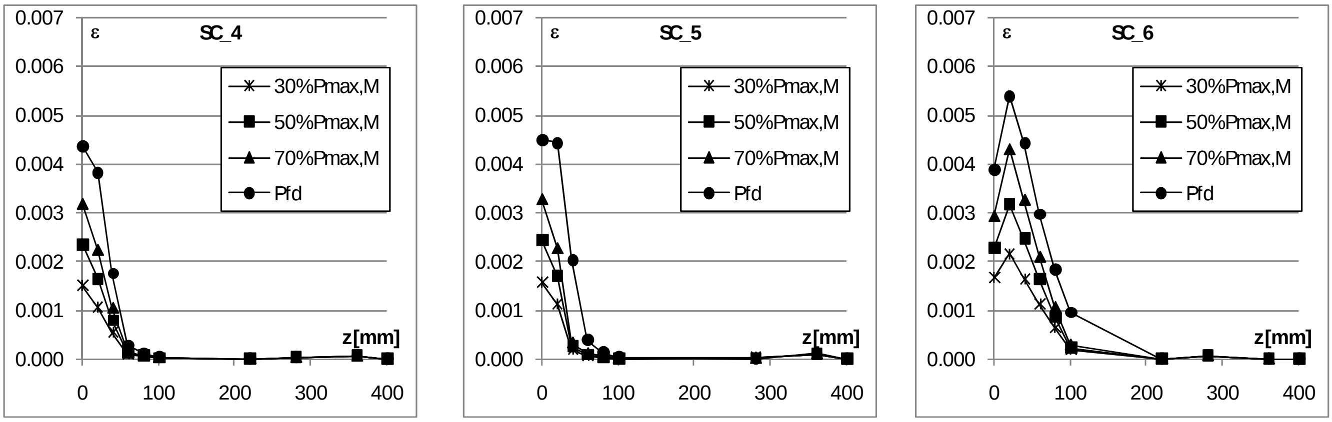
In order to investigate the influence of the number of cycles on the bonding behavior, the load path of the SC_6 test (see Table 1) was substantially different from the other cyclic tests: 300 load-unload cycles between 15kN (about 70% of $P_{max,M}$) and 19kN (about 90% of $P_{max,M}$) were imposed. The test ended with a monotonic reloading path from 15% of $P_{max,M}$ to failure during which the maximum load value P_{max} = 22.11 kN and the ultimate displacement w_u = 1.81mm were recorded (see Figure 6 (c)). After each of the 300 cycles, residual displacements Δ were recorded and their values were influenced by the number of the load-unload cycles imposed: the highest residual displacement value was Δ_1 = 0.01120mm (0.718‰ of $w_{u,M}$) and the lowest one was Δ_{300} = 0.00043mm (0.276‰ of $w_{u,M}$) recorded after the first and the last of the 300 cycles respectively. Furthermore a mean residual displacement value was 0.0006mm (0.38‰ of $w_{u,M}$). No significant exterior damage has been recorded during the cyclic action except for a very little crack after about 130 cycles. The mean effect of the cyclic actions was the premature debonding at a load value equal to P_{fd} = 19 kN, about 10% less than $P_{fd,M}$ while neither substantially differences were observed in terms of P_{dm} and P_{max} nor in terms of ultimate displacements w_u (see Table 3).



(a) (b) (c)

Figure 6 - Experimental load-displacement relationships: a) Test SC_4; b) Test SC_5; c) Test SC_6

The strain profiles recorded on sheets reinforced specimens are reported in Figure 7. Also in this case the preliminary considerations provided by the P-w relationships were confirmed: the cyclic action imposed up to 90% of $P_{max,M}$ load value did not affect particularly the interface behavior (see Figure 7 (a) and (b) related to SC_4 and SC_5 tests respectively). On the other hand, by observing the strain profiles referred to SC_6 test performed with 300 cycles between 70% and 90 % of $P_{max,M}$ (see Figure 7 (c)) the effect of the increased number of cycles is significant: for a given value of load, the experimental strains were larger than those recorded in SC_4 and SC_5 tests as consequence of the premature debonding occurred at a load value equal to 19 kN, about 10% less than $P_{fd,M}$.



