Literature Review on Reinforced Concrete Members Strengthened with FRP at Room and Elevated Temperature

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ABSTRACT

In the last 30 years, composite materials have been successfully applied as structural reinforcement to strengthen existing structures. The success of applying FRPs (Fibre Reinforced Polymers) for strengthening is due to their excellent mechanical properties and durability, their ease of application and the versatility of FRP strengthening systems. In particular Near Surface Mounted (NSM) reinforcement offers an interesting technology in terms of protection of the FRP from external influences compared to the Externally Bonded Reinforcement method (EBR).
Based on a literature review, this paper discusses the structural performance in terms of FRP to concrete bond behaviour at room and elevated temperature. To understand and characterize the bond interaction, researchers conducted bond shear tests, though the lack of a standard test methodology makes comparison of results not always straight forward. As such, this study looks into bond influencing factors such as concrete type, adhesive type, FRP roughness, groove dimensions, glass transition temperature and coefficient of thermal expansion.

INTRODUCTION

Researchers studied the behaviour of EBR and NSM systems under room and elevated temperature through different methods: 1) experimental models on real scale, 2) experimental models on medium scale measuring deformations along the bonded length (single bond test, double bond test, bending test), 3) empirical methods to characterize the best fit bond-slip relationship through semi-analytical models, and 4) numerical verifications through finite element modelling. The greatest number of reported results concerns methods 2) and 3) at room temperature. As there is not a standard procedure to analyse the bond-slip behaviour, this leads to results that are arduous to compare although some efforts to introduce an unified methodology have been proposed (e.g. Serbescu et al. [1]). In this paper a comparison is made of experimental results available in the literature, regarding the bond behaviour of EBR (Externally Bonded Reinforcement) and NSM (Near Surface Mounted) reinforcement at room and especially elevated temperature. Hereby, factors such as concrete type, adhesive type, FRP roughness, groove dimensions, glass transition temperature and coefficient thermal expansion are considered. Table 1 gives an overview of the selected literature and the scope of parameters used in the experimental work of these authors [2-11].

CONCRETE STRENGTH AND TEMPERATURE DEPENDENCY OF THE BOND STRENGTH

Tadeu and Branco [2] were among the first to study EBR bond shear interaction with increasing temperature. They realized shear tests on steel plates bonded to concrete, with different concrete strength classes (f_{cm} 27.9, 44.4, 74.1 MPa) and different temperature conditions (30˚C, 60˚C, 90˚C, 120˚C). The obtained results are shown in Figs. 1 and 2 (black curves) and can be summarized as follows:
- The maximum shear stress (described in terms of mean value along the bond length) at room temperature increases with concrete tensile strength.
- The decrease in shear strength for initial increase of temperature (20°C-60°C range) is higher for higher strength concrete classes.

Table 1. Summary of test reported in the paper

Reference	**System**	**Bond test**	**Material** $^{(1)}$	**L$^{(2)}$, w$^{(3)}$ [mm]**	**Adhesive** $^{(4)}$	**Concrete ($f_{cm}$$^{(5)}$ [MPa])**	**Temp. range**
Tadeu, Branco [2]	EBR	Double	Steel	100, 80	Epoxy	27.9, 44.4, 74.1	20-120°C
Blontrock [3]	EBR	Double	CFRP	300, 100	Epoxy (T_g=55°C)	44	20-70°C
Klamer [4]	EBR	Double	CFRP	300, 50	Epoxy (T_g=62°C)	41.1, 70.8	20-100°C
Leone, Matthys [5]	EBR	Double	CFRP, GFRP	300, 100	Epoxy (T_g=55°C)	50.3, 41.3	20-80°C
De Lorenzis [6]	NSM	Single	CFRP, GFRP	Figs.8-9	Epoxy, Cem. mortar	22*	20°C
De Lorenzis [8]	NSM	Single	CFRP, GFRP	Figs.8-9	Epoxy, Cem. mortar	22*	20°C
Palmieri [9]	NSM	Double	CFRP, GFRP	300,Fig5	Epoxy (T_g=66°C)	45	20-100°C
Kalupahana [10]	NSM	Single	CFRP	Figs.6-7	Epoxy (T_g=55°C)	30, 60	20°C

