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DOUBLE BOND SHEAR TESTS AT ELEVATED TEMPERATURE ON NSM FRP SYSTEM WITH EPOXY AND GROUT ADHESIVE

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ABSTRACT

By embedding Near Surface Mounted (NSM) bars or strips in the concrete cover, generally much higher strain levels can be achieved over the bond interface, compared to Externally Bonded Reinforcement (EBR). Both cementitious or polymer based grout or adhesive can be used to bond the NSM reinforcement. The adhesive choice has a significant influence and might be taken as a function of specific design goals, such as behaviour at elevated temperature. Indeed, elevated temperatures change the adhesive properties and can compromise the stress transfer capacity over the bond interface.

This paper will compare test results of 2 double bond shear test campaigns, studying the bond interaction between NSM and concrete at ambient and elevated temperature. In the first campaign epoxy adhesive was used, while in the second campaign a proprietary grout adhesive was used. Though epoxy was generally found to have better bond behaviour at ambient conditions, the grout system performed much better at elevated temperatures. This will be discussed into more detail in the paper.

INTRODUCTION

NSM reinforcement involves more bond influencing parameters than EBR such as filler type, FRP type (bars or strips), FRP roughness, width groove – bar diameter ratio (k), and groove roughness. De Lorenzis (2004) [1, 2] studied the bond behaviour of NSM at room temperature making shear tests with different filler types (epoxy resin and cement grout) and groove dimensions. In all specimens the author observed failure due to splitting and progressive crack propagation. Specimens filled with grout showed bond strengths lower than epoxy filler (Fig. 1, with bond length 12 and 24 times the bar diameter).

The FRP matrix and epoxy adhesive are strongly influenced by temperature. Indeed, their properties tend to reduce when temperature is close to or beyond the glass transition temperature (T_g). In some cases, where high temperature resistance is required, cementitious grout can ensure greater bond strength. Palmieri (2013) [3, 4] and Cassaert (2014) [5] conducted double bond shear tests to study the influence of temperature on NSM systems with different groove filler; epoxy resin and cementitious grout, respectively. The elevated temperature bond tests have been conducted in the framework of a larger research programme on the fire behaviour of RC beams and slabs strengthened in flexure with NSM FRP [6]. Main characteristics and results of these studies are reported in Table 1.

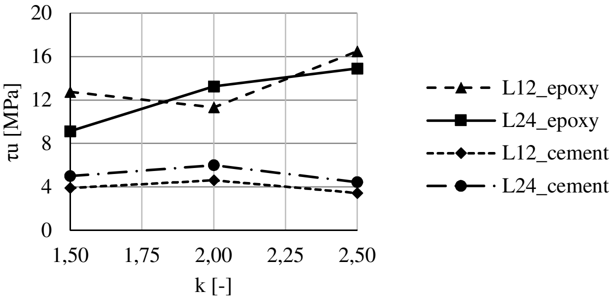

Figure 1 Bond strength for different filler type and width groove-bar diameter ratio (k) [1]

TEST SET-UP

The test set-up used for the experimental work is give in Figure 2. The specimen consists of two concrete blocks (150mm x 150mm x 400mm) with a square groove (16mm x 16mm) in the middle at both sides for embedment of the NSM bars. A thin metal plate separated the two concrete blocks. Steel bars (ø 16mm) were embedded in each prism to apply tensile load. The two concrete blocks are only joined by means of FRP bars. The block with the shortest bond length, taken equal to 300mm, is taken as test region and is equipped with strain gauges and displacement transducers. To prevent bond failure the second concrete block is restrained with an extra clamp anchorage. The main differences between the two test programs concern the materials and temperature range as reported in Table 1. During the testing the following measurements have been performed (Fig.2): 1) strains by means of five strain gauges (SG) placed along the bond length, 2) relative displacement between concrete blocks through variable transducers (LVDTs), 3) load and 4) temperatures.

For the tests at elevated temperatures an electrical hollow furnace was used. The oven was placed around the specimen in the test region (monitored side). All gaps between the furnace and the specimen were filled with mineral wool. The temperature in the furnace (by measuring the air temperature inside the furnace) and the temperature within the test region of the specimen were controlled by thermocouples (type K). Thermocouples were positioned inside the adhesive and at the adhesive surface.

The specimens were heated in the oven for at least 18 hours before testing. Hereby, the defined testing temperature (Table 1) is obtained at the measuring locations. The temperature was kept constant during testing.

