BOND OF NSM FRP STRENGTHENED CONCRETE: ROUND ROBIN TEST INITIATIVE

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Abstract

Although an extensive amount of research into the debonding behaviour of FRP strengthening systems has been conducted in literature, no standard methodology has been yet established that represent the actual behaviour. To asses the performance and reliability of small scale testing on NSM (near surface mounted) FRP strengthening systems an experimental program, in the framework of an international Round Robin Testing (RRT) has been carried out on a series of 9 NSM FRP strengthening systems. Eleven laboratories and seven manufacturers and suppliers participated in this extensive international exercise, which was initiated within the framework of the European funded Marie Curie Research Training Network, EN-CORE, with the support of Task Group 9.3 of the International Federation for Structural Concrete (*fib*). Test results obtained by the participating laboratories are discussed and compared in this paper.

Keywords: bond, standard, FRP, near surface mounted, round robin testing.

1. Introduction

In recent years, strengthening technologies for reinforced concrete structures using FRP composites have been gaining widespread interest and growing acceptance in the civil engineering industry. The most common strengthening techniques are respectively the EBR (external bonded reinforcement) technique, that consist of bonding, with a high strength adhesive, a laminate/textile onto the surface of the concrete element, and the NSM (near surface mounted) technique, that consist of placing the FRP reinforcing bars into grooves precut into the concrete members and embedding the bars with a high strength adhesive. The main property governing the design of a FRP strengthening application is the debonding of the FRP, which is generally initiated before the tensile strength of the FRP reinforcement can be reached. For this reason, some of the first investigations on the topic have specifically addressed the issue of bond using different test methods [1-6]. The bond performance of NSM FRP, however, has yet to be fully addressed and is a key area requiring further research. A round robin testing initiative was conducted to investigate the feasibility of the adopted test methods and to investigate the mechanism of bond between FRP reinforcement and concrete. Eleven laboratories and seven manufacturers and suppliers participated in this extensive international exercise, which was initiated within the framework of the European funded Marie Curie Research Training Network, EN-CORE, with the support of Task Group 9.3 of the International Federation for Structural Concrete (*fib*). Four laboratories participated in the RRT on the bond behaviour of NSM FRP strengthening system (see **Table 1**). The proposed bond test methods are analysed and discussed in detail; evidencing their positive and negative aspects. Some of the factors expected to affect the bond performance were addressed, namely the type of FRP material, FRP diameter and shape and surface configuration of the FRP rod/strip. Test results obtained by the participating laboratories are discussed and compared in this paper.

2. Experimental investigation

2.1 Test Specimen and Parameters

The experimental program has been carried out on a series of 9 NSM FRP strengthening systems for a total of 94 tests, with a minimum of 2 tests per strengthening system which has been carried out at each laboratory. Two different test set up methodologies, namely a double bond shear test set up (DB), and a single shear test set up (SB) have been adopted by the participating laboratories (both considering bond testing in a tension-tension situation) as shown in *Fig 1* and *Fig 2*. The specimens used for DB tests comprised of two concrete prisms (400x150x150mm), whilst one concrete prism (400x200x160mm) was used for SB tests. One or two steel bars were embedded in the concrete prisms to allow anchorage or application of load. The FRP rods/strips were bonded to each concrete prism for a length of 300 mm, whilst a 50 mm long region was left un-bonded at the loaded end to prevent the development of high shear stresses and avoid premature local damage of the concrete. To prevent bond failure in the second concrete prism, for the DB test, a bond length of 350 mm and extra clamp anchorage were used. The bonding adhesive recommended by the manufacturer for the specific bar being tested was used in all cases. A minimum of 5 strain gauges and 1 LVDT were used to monitor the development of strains along the bonded portion of each of the plates, and the loaded end slip, respectively (see *Figure 1* and *Fig 2*). All tests were conducted in displacement control with loading rates of 0.1 mm/min to 2 mm/min. **Table 1** summarized the main procedural differences between testing laboratories.

