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## Experimental Analysis and Modelling of the Nonlinear Shear Creep Behaviour at the Concrete–FRP Interface

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# BEHAVIOUR AT THE CONCRETE-FRP INTERFACE

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**ABSTRACT:** This paper presents a numerical investigation of the shear creep behavior of the epoxy at the concrete–FRP interface. Using the experimental data collected in a previous study (Houhou 2013), creep constitutive equations have been developed based on a modification of Völkersen’s model and have been introduced in a finite element code. Therefore, the creep behavior of a double lap adhesive joint is simulated and compared to experimental results. As a main result, it is demonstrated that due to the creep strains, the calculated stresses in the joint corners is lower than the one obtained by elastic prediction.

## 1. Introduction

Rehabilitation/strengthening of civil structures by externally bonded Fiber-Reinforced Polymers (FRP) is now considered as an effective technique [1] which presents major advantages over traditional methods, such as high corrosion resistance or high strength-to-weight ratio. In the framework of flexural strengthening applications, Carbon FRP (CFRP) materials are routinely used to increase the load carrying capacity and the serviceability of repaired structures. Tensile stress is transmitted from the concrete substrate to the CFRP reinforcement through the shear load path provided by the adhesive layer.

If pultruded FRP laminates generally demonstrate satisfactory environmental resistance and limited creep strain, the durability of the adhesive bond still remains a critical issue which hampers the extensive use of composite strengthening systems in the field. This drawback is mainly due to the environmental sensitivity and the creep response of cold curing epoxy adhesives used in construction. While many studies have investigated the influence of moisture or hydrothermal ageing on the adhesive bond properties, only limited research has been conducted on the long term creep behavior of concrete-FRP interfaces subjected to sustained load. In most cases, the authors used a double shear test configuration and the creep load was applied to the specimens by means of a sustained dead weight attached to a cantilever steel beam. Unfortunately, this type of cantilever setup is voluminous and is therefore not adapted to the characterization of numerous specimens in a limited space.

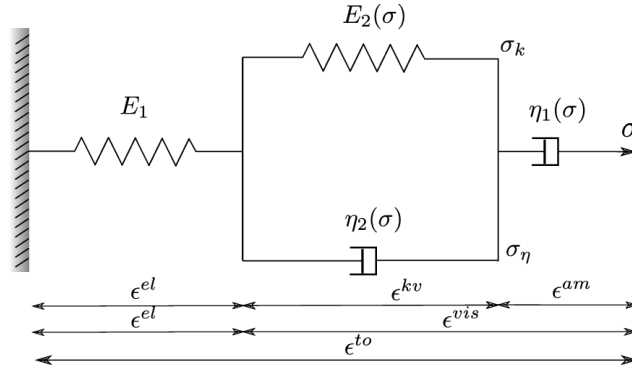
In this context, an innovative and compact experimental creep device has been developed, which makes it possible to apply a sustained load on several test bodies stored in a limited space. This setup involves a centralized hydraulic system which actuates flat jacks. Due to its reduced volume, it can be installed in a

climatic chamber so that accelerated ageing conditions can be coupled to the mechanical loading. This article presents both the experimental creep test setup and its associated instrumentation, and gives additional details regarding the validation stages: verification of i) the constancy of the applied load, ii) the symmetry of the double shear test-bodies and iii) the relevance of recorded creep strains.

## 2. Numerical modelling of the nonlinear shear creep

### 2.1. Description of 1D model

The rheological model used to describe the behavior of creep adhesives is a Burger model (associated rheological scheme shown in Fig - 1) with parameters that evolve according to the stress applied.



**Fig. 1 - Schematic diagram of Burger material**

In Figure 1,  $\sigma_k$  and  $\sigma_\eta$  respectively represent the Kelvin-Voigt solid stress in the elastic and the dashpot branches. The equations of the Burger model in a 1D formalism are given by the system (1).

$$\begin{cases} \varepsilon^t = \varepsilon^{el} + \varepsilon^{vis} \\ \sigma = E \varepsilon^{el} \\ \varepsilon^{vis} = \varepsilon^{kv} + \varepsilon^{am} \end{cases} \quad (1)$$

with  $\varepsilon^{to}$ ,  $\varepsilon^{el}$  and  $\varepsilon^{vis}$  correspond respectively to the total, elastic and viscous strains. The different viscous strains are characterized by the equation (2).