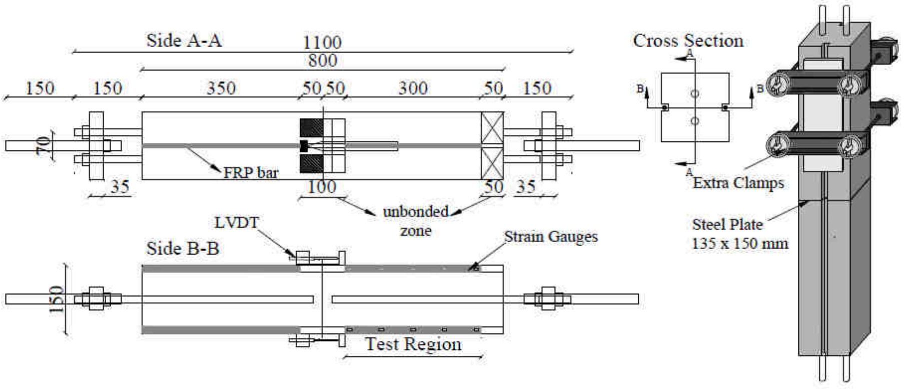

Figure 2 Test set-up

Table 1 Main characteristics and results

Author	Specimen	filler type	T [°C]	τ_{av} [MPa]	$T_g^{(1)}$ [°C]	$L_t^{(2)}$ [mm]
Palmieri (2013) [3]	C_SC_20	epoxy resin	20	6,4	66	150
	C_SC_50	epoxy resin	50	7,8	66	220
	C_SC_65	epoxy resin	65	5,8	66	270
	C_SC_80	epoxy resin	80	3,5	66	≥ 300
	C_SC_100	epoxy resin	100	2,7	66	≥ 300
Cassaert (2014) [5]	CC1-NI-20	grout	20	1,6	(220)	277
	CC2-I-220	grout	89,7	1,5	(220)	≥ 300
	CC1-NI-100	grout	99,5	1,2	(220)	≥ 300
	CC2-I-275	grout	105,9	1,2	(220)	≥ 300
	CC1-NI-180	grout	184,5	0,9	(220)	N/A
	CC2-NI-220	grout	213,2	0,6	(220)	≥ 300
	CC2-NI-275	grout	285	0,5	(220)	N/A

(1) T_g - Palmieri: groove filler, Cassaert: FRP bar matrix

(2) Palmieri: L_t is related to 20% F_u, Cassaert: L_t is related to 5kN, N/A: data not available

INFLUENCE OF TEMPERATURE FOR EPOXY AND CEMENT FILLER

The influence of temperature on NSM with epoxy filler included CFRP (C_SC-carbon, sand coated), GFRP (G_SW-glass, spirally wound) bar and CFRP (C_STR-carbon strip) strips, tested by means of double bond shear tests with a temperature range between 0-100°C (Fig.3).

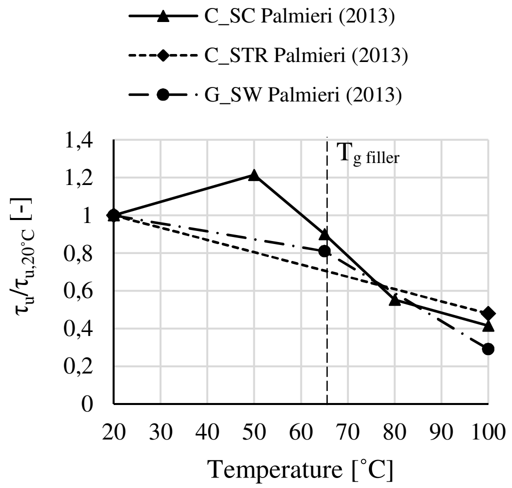

Figure 3 Normalized bond strength as a function of temperature [3]

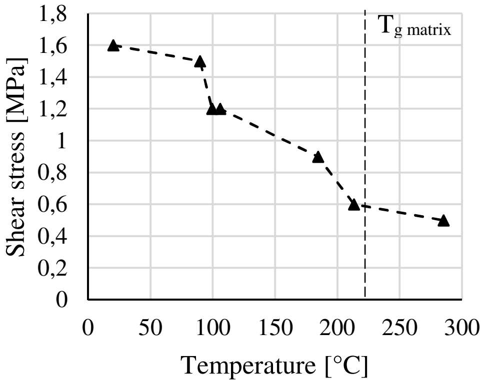

Figure 4 Bond strength in grout system as a function of temperature [5]

The main effects of temperature observed by Palmieri are: 1) initial bond strength increase for temperature lower than T_g (for CFRP systems), 2) bond shear drop with temperature greater than T_g (at temperature 1,5 T_g the residual bond strength equals 42%), 3) more homogeneous shear stress distribution along the bond and 4) initial transfer length increase. Hence, CFRP bars showed a bond strength increase with temperature lower than the glass transition temperature (T_g). This because the different coefficient of thermal expansion (CTE) between the concrete and CFRP produced a positive shear pre-stress as analytically proved by Di Tommaso (2001) [7][3].

