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Bond behavior of NSM FRP bars at elevated temperatures

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ABSTRACT: The weak performance of FRP (Fiber Reinforced Polymer) strengthening systems at elevated temperatures due to fire exposure is a primary factor that prevents the widespread application of FRPs in buildings. The low fire resistance can be attributed to the relatively poor performance of both adhesive and FRP matrix polymers at temperatures beyond the glass transition temperature. When reaching the glass transition temperature, the properties of the adhesive decrease to a large extend and bond interaction between the concrete and the FRP reinforcement may be completely lost.

In the case of NSM (Near Surface Mounted) the FRP reinforcement is not longer externally bonded, but in slits. This offers extra protection to the high temperature or fire exposure. To study the bond behavior at elevated temperature between the NSM FRP bars and the concrete a series of 18 double bond shear tests were performed at Ghent University. The present paper will discuss the experimental work and the main test results obtained.

1 INTRODUCTION

Extensive research has been carried out in recent years on strengthening reinforced concrete structures with near surface mounted (NSM) FRPs (De Lorenzis 2002,2004; Seracino et al 2007, Palmieri et al 2010). In this technique FRP reinforcing bars or strips are inserted into grooves pre-cut into the concrete cover member and inserted along with a high strength adhesive (epoxy or mortar). This method is relatively simple and considerably enhances the bond of the FRP reinforcement, thereby using the material more efficiently. NSM techniques have become increasingly popular in recent years due to specific advantages over the externally bonded technique (EBR) such as a better anchoring capacity of the FRP, better bond characteristics and more ductile behavior. Moreover it has been suggested in literature that the NSM technique has a better protection from the environment, vandalism and fire due to the protection provided by the partial embedment in the concrete. To the knowledge of the authors, no research has been presented to support this idea: thus, an initial scoping study was conducted to improve the understanding on the influence of temperature on the bond capacity of NSM FRP.

2 RESEARCH SIGNIFICANCE

Based on the available literature (Blontrock et al 1999, 2001; Bisby et al 2005; Kodur et al 2007; Burke 2007; Leone et al. 2009; Palmieri et al 2010) FRP strengthening systems are known to perform weak at elevated temperatures. Temperatures changes are expected to affect the material properties of the concrete, FRP and the adhesive, but also the bond between these materials. Increasing the temperature is expected to have a negative effect on the adhesive properties, especially when the glass transition temperature (T_g) is exceeded. For polymer resins currently used as primer, adhesive and matrix for FRP strengthening systems, their strength and stiffness significantly drops when the temperature reaches T_g (the T_g of ambient cured epoxies is usually in the range of 50-90 ºC). Moreover temperature changes will induce additional thermal stresses, due to the differential thermal expansion between concrete and FRP in the longitudinal direction. Furthermore, differential temperature in a strengthened structure causes imposed deformations. Both phenomena will induce additional stresses in the FRP and concrete and may affect the bond behavior of the strengthening system, reducing the load level at which debonding may occur.

In order to investigate the influence of temperature on the bond behavior between NSM FRP and concrete a series of 18 double shear tests at different temperatures (20, 50 , 65, 80, 100 ºC) were performed at Ghent University. The paper presents the results of the effects of elevated temperature on debonding of NSM FRP bars in terms of failure load, strain distribution, bond strength and failure aspect.

3 EXPERIMENTAL PROGRAM

3.1 Preparation of the test specimen

The specimens for the double-lap shear tests were produced in three series of seven concrete specimens. The specimen (nominal dimensions 150 x 150 x 800 mm^3) is composed of two concrete blocks (150 x 150 x 400 mm^3) with a groove in the middle at both sides, for embedment of the NSM rod/strip. A thin metal plate separates the two concrete blocks; the height of this plate is 15 mm less than the height of the prisms so that both prisms remain aligned during specimen manipulation and FRP application. To be able to connect the specimen to the tensile testing machine two steel rebars, with a diameter of 16 mm, are embedded in each prism. These internal steel bars do not connect the two concrete parts, which means that the two blocks are only joined through the NSM FRP bars. The FRP reinforcement is left un-bonded over a central zone of 100 mm (where the two concrete blocks connect each other). Only one block is the test region, with a bond length of 300 mm. To prevent bond failure in the second concrete block a bond length of 350 mm and extra clamp anchorages are used. The double face shear bond test is schematically represented in fig 1.