$$\begin{cases} \eta_2(\sigma) \dot{\varepsilon}^{kv} + E_2(\sigma) \varepsilon^{kv} = \sigma \\ \varepsilon^{am} = \frac{\sigma}{\eta_1(\sigma)} \end{cases} \quad (2)$$

where  $\eta_1$ ,  $\eta_2$ , and  $E_2$  are the parameters of Burger model. Experimental tests from literature [Dean07, Houhou14] put in perspective the nonlinear behavior of adhesive creep. To take into account these nonlinearities, the model's parameters are taken as a function of stress level. The functions used are chosen as decreasing exponential:

$$\begin{cases} \overline{\eta_1(\sigma)} = \exp(-a_1 \overline{\sigma} + b_1) \\ \overline{\eta_2(\sigma)} = \exp(-a_2 \overline{\sigma} + b_2) \\ \overline{E_2(\sigma)} = \exp(-a_3 \overline{\sigma} + b_3) \end{cases} \quad (3)$$

With  $a_i$  and  $b_i$  scalars identified on experimental values and  $\overline{\sigma}$  a scalar variable function of stress level.

## 2.2. Multiaxial variable

Tests of (Dean 07) show that the creep behavior of these adhesives depends not only on the intensity of the stresses but also on the state of stress. Thus, the material may possibly have more creep in tension than in compression even if there does not seem to be a consensus on this point. To take this characteristic into account, the 1D stress is replaced by an effective stress  $\bar{\sigma}$  which is a function of both hydrostatic and deviating components. A way of defining  $\bar{\sigma}$ , used for instance in the work of (Dean) is given by a combination of the first invariant of the stress tensor and the second invariant of the deviatorial stresses:

$$\left\{ \begin{array}{l} \bar{\sigma} = \frac{(\lambda + 1)}{2\lambda} \sigma_e + \frac{3(\lambda - 1)}{2\lambda} \sigma_m \\ \sigma_e = \left[ \frac{1}{2} [(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_I - \sigma_{III})^2] \right]^{\frac{1}{2}} \\ \sigma_m = \frac{1}{3} (\sigma_I + \sigma_{II} + \sigma_{III}) = \frac{I_1}{3} \end{array} \right. \quad (4)$$

with  $\sigma_I, \sigma_{II}, \sigma_{III}$  the main components of the stress tensor and  $\lambda$ , a scalar that captures the sensitivity of the average relaxation time with respect to hydrostatic loading. Note that the asymmetry of behavior can be considered through the parameter  $\lambda$ . In this study it is assumed to be equal to 1.

## 2.3. Extension of the model to the 3D frame

In order to take into account multi-axial loading, the one dimensional model is extended to a three dimensional problem thanks to the isotropic elastic behavior law:

$$\left\{ \begin{array}{l} \underline{\underline{\varepsilon}}^{kv} = \left[ \frac{1 + \nu}{E_2(\sigma)} \underline{\underline{I}} - \frac{\nu}{E_2(\sigma)} \underline{\underline{I}} \otimes \underline{\underline{I}} \right] : \underline{\underline{\sigma}}^{kv} \\ \underline{\underline{\varepsilon}}^{kv} = \left[ \frac{1 + \nu}{\eta_2(\sigma)} \underline{\underline{I}} - \frac{\nu}{\eta_2(\sigma)} \underline{\underline{I}} \otimes \underline{\underline{I}} \right] : \underline{\underline{\sigma}}^\eta \\ \underline{\underline{\varepsilon}}^{km} = \left[ \frac{1 + \nu}{\eta_1(\sigma)} \underline{\underline{I}} - \frac{\nu}{\eta_1(\sigma)} \underline{\underline{I}} \otimes \underline{\underline{I}} \right] : \underline{\underline{\sigma}} \end{array} \right. \quad (5)$$

with  $\underline{\underline{\sigma}}^\eta$  et  $\underline{\underline{\sigma}}^{kv}$  the stress tensor respectively in the viscous dashpot and elastic stiffness of Kelvin-Voigt unit. Here,  $\nu$  is the elastic Poisson ratio,  $\underline{\underline{I}}$  and  $\underline{\underline{I}}$  are respectively the four order and second order unit tensor.

