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BOND SHEAR STRESS-SLIP RELATIONSHIPS FOR FRP-NSM SYSTEMS AT ELEVATED TEMPERATURE

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ABSTRACT

In the last years Near Surface Mounted (NSM) reinforcement has mainly been applied at ambient temperature, to strengthen reinforced concrete (RC) beams with FRP (fibre reinforced polymer) materials. Thereby, FRP bars/strips are embedded inside the concrete section by means of grooves filled with adhesive. The behaviour of FRP-NSM strengthening systems at elevated temperature is signicantly influenced by the type of adhesive (e.g. cementitious grout is usually more stable than epoxy resin at high temperature). To characterize the FRP-NSM behaviour two steps are needed: 1) shear tests performed in order to determine the FRP-concrete interaction via bond stress-slip curves and 2) constitutive bond stress-slip relationships for use in structural design (analytical and numerical). Hereby, the bond behaviour is to be considered temperature dependent. During two experimental campaigns, double bond shear tests were performed in order to study the behaviour of FRP-NSM systems at elevated temperature using different types of adhesive, epoxy resin and cementitious grout respectively. The bond shear stress-slip curves are discussed including the effect of different types of adhesive. Simplified bond stress-slip relationships are proposed to model the FRP-concrete interaction at high temperature.

1 INTRODUCTION

Thanks to their endurance under aggressive environmental conditions, FRPs materials have found application in the civil engineering field as structural members (i.e. pultruded elements) and as internal/external reinforcement in new/existing concrete elements. FRP reinforcement is generally formed by continuous fibres (i.e. glass, carbon, basalt, aramid) immersed into an epoxy matrix. In this configuration the bearing capacity of the FRP element depends on the tensile strength of the fibres and the internal shear transfer between the matrix and the fibre surfaces. In case of new concrete structures, FRP bars may be used alternatively to steel reinforcement, whereas externally bonded reinforcement (EBR) and near surface mounted (NSM) techniques may be executed to strengthen existing structures. In EBR, laminates or sheets are surface bonded to the tensile face of

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the member, while in NSM, FRPs are embedded into the concrete cover through grooves. Glueing and embedding are usually done by epoxy or cementitious grout. Experimental results have shown that the performance of EBR/NSM strengthening systems is significantly influenced by the debonding of FRP from the concrete member. This behaviour is accelerated when FRP strengthened concrete beams are exposed to elevated temperature. Indeed, at high temperatures constitutive materials (i.e. concrete, steel, FRPs and epoxy) react in different ways, generally degrading their strength and bond capacity. In particular, the mechanical properties of epoxy adhesive significantly drop at temperatures close to or beyond their glass transition temperature (T_g). Because of the limited T_g of ambient cured epoxy adhesive (60°C-80°C), debonding in FRP strengthened members may happen in the case of fire during the early-stage heating up. T_g of the epoxy matrix inside FRP elements shows higher T_g values (~120°C) whereas during the pultrusion process FRPs are cured at elevated temperature.

In the last years, researchers have focused on the study of the bond behaviour between FRP and concrete in order to predict the bearing capacity of FRP strengthened members mainly at ambient temperature. This bond behaviour may be described by means of shear stress-slip relationships obtained using shear tests (single, double or beam configuration). Data on the bond behaviour provided by shear tests performed at elevated temperature should be treated with care because of the possible influence of thermal effects. In this work, double bond shear tests at room and elevated temperature conducted on NSM strengthening are presented and obtained results are compared and discussed. The influence of the adhesive material will be shown. Finally, a temperature dependent bilinear bond stress-slip relationship is tentatively proposed.

2 DOUBLE BOND SHEAR TEST: TEST SET-UP

The specimen is formed by two different concrete blocks (150mm x 150mm x 400mm) separated by a thin metal plate. A square groove (16mm x 16mm) was incised in the middle at both sides for embedment of the NSM CFRP (carbon fibre reinforced polymer) bars by adhesive material. The tensile load was applied by means of two steel bars (ø 16mm) embedded in each prism. The two concrete blocks are only joined by means of the 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. During testing the following measurements have been performed: 1) strains by means of five strain gauges (SG) placed along the bond length, 2) relative displacement between the concrete blocks through linear variable displacement transducers (LVDTs), 3) load and 4) temperatures at different locations. The specimen were heated by an electrical hollow furnace place around 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. To reach an uniform temperature distribution inside the concrete block, the oven temperature was kept constant for at least 18 hours before testing. The temperature was maintained constant during testing. The main differences between the two test programs concern the materials and temperature range, as reported in *Table 1*.