(1) CFRP: carbon fibre based FRP, GFRP: glass fibre based FRP
(2) L: bond length
(3) w: FRP width (EBR) or FRP bar diameter (NSM)
(4) T_g: glass transition temperature as far as mentioned by the authors
(5) f_{cm}: mean value of compressive (cube, *cylinder) strength of concrete

- At elevated temperature beyond 70°C the bond strength becomes indifferent to the concrete strength. This latter conclusion can be explained by also looking to the failure mode, as done by Leone et al. [5] amongst others. They observed different failure modes at room (20°C) and elevated (80°C) temperature. At ambient temperature, a thin concrete layer was attached to the laminates (cohesion failure) when the specimen reached the ultimate load. At elevated temperature, the failure surface was in the interface between the adhesive and the FRP reinforcement (adhesion failure). This change in failure mode is due to the loss of mechanical properties when the adhesive is subjected to a temperature beyond the glass transition temperature (T_g).

The influence of concrete strength has also been analysed in the study by Klamer [4], who studied the bond behaviour of a concrete-epoxy-CFRP joint in connection with different concrete strengths (41.1-70.8MPa) and temperature (20°C-100°C range). As illustrated in Fig.1 and in contradiction with the work by Tadeu and Branco, Klamer [4] observes no influence of concrete strength on the bond shear strength at room temperature. Data reported by Lu et al. [12] provides unclear results as well (see Fig. 3). These results indicate that surface roughness, surface preparation and lower adhesive strength might govern over concrete strength properties.
From the work by Klamer [4] and similar work by Blontrock et al. [3] and Leone et al. [5] a tendency of an increasing bond strength of concrete-CFRP joints is observed with increasing temperature lower than T_g. When the temperature overtakes T_g, the failure load starts decreasing significantly, though some remaining capacity is still observed for the tested temperature ranges.

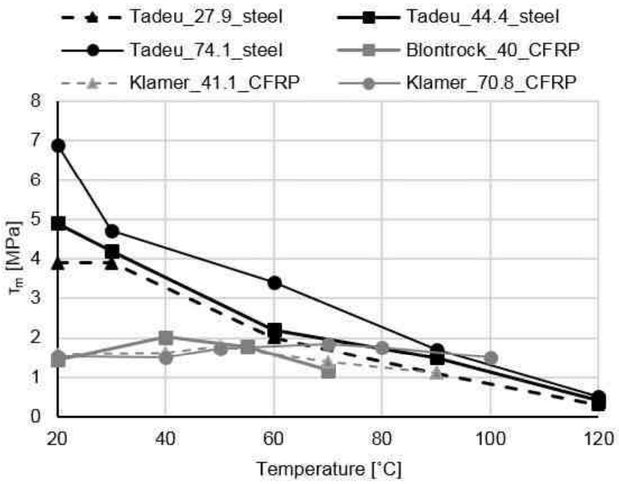

Figure 1. Bond strength as a function of temperature for different concrete type (EBR)

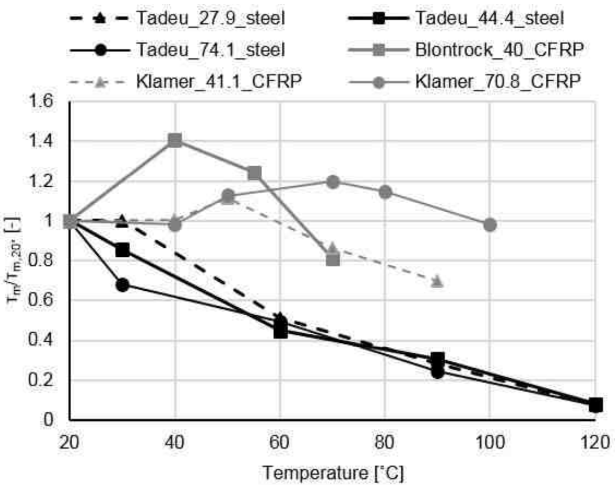

Figure 2. Normalized bond strength as a function of temperature for different concrete type (EBR)

