A NEW METHODOLOGY FOR ASSISTING QUALITY CONTROL OF NSM-CFRP SYSTEMS SINCE VERY EARLY AGES

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ABSTRACT: The performance of NSM systems directly depends on the performance of the adhesive which can only be reached if a proper curing conditions and time are assured. In order to assess the curing process of the adhesives, as well as the corresponding bond behavior, adequate non-destructive testing approaches are required. Nonetheless, scarce information could be found in the literature in concern to this relevant topic. To fill such gap, the present paper proposes a new method for continuous quality control of epoxy adhesives, based on adaptations of an existing technique originally devised for continuous monitoring of concrete E-modulus since casting, called EMM-ARM (Elasticity Modulus Monitoring through Ambient Response Method). This work reports the simultaneous study of the adhesive through EMM-ARM, together with direct pullout tests at several ages on concrete specimens strengthened with NSM CFRP laminate strips using the same epoxy. The tests are described, and the obtained results are presented and discussed, highlighting the potential of applying EMM-ARM for quality control and decision-making assistance of NSM systems.

1. Introduction

In the last decade the near-surface mounted (NSM) strengthening technique using fiber reinforced polymers (FRP) has been increasingly used to improve the load carrying capacity of concrete members. Up to now, research efforts have been mainly focused on several structural aspects, such as: bond behavior, flexural and/or shear strengthening effectiveness, and energy dissipation capacity of beam-column joints (De Lorenzis and Teng, 2007). In such research works (as well as in field applications), the most widespread adhesives that are used to bond reinforcements to concrete are epoxy resins. It is largely accepted that the performance of the whole application of NSM systems strongly depends on the mechanical properties of the epoxy resins, for which proper curing conditions must be assured. Therefore, the existence of non-destructive methods that allow monitoring the curing process of epoxy resins in the NSM-CFRP system is desirable, in view of obtaining continuous information that can provide indication in regard to the effectiveness of curing and the expectable bond behavior of CFRP/adhesive/concrete systems.

The present work has the main objective to develop and propose a new method for continuous quality control of the curing of epoxy resins applied in NSM CFRP strengthening systems. This objective is pursued through the adaptation of an existing technique, termed EMM-ARM (Elasticity Modulus Monitoring through Ambient Response Method) (Azenha *et al.*, 2010; Silva *et al.*, 2013) that has been developed for monitoring the early stiffness evolution of cement-based materials such as cement paste, concrete or cement-stabilized sand.

2. Experimental program

The experimental program was composed of two parts: (i) EMM-ARM tests were conducted for monitoring the progressive hardening of the structural adhesive used in CFRP applications; and, (ii) direct pullout tests with concrete specimens strengthened with NSM CFRP laminate strips were carried out to assess the evolution of bond behavior between CFRP and concrete since early ages. In order to verify the capability of the proposed method for evaluating the elastic modulus of the epoxy, static E-Modulus was determined through tension tests, carried out according to ISO 527-2 (1993). All the specimens were simultaneously prepared using the same epoxy adhesive mixture. The experimental procedures were performed inside a climatic chamber at a constant temperature and humidity of 20ºC and 60%, respectively.

2.1. EMM-ARM

The EMM-ARM was initially devised for the study of concrete specimens, and it basically consists in constantly monitoring the resonant frequency of a composite beam, which is internally filled with the material to be tested (Azenha *et al.*, 2010). The beam is continuously monitored immediately after casting, and its resonant frequency is identified through modal identification techniques. The evolving resonant frequency can thus be related to the stiffness of the tested material through application of the dynamic equations of motion of the composite beam.

As the grain size of epoxy resins used for NSM-CFRP is comparable to that of cement paste, it was decided to use a similar mold to the one already adopted in the EMM-ARM version devised for cement pastes. In such implementation, the EMM-ARM specimen consists in a cantilever beam where the accelerations are monitored at its free end (Azenha *et al.*, 2012). However, due to the fact that the epoxy has a lower stiffness than the cement paste, in order to maintain the frequency resolution in agreement with the criteria given in the work of Azenha *et al.* (2012), it was decided to reduce the span of the beam to 250 mm, as shown in Fig. 1. This span reduction also facilitates the filling of the mold with epoxy to be tested.