Table 1. Material properties

Author	T range [°C]	filler type	Øbar [mm]	Bar texture	T_g [°C]
Palmieri (2013) [1]	20 - 100	epoxy	9,56	sand coated	63 $^{(1)}$
Cassaert (2014) [2]	20 - 285	grout	7,86	ribbed	220 $^{(2)}$

(1) T_g of epoxy groove filler, (2) T_g of FRP bar matrix: the cementitious grout, for which no T_g can be determined, has a high temperature resistance, similar to that of concrete.

3 BOND BEHAVIOUR OF EPOXY BONDED MSM AT ELEVATED TEMPERATURE

To characterize the bond behaviour between the adhesive and the concrete by means of bond stress-slip relationships, bond parameters need to be defined. Indeed, several bond stress-slip shapes have been proposed in the literature to described the bond interaction. In the following (*Fig. 1*), a bilinear bond model is used as a good compromise between the theoretical bond behaviour and the quality of the bond shear stress-slip obtained by the double bond shear tests. At each test temperature, three parameters need to be obtained to describe the bilinear bond model: the maximum bond strength or peak shear stress (τ_{f1}), the slip at the maximum bond strength (s_1) and the ultimate slip (s_u). The surface under the τ-s curve is defined as the fracture energy (G_f) and the stiffness of the initial branch is indicated as (k). To express the experimental results in terms of the bilinear relationship, the following equations are used:

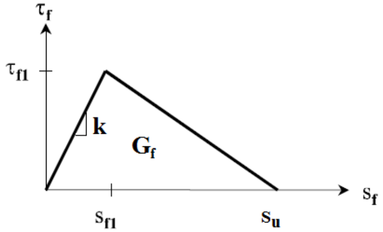

Fig. 1. Bilinear bond shear stress-slip model

$$s_{f1} = \frac{\tau_{f1}}{k} \tag{1}$$

$$s_u = \frac{2G_f}{\tau_{f1}} \tag{2}$$

$$G_f = \frac{P_u^2}{2E_f A_f u_b} \tag{3}$$

where A_f is the FRP cross-section area, u_b the bond perimeter and P_u the failure load (note that total failure load of the double bond test is divided by 2 to consider the epoxy bonded FRP at both side faces of the specimen).

In *Eq. (1) and (3)*, the maximum bond strength, the initial stiffness and the failure load are experimentally evaluated. In order to compare the behaviour of NSM, the experimental investigation carried out on EBR by Blontrock [3,4] has been assumed as a reference. EBR double shear tests were performed using the same test set-up described in *Section 2*, however with surface (epoxy with T_g=63°C) bonded CFRP laminates (width=100mm, thickness=1,2mm), instead of CFRP bars in grooves. In both the NSM and EBR test campaign strain gauges, glued on the FRP surface, have allowed to recreate the bond shear stress-slip along the bond length. The results of the comparison are shown in *Figs. 2 till 7*. The maximum shear capacity in function of the temperature tends to be higher in NSM than EBR as shown in *Fig. 2*. The increase in bond strength may be attributed to the improved aggregate interlocking of NSM as a reaction to the radial compression stresses caused by the pull-out force. The bond strength is visibly influenced by the temperature, indeed close to or beyond the T_g, the maximum shear stress decreases. At 100°C the residual bond strength in NSM is 82% less than τ_{f1} at room temperature. At first glance, τ_{f1} seems more significantly affected by temperature in NSM than EBR but *Fig. 3* reveals essentially the same behaviour. The observation of the failure mode in EBR and NSM shows that at elevated temperature the failure mode is governed by the degraded mechanical properties of the epoxy adhesive. In EBR, the failure surface shifts from the concrete substrate to the concrete-FRP interface and, in NSM, concrete cracking around the grooves decreases because of the softer epoxy which reduces the radial compression action around the bars. The aggregate interlocking effect may also explain the higher initial stiffness (k) of NSM shown in *Fig. 4*. The recorded stiffness values are subjected to a steep decrease close to T_g especially for EBR (*Fig. 5*). The more confined pull-out effect of NSM might be able to somewhat counteract the negative effect of the temperature on the stiffness reduction in NSM configuration.

