MECHANICAL BEHAVIOR OF STRUCTURAL ADHESIVES: MODELING AND TESTS.

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Abstract

The main objective of this paper is to show the response of a structural adhesive in a bulk form. In order to do so, several tests are performed to observe how the adhesive behaves under different unidirectional tests. It is very important to understand the mechanical behavior of the adhesive, so developing a model based on tests observations will be required. The experimental stress-strain curves provided by unidirectional tests will be used in a 1D model. Many authors propose models that predict the non-linear behavior response in structural adhesives. However, the models lack in accuracy, this is because most of them do not include complex phenomena such as plasticity or viscoplasticity, temperature, damage, etc. Experimental data obtained from creep and cyclic tensile tests are used in order to identify parameters in the model equations. The originality of the model is the inclusion of a kinematic hardening, damage and Norton's law [1] to predict the plastic strain rate. Experimental results show a decrease of the elastic modulus, due to damage after unloading and reloading in a cyclic test. The 1D model results are compared with the 1D test results in order to validate the model. The 1D application is programed in MATLAB and it can be used in the future to develop a more general 3D model.

Introduction

The structural behavior of the adhesive is more complex than metals and other structural materials [2]. The main purpose of the use of adhesive in structures is to reduce weight and costs. The analysis of adhesives has to include plasticity and other non-linear phenomena [3]. The non-linear behavior (viscosity, damage, plasticity) is observed on uniaxial tests (tension or compression). However, it is well known that on these materials, multiaxial loads affect the behavior and resistance of the material significantly. Applications in real world are multiaxial. Therefore, models based on unidirectional tensile tests are useless to predict multiaxial stress distributions on adhesive joints. Furthermore, the adhesives are polymer materials; therefore viscosity at room temperature is important for rate tests. But for a 3D model (a more general model), is necessary to understand the 1D problem first. In fact, the model presented in this paper simulates the behavior of the adhesive in a bulk form during 1D cyclic or creep tests.

Methodology

As it was said, plasticity, viscoplasticity, hardening and damage are non-linear phenomena. These phenomena are modeled by four equations that will be described in detail in the section named "One dimensional simulation". In order to simulate the 1D problem including damage, viscoplasticity and hardening, it's necessary to identify which equations predict the behavior of the adhesive in a one-dimensional problem. For that purpose the experiments are used to identify the different phenomena acting in the adhesive bulk sample. To validate the 1D model the simulation is compared with the 1D experimental data.

Results

Experimentation

The following tests were performed so as to identify the material parameters that appear in the models.

Creep test. The creep test consists on applying and ensuring a constant stress level until failure occurs (see figure 1 (a)). This type of test is helpful to see how the plastic strain ε_p evolves after applying the constant stress (see figure 2).

Cyclic test. This type of test is divided basically in three parts: loading, unloading and reloading (see figure 1 (b)). In a cyclic loading test the influence of damage is revealed if the apparent Young's decreases at the end of the test. Also, the influence of the plastic strain rate is observed.

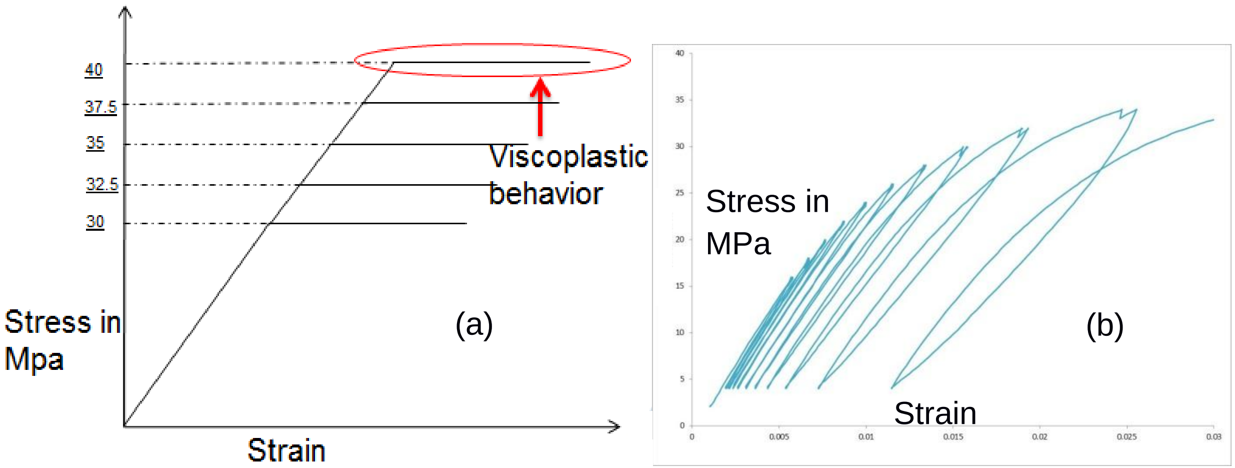


Figure 1. (a) Stress vs. strain curve for creep tests at different stress levels, (b) stress vs. strain curve for a cyclic loading.