## 2.4. Implementation

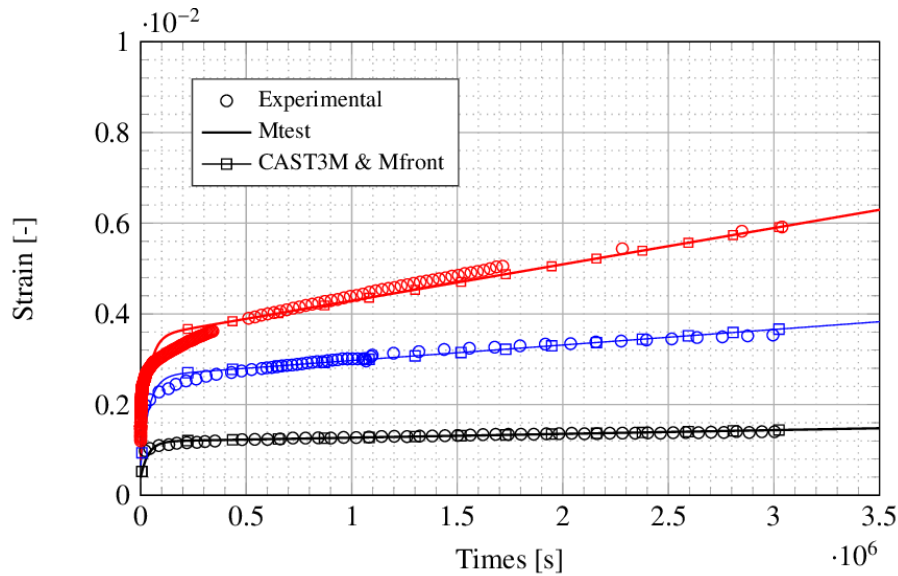
The implementation of the model was done through the Mfront behavior law generator (Helfer 15). The different equations are not developed in this paper. Nevertheless, integration is done through an implicit method with a  $\theta$ -schema.

## 3. Application cases

### 3.1. Homogeneous creep test (Houhou 2012)

The behavior model is first confronted with the experimental data obtained in Houhou PhD thesis. A model of a creep test on adhesive is carried out. The experimental system exhibits a homogeneous state

of stress. It is therefore possible to simulate the problem either in 0D (on a gauss point) or on a cube. Both simulations are undertaken through a 0D module called *Mtest* (Helfer 2015) and on an elementary EF cube. Creep is taken into account over a 30-days period. The material parameters used in the following section are identified on the experimental data.

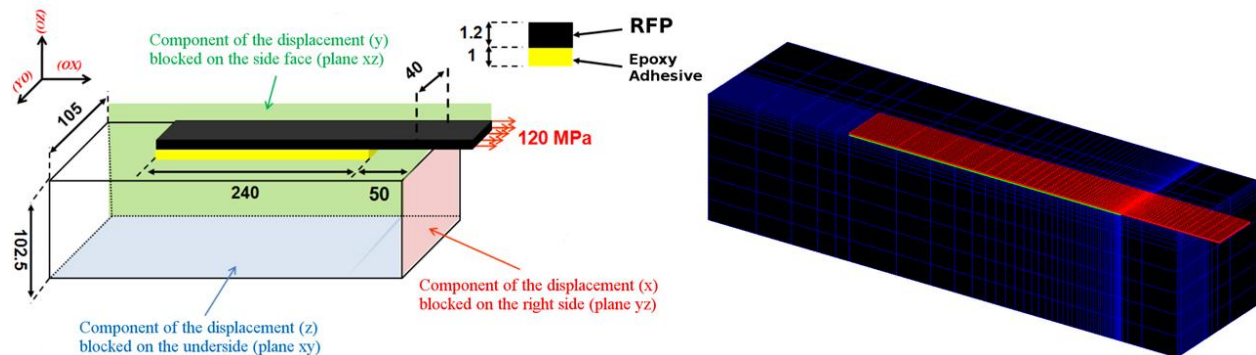


**Fig. 2 – Model behavior regarding experimental value for three different stress levels: 5 MPa (black), 8 MPa (blue) and 10 MPa (red)**

The figure shows the modeling outputs for both cases (*Mtest* and EF under CAST3M (Verpeaux 1988)). The results obtained are similar in both cases.

### 3.2. Structural modelling (Houhou 2014)

In this second part, we are interested in modelling the creep system developed within (Houhou 13). The system is shown in Fig-2 on the left side with the associated Cast3m mesh on the right. This mesh is composed of 24280 3D linear elements and all elements except the glue are modelled by an elastic model. The boundary conditions imposed are those considered in the schematic representation and the loading is applied in the CFRP. The simulation is run for a 30-days creep period.