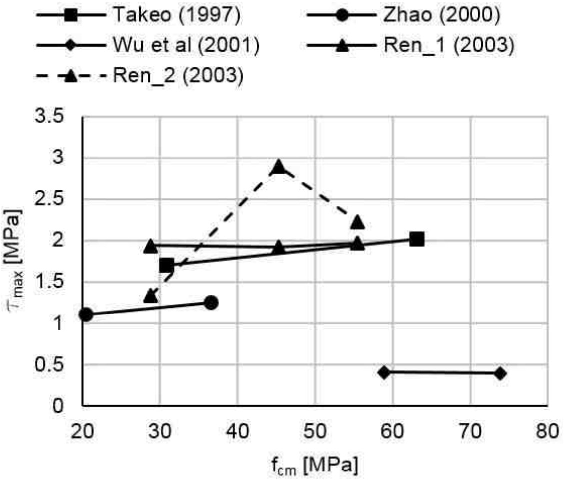

Figure 3. Influence of concrete strength reported by Lu et al. [12]

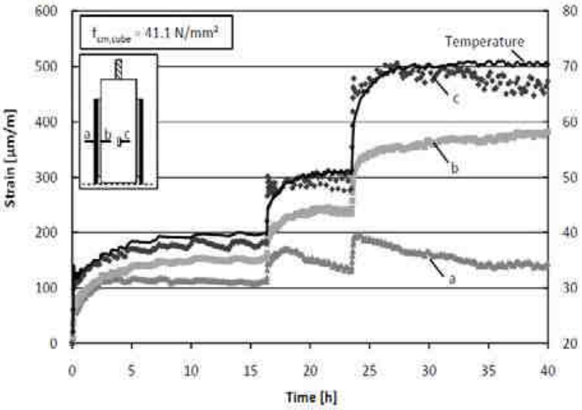

Figure 4. Strain development due to heating up to 40°C, 50°C and 70°C [4]

This indicates that besides reduction of mechanical properties of the adhesive with increasing temperature and especially at T_g, other phenomena are of influence. Different authors attribute the observed initial strength increase with temperature to the difference of coefficient of thermal expansion (CTE) between the concrete (~$10x10^{-6}$ 1/°C) and the CFRP
(~$0x10^{-6}$ 1/°C), and the related restrained deformations. Indeed, whereas the initial increase of strength has been reported for CFRP, this is not the case for steel plates (Fig. 2) or GFRP strips, as these materials have a CTE more close to that of concrete. In Fig. 4, the different strain development in the CFRP and concrete due to heating and restrained thermal expansion is shown, as has been observed by Klamer [4]. Upon expansion of the concrete, axial stresses are introduced in the CFRP and in relation to this compressive stresses in the substrate.

To explain the initial increase in bond strength, analytical models have been reported. Klamer uses an elastic shear stress model, as proposed by Di Tommaso [13], to calculate the CFRP axial and shear stresses along the bond length resulting from a temperature increase. These shear stresses might appear opposite to the shear stresses due to acting load. The model is further refined by Klamer taking into account the substrate and adhesive layers, and considering their stiffness being temperature dependent. As such 3 effects can be considered: 1) decreasing mechanical strength of the adhesive with increasing temperature, 2) effect of thermal shear stress versus acting load shear stress, and 3) stiffness reduction of the adhesive with increasing temperature and resulting increase in bond transfer length.
In their work, Abdel Baky et al. [14] propose a multi-axial failure stress envelope, in which the axial compression stress in the substrate (due to restrained thermal effects) increases the maximum shear stress.
In Palmieri [9] the author reports a double shear tests on NSM FRP bars/strips at elevated temperature.

