International Journal of Adhesion & Adhesives 59 (2015) 115–124

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Tensile creep of a structural epoxy adhesive: Experimental and analytical characterization

Inês Costa*, Joaquim Barros

ISISE—University of Minho Department of Civil Engineering, Campus de Azurém, 4800-058 Guimarães, Portugal

ARTICLE INFO

Article history:
Accepted 13 February 2015
Available online 24 February 2015

Keywords:
Epoxides
Concrete
Experimental characterization
Rheology
Mechanical properties

ABSTRACT

Epoxy adhesives are nowadays being extensively used in Civil Engineering applications, mostly in the scope of the rehabilitation of reinforced concrete (RC) structures. In this context, epoxy adhesives are used to provide adequate stress transference from fibre reinforced polymers (FRP) to the surrounding concrete substrate. Most recently, the possibility of using prestressed FRPs bonded with these epoxy adhesives is also being explored in order to maximize the potentialities of this strengthening approach. In this context, the understanding of the long term behaviour of the involved materials becomes essential. Even when non-prestressed FRPs are used a certain amount of stress is permanently applied on the adhesive interface during the serviceability conditions of the strengthened structure, and the creep of the adhesive may cause a continuous variation in the deformational response of the element. In this context, this paper presents a study aiming to experimentally characterize the tensile creep behaviour of an epoxy-based adhesive currently used in the strengthening of concrete structures with carbon FRP (CFRP) systems. To analytically describe the tensile creep behaviour, the modified Burgers model was fitted to the experimental creep curves, and the obtained results revealed that this model is capable of predicting with very good accuracy the long term behaviour of this material up to a sustained stress level of 60% of the adhesive's tensile strength.

1. Introduction

One of the most common uses of fibre reinforced polymers (FRP) in Civil Engineering applications is in the scope of rehabilitation and strengthening of reinforced concrete (RC) structures. For that purpose, the FRPs, in the form of sheets, laminates or bars, are bonded to the existing structures by means of an adhesive. The research group at Minho University has already applied these FRPs externally (externally bonded reinforcement - EBR), near surface mounted (NSM) [1] or even embedded through-section (ETS) [2]. The installation of NSM-FRPs is able of increasing the load carrying capacity of a structural element with minor aesthetical impact and negligible structural weight increase, among a number of other advantages as referred by De Lorenzis and Teng [3]. Most recently, in order to take advantage of the high tensile strength of the FRP, the possibility of applying FRPs with a certain prestress is being further explored for increasing the load carrying capacity of a strengthened element at serviceability limit state conditions [4–5].

Generally, the effectiveness of these strengthening systems is, in a first phase, evaluated by means of monotonic tests, meaning that a model of the structural system is constructed and loaded up to failure. However, this type of characterization only provides the maximum expectable strength and not the real deformational behaviour of the strengthening system during the working life of the structure.

Mainly motivated by the interest of using prestressed NSM-FRPs (Fig. 1), the knowledge of the long term deformability of the intervening materials becomes essential. The creep of structural adhesives is already recognized to be a material property of major importance to guarantee adequate stress transfer between the FRP and surrounding material over time. In fact, Quantrill and Hollaway, Nordin and Täljsten and Wang et al. have already exposed that this property plays an important role on the long term efficacy of the strengthening system [6–8]. However, the investigation in this area is scarce, despite the potentially negative effects the creep behaviour of adhesives can have in terms of the strengthening effectiveness of a FRP-based system.

Creep, usually defined as the increase of deformation over time under sustained stress, is recognized to be a relevant phenomenon when dealing with adhesives, and ISO and ASTM already define the methods to assess this property [9–10]. Additionally, the analysed specialized bibliography on this topic revealed that the mechanical performance of adhesives changes in fact with time, mainly due to the level of applied stress, but also due to environmental conditions such as temperature and humidity, as referred by ASTM, Dean and Feng et al. [10–12].

---

* Corresponding author. Tel.: +351 252 315 199.
E-mail addresses: inescosta@civitest.com (I. Costa), barros@civil.uminho.pt (J. Barros).

http://dx.doi.org/10.1016/j.ijadhadh.2015.02.006
0143-7496/

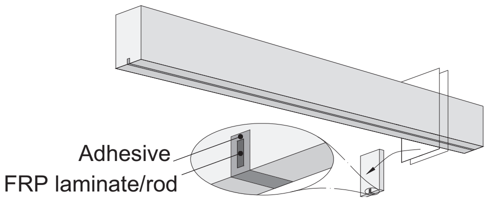

Fig. 1. Representation of a NSM-FRP application on a RC beam.

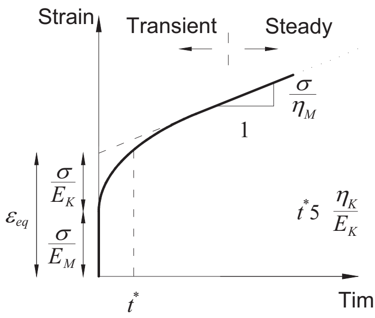

Fig. 2. Strain evolution with time in Burgers Model.

