BOND ON NSM CFRP SYSTEMS: RECENT CONTRIBUTIONS OF UMINHO ON DURABILITY, QUALITY CONTROL AND DESIGN

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ABSTRACT

In the last years, significant research in the context of bond of near-surface mounted (NSM) fibre reinforced polymer (FRP) systems in concrete has been conducted at the Department of Civil Engineering of the University of Minho. This paper presents a brief summary of the major results obtained in that research, namely in terms of durability, quality control and design topics. Accelerated ageing tests on NSM FRP bond specimens were conducted to simulate different environmental conditions. A new method was developed and applied to investigate the evolution of the adhesive stiffness and the bond behaviour of NSM systems for different curing conditions used for quality control of FRP installations. Regarding the bond design, two existing guidelines' formulas were adapted to the partial safety factors framework.

KEYWORDS

Concrete, NSM, CFRP, Bond, Durability, Design.

INTRODUCTION

The near-surface mounted technique (NSM) is one of the most effective techniques to strengthen concrete structures in flexure, which presents several advantages when compared to the externally bonded reinforcement (EBR) that preceded it. The use of fibre reinforced polymer (FRP) as reinforcing material in the context of the NSM technique has significantly evolved in the last decades, both in terms of scientific investigations and practical applications (Coelho *et al.* 2015; Sena-Cruz *et al.* 2015).

One of the most critical aspects regarding the NSM technique is related to the bond behaviour of the composite system, i.e. the stresses transfer between concrete and the FRP reinforcement. To better understand that behaviour, bond tests have been carried out worldwide. Despite the existence of a manifold of test setups, those can be grouped in two main types: (i) direct (DPT) and (ii) beam (BPT) pullout tests (Coelho *et al*. 2015). The effectiveness and reliability of FRP-based strengthening systems depends fundamentally on the bond between the composite material and the concrete substrate. In recent years, the application of thermosetting resins in civil engineering applications has largely increased, mainly for their use in structural strengthening systems such as FRP reinforcements. The most common resins employed as structural adhesive for bonding FRP to structural elements to be strengthened are two-component epoxy resins (ACI 2008; Coelho *et al*. 2015; Sena-Cruz *et al.* 2015).

The lack of a comprehensive, validated, and easily accessible database about the durability and long-term performance of FRP systems (such as NSM FRP and EBR FRP systems) used in civil infrastructure applications has been identified as a critical barrier to widespread acceptance of these systems/materials by structural designers and civil engineers (Al-Mahmoud *et al.* 2014). Furthermore, the importance of developing procedures for quality control of FRP reinforcements, installation procedures and strengthening systems is recognized by several design guidelines (e.g. FIB 2001; ACI 2008). The development of methodologies could be essential to the definition of monitoring protocols for FRP installation and it could allow to quantitatively evaluate of its installation. Despite the significant research that has been conducted in the structural behaviour of NSM as a strengthening technique, there is not enough knowledge about the durability and quality control of NSM FRP systems, a critical aspect that must be taken into account when designing a structural strengthening. With the aim of improving the knowledge on these relevant issues, experimental research was developed.

Finally, in the absence of design formulations to estimate the bond strength of NSM FRP systems based on the Eurocodes philosophy, a design proposal was developed based on existing guidelines that were adapted to the partial safety factors framework.

