

## Time-dependent bond behavior between NSM CFRP strips and concrete

Mohamed Emara<sup>1</sup>, Marta Baena<sup>1</sup>, Cristina Barris<sup>1</sup>, Lluís Torres<sup>1</sup>, Mohamed Moawad<sup>1</sup>, and Ricardo Perera<sup>2</sup>.

<sup>1</sup> AMADE, Universitat de Girona, Girona, Spain

<sup>2</sup> Universidad Politécnica de Madrid, Madrid, Spain

**ABSTRACT:** Although some studies have been carried out to understand the long-term bond performance of concrete structures strengthened with Near Surface Mounted (NSM) Fiber Reinforced Polymers (FRPs), which is being considered an important design aspect of safe design, there is still more effort required. This work presents an experimental campaign to investigate the effect of sustained load, bonded length and groove width on the time-dependent behavior of concrete strengthened with NSM CFRP strips. Single shear pull-out tests have been carried out. Both instantaneous and time-dependent slip values were found to be affected by the investigated parameters, and the increase of slip due to bond deterioration was more accentuated in those specimens loaded at 50% of sustained load than those at 25%.

### 1 INTRODUCTION

Near Surface Mounted (NSM) Fiber Reinforced Polymers (FRP) has been recognized as an efficient methodology for strengthening Reinforced Concrete (RC) members. NSM reinforcement is less prone to debonding from the concrete substrate when compared to other techniques. Bond controls the composite action between FRP and concrete and is considered the main factor governing the success of the strengthened system (De Lorenzis & Teng 2007; Coelho et al. 2015; Parvin & Shah 2016), greatly affecting its load carrying capacity.

An important design concern that may compromise the safety of strengthened structures is the long-term performance under service load. However, limited data concerning the long-term bond behavior between NSM FRP and concrete are available in the literature. Borchert and Zilch (2008) carried out an experimental program, studying the effect of adhesive properties on the long-term bond behavior of concrete blocks strengthened with NSM CFRP strips, in which a distinctive influence of the adhesive properties and the applied sustained load level on the long-term bond behavior was proved. Silva et al. (2014) performed an experimental program, concerning the long-term bond performance of concrete elements strengthened with NSM CFRP strips through beam tests, in which they found that the creep effect is practically negligible and the loaded end slip was mainly controlled by the laboratory temperature. Derias et al. (2008) studied the durability of RC beams strengthened with NSM CFRP strips. Sustained load equal to 40% of the ultimate load carrying capacity was applied. Some beams were subjected to high temperature and some other were left in room conditions. Results showed a deterioration in the epoxy-concrete interface and changes in failure modes due to the extreme environmental conditions.

From the literature review, it is seen that studies on the effect of sustained load on the behavior of NSM CFRP strengthened elements is very scarce, thus being an issue in which further research is still needed.

This paper presents results of an experimental program aiming at investigating the long-term bond behavior between NSM CFRP strips and concrete. Eighteen single shear pull-out specimens were subjected to sustained load for a period of 1000 hours. The main variables of the tests were the bonded length, the groove thickness and the sustained load level. Results in terms of bond-slip response are presented and discussed.

## 2 EXPERIMENTAL PROGRAM

### 2.1 Program description

Ready mixed concrete with a compressive strength of 32 MPa after 28 days from casting and tensile strength of 3 MPa, was used in this experimental program. The CFRP laminates used as NSM reinforcement, with the commercial name S&P laminates CFK 150/200, had the dimensions of 1.4 mm thickness and 10 mm width. The two component epoxy S&P 220 was used to bond the CFRP laminates to concrete. The tensile strength and modulus of elasticity of CFRP laminate were 2400 MPa and 160 GPa, respectively, while the epoxy adhesive presented a tensile strength of 20 MPa, and a modulus of elasticity of 7.3 GPa.

Eighteen concrete blocks of 200 mm x 200 mm x 250 mm (Figure 1) were prepared to be tested under single shear pull-out test (Figure 2). After casting, concrete specimens were left for curing for 28 days. Saw-cut grooves were introduced with 15 mm depth, then cleaned with compressed air and filled with resin. CFRP strips were covered with resin, introduced and centered into the groove. Finally, the surface was leveled. The short-term and long-term pull-out tests were carried out after curing the resin for 10 days in laboratory conditions (20 °C of temperature and 55% of relative humidity).

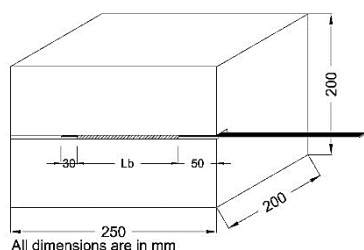


Figure 1. Test specimen configuration.