The results, in terms of normalized bond capacity, are shown in Fig. 5 and further compared with EBR double shear test results by Leone et al. [5]. On overall similar trends are obtained between NSM and EBR as a function of temperature, as similar thermal effects take place. To explain the increasing bond strength for initial temperature increase before T_g, Palmieri considers an adapted version of the Di Tommaso model, to be applicable for NSM.

Looking further into the result of Palmieri, after the glass transition temperature, bars and strips tend to experience the same failure load. This fact reveals that FRP texture (ribbed, sand coated, spirally wound) become less important when the adhesive shear modulus decreases. De Lorenzis [6, 15] offer a detailed description of the failure mode at room temperature for NSM bars with different FRP surface texture. The authors claim that the adhesive strength becomes more important for an embedded bar with a deformed surface.

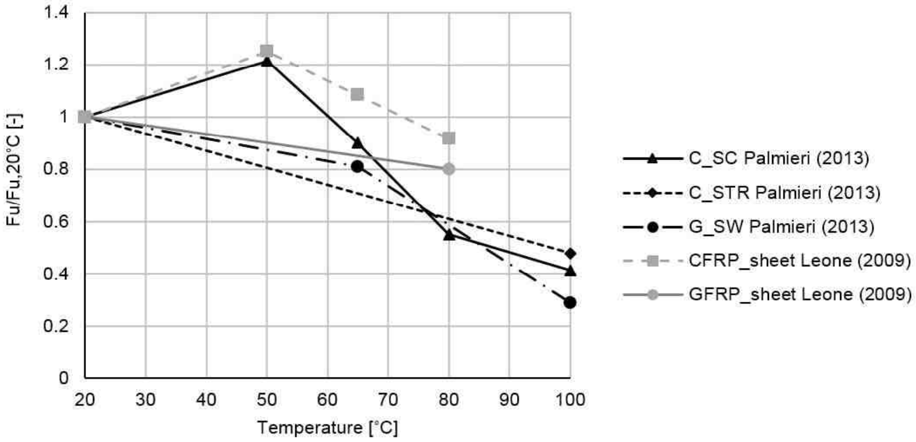

Figure 5. Bond capacity as a function of temperature (C_SC–CFRP sand coated bar Ø9.53mm, G_SW-GFRP spirally wound bar Ø10mm, C_STR-CFRP strip 2mmx16mm) [5] [9]

NSM GROOVE SURFACE AND FILLER TYPE DEPENDENCY

NSM reinforcement being bonded into grooves, its bond behaviour is affected by more parameters, such as FRP type (bars or strips), FRP roughness, width groove – bar diameter ratio (K), and groove roughness. To capture how these factors impact on bond failure load, a parametric study result is undertaken and compared to pre-existing data. De Lorenzis et al. [6, 8] analysed CFRP and GFRP rods with a deformed surface, as well as CFRP spirally wound bars in smooth and rough grooves; for different groove width – bar diameter ratios and groove fillers (epoxy and cement mortar). Kalupahana et al. [10] studied the failure load of CFRP, GFRP bars and CFRP strips in epoxy filler with different groove dimensions and concrete type. Laraba et al. [11] made tests on CFRP smooth bars and strips in epoxy filler with different concrete types.

As reported in Fig. 6 CFRP ribbed (and smooth) bars increase their failure load with higher concrete strength classes. Indeed, the concrete strength influence is especially observed in relation to failure modes which are localized in the concrete substrate. Although there is a correlation between failure load and concrete strength (Fig. 6) some researchers did not observe this behaviour. Organizing the results of Takeo, Zhao, Wu et al. and Ren reported by Lu et al. [12] an unclear failure load-concrete strength relationship comes to light (Fig. 3). Cruz and Barros [16] underline how NSM bond failure at room temperature was not influenced by the concrete type. According to the authors sliding happens in the concrete-adhesive interface and failure load did not rise with the concrete strength.
These different behaviours can be related to the adhesive strength and groove roughness. Indeed concrete strength might not be of influence if the adhesive is not able to transfer shear stresses into the substrate.