Fig. 1 – Experimental setup for EMM-ARM testing of epoxy adhesive [dimensions: mm]

Due to the fluidity characteristics of the epoxy adhesive after mixing, the experimental procedure had to be adapted. In its original application to the study of cement pastes, the acrylic tube mold was already prepared with an extremity cap before the tube filling, since cement pastes have a large fluidity. However, the epoxy adhesive needs to be injected into the tube through a syringe. Thus, the caps are placed on the mold extremities only after filling the acrylic tube with the epoxy adhesive. When the mold is filled, it is placed in the final test position (see Fig. 1) and a small accelerometer placed in the free end of the mold for acceleration monitoring. Then it is possible to obtain the frequency of the first vibration mode of the beam. For details about this procedure consult the reference Maia *et al.* (2012). After determining the first flexural resonant frequency of the composite beam, it is possible to infer the stiffness of the tested material, using the vibration equation of a cantilevered structural system (see Fig. 1). The full derivation of the free vibration equation of a cantilevered beam is explained in Azenha *et al.* (2012). The final solution is the differential equation shown below:

$$a^3\left[\cosh(a\cdot L)\cdot\cos(a\cdot L)+1\right]+\frac{w^2\cdot m_p}{EI}\left[\cos(a\cdot L)\cdot\sinh(a\cdot L)-\cosh(a\cdot L)\cdot\sin(a\cdot L)\right]=0 \quad (1)$$

where $a=\sqrt[4]{w^2 \cdot \overline{m}/EI}$, *EI* is the product of the elasticity modulus by the homogenized second area moment of the composite cross-section (Pa·m^4), $\overline{m}$ is the uniformly distributed mass along the cantilever (kg/m), m_p is the concentrated mass located at the extremity of the cantilever that represents the masses of the accelerometer and lid (kg), *L* is the span of the cantilever (m), *f* is the first flexural resonant frequency (Hz), and the corresponding angular frequency is denoted by $w = 2\pi f$. In order to evaluate the method's ability to obtain results with good repeatability, two tests were performed simultaneously (E1 and E2). The acrylic tubes used for the EMM-ARM had an average elastic modulus of 4.27 GPa at 20ºC (with a variation of ±0.13 GPa) and an average density of 1226 kg/m^3. The values of E-modulus and density of the acrylic were verified in the laboratory through modal identification of the empty molds, which were weighed before each test. The geometric characteristics of the used molds, as well as the density of the epoxy adhesive, are shown in Table 1.

Table 1 – Characteristics of the specimens used in the test.

Reference	L (mm)	$Ø_{ext}$ (mm)	$Ø_{int}$ (mm)	m_p (kg)	Epoxy density (kg/m^3)
E1	250.0	20.099	15.975	0.010	1702.98
E2	250.0	20.086	16.030	0.010	1749.43

2.2. Direct pullout test

As previously referred, in order to assess the evolution of bond behavior of NSM strengthening system between CFRP and concrete during the hardening of the epoxy adhesive, fourteen monotonic direct pullout tests were carried out for the following ages: 6, 9, 11, 12, 24, 25, 36, 37, 48, 49, 72, 73, 168 and 169 hours. Fig. 2 shows the geometry and the configuration adopted for the monotonic direct pullout tests (DPT). The specimen's geometry consisted of concrete cubic blocks of 200 mm edge, in which a NSM CFRP laminate strip was embedded. A groove size of 15 × 5 mm^2 was cut for introducing CFRP laminate strips with a rectangular cross-section of 10×1.4 mm^2. A constant bond length (L_b) of 60 mm was adopted. To avoid premature failure due to the formation of a concrete fracture cone at the loaded end, bond length started 100 mm from the top. A steel plate with 20 mm thickness was placed at the top of the concrete block to assure negligible vertical displacements at the top of the concrete specimen during pullout test. Four M10 threaded rods fixed this steel plate to the base. A torque of 30 N·m was applied to fasten these rods. This torque induced an initial compressive state on the concrete block of about 2.0 MPa. A LVDT was used to measure the slip at the loaded end, s_l. The applied force, *F*, was registered by a load cell placed between the grip and the actuator. The tests were performed with displacement control at a rate of 2 µm/s, assessed by another LVDT placed between the actuator and the grip.