The effect of thermal pre-stress is also visible on the strain distribution of Figure 5. Looking at the strain levels for 80% F_u, the highest values are found at 50°C. Furthermore, looking to the shear stresses along the bond length (Fig.6), with increasing temperature beyond T_g a more uniform shear stress is observed.

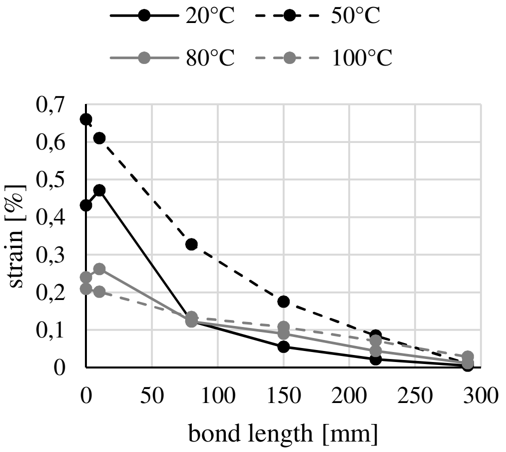

Figure 5 Strain along the bond length for 80%F_u with epoxy filler [3]

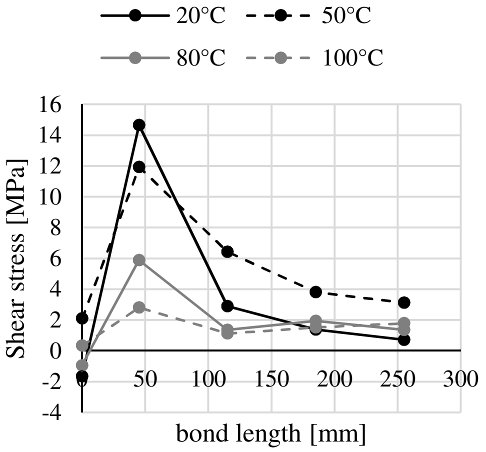

Figure 6 Shear stresses along the bond length for 80%F_u with epoxy filler [3]

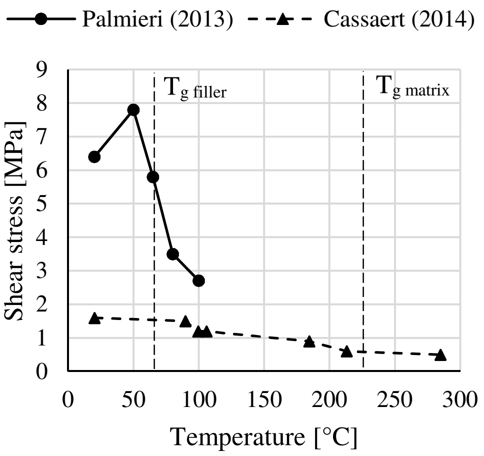

Figure 7 Bond strength as a function of temperature [3, 5]

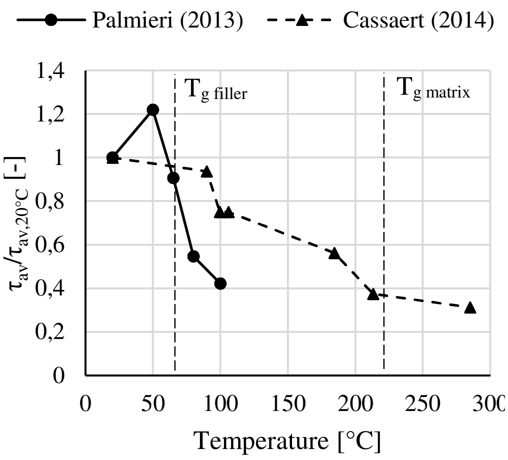

Figure 8 Normalized bond strength as a function of temperature [3, 5]

The failure mode changed from debonding at the concrete/epoxy interface at room temperature (20°C) into debonding at the FRP/epoxy interface for temperatures beyond T_g.

The bond shear strength-temperature dependency for CFRP bars embedded with grout is reported in Fig.4. The following is observed:

1) for low temperature increase the bond strength remains more or less constant and starts decreasing at about 100°C,
2) with increasing temperature beyond 100°C the bond strength further decreases, with a further drop when reaching the glass transition temperature of the FRP bar,
3) no test at 50°C was performed, so that it is unclear if the thermal pre-stress effect as observed in Fig.3 also applies.