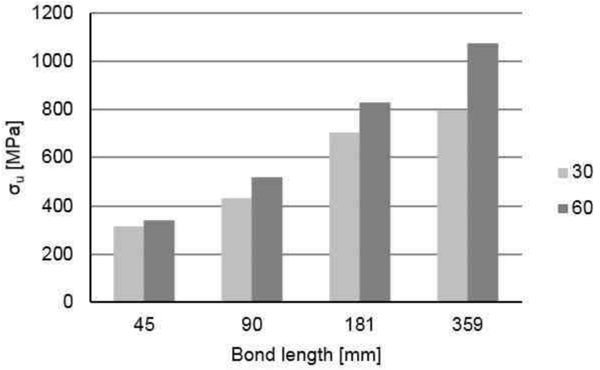

Figure 6. Ultimate stress CFRP ribbed Ø9mm with different concrete strength (groove 13x13 – K=1.44) [10]

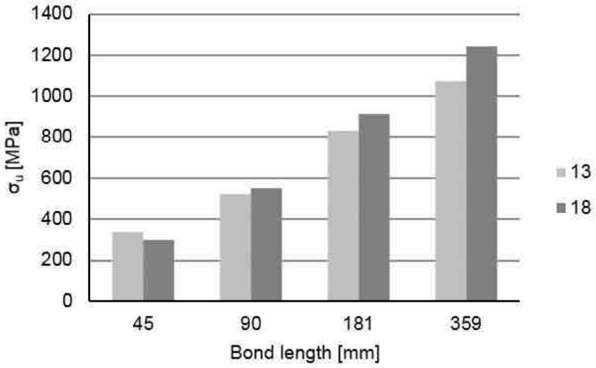

Figure 7. Ultimate stress CFRP ribbed Ø9mm bars with different width grooves (f_{cm}=60MPa) [10]

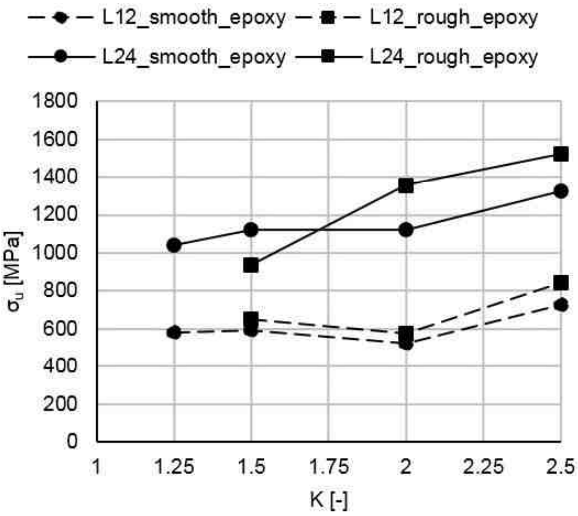

Figure 8. Ultimate stress CFRP spirally wound Ø7.5mm with different K ratio and groove type [6] [8].

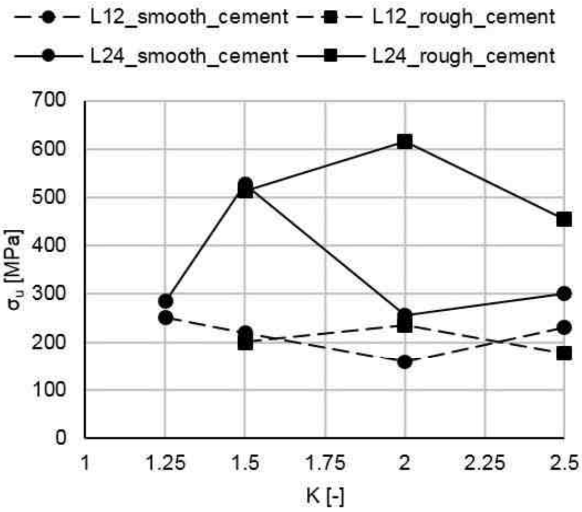

Figure 9. Ultimate stress CFRP spirally wound Ø7.5mm with different K ratio, groove and filler type [6] [8].