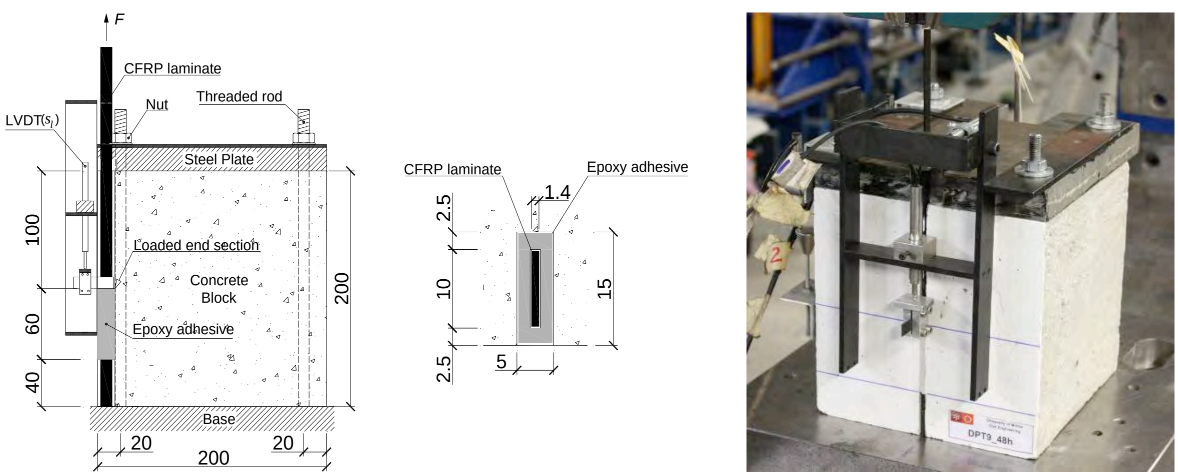

Fig. 2 – Direct pullout tests: specimen geometry and configuration [dimensions: mm].

The preparation of the strengthened specimens required several steps, mainly: (i) opening the grooves with a saw cut machine; (ii) cleaning the grooves with compressed air and the laminates with acetone;

(iv) preparation of the adhesive according to the technical data sheet of the supplier; (v) application of the adhesive on the groove and lateral surfaces of the laminate; (vi) introducing carefully the laminate into the groove; (vii) level the surface. All specimens were simultaneously strengthened using the same epoxy adhesive mixture. After strengthening, the specimens were kept in the climatic chamber environment until they were tested. The age of the concrete cubic specimens at the date of experimental program was about three years, and the average concrete compressive strength in cylinders was 42.35 MPa with a coefficient of variation of 5.22%. The main properties of the CFRP laminate strip used in this work can be found elsewhere (Sena-Cruz *et al.*, 2013).

3. Results and discussion

The results are cumulatively presented below, beginning with the EMM-ARM results followed by the results of the direct pullout tests. Finally, a comparison between the E-Modulus evolution of the epoxy adhesive and the pullout force is presented.

3.1. E-Modulus evolution

The resonant frequencies identified by the EMM-ARM method for the two specimens (E1 and E2) are shown in Fig. 3a. It is worth mentioning that a wide range of frequencies was covered throughout the curing process of the cement pastes, ranging from 49.9 Hz to 77.8 Hz within the testing period. Moreover, the frequency evolution curves appear to be plausible, showing an initial dormant period of 6.45 hours (where the frequency remains almost constant within ±0.6 Hz). After this threshold, the frequencies evolved significantly for both tested specimens until approximately 35 hours of curing. After such period, the slope of variation exhibit a significant decrease to near-negligible values. The E-modulus evolution, estimated by applying equation 1 to the resonant frequencies presented in Fig. 3a, is shown in Fig. 3b. Firstly, is should be noted that the E-modulus evolution curves have very good coherence with each other, demonstrating adequate repeatability of EMM-ARM. In the initial period (during the first 6.45 hours) the epoxy adhesive stiffness was zero. Then a drastic increase in the stiffness occurred, reaching 8.6 GPa at 35 hours. After this point the E-modulus evolution reached a plateau, were the stiffness evolved from 8.6 to 8.8 GPa during 109 hours. A comparison of E-modulus obtained by EMM-ARM and through tensile tests shows a non-negligible difference: the last monitored value of E-modulus monitored by EMM-ARM at the age of ~150h (~8.8GPa) is significantly higher than the value obtained in the tensile test at the age of 240h and amounted to 7.6GPa. This deviation may possibly be explained by the fact that the E-modulus collected in the tensile tests was obtained from a single loading. In fact, as it happens in cementitious materials, during the application of first loading cycle the response currently has a lower stiffness than the following cycles. Despite this difference, the results of this study are consistent with the work reported by Moussa *et al.* (2012).