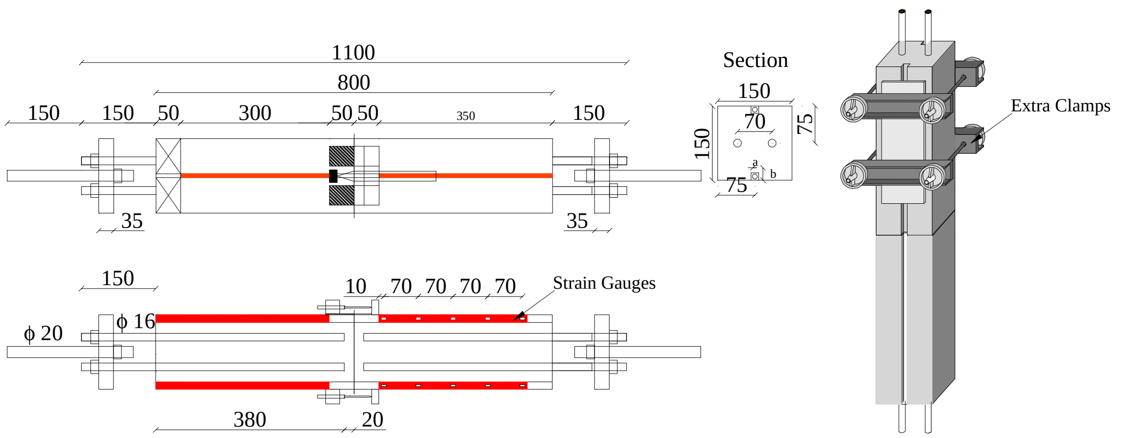

Figure 1. Test set up.

The FRP NSM rods/strips were applied according to the procedures specified by the manufacturers. After hardening of the concrete, the grooves were saw-cut and then air-blasted to remove the powdered concrete produced by the cutting. The grooves were filled half way with epoxy resin and the bars were then positioned and lightly pressed. More material was applied if needed and the surface was leveled. Curing of FRP NSM was allowed for at least 7 days under laboratory environment. No pressing devices were applied during curing.

An overview of the different test specimens and the main test parameters is given in table 1 in terms of specimen designation, FRP reinforcement, test temperature and concrete batch number. As can be noted, bond tests have been executed for different temperatures and types of FRP. Four different level temperatures were used: 50, 65, 80 and 100 ºC. The temperature level was chosen in relation to the glass transition temperature (T_g) of the utilized epoxy resin which equals 65ºC as provided by the manufacturer. The NSM FRP reinforcement used comprised CFRP (Carbon Fiber Reinforced Polymer) rods and strips, and GFRP (Glass Fiber Reinforced Polymer) rods.

Table 1. Test Matrix.

Specimens	FRP	Test temperature ºC	Batch no
C_SC_20_a	CFRP rod	20	2
C_SC_20_b	sand coated		2
C_SC_50_a		50	2
C_SC_50_b			2
C_SC_65_a		65	2
C_SC_65_b			2
C_SC_80_a		80	3
C_SC_80_b			3
C_SC_100_a		100	3
C_SC_100_b			3
G_RB_20_a	GFRP rod	20	1
G_RB_20_b	ribbed		1
G_RB_65_a		65	1
G_RB_65_b			1
G_RB_100_a		100	1
G_RB_100_b			1
C_STR_20_a	CFRP strip	20	3
C_STR_20_b	sand coated		3
C_STR_100_a		100	3
C_STR_100_b			3

The specimens are listed using the following designation: the first letter C or G indicates carbon fibers or glass fibers, respectively; the second notation, SC, RB and STR indicates the type of reinforcement: sand coated rods, ribbed rods or sand coated strips; the third notation indicated the test temperature, 20, 50, 65 80 and 100 ºC, respectively. The last letter indicates the test procedure of the two similar specimens tested for each analyzed parameter.

3.2 Material properties

Three concrete batches with the same concrete composition were used. The mean cylinder compressive strength (f_c), at 28 days equals 43,7 N/mm^2, 45,1 N/mm^2, 45,5 N/mm^2 respectively. Three types of FRP reinforcement were used in this study: CFRP rods and strips (type Aslan

200 and Aslan 500, supplied by Hughes Brothers/Fortius) and GFRP rods (type Aslan 100, supplied by Hughes Brothers/Fortius). The tensile properties of the NSM FRP reinforcement, as provided by the manufacturer, in terms of bar type, nominal dimensions, surface treatment, FRP tensile strength f_f, and modulus of elasticity E_f is given in table 2. The epoxy resin (type Fortresin CFL, supplied by Fortius) has a tensile strength of 50 MPa and a glass transition temperature (T_g) of 65 ^oC.