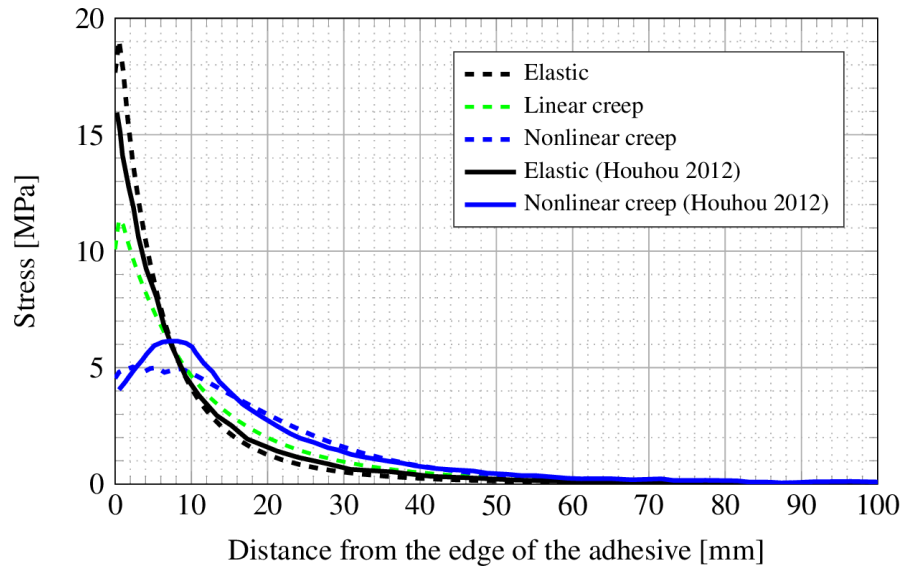
**Fig. 3 – Creep system developed in (Houhou 2012): on the left side schematic representation, on the right side associated mesh in CAST3M**

Different modelling cases are carried out. The parameters used for the modelling are summarized in the table 1.

**Table 1 – Modelling parameter regarding case scenario**

Modelling cases	$E_{el}$ [GPa]	$\nu$ [-]	$\eta_1$ [GPa/s]	$E_2$ [GPa]	$\eta_2$ [GPa/s]
Elastic	12.7	0.3	-	-	-
Linear creep	12.7	0.3	$59.1 \times 10^6$	6.3	$19.0 \times 10^4$
Nonlinear creep	12.7	0.3	$\eta_1(\bar{\sigma})$	$E_2(\bar{\sigma})$	$\eta_2(\bar{\sigma})$

In this communication, the different mechanical fields will not be presented. To study the impact of creep, the measurement of tangential stresses along the adhesive is compared with the experimental and modelling data obtained in Houhou's thesis. The Fig-4 shows the evolution of the tangential stress for different modeling cases presented in tab -1.



**Fig. 4 – Evolution of the tangential stress after 30 days. Full line chosen as a reference and dotted lines obtained modelling.**

If we note in the fig-4 the evolution of the stress in an elastic case, we can see that the modelling is close to the chosen reference. The value on the edge of the joint is respectively 17.7 MPa compared to a reference close to 16 MPa. There is also a slight relocation of the maximum stress that is not found on the reference solution. If we then look at the modelling with the non-linear creep model we see that the tangential stresses obtained at the edge of the adhesive for both models are again close (4.5 MPa versus 4.1 MPa). On the other hand, we do not find the strong delocalization of the maximum stress observed on the reference model. Rather, we observe an almost isostressing zone on 10 mm followed by a decrease that will tend towards evolution similar to the reference. This difference between the two models can possibly be explained by the difference modelling approach. The one developed in this communication is nonlinear whereas in the approach proposed by (Houhou 2012) the adhesive mesh is discretized in zone with a linear creep model with different parameters for each zone. Finally, if we conclude with a linear creep model, realized here by transforming non-linear functions into constants, we note that the solution logically evolves between the elastic model and the non-linear creep model. In this case, there is almost no relocation of the stress.

## 4. Conclusion

The stated objective of the work undertaken was to implement a creep behaviour law for reinforcing adhesives made of carbon fibre reinforced polymers. To achieve this objective, the work carried out has been based on the model proposed by Houhou (Houhou 2014). The model being a 1D rheological model, the first work focused on passing the law in a multi-axial framework. The implementation was done under MFront by choosing an implicit method. After initial tests on conclusive homogeneous systems, the law was tested under Cast3m by modelling a structure representing IFSTTAR's creep system. The results obtained were compared with experimental and simulation data from (Houhou 14). Results show that due to the creep strains, the calculated stresses in the joint corners is lower than the one obtained by elastic prediction.

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