BOND DURABILITY OF NSM CFRP SYSTEMS

Experimental Programs, Test configuration and Materials

In order to contribute for bridging the gap on the knowledge on durability of bond behaviour of NSM CFRP-concrete systems, an extensive experimental program composed of 23 series (each one composed of 4 specimens) of DPT tests was carried out to study the effects of different environmental conditions. In addition, the mechanical characterization of the involved materials was also assessed over the time. The specimens were firstly exposed to different environmental conditions for different periods of time ranging between 4 and 24 months, and then they were monotonically tested up to failure. The code name given to each series follows the format "Xn" where "X" defines the environmental condition (LE – laboratory environment; TW – tap water immersion; CW – immersion in water with chlorides; WD – wet/dry cycles in water with chlorides; TCA – thermal cycles with temperatures ranged between –15 °C to +60 °C; TCB – thermal cycles with temperatures ranged between +20 °C to +80 °C; FT – freeze/thaw cycles; real environments: REA – airborne salt/Mediterranean environment; REB – temperate environment), and "n" indicates the time of exposure, i.e. the number of days/cycles that the series was submitted to the environmental condition (120, 180, 240, 480, and 720 days). For the case of the series TCA, TCB, FT, REA and REB in addition to the aged series, corresponding reference (R) series were also tested at the same time. The DPT specimens (see Figure 1a) consisted on concrete cubic blocks with 200 mm of edge, where a CFRP laminate with a cross-sectional area of 10×1.4 mm^2 was installed in a pre-cut groove opened in the concrete cover. The depth and the width of the groove were, respectively, 15 and 5 mm. A constant bond length of 60 mm, filled with the epoxy adhesive was adopted. The monotonic DPT tests were undertaken under force control at a load rate of 0.013 kN/s up to 10 kN and then under displacement control by a LVDT in loaded end section, at a rate of 2 μm/s. Mechanical properties of the CFRP laminate and epoxy resin are determined by performing the tensile tests (TT), while the mechanical characterization of the concrete was assessed by means of compression tests. Detailed information about the configuration of the DPT test, tensile tests on CRFP and epoxy adhesive and compressive tests on concrete, specimen preparation and ageing test procedures can be found elsewhere (Fernandes 2016).

Results and Discussion

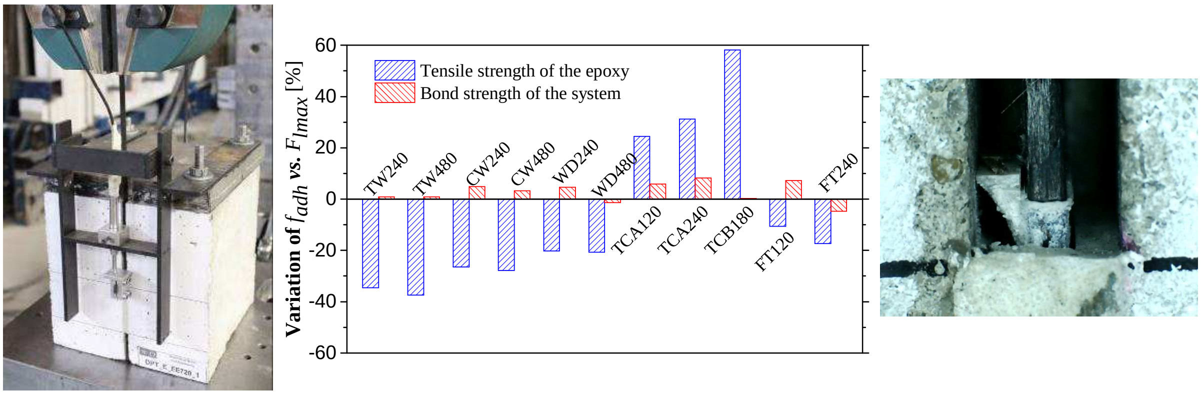
The results obtained in the compressive tests on concrete specimens indicated an average compressive strength in cylinders, f_{cm} of 36.0 MPa, with a coefficient of variation (CoV) of 3.9%, and an average Young's modulus of 28.4 GPa (CoV = 5.8%), at 28-days of concrete age. However, due to the inclusion of fly ash (40% of the total binder content) in the concrete composition, the f_{cm} continues to evolve up to one year of age; and, a maximum compressive strength of about 52 MPa (CoV = 2.5%) was achieved. Table 1 summarises the main results obtained in durability tests on the used CFRP and epoxy adhesive and the NSM CFRP-concrete system. In this table the meaning of each entity is the following: f_{FRP} is the tensile strength of the CFRP laminate; f_{adh} is the tensile strength of the epoxy adhesive; F_{lmax} is the maximum pullout force of the bond system; s_{lmax} is the slip at the loaded end at F_{lmax}. Table 1 also provides information about the failure mode (FM) of the bond tested specimens. Based on the obtained results, the following major observations can be drawn: (i) in general, all the environmental conditions investigated did not cause remarkable changes on the concrete compressive strength, except for the thermal cycles TCB which lead to a maximum reduction of 15%; (ii) CFRP samples presented negligible losses on their tensile properties when exposed to different environmental conditions; (iii) on the epoxy adhesive an increase up to 58% and 33% on the mechanical properties (tensile strength and elastic modulus, respectively) was observed, when the specimens were exposed to thermal cycles, due to a post-curing phase which occurs when temperatures higher than the ones experienced at the first curing are achieved. Contrarily, a significant reduction on its mechanical properties (up to 38% and 47% for the tensile strength and elastic modulus, respectively) was verified when the epoxy samples were submitted to wet environments due to water absorption (water uptake – plasticization phenomenon); (iv) the maximum reduction of about 12% on bond strength of the system was verified for the real environmental conditions (REA and REB); (v) thermal cycles between –15 °C and +60 °C improved the bond behaviour, with a maximum increase of 8% on bond strength; (vi) the effect of the exposure time also played an important factor on the degradation of bond properties, being greater on the specimens that aged for longer periods. It is important to note that the strong reduction on mechanical properties of the epoxy resin verified due to effect of some environmental actions did not have the correspondence on the global bond response of the NSM CFRP-concrete system, as can be seen in Figure 1b. One of the reasons that can be justified is associated to the obtained FM on bond specimens. As the maximum pullout force is limited by the type of FM and since the failure occurs mainly by debonding at adhesive/laminate interface, it means that the weakest component is the bond at adhesive/laminate interface (adhesion strength). Thus, the tensile strength of the epoxy adhesive is not directly comparable with adhesion strength at the interface between adhesive and laminate.