(a) (b) (c)

Figure 7 - Experimental strains: a) Test SC_4; b) Test SC_5; c) Test SC_6

4. CONCLUSIONS

At present, the bonding tests under cyclic actions performed on CFRP sheets applied on concrete blocks are not so numerous as monotonic ones; particularly lacking are the cyclic tests performed on CFRP plates. Thus a series of cyclic SST bonding tests under both monotonic and cyclic actions, without inversion of action sign, have been performed in order to provide a preliminary investigation on the influence of cyclic external actions on the bond between FRP reinforcement and concrete substrate. The experimental outcomes indicated that:

- the influence of load-unload cycles up to 70% of $P_{max,M}$ was negligible for CFRP sheets and plates;
- a low number of load-unload cycles (40) up to 90% of $P_{max,M}$ reduced the debonding load of about 10% in the case of CFRP plates, but did not affect particularly the bonding behaviour of CFRP sheets;

- by increasing the number of load-unload cycles (up to 300) between 70% and 90% of $P_{max,M}$, the debonding load of concrete specimens reinforced with CFRP sheets decreased by a percentage factor equal to 10%.
- the transfer of shear stresses at the FRP-to-concrete interface due to the CFRP reinforcement bond length larger than effective one, allowed to mitigate noticeably the effect of cyclic actions imposed up to 90% of $P_{max,M}$.
- the effects of cyclic actions were more significant on plates rather than sheets and its influence increased with number of cycles.

The data collected by the cyclic bonding tests represent only preliminary results; however, they could provide a reference database to the development and calibration of mathematical models accounting also for the effect of cyclic external actions.

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REFERENCES

[1] Faella C., Martinelli E., Nigro E., (2003), Interface Behaviour in FRP Plates Bonded to Concrete: Experimental Tests and Theoretical Analyses, *Proceedings of the 2003 ECI Conference on Advanced Materials for Construction of Bridges, Buildings, and Other Structures III, Davos (Switzerland), 7-12 September.*

[2] K. Brosens D. Van Gemert, L. Vandewalle (2001). Anchorage of externally bonded steel plates and CFRP laminates for the strengthening of concrete elements. *Faculteit Toegepaste Wetenschappen, Katholieke Universiteit Leuven*

[3] Z. G. Guo, S. Y. Cao, W. M. Sun, X. Y. Lin (2005). Experimental study on bond stress-slip behaviour between FRP sheets and concrete. *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures*.

[4] L. De Lorenzis, B. Miller, A. Nanni (2001). Bond of Fiber-Reinforced Polymer Laminates to Concrete. *ACI Materials Journal*. **98-M29,** 256-264.

[5] Faella C., Martinelli E., Nigro E., (2007). Direct versus Indirect identification of FRP-to-concrete interface relationships, *Asia-Pacific Conference on FRP in Structures. Hong Kong (China), 12-14 December 2007*.

[6] Nigro E., Di Ludovico M., Bilotta A. (2008). Fourth International Conference on FRP Composites in Civil Engineering (CICE2008) 22-24 July 2008, Zurich, Switzerland.

[7] Lu, X.Z., Teng, J.G., Ye, L.P and Jiang, J.J. (2005), Bond-slip models for FRP sheets/plates bonded to concrete. *Engineering Structures* 27(6), 920-937.

[8] Savoia M., Ferracuti B., Mazzotti C. (2003), Non linear bond-slip law for FRP-concrete interface. *Proceedings of the conference FRPRCS-6, Singapore.*

[9] M. Chajes, W. Finch, T. Januszka, T. Thomson (1996) Bond and force transfer of composite material plates bonded to concrete. *ACI structural journal*. **93-S19**, 208-217.

[10] J. Yao, J.G. Teng, J.F. Chen (2005) Experimental study on FRP-to-concrete bonded joints. *Composites: Part B Elsevier* **36**:99-113.

[11] C. Pellegrino , G. Boschetto, D. Tinazzi, C. Modena (2005). Progress on under standing bond behaviour in rc elements strengthened with FRP. *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures.* 7-9 December 2005, Hong Kong, China.

[12] L. Bizindavyi, K. W. Neale (1999) Transfer lengths and bond strengths for composites bonded to concrete *Journal of composites for construction*. 153-160

[13] B. Ferracuti, E. Martinelli, E. Nigro, M. Savoia (2007), Fracture Energy and Design Rules against FRP-Concrete Debonding, *Proceedings of FRPRCS-8 Conference*, *Patras (Greece), July 16-18,2007.*

[14] ACI 440.2R-02, (2002). *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, ACI440.2R-02 American Concrete Institute, Farmington Hills, MI, 2002, 92 pp.

[15] CNR-DT 200. (2004). *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening.*

[16] *fib*, (2001) *Externally Bonded FRP Reinforcement for RC Structures.* fib Bulletin 14, Technical Report prepared by the Working Party EBR of Task Group 9.3, International federation for Structural Concrete.

[17] L. Bizindavyi, K. W. Neale, M. A. Erki (2007). Experimental Investigation of Bonded Fiber Reinforced Polymer-Concrete Joints under Cyclic Loading. *Journal of composites construction ASCE*, 7:2 127-134.

[18] Diab H., Wu Z., Iwashita K. (2007). Experimental and numerical investigation of fatigue behavior of FRP-concrete interface. *Proceding of FRPRCS-8. Patras (Greece) - July 16-18,2007.*