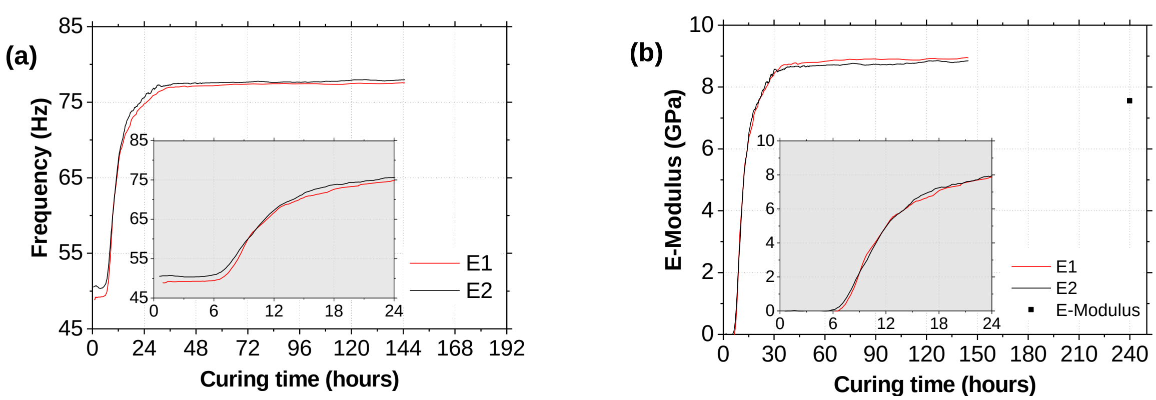

Fig. 3 – EMM-ARM results: (a) Frequency evolution; (b) E-Modulus evolution.

3.2. Pullout force *versus* curing time

Fig. 4a depicts the pullout force *versus* loaded end slip (F_l-s_l) relationship for the tested specimens up to 36 hours and for the last specimen tested at 169 hours. It is possible to observe the increase on bond stiffness along the curing of epoxy adhesive. This evolution process seems to be totally controlled by the state of hardening of the adhesive. At the age of 24 hours, the F_l-s_l curves start exhibiting the characteristic bond-slip behavior observed at testing ages such as 2160 hours, when the epoxy is considered as completely cured (Sena-Cruz *et al.*, 2013). Fig. 4b presents the evolution of maximum pullout force ($F_{l,max}$) and corresponding loaded end slip ($s_{l,max}$) during the curing process. It could be observed that $F_{l,max}$ has a significant increase from 6 to 24 hours when the maximum value was reached. After the first 24 hours the maximum pullout force remained at a plateau value of 25.2 kN ±5.18 %. As expected, the $s_{l,max}$ was much higher during the early hours, due to the fact that the epoxy was not yet completely hardened. It should be noted that in almost all specimens the failure occurred by debonding at adhesive/laminate interface. However, the tests performed at 36, 48 and 73 hours lead also to concrete splitting. For the specimen tested at 11 hours cohesive shear failure in the epoxy was observed.

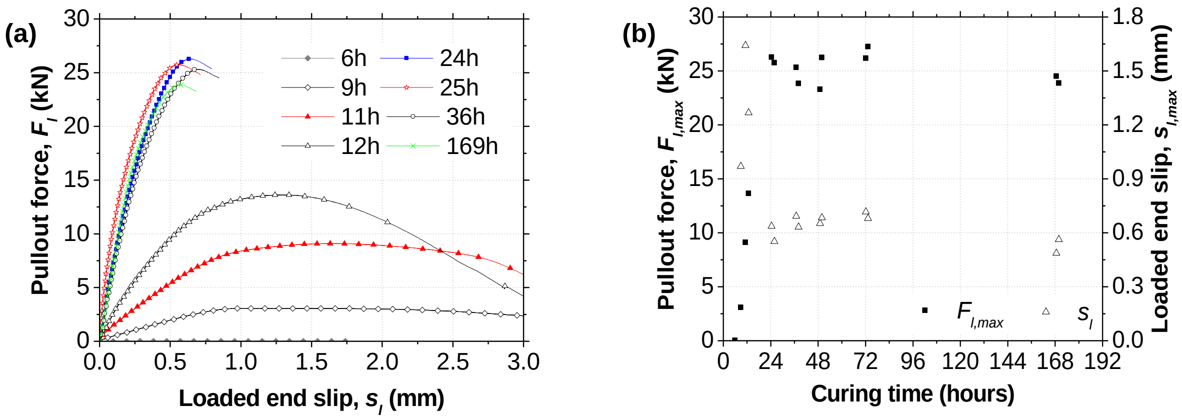

Fig. 4 – (a) Pullout force *versus* loaded end slip; (b) Evolution of maximum pullout force and corresponding loaded end slip during the curing time.