Table 1 Main results obtained in environmental tests.

Series	***CFRP***	***Adhesive***	***NSM CFRP-concrete system***		
	f_{FRP} [MPa]	f_{adh} [MPa]	F_{lmax} [kN]	s_{lmax} [mm]	Failure mode
LE0	2648.26 (1.76%)	22.0 (4.5%)	24.25 (1.6%)	0.55 (11.1%)	I-FA(3)*
TCA120R		-	28.24 (6.8%)	0.69 (21.4%)	I-FA(2)*; I-FA+CS(1)*
TCA240R		-	27.48 (3.4%)	0.70 (2.7%)	I-FA(4)*
LE240 FT120R		-	26.71 (3.2%)	0.70 (3.9%)	I-FA(4)*
FT240R		-	28.77 (3.3%)	0.79 (5.5%)	I-FA(3)*; I-FA+CC(1)*
LE480		20.8 (2.2%)	26.72 (4.5%)	0.58 (12.0%)	I-FA(2)*; I-FA+CC(1)*
TCB180R		-	28.59 (3.3%)	0.69 (6.2%)	I-FA(3)*; C-C(1)*
REA720R REB720R		-	28.63 (1.9%)	0.59 (9.4%)	I-FA(4)*
TW240	2629.58 (1.48%)	13.6 (4.9%)	26.93 (0.5%)	0.69 (9.2%)	I-FA+CS(1)*; C-C(1)*; I-FA+CC(1)*; I-FA(1)*
TW480	2573.58 (2.46%)	13.0 (2.1%)	26.94 (1.2%)	0.66 (10.1%)	I-FA(3)*; I-FA+CC(1)*
CW240	2504.52 (2.13%)	15.3 (2.9%)	28.01 (3.9%)	0.70 (11.2%)	I-FA+CC(3)*; I-FA(1)*
CW480	2459.38 (1.31%)	15.0 (1.7%)	27.58 (3.7%)	0.73 (13.5%)	I-FA(2)*; I-FA+CC(2)*
WD240	2601.36 (1.12%)	16.6 (4.2%)	27.93 (3.6%)	0.70 (4.4%)	I-FA+CS(2)*; C-C(1)*; I-FA+CC(1)*
WD480	2455.77 (2.34%)	16.5 (2.5%)	26.34 (3.0%)	0.66 (6.5%)	I-FA(3)*; I-FA+CC(1)*
TCA120	2809.86 (1.89%)	25.9 (4.0%)	29.88 (1.6%)	0.75 (7.6%)	I-FA+CS(2)*; I-FA(2)*
TCA240	2642.79 (3.04%)	27.3 (2.3%)	29.75 (1.9%)	0.76 (7.3%)	I-FA+CC(2)*; I-FA(2)*
TCB180	2636.06 (2.74%)	32.9 (2.3%)	28.64 (4.0%)	0.71 (10.7%)	I-FA(4)*
FT120	2609.14 (1.37%)	18.6 (0.6%)	28.63 (1.7%)	0.79 (5.5%)	C-C(4)*
FT240	2666.74 (1.82%)	17.2 (2.5%)	27.40 (5.2%)	0.72 (11.5%)	I-AC+CS(3)*; I-FA+CS(1)*
REA720	-	-	25.34 (4.6%)	0.56 (10.9%)	I-FA(3)*; I-FA+CC(1)*
REB720	-	-	25.31 (1.0%)	0.56 (9.2%)	I-FA(4)*

Notes: the values between parentheses are the corresponding coefficients of variation; *the value between parentheses is the number of specimens with this type of failure mode; I-FA = debonding at the interface FRP/adhesive; I-AC = debonding at the interface adhesive/concrete; C-C = cohesive shear debonding in concrete; CS = concrete splitting; CC = concrete cracking; AC = adhesive cracking.