The fracture energy (*Figs. 6 and 7*), calculated by *Eq. 3*, seems affected by the influence of the different CTE (coefficient of thermal expansion) between CFRP and concrete. Indeed, before T_g (when epoxy is still able to manifest its full properties), the failure load first increases and the expected decay only starts close and beyond T_g. The ultimate failure load decreases at high temperature because of the reduced epoxy strength properties and the increase of the effective transfer length which becomes eventually longer than the available bond length.

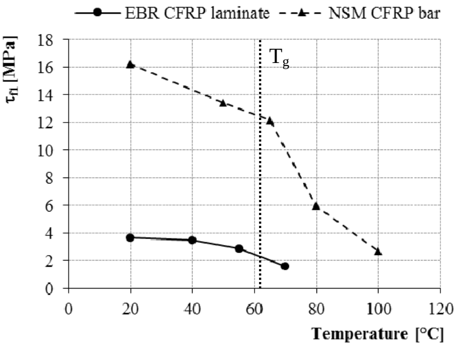

Fig. 2. Shear stress peak in EBR and NSM FRPs as a function of the temperature

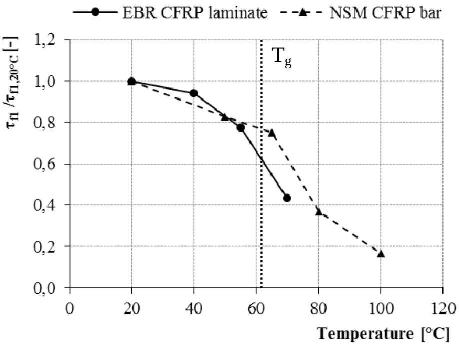

Fig. 3. Relative shear stress peak in EBR and NSM FRPs as a function of the temperature

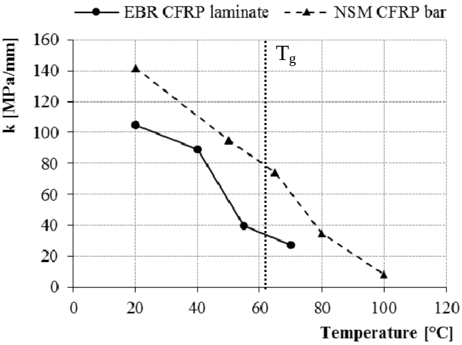

Fig. 4. Initial bond stiffness in EBR and NSM FRPs as a function of the temperature

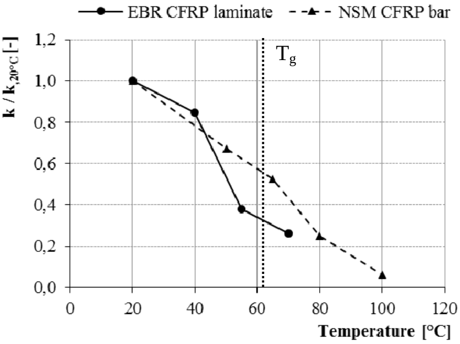

Fig. 5. Relative initial bond stiffness in EBR and NSM FRPs as a function of the temperature

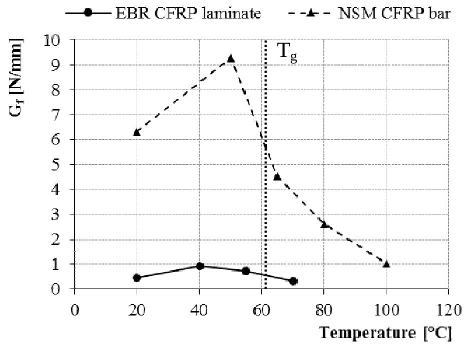

Fig. 6. Fracture energy in EBR and NSM FRPs as a function of the temperature

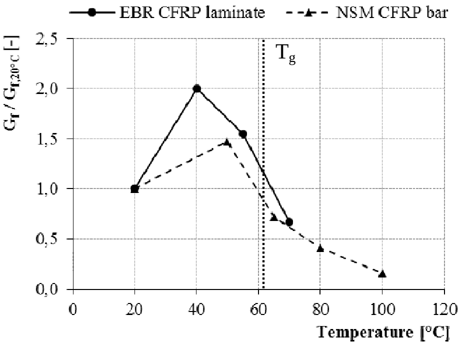

Fig. 7. Relative fracture energy in EBR and NSM FRPs as a function of the temperature