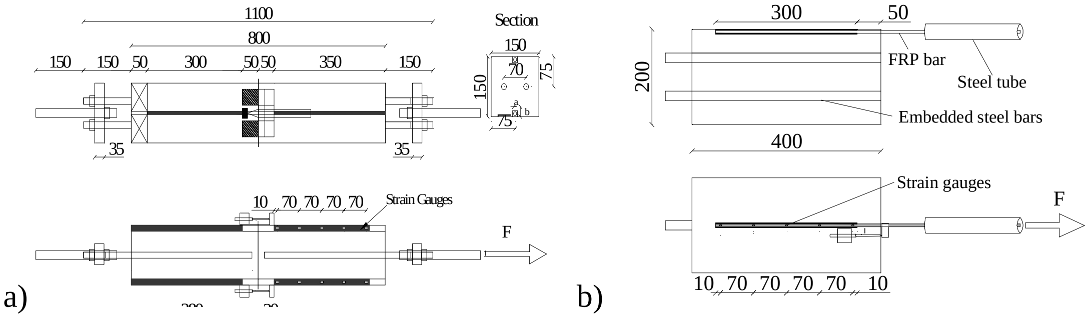

Figure 1. Specimens details for a) DB and b) SB tests.

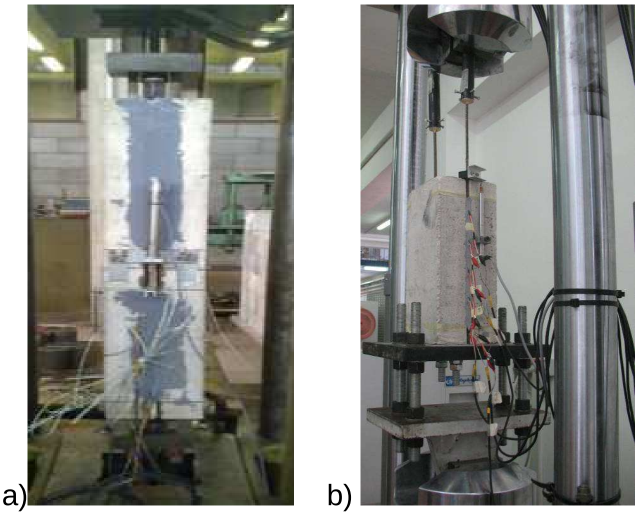

Figure 2. Test set-up a) DB and b) SB tests.

Table 1. Summary of main procedural differences between testing laboratories.

TESTING LABORATORY	TYPE OF TEST	LOADING RATE [mm/min]	f_{cu} [MPa]	EMBEDDED BARS n°/diam (mm)
Ghent	DB	0.1	30	2/16
Minho	DB	1	32	2/16
Naples/Sannio	SB	0.3	23	2/20
Budapest	DB	2.0	42	2/16

The influence of FRP reinforcement shape (rods versus strips), the type of fibers, as well as the type of surface treatment (sand coated, smooth and ribbed bars) were evaluated. An overview of the different test specimen and the main test parameters is given in **Table 2**. The specimens are listed using the following designation: the first letter C, B, or G indicates carbon, basalt or glass fibers, respectively; the second notation, SC, RB, SM and STR indicates the type of reinforcement: sand coated rods, ribbed rods, smooth rods and smooth strips; the third notation indicates the dimension of the rod/strip FRP reinforcement system.

Table 2. Test matrix.

Specimens	Fibers	Surface	Dimension [mm]	Groove dim. [mm]
C_SC_6	Carbon	Sand coated	6	12x12
B_SC_6	Basalt	Sand Coated	6	12x12
B_SC_8	Basalt	Sand Coated	8	14x14
C_S_1.4x10	Carbon	Smooth strips	1.4x10	5x15
G_RB_8	Glass	Ribbed	10	14x14
C_STR_2x16	Carbon	Smooth strips	2x16	8x25
C_SM_8	Carbon	Smooth	8	14x14
C_STR_10x10	Carbon	Smooth strips	10x10	15x15
G_RB_8	Glass	Ribbed	8	14x14