The failure modes were classified with the generic denomination "X-Y", where X defines the type of failure mode (interfacial - I or cohesive - C) and Y identifies the location where it occurred (concrete - C, adhesive - A, interface FRP/adhesive - FA or interface adhesive/concrete - AC). Besides to the three main failure modes above described (I-FA, I-AC and C-C), in some specimens the final appearance also included one (or more) of the following damages (see Table 1): CS, CC and AC. The predominant failure mode occurred by I-FA (see Figure 1c). In fact, the pure interfacial failure is critical for FRP bars with a smooth surface since the smooth surface of CFRP strips used in this work is insufficient to provide mechanical interlocking between the laminate and the adhesive, and the rougher surface of the concrete leads to better bonding with the adhesive, the bond resistance relies primarily on chemical adhesion between the strip and the epoxy.



(a) (b) (c)

Figure 1 Durability tests: (a) DPT configuration; (b) Comparison between the variations of the f_{adh} and F_{lmax} due the distinct environmental conditions; (c) Main failure mode occurred in bond tests (I-FA).

QUALITY CONTROL OF NSM CFRP SYSTEMS

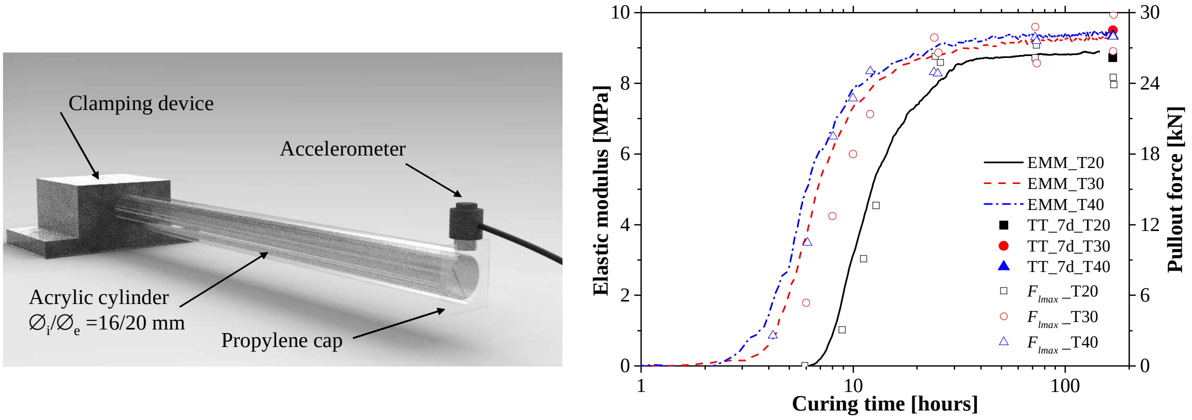
A new methodology for continuous monitoring of the evolution of elastic modulus of an epoxy adhesive used in FRP applications, based on adaptations of an existing technique originally devised for continuous monitoring of concrete elastic modulus since casting, called EMM-ARM (Elasticity Modulus Monitoring through Ambient Response Method) was proposed and validated (Granja *et al.* 2015). Afterwards, the influence of temperature on the curing process of the structural epoxy and its impact on the bond behaviour of NSM CFRP strengthening applications was investigated. For this purpose, an experimental program composed of three groups of tests, considering three different curing and testing temperatures (20 °C, 30 °C, and 40 °C) were developed:

(i) EMM-ARM tests (see Figure 2a) on adhesive samples to assess the evolution of the adhesive elastic modulus of the epoxy at different curing temperatures;
(ii) DPT tests on concrete cubic specimens strengthened with CFRP laminate strips, aimed at describing the development of the interface behaviour under variable curing conditions;
(iii) Tensile tests (TT) performed according to EN ISO 527-2:2012, to evaluate the elastic modulus value of the hardened epoxy.