A further evaluation of the temperature dependent NSM bond behaviour is given in *Figs. 8 and 9*. In *Fig. 8*, the peak shear strength (τ_{f1}) and the average shear strength (τ_{av}) are compared in function of the temperature in order to understand in which condition the average shear stress can represent the peak shear strength.

$$\tau_{av} = \frac{P_u}{L_b u_b} \tag{4}$$

where L_b is the bond length.

At elevated temperature the average shear stress tends to get equal to the peak shear strength (recorded by strain gauges). Indeed, beyond the glass transition temperature the FRP strains and shear peak stresses become more uniformly distributed along the bond length (*Fig. 9*).

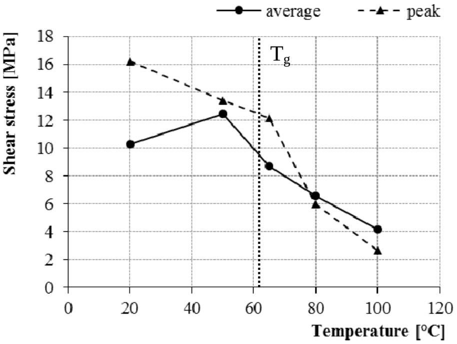

Fig. 8. Average and peak shear stress in CFRP NSM system as a function of the temperature

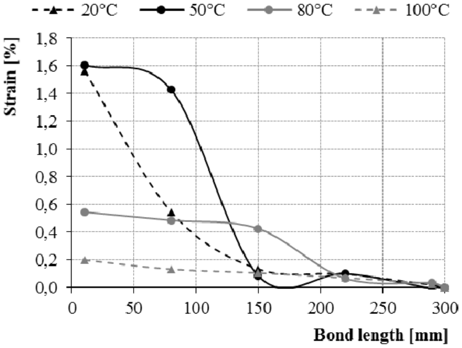

Fig. 9. CFRP strain distribution along the bond length as a function of the temperature

4 BOND BEHAVIOUR OF GROUT BONDED NSM AT ELEVATED TEMPERATURE

The behaviour of the average shear stress (τ_{av}) in NSM bonded with cementitious grout is shown in *Figs. 10 and 11*, relative to epoxy bonded NSM. For the grouted system two different critical temperature points are obtained (Cassaert 2014): 100°C (evaporation point) and 220°C (T_g of the FRP bar matrix). Indeed close to the evaporation point the failure load reduces by 20%. This relates to the dehydration effect in the grout. At 220°C, the NSM system reaches the T_g value of the FRP bar matrix

and starts to decay further because of the reduction in interlaminar shear capacity inside the FRP bar.

Comparing epoxy with grout bonded NSM, epoxy filler seems more efficient at room temperature due to its higher initial bond capacity, compared to grout. Unfortunately, the endurance temperature range of epoxy appears quite short because of the T_g of the adhesive. It means that epoxy bonded FRP NSM strengthened members, need to be properly protected by thermal insulation systems in case fire resistance is required.

It should be clearly stated that the obtained results are specific to the material properties and configurations used in the bond tests. This is especially for the grout bonded FRP-NSM, for which a high temperature resistant FRP bar has been used to benefit better from the higher intrinsic temperature resistance of the cementitious grout.

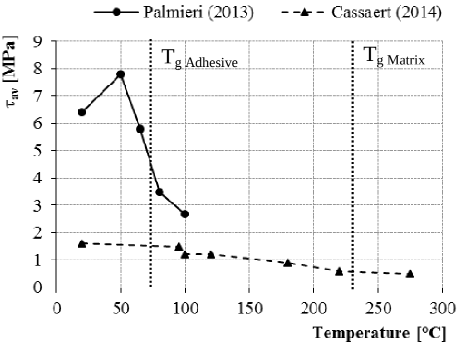

Fig. 10. Average bond strength in [1] and [2] as a function of the temperature

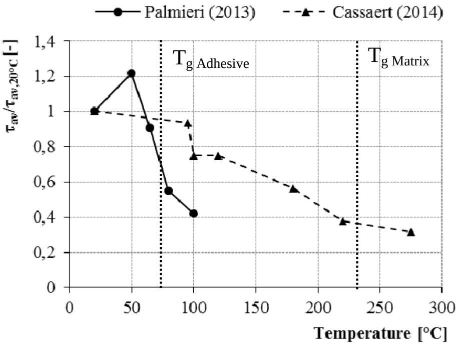

Fig. 11. Relative average bond strength in [1] and [2] as a function of the temperature [3, 5]