2.2 Materials

Concrete blocks were prepared by the laboratories (the mean compressive cylinder strength, f_{cm} is summarized in **Table 1** for each participating laboratory). The tensile properties of the NSM FRP reinforcement, as provided by the manufacturers, in terms of type of fibers, cross section area, A_f, tensile strength, f_f, modulus of elasticity, E_f, ultimate failure strain ε_f and axial stiffness, E_fA_f, are given in **Table 3**. All the NSM FRP reinforcement, were embedded into the grooves by means of epoxy resin as suggested by the manufacturers. The CFRP rods and strips were embedded with an epoxy resin (type Fortresin CFL, supplied by forties) with a tensile strength of 50 MPa, while the GFRP and BFRP rods with an epoxy resin (type Sikadur-30, supplied by Sika) with a tensile strength of 30 MPa and an elastic modulus if 12.8 GPa.

Table 3. NSM FRP Properties

Specimens	Fibers	A_f [mm^2]	f_f [MPa]	E_f [GPa]	ε_f [%]	E_fA_f [kN]
C_SC_6	Carbon	29.9	2068	124	1.7	3708
B_SC_6	Basalt	29.9	1470*	52.5*	3.0*	1570
B_SC_8	Basalt	50.2	1324*	51.0*	2.9*	2560
C_S_1.4x10	Carbon	14	1850	165	1.6*	2310
G_RB_8	Glass	50	1500	60	2.4*	3000
C_STR_2x16	Carbon	37.5	3100	165	1.7	6190
C_SM_8	Carbon	50.2	2800	155	1.8	7780
C_STR_10x10	Carbon	100	2000	155	1.5	15500
G_RB_8	Glass	50.2	1290*	55*	2.3*	2761

* Average values obtained from tensile tests by each laboratory

3. Experimental results and discussions

3.1 Failure mode

Debonding at the concrete/epoxy interface, with varying degrees of concrete damage was the predominant observed failure mode (see *Fig 3* a-b). Other types of failure, however, were also observed (as example see *Fig 3* c), including longitudinal splitting of the epoxy and bar/strip pull-out (gradual and extensive slipping of the bar/strip). For a small percentage of the specimens, no matter which test set-up was adopted, the stress development along the embedded steel bars in addition to the stresses into the concrete (induced by the FRP reinforcement bars) have caused a premature failure of the concrete specimen by splitting (see *Figure 3* d) or extensive concrete crush. For 10 specimens failure occurred at the opposite side. In addition for the DB test the alignment of specimens was, for some cases, difficult to achieve and the occurrence of bending effects was observed during testing.

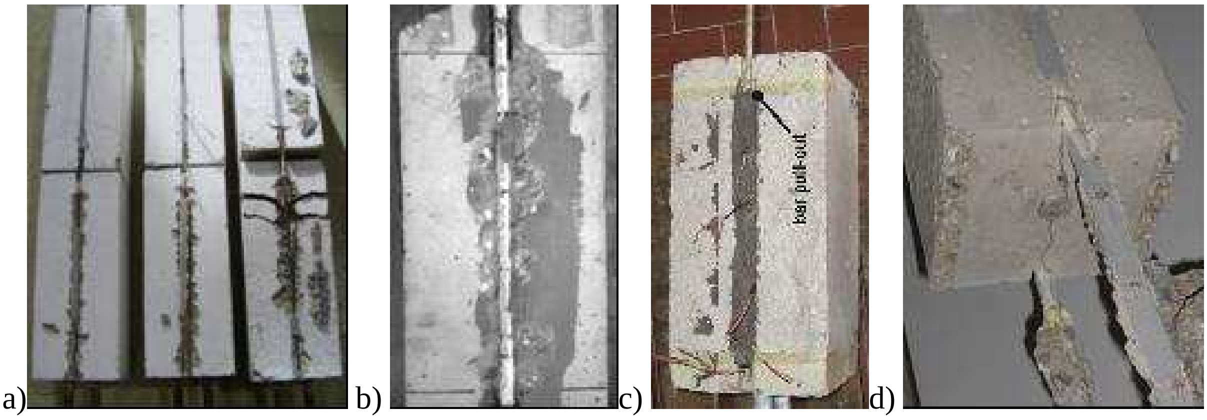

Figure 3. Failure modes: a-b) debonding concrete epoxy interface; c) bar pull out; d) concrete splitting