The development of the epoxy elastic modulus obtained through EMM-ARM and the evolution of F_{lmax} obtained in bond NSM CFRP-concrete specimens along the curing time, at the three curing temperatures under test are presented in Figure 2b. The results of TT at 7-days of epoxy curing are also added to Figure 2b. The elastic modulus was calculated from TT results, according to the American Standard ASTM D638M-93. EMM-ARM applications on epoxy have demonstrated good repeatability of the experimental setup and procedures (Benedetti *et al.* 2016). The elastic modulus values estimated through the TT were lower than the values provided by EMM-ARM tests, with stiffness differences under 12.6% (~1.22 GPa for the 20 ºC test). In addition, the results show that the reaction rates intensify with the increase of the curing temperature. For instance, the elastic modulus of 4 GPa is achieved at approximately 10.7 hours at 20 ºC as opposed to the approximately 6.2 and 5.5 hours at 30 ºC and 40 ºC, respectively. These variations also occur in the duration of the dormant period, where adhesive stiffness is nearly null. With the increase in the curing temperature the duration of the dormant period becomes shorter, as can be observed in Figure 2b. At the reference temperature (20 ºC) the setting time (herein defined as the time when the elastic modulus reached 0.25 GPa) is 4.5 ± 0.2 hours, as opposed to the shorter 2.6 hours observed in the test at 40 ºC.

Figure 2b highlights that the peak pullout force and the epoxy elastic modulus obtained by EMM-ARM exhibit very similar evolution kinetics, thus indicating that the bond performance of NSM CFRP-concrete system strongly depends on the stiffness of the adhesive regardless of the curing temperature. The increase on bond stiffness is consistent with the stage at which the rate of thermosetting reactions is higher, although its development was slightly delayed compared to elastic modulus development. In general, F_{lmax} has a significant increase from 6 to 24 hours for the three analysed temperatures. For 20 ºC, between 6 and 9 hours the peak pullout force increases by 3 kN and even by 10.56 kN in the subsequent 4 hours.

The slight difference on the kinetics of the two properties seems to be similar for all temperatures and may be attributed to a delay in the development of the molecular bond quality, which usually has less influence on the stiffness of the epoxy resin than on its strength (Moussa *et al.* 2012). Based on this kind of relationship, EMM-ARM can be employed for estimating the F_{lmax} and the minimum curing time to reach a threshold value of pullout force. In this manner it is possible to know the time required to put the strengthened structure in service, taking into account the influence of different environmental curing conditions.



(a) (b)

Figure 2 Quality control tests: (a) Experimental setup of EMM-ARM; (b) Epoxy elastic modulus *vs*. peak pullout force along the curing time.

DESIGN OF BOND OF NSM CFRP SYSTEMS

In Coelho *et al.* (2015), the existing guidelines for the design and use of NSM FRP systems in concrete were analysed. At least four guidelines were identified: firstly, the CAN/CSA S6–06:2006 does not propose a closed-form formulation for evaluating the bond strength of NSM FRP systems. Alternatively, it refers that the bond strength should be obtained either by testing the NSM FRP system to be used, or it should be provided by the manufacturer; secondly the new annex of EN 1992-1-1:2013 is only applicable to FRP bars with rectangular cross-section (strips). In addition, its formulation requires some adhesive properties, such as tensile and compressive strengths, which are not often provided by the adhesives' manufacturers. Furthermore, the formulation proposed by this guideline to estimate the bond strength depends on some coefficients which shall be provided by the manufacturer for each NSM FRP system, or adjusted by testing; the last two guidelines are the ACI 440.2R-08 (ACI 2008) and HB 305-2008 (SA 2008). These do not present the aforementioned drawbacks. In fact, they provide a set of closed-form expressions which are straightforward to apply since they depend on geometrical and mechanical parameters simple to obtain.