5 TEMPERATURE DEPENDENT BILINEAR BOND SHEAR STRESS-SLIP MODEL

In this section, by means of the available experimental results, a bilinear bond shear stress-slip model is tentatively proposed in function of the temperature. Bond models have been drawn, as explained in *Section 3,* for NSM-CFRP epoxy bonded (*Figs. 12 till 15*) and grout bonded systems (*Figs. 16 till 19*). The temperature dependency of the experimental bond parameters (G_f, τ_{f1} and k) are presented in relation to the their values at ambient conditions. The resulting τ-s model for increasing temperature is given in *Figs. 15 and 19* respectively. In case of epoxy bonded NSM-CFRP, the proposed model in *Fig. 15,* has been calibrated based on [1] between 20°C-100°C. The degradation of the bond parameters is significantly influenced by the T_g and any general formulations of the bond parameters should be considered in relation to T_g. In addition, the surface deformation pattern of the FRP bars should be also taken into account because of the influence on the failure mode [6]. To increase the accuracy of the bond-parameter interpolation in *Fig. 12,* the fracture energy value at 40°C has been added from [2].

In case of grout bonded NSM-CFRP, the proposed model in *Fig. 19* has been calibrated based on [2] between 20°C-180°C. The limited number of the considered reliable experimental results allowed to only use a linear approximation in order to describe the behaviour of the shear stress peak and the initial stiffness.

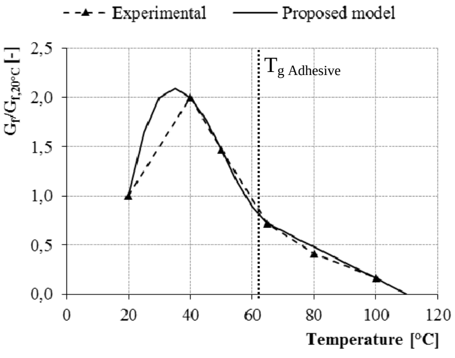

Fig. 12. Relative fracture energy as a function of the temperature in FRP-NSM epoxy bonded

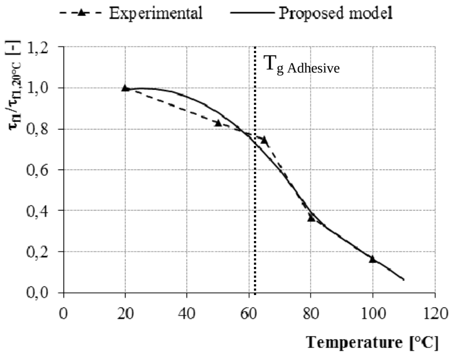

Fig. 13. Shear stress peak as a function of the temperature in FRP-NSM epoxy bonded

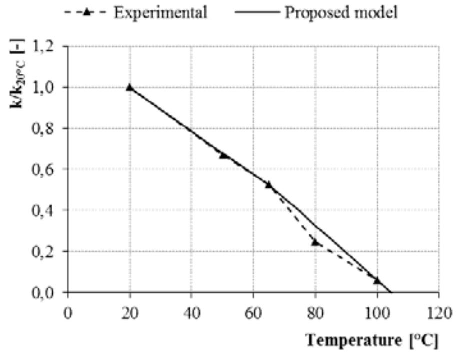

Fig. 14. Relative initial stiffness as a function of the temperature in FRP-NSM epoxy bonded

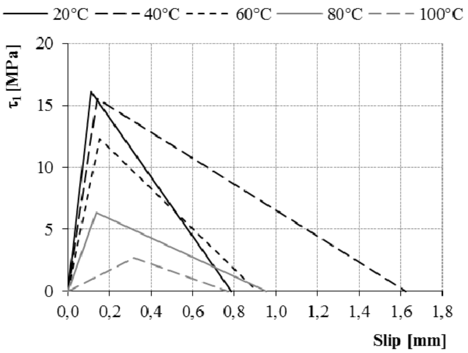

Fig. 15. Bilinear bond model as a function of the temperature in FRP-NSM epoxy bonded