### 2.2 Short-term pull-out test

Six specimens were tested under single-shear pull-out test configuration (Figure 2) by applying a short-term monotonic loading with the aim of obtaining the failure loads, which were used to determine the sustained loads as a percentage of them. Three bonded lengths of 60 mm, 90 mm and 120 mm were used, being the groove dimensions of 5 mm thickness and 15 mm depth. Two identical specimens were tested for each bonded length. Specimens were tested under displacement controlled mode at rate of 0.2 mm/min using a servo-hydraulic testing machine.

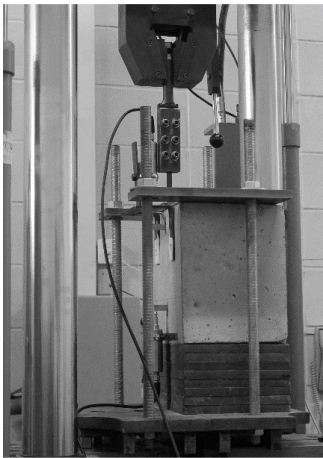


Figure 2. Pull-out test setup.

### 2.3 Sustained loading pull-out test

Specimens with different arrangements were grouped into three sets (Table 1), and tested under sustained loading. The first group was subjected to a sustained load of 25% of the failure load, while the second and the third were subjected to sustained load of 50% of the failure load. The groove width was 5 mm for the first and second groups, and 10 for the third. All test groups had specimens with bonded lengths of 60 mm, 90 mm and 120 mm. In Table 1, the first column contains the specimen identification, the second column indicates the bonded length of each specimen, the third column shows the applied sustained load level as a percentage of the maximum load, and the fourth column contains the groove width. Specimens' identification in the first column are as follows: the letter S is followed by the sustained load level (25% and 50%), then the letter L is followed by the bonded length (60mm, 90 mm and 120 mm), finally, the letter G is followed by the groove width (5 mm and 10 mm). Slip evolution with time was registered using LVDTs. The sustained load was applied by means of gravity loading systems based on lever-arms (see Figure 3). Specimens were kept loaded for 1000 hours.

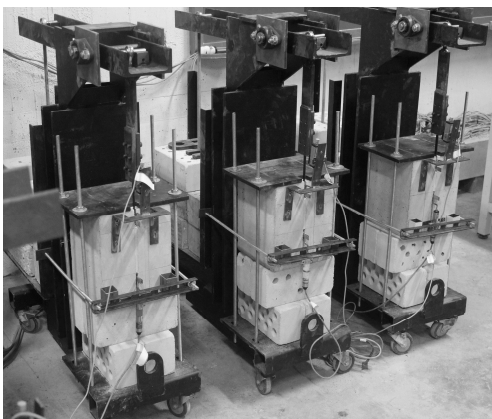


Figure 3. Sustained loading test setup.

Table 1. Test matrix configuration for sustained loading

Specimen	Bonded length (mm)	Sustained load level (%)	Groove width (mm)
S25L60G5	60	25	5
S25L90G5	90	25	5
S25L120G5	120	25	5
S50L60G5	60	50	5
S50L90G5	90	50	5
S50L120G5	120	50	5
S50L60G10	60	50	10
S50L90G10	90	50	10
S50L120G10	120	50	10

### 3 EXPERIMENTAL RESULTS AND DISCUSSION

#### 3.1 Short-term pull-out test results

Figure 4(a) shows the load vs. slip curves of specimens tested under monotonic loading up to failure. Similar behaviors, failure loads and failure modes were observed for specimens with bonded length ( $L_b$ ) of 90 mm and 120 mm, which can be attributed to the fact that the provided bonded length in both specimens was higher than the effective bonded length, this meaning that increasing  $L_b$  would not affect the load carrying capacity of the specimen. Specimens with  $L_b$  equal to 60 mm showed lower load capacity and different failure characteristics. The failure loads were 25 kN, 32 kN and 33 kN for specimens with  $L_b$  of 60 mm, 90 mm and 120 mm, respectively. Specimens with  $L_b$  of 90 mm and 120 mm failed with CFRP rupture while specimens with  $L_b$  of 60 mm failed with concrete crushing (see Figure 4(b)).