Hence, the ACI 440.2R-08 and HB 305-2008 guidelines were further analysed. Firstly, their accuracy was assessed based on a database with 363 and 68 direct and beam pullout tests, respectively (Coelho *et al.* 2015). The obtained results showed average errors of about 30% and 40% when ACI 440.2R-08 is applied to DPT and BPT, respectively; and 30% when HB 305-2008 is used for both DPT and BPT. These errors were computed by applying Eq. 1 to the total tests (N) in each database where, $F_{fmax,Exp}$ and $F_{fmax,Num}$ are the maximum pullout force values obtained in the experimental tests and by applying the corresponding guideline formulation, respectively.

$$\sum_{i=1}^{N}\frac{\left|F_{f\,\max,Exp}-F_{f\,\max,Num}\right|}{F_{f\,\max,Exp}}\Big/N \tag{1}$$

Then, a reliability analysis was conducted in order to allow using these guidelines under the framework of the Eurocodes design philosophy (Coelho *et al.* 2016). Since the amount of tests using CFRP strips was larger than the other types of FRP fibres/cross-sections, it was decided to conduct this task only for these types of tests. Table 2 presents the final formulas of each guideline (including the corresponding partial safety factors) that can be applied to estimate the bond strength of NSM CFRP strips. As can be seen, both formulations are based on the assumption that a certain length is required to develop the entire strength of the NSM FRP system (development length, L_d). If the bonded length, L_b, is lower than L_d, the maximum pullout force, F_{fmax}, will be linearly reduced according to L_b/L_d. In Table 2 the following parameters are involved: A_f, p_f, E_f, f_{fk} and $\gamma_f = 1.4$ (FRP area, perimeter, elasticity modulus, characteristic tensile strength and partial safety factor), b_g and d_g (groove width and depth), f_{ck} and $\gamma_c = 1.5$ (concrete characteristic compressive strength and partial safety factor), τ_d and δ_d (design bond strength and slip), L_{per} and φ_{per} (failure perimeter length and ratio), η_c and η_b (safety factors). Detailed description and values of all parameters can be obtained in (Coelho *et al.* 2016).

Table 2 ACI 440.2R-08 and HB 305-2008 formulas ncluding partial safety factors.

Parameter	ACI 440.2R-08	HB 305-2008
Development length [L_d]	$\dfrac{A_f\, f_{fk}/\gamma_f}{p_f\tau_d}$	$\dfrac{\pi}{2\sqrt{\dfrac{\tau_d L_{per}}{\delta_d (EA)_f}}}$
Maximum pullout force [$F_{fmax,d}$]	$\begin{cases} A_f\, f_{fk}/\gamma_f & if\ L_b \geq L_d \\ A_f\, \dfrac{f_{fk}}{\gamma_f}\dfrac{L_b}{L_d} & if\ L_b < L_d \end{cases}$	$\begin{cases} \eta_c\sqrt{\tau_d\delta_d L_{per}(EA)_f} \leq A_f\, f_{fk}/\gamma_f & if\ L_b \geq L_d \\ \eta_b\sqrt{\tau_d\delta_d L_{per}(EA)_f}\,\dfrac{L_b}{L_d} \leq A_f\, f_{fk}/\gamma_f & if\ L_b < L_d \end{cases}$
Other relevant information	$\tau_d = 1.77$ MPa	$\tau_d = (0.8+0.078\varphi_{per})\left(\dfrac{f_{ck}}{\gamma_c}\right)^{0.6}$ $\delta_d = \left[0.73\varphi_{per}^{0.5}\left(\dfrac{f_{ck}}{\gamma_c}\right)^{0.67}\right]\Big/\tau_d$ $\varphi_{per} = \left(d_g+1\right)/\left(b_g+2\right)$ $L_{per} = 2\left(d_g+1\right)+b_g+2$

CONCLUSIONS

This paper has presented a summary of the research conducted at the Department of Civil Engineering of the University of Minho in the context of bond of FRP NSM systems in concrete. Important contributions were made namely in the topics of durability, quality control and design. The environmental conditions investigated, which were considered to be quite severe, did not lead to significant changes on global bond performance of the NSM CFRP-concrete strengthening system, with a maximum reduction of about 12% on bond strength occurred under real environmental actions. EMM-ARM has potential to be employed for in-situ monitoring of the hardening of an epoxy adhesive curing in un-controlled conditions used in FRP applications. The bond behaviour of NSM CFRP-concrete systems is totally governed by the state of hardening of the adhesive. The peak pullout force and the epoxy elastic modulus obtained by EMM-ARM exhibit very similar evolution kinetics, thus indicating that the bond performance of NSM CFRP system strongly depends on the stiffness of the adhesive regardless of the curing temperature. Regarding the bond design, the major contribution consisted of adapting two existing guidelines' formulas (American and Australian) to the partial safety factors framework (European philosophy). However, these formulas are not yet sufficiently accurate, thus further work should be carried out in this aspect and a newer and more accurate formulas should be developed.

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