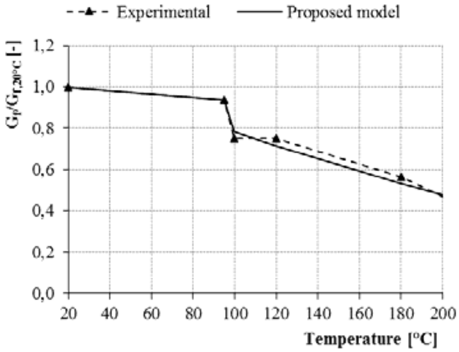

Fig. 16. Relative fracture energy as a function of the temperature in FRP-NSM grout bonded

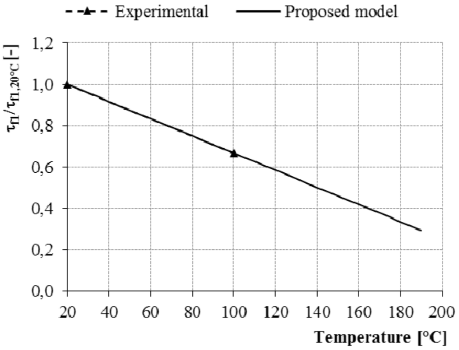

Fig. 17. Relative shear stress peak as a function of the temperature in FRP-NSM grout bonded

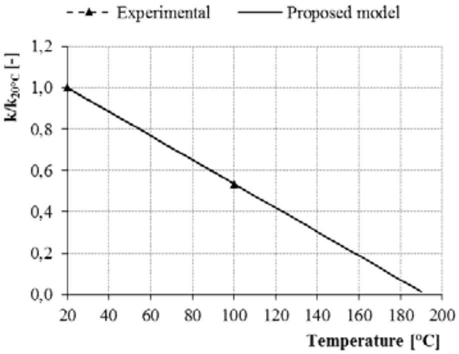

Fig. 18. Relative initial stiffness as a function of the temperature in FRP-NSM grout bonded

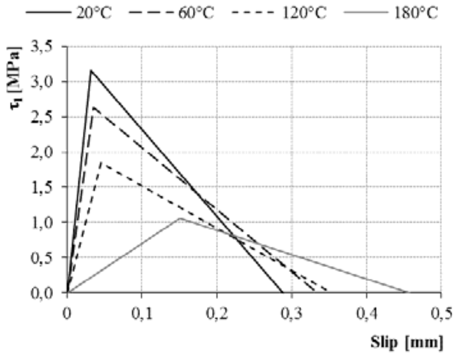

Fig. 19. Bilinear bond model as a function of the temperature in FRP-NSM grout bonded

6 CONCLUSIONS

The study reported in this paper confirms the significant influence of the temperature on the bond behaviour in FRP NSM strengthening systems. The observations previously made can be summarized by the following points:

1) At elevated temperature, bond shear stress-slip relationships obtained by strain gauge recordings tend to be less reliable. For this reason, the three parameters of the bilinear bond model represent a more practical solution to model the bond behaviour between FRP and concrete.
2) Although epoxy bonded FRP NSM systems show a higher bond strength than FRP EBR, both systems reveal the same behaviour at elevated temperature. The bond strength tends to significantly decrease close to or beyond the T_g (63°C-for this study). In the NSM system, at 100°C the residual bond strength is 18% of the strength evaluated at 20°C. At temperatures beyond T_g, the peak shear stress of the bond shear stress-slip can be approximated with the average shear stress obtained by the failure load.
3) Fracture energy and bond stiffness show a reduction with increase of the temperature. In particular, in FRP NSM system the stiffness reduction around T_g tends to be less pronounced than for EBR.
4) A temperature-dependent bilinear model based on the experimental results [1] [2], has been tentatively proposed. In epoxy and grout bonded FRP-NSM the degradation of the bond parameters is mainly governed by the glass transition temperature of the adhesive and the bar matrix without underestimating the influence of the surface texture on the failure mechanism.

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