3.2 Ultimate load and local shear bond stresses

The ultimate load F_u of one bar/strip (half of the load applied on the specimen) at bond failure and the maximum local bond stress, τ_{max}, are summarized in **Table 4**. Bond stresses have been evaluated by utilizing experimentally recorded strains along the FRP. Referring to two consecutive strain gauges, ranging Δ_{xi}= 70 mm, the equilibrium equation (1), assuming uniform distribution of the bond stress in the analyzed discrete interval, gives:

$$\tau_x = E_f \frac{A}{u} \frac{\Delta\varepsilon_i}{\Delta x_i} \tag{1}$$

Where τ_x is the bond stressing the FRP reinforcement between two consecutive strain gauges, E_f the elastic modulus of the FRP reinforcement, A is the FRP's cross section area, u is the perimeter of the FRP reinforcement, $\Delta_{\varepsilon i}$ is the measured strain difference between the two considered strain gauges and Δ_{xi} is the distance between two consecutive strain gauges . In **Table 4**, reference is made to the average tests results obtained by the two/three equivalent specimens tested for each parameter combination.

Table 4. Failure load and maximum local bond shear stress of the NSM reinforcements

Specimens	Ghent		Minho		Naples/Sannio		Budapest	
	F_u [kN]	τ_{max} [MPa]	F_u [kN]	τ_{max} [MPa]	F_u [kN]	τ_{max} [MPa]	F_u [kN]	τ_{max} [MPa]
C_SC_6	33.0	11.4	36.7	26.5	-	-	33.9	15.9
B_SC_6	38.4	13.9	26.5	17.5	33.0	9.8	30.6	11.6
B_SC_8	39.8	11.8	33.5	12.3	31.6	11.5	-	-
C_S_1.4x10	24.6	17.8	39.1	15.7	-	-	25.1	10.6
G_RB_8	51.7	13.9	40.3	11.7	47.6	13.9	44.7	16.0
C_STR_2x16	59.9	15.1	48.0	12.4	51.7	9.5	40.4	8.3
C_SM_8	56.9	14.7	47.4	14.0	49.6	9.0	41.6	11.3
C_STR_10x10	61.0	11.8	58.9	7.7	50.3	11.8	58.3	11.1
G_RB_8	43.7	4.7	-	-	32.2	5.6	-	

Experimental results show that the maximum failure load (F_u) and the maximum bond stress (τ_{max}) varies with the type of reinforcement. It is observed that (although has to be noticed that the bars have a different surface configuration and axial stiffness E_fA_f)., neglecting the extreme values (maximum and minimum values), the maximum bond stress range is similar for all the laboratories (11-17 MPa for DB test and 9-14 MPa for SB). The smaller values observed for specimens tested with SB test are mainly due to the lower concrete strength (f_c= 23MPa) with respect of the concrete strength (f_c in a range of 32-42 MPa) of specimens tested with DB tests. The standard deviation observed at individual laboratories for each set of specimens is represented graphically through error bars in *Fig 4.*