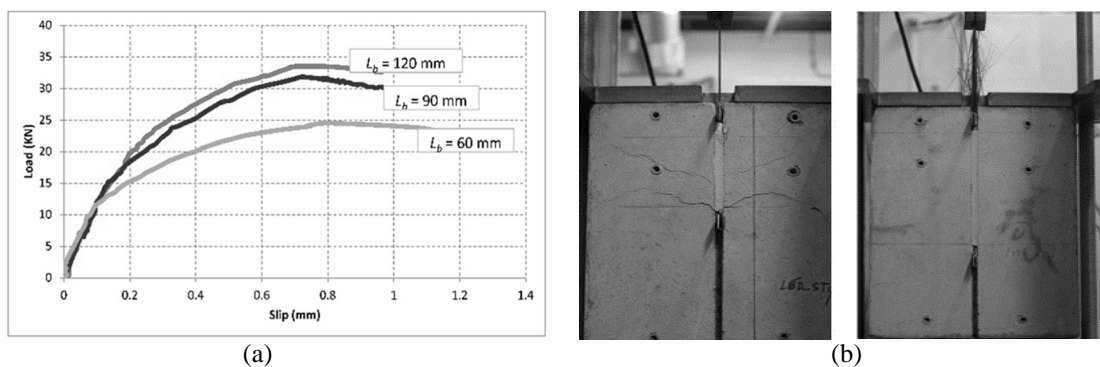


Figure 4. Short-term pull-out test results (a) Load v. slip curves and (b) Failure modes.

### 3.2 Sustained loading pull-out test results

Concerning the immediate slip (Figure 5), results show that the instantaneous displacement was influenced by bonded length, applied sustained load and groove width. When subjected to sustained load level of 25%, specimens S25L90G5 and S25L120G5 showed similar values of instantaneous displacement which was higher than specimen S25L60G5 by 70%, however, the observed values can be considered relatively low. The reason for it should be attributed to the low level of applied sustained stress. By increasing the sustained load level to 50%, the observed instantaneous displacements were similar for specimens S50L90G5 and S50L120G5 which were 40% higher than specimen S50L60G5, and 212% higher than similar specimens, S25L90G5 and S25L120G5, subjected to sustained load of 25%. On the other hand, increasing the groove width at a sustained load of 50% increased the instantaneous displacements by 40%, 26% and 28% for specimens with bonded length of 60 mm, 90 mm and 120 mm, respectively. This increase can be attributed to the increase of the adhesive thickness which may cause stress redistribution at the loaded end leading to more deformation in the adhesive layer. Specimens S50L90G10 and S50L120G10 showed instantaneous displacements which were 22 and 29%, respectively, higher than that for specimen S50L60G10 due to the application of higher load.

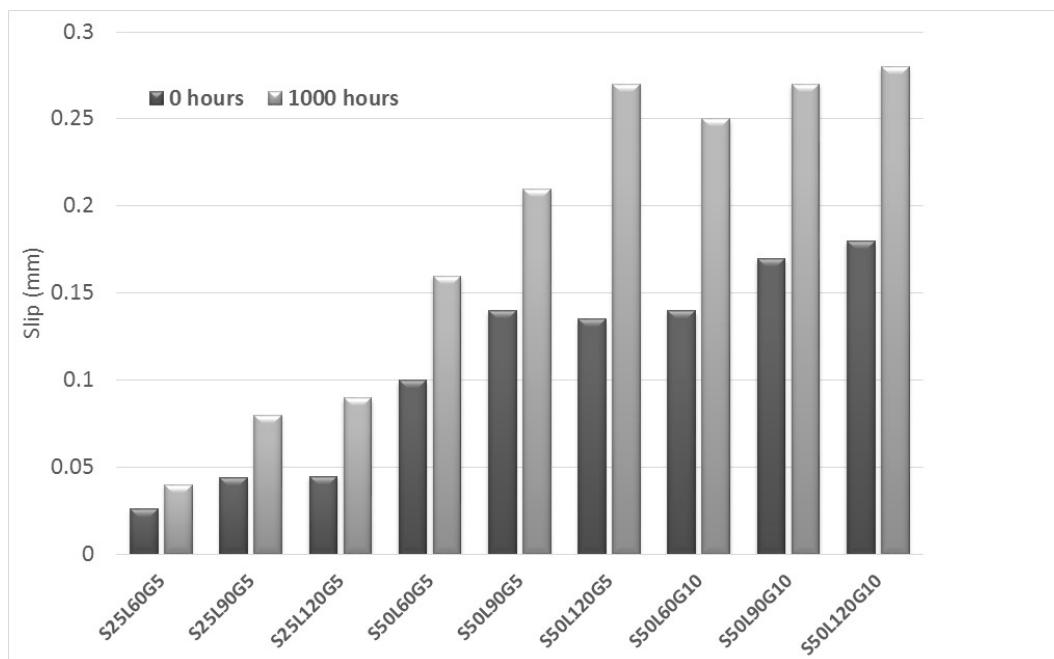


Figure 5. Slip at loading (0 hours) and after 1000 hours of loading

Concerning the long-term slip after 1000 hours (Figure 5), results show that at 25% of sustained load level specimens S25L90G5 and S25L120G5 showed similar behavior with 0.08 and 0.09 mm total displacement, respectively, which were 100% and 125% higher than specimen S25L60G5.