Figs. 8 and 9 report the failure load-groove dimension dependence of CFRP spirally wound bars embedded with different groove filler (epoxy and cement mortar) and groove surface types (rough and smooth). This comparison allows to make 4 observations: 1) when K rises the bond failure shows a tendency to increase for bars embedded with epoxy in rough and smooth grooves, 2) bars embedded with epoxy filler in rough grooves reach failure loads similar yet somewhat greater than smooth grooves, 3) the failure load does not reveal a K dependency for cement filler in rough and smooth grooves, and 4) epoxy filler allows to reach higher bond strength than cement mortar due to the limited tensile (or shear) strength of the latter.

EFFECT OF TEMPERATURE ON BOND-SLIP AND TRANSFER LENGTH

Bond stress-slip studies (Leung et al. [17], Pan et al. [18]) relate the initial slope of the bond-slip relationship to the adhesive shear modulus. This adhesive influence can be observed in Figs. 10-13 where the initial bond stress-slip slope decreases, especially for temperatures beyond T_g.

Looking to the CFRP NSM specimen C_SC in Fig. 10, a shear peak gain of 30% is observed between 20˚C and 50˚C. Between 20˚C and 65˚C the peak stress is similar. These observations are in line with Fig. 2. For the GFRP specimen G_SW (Fig. 11) the peak stress seems to decrease more quickly. This different behaviour is due to the different CTE between carbon and glass fibres. As already reported, thermal effects create axial compression stresses into the substrate, increasing the shear strength.

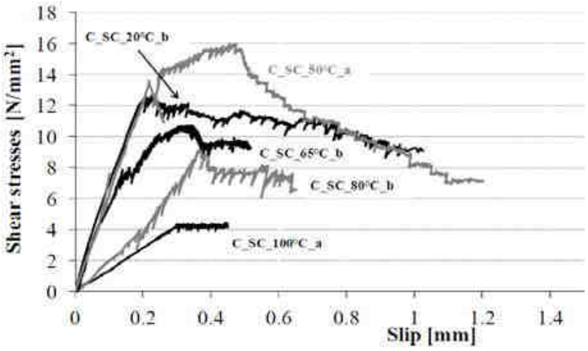

Figure 10. Bond stress-slip curves specimen C_SC at different temperature (NSM) [9]

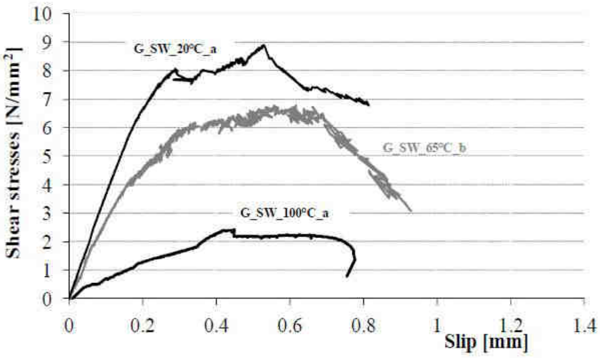

Figure 11. Bond stress-slip curves specimen G_SW at different temperature (NSM) [9]

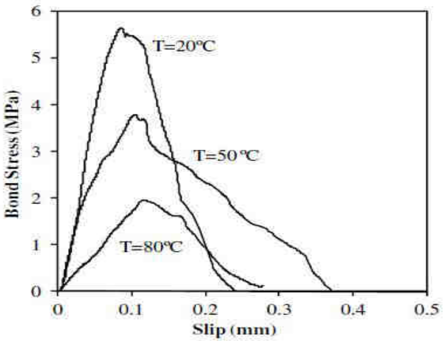

Figure 12. Bond stress-slip curves for varying test temperatures – CFRP laminates (EBR) [5]