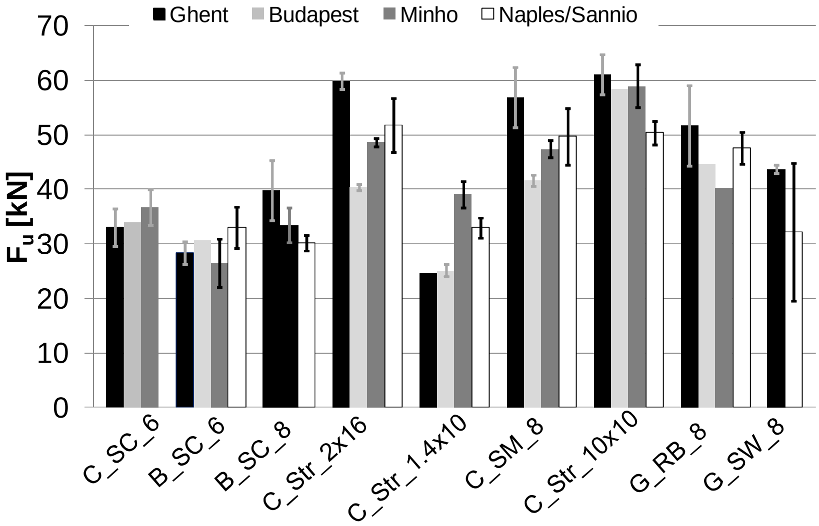

Figure 4. Average ultimate load (error bars represent standard deviation)

Experimental outcomes, in terms of ultimate load, seems to be in agreement for the two different test set up adopted, excluding some differences caused by unexpected failure modes (see section 3.1). The standard deviation seems to be generally quite low and comparable in the results of the different participating laboratories.

Given the strain distribution, the slip between the FRP reinforcement and the concrete can been calculated through integration of the strain along the bonded length and the bond stress-slip relation can be derived. Assuming that the slip at the unloaded end can be considered negligible before debonding and neglecting strain the local slip is calculated through equation 2:

$$s_x = \sum_{i=1}^{n} \varepsilon_i \Delta_x \qquad (2)$$

Where s_x is the slip along the bond length, n is the number of strain measurements along the bond length, Δ_x is the distance between two consecutive measurement points (Δ_x=70 mm).

The bond stress-slip (τ–s) and the load- displacement (average of measurement of two LVDTs) curves of specimens G_RB_8 and C_SC_6 are given in *Fig5* and *Fig 6*. From the examples shown it can be noted a generally fair repeatability of results between the participating labs and different test set-up for similar type of failure mode.