Table 2. FRP properties.

Name	Type	Dimensions [mm]	Surface	f_f [MPa]	E_f [GPa]
Aslan 200	CFRP	9,53	Sand coated	1900	126
Aslan 500	CFRP	2 x 16	Sand coated	2068	124
Aslan 100	GFRP	10	Ribbed	760	40,8

3.3 Test set-up and procedure

A view of the test set-up is given in Figure 2. The specimens are aligned in an universal testing machine. Testing was conducted in displacement control mode with a 0.1 mm/min cross-head displacement rate. For the tests at elevated temperature an electrical hollow furnace is used. The oven is placed around the lower concrete prism (test zone). All gaps between the furnace and the test specimen are filled with mineral wool. The temperature in the furnace is controlled by a thermocouple (type K) that measures the air temperature inside the furnace. The temperature within the test region of the specimen is controlled by two thermocouples (type K) placed inside the epoxy resin at respectively 60 and 240 mm from the end of the rod/strip and one additional thermocouple was fixed on the epoxy surface at 240 mm from the end of the rod/strip (see figure 3). The specimens were heated in a oven for at least 12 hours before testing. Hereby, the defined testing temperature (table 1) is obtained at the measured locations (figure 3). The temperature was kept constant during testing.

Figure 2. Specimen in the tensile machine without and with oven

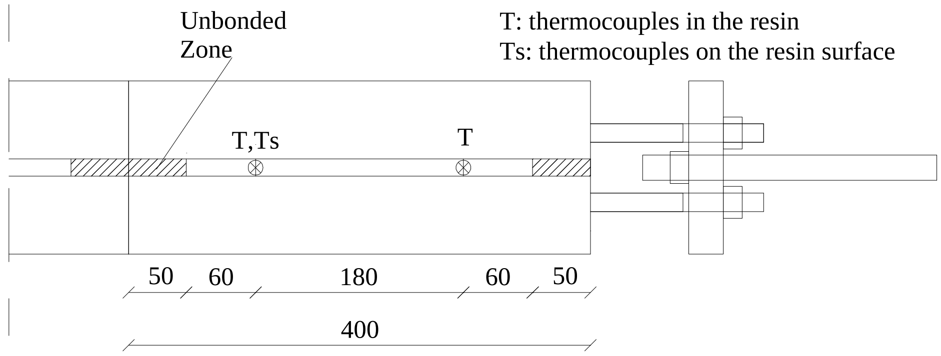

Figure 3.Thermocouples location within the test specimen.

During the bond shear test the following measurements are performed. The total tensile force applied on the test specimen is recorded by the pressure transducer of the tensile testing machine. The relative displacement between the FRP rods/strips and the concrete was recorded with two displacement transducer, one for both monitored sides. The transducers are fixed to the concrete and directly connected to the FRP reinforcement at the loaded end (at the location of the transition between the central un-bonded and the bonded zone). Electrical strain gauges were used on the FRP reinforcement on both sides, to measure the strains along the bonded length. The gauges were applied at 10, 80, 150, 220 and 290 mm from the end of the rod/strip (see figure 1).

4 TEST RESULTS

The main tests results are reported in table 3 where Q_u is the ultimate load of one bar/strip (half of the load applied on the specimen) at bond failure; $Q_u/Q_{u,20}$ is the ratio between the ultimate load at different temperatures and the ultimate load at room temperature (20 ºC), ε_u the recorded maximum strain of the bar at bond failure, s_{LVDT} is the maximum slip recorded by the LVDTs (average value of the two LVDTs) and $\tau_{x,max}$ the maximum bond stress. 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, assuming uniform distribution of the bond stresses in the analyzed discrete interval gives:

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

With τ_x the bond stress in the FRP reinforcement between two consecutive strain gauges, E_f the elastic modulus of the FRP reinforcement, A the cross-section area of the FRP reinforcement, u the perimeter of the FRP reinforcement and $\Delta_{\varepsilon i}$ the measured strain difference between the two considered strain gauges. In tables 3, reference is made to the average tests results obtained by the two equivalent specimens tested for each parameter combination.

Table 3. Average experimental results.