The creep behaviour of adhesives is frequently modelled using rheological models and is usually illustrated by means of Hookean springs and Newtonian dashpots that replicate, respectively, the elastic and viscous components of the material's behaviour (Brinson and Brinson, [13]). Burgers model, depicted in Fig. 2, is the most common and generalist creep model. This model is able of describing the time-strain variation of most of the existing epoxy-based adhesives, and will therefore be taken as reference to describe the behaviour of the adhesive adopted in the present research programme. This model is simulated by the following equation:

$$\varepsilon_{creep}(t)=\frac{\sigma}{E_M}+\frac{\sigma}{\eta_M}t+\frac{\sigma}{E_K}\left(1-\exp\left(-\frac{E_K}{\eta_K}t\right)\right) \tag{1}$$

where $\varepsilon_{creep}(t)$ is the strain evaluated at a certain time instant t, σ is the applied stress, E_M and η_M are Maxwell's elastic modulus and coefficient of dynamic velocity, E_K and η_K are Kelvin's elastic modulus and coefficient of dynamic velocity.

Feng et al. [12] suggested that the tensile creep strain, $\varepsilon_{creep}(t,T)$ can be estimated by the exponential function shown in Eq. 2, which was re-written to improve the resemblance with the rheological model that will be afterwards reported in the present document

$$\varepsilon(t,T)=\frac{\sigma_0}{E_0}+\sigma_0\left(\frac{1}{E_e}-\frac{1}{E_0}\right)\left(1-e^{-(t/t^*)^{1-n}}\right) \tag{2}$$

where σ_0 is the applied stress level, E_0 the initial Young modulus, E_e is the equilibrium modulus given in Eq. 3, t^* is the retardation time and n is a coupling parameter related to moisture absorption

$$E_e=2G_r(1+\nu) \tag{3}$$

where G_r is the rubbery plateau shear modulus and ν is Poisson's ratio (ν=0.5 since the material is in the rubbery state).

The unique feature of this model is related to the n parameter, whose value is basically related to the activation energy of the molecular motion. If a specimen is saturated, the presence of moisture enhances the molecular mobility and, therefore, decreases the amount of activation energy required, resulting in lower values of n. As reference, it can be mentioned that Feng et al. [12] obtained in their tests an initial Young modulus, E_0, of 2.5 GPa, retardation times, t^*, ranging between 54 and 16204 days and values of n ranging from 0.51 to 0.73 for varying degrees of relative humidity.

In another paper, Majda and Skrodzewicz [14] proposed a model purely based on Burgers Model (Eqs. (4) and (5)). The singularity recognized in this paper is the suggestion that the coefficients of dynamic viscosity, η_0 and η_1, are primarily dependent on the applied stress (see Eqs. (6) and (7)). Additionally, the elastic modulus of the relaxation response, herein designated as E_1, was also defined as a function of the applied stress (Eq. (8))

$$\varepsilon(t,T)=\frac{\sigma_0}{E_0}+\frac{\sigma_0}{\eta_0}t+\frac{\sigma_0}{E_1}\left(1-e^{-t/t^*}\right) \tag{4}$$

$$t^*=\frac{\eta_1}{E_1} \tag{5}$$

$$\eta_0(\sigma_0)=e^{a_1-a_2\sigma_0} \tag{6}$$

$$\eta_1(\sigma_0)=e^{a_3-a_4\sigma_0} \tag{7}$$

$$E_1(\sigma_0)=a_5{\sigma_0}^2-a_6\sigma_0+a_7 \tag{8}$$

As an indication, Majda and Skrodzewicz [14] obtained an initial elastic modulus, E_0, of 2.323 GPa and retardation times, t^*, of 3–24 min. Note that this last value is exceptionally lower when compared to the one obtained by Feng et al. [12].

Taking into account the information previously exposed, and in order to address the lack of research in this topic, an experimental programme was carried out aiming the assessment of the tensile creep behaviour of an epoxy-based structural adhesive, traded under the commercial name “S&P Resin 220 epoxy adhesive”, used in a commercial NSM-CFRP (carbon FRP) system. According to the material safety sheet, the epoxy resin solution is composed of bisphenol A and neopentyl glycol diglycidyl ether while the hardener contains poly(oxypropylene)diamine, triethylentetramine, piperazine and aminoethylpiperazine. For that purpose, nine dumbbell-shaped samples of adhesive were tested under three different load levels. Later, a modified Burgers equation was used to model the creep strain curves obtained, as well as the corresponding creep modulus curves.

2. Material characterization

In the first phase of the experimental programme the instantaneous properties of the epoxy adhesive to be tested under tensile creep were evaluated. For this purpose dumbbell-shaped specimens of adhesive were prepared observing ISO 527-2 recommendations [15]. According to this standard, the effective cross section under tensile stress should be 10 × 4 mm^2. Note that these dimensions are representative of the thickness of the adhesive layer used in the NSM-CFRP strengthening technique for bonding the CFRP reinforcement to the surrounding concrete. In the prestressed NSM-CFRP technique developed in the research project that the present work is part of it, a thickness of about 3 mm was adopted. To maintain the constituents of the adhesive at 20 °C and 60% of relative humidity while manufacturing the specimens, the containers of the constituents were transported to a climatic chamber 24 h prior the moulding process of the specimens. The epoxy adhesive analysed is a bi-component material that, according to the supplier, should be mixed in a proportion of 1:4 (in weight). After weighting both components in the recommended ratio, the mixture was performed manually inside a bowl and using a spatula, as it would be in a real case application, and at room temperature. After obtaining a uniform colour, the mixture was poured into a silicon mould, and no efforts were made to remove air bubbles, in order to produce a final product that is in every way similar to the one obtained in an actual application. After moulding, all the specimens to be tested were again transported to the climatic chamber until the curing time was over. When the specimens were removed from the mould, the edges were gently scraped in order to remove occasional sharp edges. For the measurement of the strain during the test, a control