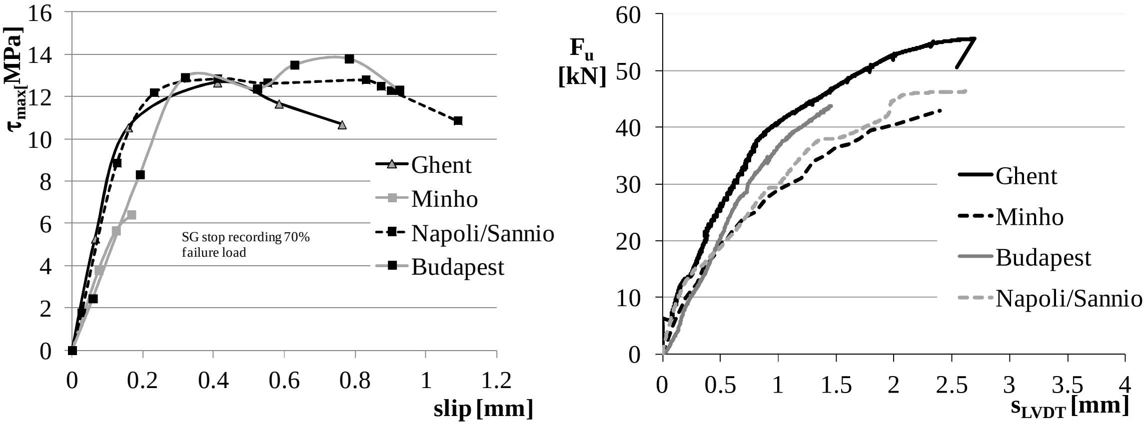

Figure 5. Bond stress-slip curve and load – displacement curve specimen G_RB_8

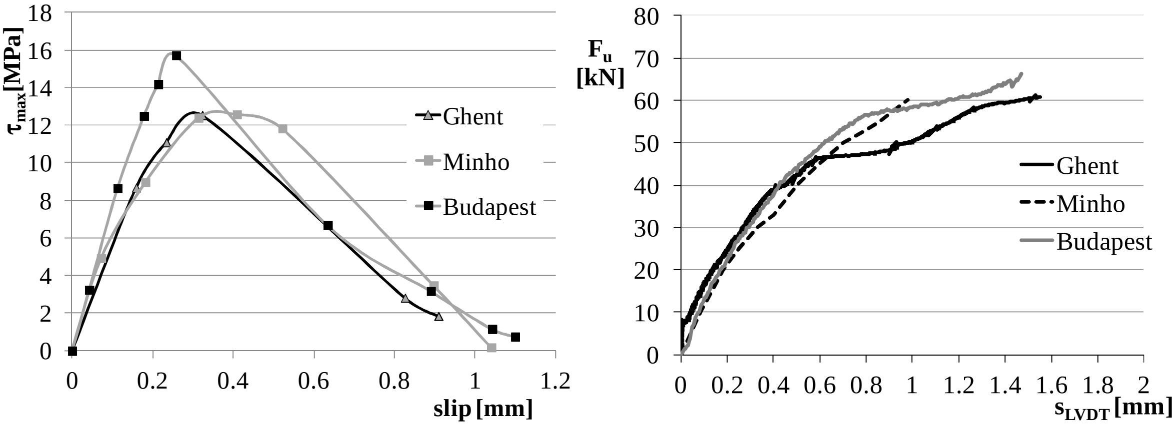

Figure 6. Bond stress-slip curve and load – displacement curve specimen C_SC_6

4. Conclusions

A round robin testing initiative was conducted to investigate the feasibility of the adopted test methods and to investigate the mechanism of bond between NSM FRP reinforcement and concrete. Four laboratories and seven manufacturers and suppliers participated in this extensive international exercise, which was initiated within the framework of the European funded Marie Curie Research Training Network, EN-CORE, with the support of Task Group 9.3 of the International Federation for Structural Concrete (*fib*). The maximum failure load (Q_u) and the bond stress (τ_{max}) varies with the type of reinforcement. Debonding at the concrete/epoxy interface, with varying degrees of concrete damage was the predominant observed failure mode. For the DB test set-up the observed concrete fracture and high stresses development at steel re-bars can decrease the bond strength and/or cause a premature failure due to splitting of concrete. The preparation of specimens for DB tests has proven to be cumbersome. Difficulties to achieve the specimen alignment for the DB test and/or the influence of the embedded steel bars, in the DB and SB tests, need to be further analyzed in order to make the test set up more feasible. Nevertheless a comparison in terms of bond stress-slip curves and ultimate loads seems to give a good agreement in between the participating labs and different test set-up for similar type of failure mode.

5. Acknowledgments

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6. References

[1] BLASCHKO, M., “Bond behaviour of CFRP strips glued into slits”, *6th Int. Symposium on FRP Reinforcement for Concrete Structures (FRPRCS-6),* K. H. Tan ed World Scientific, Singapore, July 2003, pp. 205-214.

[2] De LORENZIS, L.,RIZZO, A, LA TEGOLA, A, “A modified pull-out test for bond of near surface mounted FRP rods in concrete”, *Composites Part B: Engineering,* Vol. 33, No. 8, November 2002, pp. 589-603.

[3] De LORENZIS, L., LUNDREGEN K., RIZZO A. “Anchorage length of near surface mounted FRP bars for concrete strengthening- Experimental investigation and numerical modelling”, *ACI Structural Journal,* Vol. 101, No. 2, March 2004, pp 269-278

[4] Hassan T., Rizkalla S., “Investigation of bond concrete structures strengthened with near surface mounted carbon fiber reinforced polymer strips”, *ASCE Journal of Composites for Construction,* Vol. 7 No 3, May 2003, pp 248-257

[5] Kotynia R., “Strain Efficiency of Near Surface Mounted CFRP-strengthened Reinforced Concrete Beams, *International Conference of Composites in Construction,* Lyon, July 11-13, 2005

[6] Seracino R., Saifulnaz M. R., Oehlers D. J. “ Generic Debonding Resistance of EB and NSM Plate-to Concrete Joints”, *Journal of Composites for Construction ASCE,* Vol 11, No. 1, January-February 2007, pp 62-70.