3.3. Comparison between pullout force and E-modulus epoxy

The comparison between the elastic modulus results obtained through EMM-ARM and pullout testing is shown in Fig. 5a. It can be seen that the results of both experimental techniques exhibit similar evolution kinetics. In regard to the beginning of the setting of the epoxy adhesive, there is also a good coherence between E-modulus and pullout force. However it should be noted that the evolution of the epoxy adhesive E-modulus seems to exhibit a slightly more accelerated evolution kinetics than the pullout force during the phase of higher reaction of the epoxy adhesive. Despite this small difference it is possible to obtain a correlation between the E-modulus and pullout force, as shown in Fig. 5b. After obtaining that correlation, the EMM-ARM can be employed for quality control of the reinforcement both in terms estimating the maximum pullout force 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.

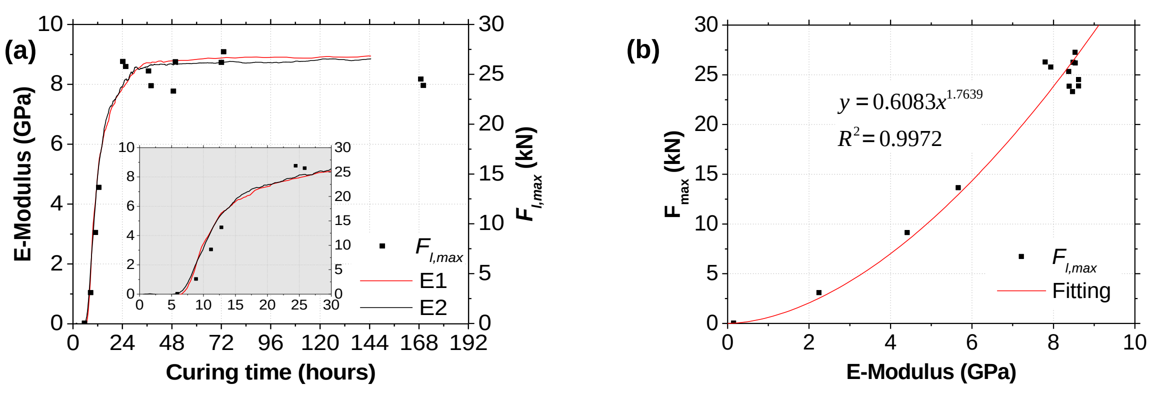

Fig. 5 – (a) Comparison between the evolution of the epoxy E-modulus and the pullout force; (b) Correlation between the epoxy E-modulus and the pullout force.

4. Conclusions

The present paper detailed an adaptation of an existing method (EMM-ARM) for monitoring the E-modulus evolution of cement-based materials since casting, which is based on the non-destructive technique of ambient vibration testing, and on the continuous identification of the vibration frequency of the first flexural mode of a cantilever beam. EMM-ARM has been adapted to the monitoring of the stiffening of an epoxy adhesive. The pilot tests reported in this work have demonstrated encouraging results.

The bond behavior of concrete elements strengthened with NSM CFRP laminate strips was accessed since the early age of the epoxy curing and a wide variation of pullout force was observed in the first 24 hours of the epoxy curing, after which the force evolution almost stops.

The results obtained by EMM-ARM were compared with the observed bond behavior of the NSM CFRP strengthening technique, and a correlation between the epoxy E-modulus and the maximum pullout force was obtained. Through the use of such type of correlation it is plausible to use the EMM-ARM for quality control and assistance to decision-making for the reinforcement technique.

5. Acknowledgements

This work is supported by FEDER funds through the Operational Program for Competitiveness Factors - COMPETE and National Funds through FCT - Portuguese Foundation for Science and Technology under the project CutInDur PTDC/ECM/112396/2009 and the project VisCoDyn EXPL/ECM-EST/1323/2013. The authors also like to thank all the companies that have been involved supporting and contributing for the development of this study, mainly, S&P Clever Reinforcement Ibérica Lda. The first and second authors wish also to acknowledge the grants SFRH/BD/80338/2011 and SFRH/BD/80682/2011, respectively, provided by FCT.

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