The specimens collapsed following two main failure modes: splitting with fractures in the concrete cover at room temperature (20°C) and debonding of the CFRP bar at elevated temperature (275°C). The glass transition temperature of the FRP bar matrix was 220°C, therefore, this high value allowed to delay failure at higher temperature.

A comparison between the epoxy and grout system in terms of bond strength is provided in Figs. 7 and 8. For the epoxy system (black line), the results are affected by the thermal shear pre-stress (50°C) and the T_g of the adhesive (66°C); while the grout system (dashed line) is influenced by the evaporation of free water (100°C) and the T_g of the FRP bar matrix (220°C). The influence of free water on the bond strength decrease is underlined by the different slope curve before and beyond the evaporation point.

Indeed free water slows down the overall heating process from 20°C to 100°C. From Figs. 7 and 8, the following further observation can be made. At 100°C the grout based system is at 75% of its initial capacity, while the epoxy filler based system is at about 40%. In absolute bond strength terms - yet keeping in mind that two different FRP bars are compared and different results might be found for other FRP/filler combinations - the bond strength ratio between epoxy and grout filler reduces from 4 at 20°C to 2,25 at 100°C.

From Table 1 it can be observed that the initial bond strength transfer length of the epoxy system is shorter than for the grout system. With increasing temperature, for both systems an increase of the bond transfer length is observed.

Fig.9 makes a comparison of the strain distribution along the bond length evaluated at F=5kN (epoxy: 20°C-22%F_u, 100°C-30%F_u, grout: 20°C-5%F_u, 100°C-10%F_u). Stress transfer (decrease of strains along the bond length) acts faster in epoxy filler than for grout. This behaviour, observed at 20°C, reveals that it depends on the different Young's modulus between epoxy and grout. At 100°C the epoxy based system is more sensitive to the temperature than grout, indeed strains decrease quickly from the load end.

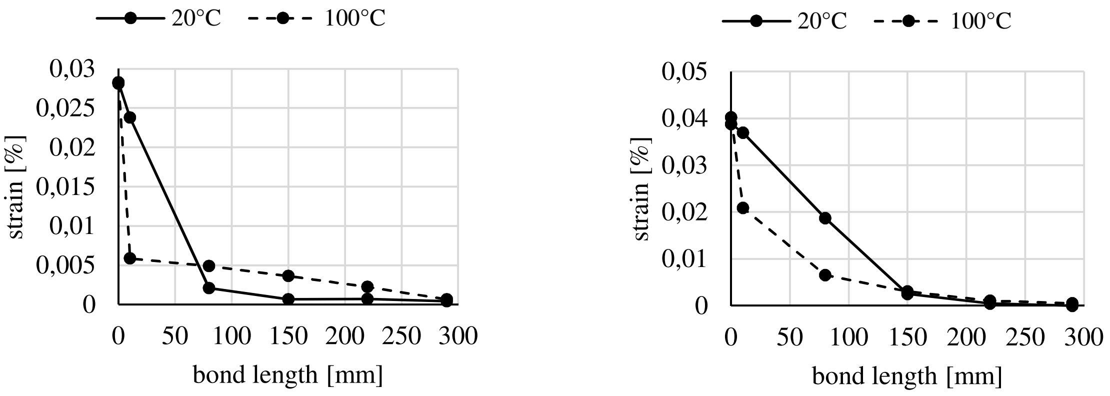

Figure 9 Strains along the bond length at F=5kN in epoxy (left) and grout (right) based systems

CONCLUSIONS

The bond interaction between concrete and near surface mounted FRP reinforcement has been investigated for different FRP bar/filler systems, by means of two test campaigns [3, 5] and looking into elevated temperatures. This work allows to show the importance of the filler type in NSM systems.

Indeed, epoxy and grout filler revealed some relevant different behaviours.

- Thermal shear pre-stress increased bond strength in CFRP bars embedded with epoxy filler at 50°C.
- NSM with epoxy and grout filler are both sensitive to T_g. For the former, the bond strength especially decreases with temperature beyond T_g of epoxy adhesive and the latter with temperature greater than T_g of the FRP bar matrix.
- Bond strength decrease in grout is less affected by temperature than epoxy. Indeed, at 100°C the grout based system is at 75% of its initial capacity, while the epoxy filler based system is about 40%.
- For grout systems, the bond strength is also influenced by evaporation of free water, starting at temperatures close or beyond 100°C.

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