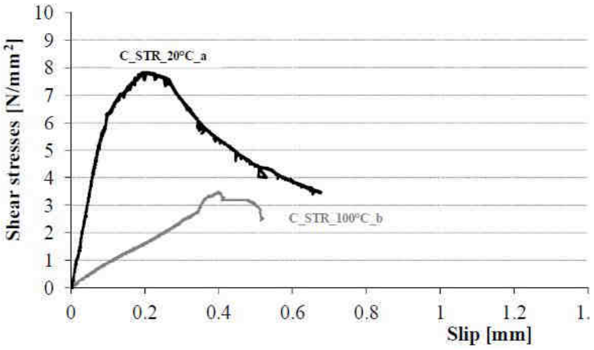

Figure 13. Bond stress-slip curves specimen C_STR at different temperature (NSM) [9]

Looking into the post-peak branch of the bond stress-slip curves, it can be observed that there is a difference between EBR (Fig.12) and NSM (Fig.10, 11, 13) for T=20˚C - 100˚C.

In NSM the bars and strips embedded in the concrete groove tend to slip upon bond failure creating shear stresses related to the friction coefficient between concrete-adhesive, while EBR does not show residual shear stress. Temperature changes the NSM failure mode and this can be observed from the magnitude of the last branch of bond stress-slip curve. At 20˚C the failure load involves sliding between a concrete-adhesive interface and at 100˚C bars slip in the adhesive with a different friction coefficient.

In Fig.14 the ratio of the bond transfer length at temperature T over that at 20˚C is shown for NSM (C_SC-CFRP sand coated bar) and EBR (C_S-CFRP sheet, C_L-CFRP laminate). As the adhesive stiffness decreases with increasing temperature, the bond transfer occurs over a longer length. Following Fig.14, the transfer length might double beyond T_g.

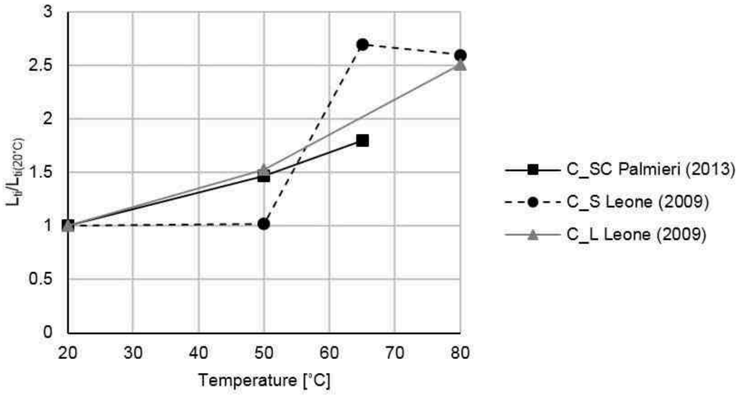

Figure 14. Influence of temperature on the bond transfer length for EBR [5] and NSM [9]

CONCLUSIONS

Considering the experimental works reported in literature, the concrete-FRP bond behaviour has been compared at room and elevated temperature. From these observations, the following main conclusions can be drawn:

- The maximum shear stress at room temperature increases with concrete tensile strength, yet only in those cases where the failure mode is taking place in the concrete substrate.
- The decrease in bond shear strength observed for steel plates bonded to concrete, for low temperature increase (20°C-60°C range), tends to be higher for higher concrete classes. On the other hand for CFRP, an increased bond strength is observed at temperatures lower than T_g. This is due to thermal shear pre-

stress in the adhesive and axial compression stresses in the substrate when there is a significant difference between CTE of concrete and FRP material.
- At elevated temperature beyond 70°C the bond strength becomes indifferent to the concrete strength. This behaviour is due to the loss of mechanical properties when the adhesive is subjected to a temperature beyond the glass transition temperature (T_g) and results in a related shift to adhesion controlled failure modes.
- In NSM systems with epoxy filler of the groove, the groove dimensions influence the bond strength. Hereby, the failure load has a tendency to increase with K (groove width to bar diameter ratio). For cement mortar filler however, this is generally not the case.
- A similar order of magnitude has been observed for smooth and rough grooves (properly prepared and cleaned). Yet, groove roughness positively influences the bond strength.
- Temperatures over T_g imply an adhesive stiffness decrease that leads to an increase of the bond transfer length.

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