Specimens	Q_u [kN]	$Q_u/Q_{u,20}$ [%]	ε_u [%]	s_{LVDT} [mm]	$\tau_{x,max}$ [MPa]	Failure Mode
C_SC_20	57,9	1,00	0,98	1,49	14,55	DB-SP
C_SC_50	70,4	1,22	1,26	4,27	18,50	DB-SP
C_SC_65	52,2	0,90	0,76	4,36	12,12	DB-PO
C_SC_80	31,9	0,55	0,73	6,01	11,22	DB-PO
C_SC_100	24,0	0,41	0,96	6,31	5,15	DB-PO
G_RB_20	50,6	1,00	1,46	1,75	9,32	DB-SP
G_RB_65	41,0	0,81	0,85	6,03	6,73	DB E/C
G_RB_100	14,7	0,29	1,11	6,23	2,40	DB-PO
C_STR_20	46,4	1,00	1,14	1,16	7,89	DB-SP
C_STR_100	22,2	0,48	0,59	5,13	4,01	DB-PO

* DB-SP : debonding with splitting of the epoxy
DB-PO: debonding at FRP/resin interface with pull out of the FRP bar
DB-E/C: debonding at epoxy/concrete interface

The specimens, tested at 20ºC, failed by debonding with longitudinal splitting of the epoxy resin (DB-SP). When increasing the temperature for specimens C_SC to 50 ºC (C_SC_50) and with respect to the reference at 20 ºC, the failure load increased about 22%. Further increasing the temperature to 65 ºC, 80ºC and 100ºC resulted in a lower failure load than at 20 ºC for both types of specimen, C_SC and G_RB, though the extent of the reduction in failure load differs significantly. In particular, Q_u decreases 10% at 65 ^oC, 45% at 80 ^oC and 58% at 100 ^oC in the case of specimens C_SC; the decrease of the failure load for specimens G_RB is equals to 18% and 71% respectively at 65 ^oC and 100 ^oC. The reduction in strength for the higher temperatures can be understood when it is realized that the glass transition temperature of the applied adhesive was 65 ºC.

Also for the specimens reinforced with NSM strips (C_STR) a decrease of the maximum load is observed at 100 ^oC. The tendency of smaller decrease of ultimate load of specimens with CFRP strips with respect to specimens reinforced with NSM round bars can be explained as follow. Considering that all the specimen were embedded into the grooves with the same epoxy resin, the relative smaller width of the grooves induce a better protection of the resin to elevated temperature exposure. Other influencing aspects are the higher confinement effect of the concrete on NSM strips, the bond stiffness and the surface texture.

Moreover it was found that the bond failure aspect was significantly influenced by the temperature. While for specimen C_SC tested at 50 ºC the failure mode was still characterized by debonding with splitting of the resin, increasing the temperature, a debonding at the FRP/resin interface (DB-PO) with pull out of the bar/strip occurred (see figure 4). Indeed, by increasing the temperature the mechanical properties of the glue dropped below that of concrete. Above T_g all specimens failed by debonding with pull-out of the bar/strip (DB-PO) except the ribbed bars at 65 ºC, which debonded at the epoxy/concrete interface (DB-E/C). This different behaviour may be related to the different surface configuration that aids a higher adhesion of the ribbed area of GFRP bars, avoiding the failure at the interface bar/resin. Increasing the temperature to values above the glass transition temperature (80 and 100ºC) the failure aspect becomes similar for all the specimens, as in this condition the adhesive is always the critical component.

a) 
b) 
c) 

Figure 4.Failure modes a) debonding with splitting of the resin, b) debonding at epoxy/concrete interface, c) debonding with pull-out of the bar.

5 CONCLUSIONS

A series of 18 double shear bond tests at different service temperature were carried out in order to investigate the influence of the temperature on the bond behavior of NSM FRP bars/strips in concrete. On the basis of the performed experimental investigation the following conclusions can be made:

- For the specimens in this study the failure load first increases with elevated temperature and only decrease for temperatures equal to or beyond the glass transition temperature. However the decrease of the failure load at the glass transition temperature was only 10% for C_SC and 18% for G_RB with respect to the failure load at room temperature.
- For the temperature range tested in this program till about 1,5 T_g (100 ^oC), no complete degradation of bond strength was found.
- The type of failure changes with increasing test temperature. For the specimens tested at 50 ^oC the failure mode was still characterized by debonding with splitting of the resin, increasing the temperature, a debonding at the FRP/resin interface with pull out of the bars/strips occurred (figure 4c). Indeed, by increasing the temperature the mechanical properties of the glue dropped below that of concrete causing lower failure load and related change in failure mode.

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