By increasing the sustained load to 50%, the displacements increased for all specimens as increasing the load caused more creep in the adhesive layer leading to more deformation. Also, it was observed that the longer the bonded length was, the more displacement was observed; for

example, specimens S50L90G5 and S50L120G5 (with bonded length 90 mm and 120 mm) showed total displacements 30% and 69 %, respectively, higher than specimen S50L60G5 which has a bonded length of 60 mm.

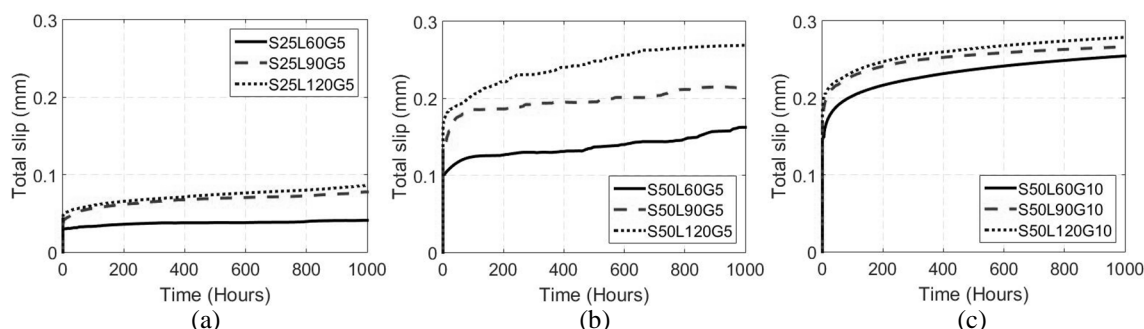


Figure 6. Total slip with time under (a) Sustained load 25%, (b) Sustained load 50% and (c) Sustained load 50% with wider groove.

At 50% of sustained loading, specimens S50L120G5 and S50L120G10 with bonded length of 120 mm started to behave in a similar way after 700 hours of loading (see Figure 6). In the case of bonded length 90 mm, specimen S50L90G10 showed total displacement 28% higher than specimen S50L90G5 after 1000 hours of loading. Higher increase was observed in case of bonded length 60 mm as specimen S50L60G10 showed a total displacement 56% higher than specimen S50L60G5. Increasing both the bonded length and groove width caused an increase in epoxy volume, which may have been the reason for the increase in creep displacement.

#### 4 CONCLUSIONS

Results of an experimental program concerning the long-term bond behavior between FRP NSM strips and concrete have been presented. Specimens were divided into three groups, in which the sustained load level, the bonded length and the groove width were introduced as the main parameters. The following conclusions can be derived from the analysis of results obtained from this limited number of tests: (i) both instantaneous and creep displacements showed dependence on the applied sustained load level, bonded length and the groove width; (ii) the long-term deformation increased by increasing the bonded length; (iii) the increase of slip due to bond deterioration was more accentuated in those specimens loaded at 50% of sustained load than in those at 25%; and (iv) for high bonded length, increasing the groove width had a negligible effect on the long-term behavior.

#### 5 ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the Spanish Government (Ministerio de Economía y Competitividad), Projects Ref. BIA2013-46944-C2-1-P, BIA2013-46944-C2-2-P. The first author would like to acknowledge the support from the European Network for Durable Reinforcement and Rehabilitation Solutions (endure), a Marie Skłodowska Curie Initial Training Network (European Commission, Contract number MC-ITN2013-607851). The authors also wish to acknowledge the support of S&P Clever Reinforcement Iberica Lda. company for supplying the materials.

## 6 REFERENCES

- Borchert, K. & Zilch, K., 2008. Bond behaviour of NSM FRP strips in service. *Structural Concrete*, 9(3), pp.127–142.
- Coelho, M.R.F., Sena-Cruz, J.M. & Neves, L.A.C., 2015. A review on the bond behavior of FRP NSM systems in concrete. *Construction and Building Materials*, 93, pp.1157–1169.
- Derias, M., El-Hacha, R. & Rizkalla, S., 2008. DURABILITY OF NSM FRP STRENGTHENING SYSTEMS FOR RC FLEXURAL MEMBERS. In *Forth International Conference on FRP Composites in Civil Engineering (CICE)*. Zurich, Switzerland.
- De Lorenzis, L. & Teng, J.G., 2007. Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures. *Composites Part B: Engineering*, 38(2), pp.119–143.
- Parvin, A. & Shah, T.S., 2016. Fiber reinforced polymer strengthening of structures by near-surface mounting method. *Polymers*, 8(8).
- Silva, P. et al., 2014. Creep behavior and durability of concrete elements strengthened with NSM CFRP strips. In *Proceedings of the 7th International Conference on FRP Composites in Civil Engineering, CICE 2014*. Vancouver, Canada.