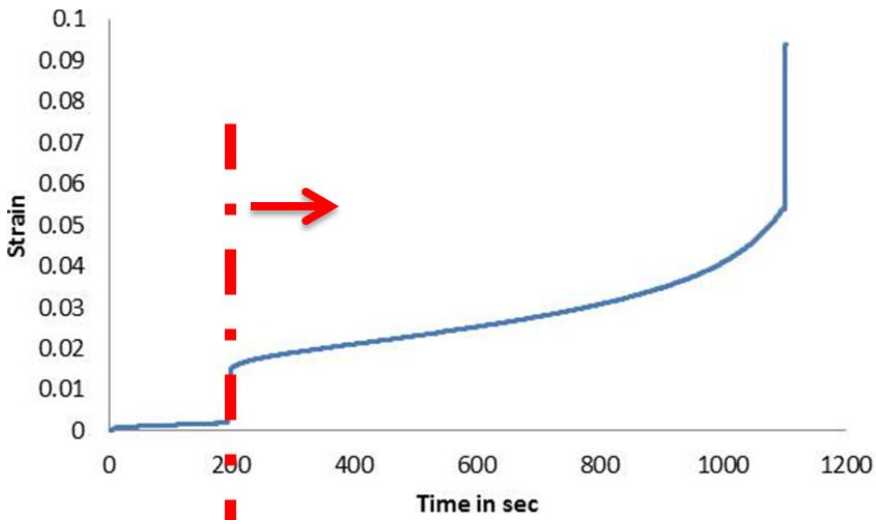


Figure 2. Plastic strain evolution for a creep test.

One dimensional simulation

As part of the results, a 1D model has been developed in order to predict the adhesive behavior for the one dimensional tests. The model uses the following equations [1] to determine stresses and strains considering the influence of damage, viscoplasticity, hardening and a plastic yield criterion:

Elastic behavior $$\sigma = E_o(1-d)(\varepsilon_t - \varepsilon_p) \tag{1}$$

Norton's law $$\dot{\varepsilon}_p = \left(\frac{\left|\frac{\sigma}{(1-d)} - \chi\right| - \sigma_y}{K_v}\right)^N \tag{2}$$

Kinematic hardening equation $\chi = c\varepsilon_p$ (3)

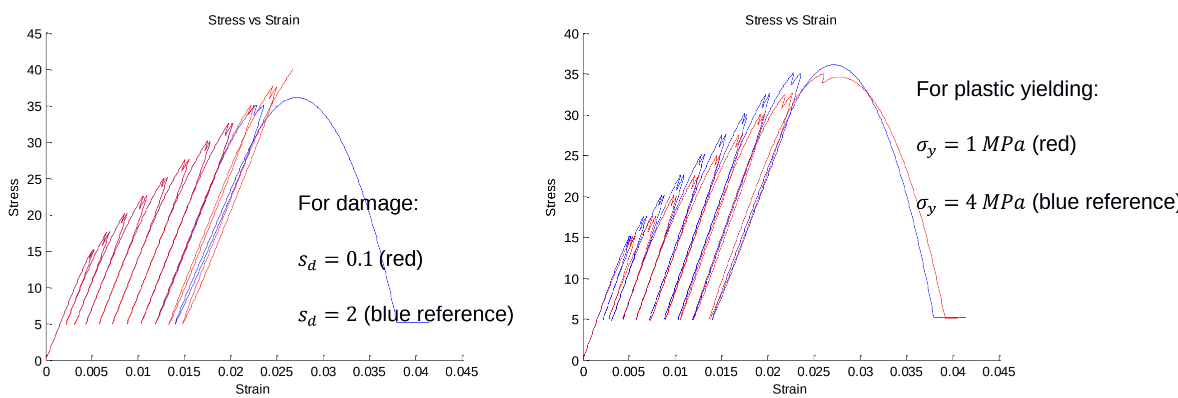
Damage evolution $\dot{d} = \left(\frac{Y}{S}\right)^s |\dot{\varepsilon}_p|$ (4)

where equation 1 relates stresses (σ) with the elastic strain ($\varepsilon_t - \varepsilon_p$) including damage ($1 - d$) and the apparent Young's modulus (E_o). Equation 2 is called the Norton's law and describes the plastic strain rate $\dot{\varepsilon}_p$ for a yield function $\left|\frac{\sigma}{(1-d)} - \chi\right| - \sigma_y$ where χ is called the material hardening and σ_y is the yield stress. K_v and N are material properties that can be determined by a creep test. Equation 3 relates the hardening χ with the plastic strains ε_p by a constant c. Finally equation 4 describes the damage rate $\dot{d}$ as a function of the absolute value of the plastic strain rate $|\dot{\varepsilon}_p|$ and it also includes material parameters like *S* and *s*. The parameter *Y* is a function of the stress level and the initial Young's modulus, it is defined as follows:

$$Y = 0.5\left(\frac{\sigma}{(1-d)}\right)^2 \frac{1}{E_o} \quad (5)$$

The equations system formed by equations 1, 2, 3 and 4 is a highly non-linear system, therefore, to solve this type of problem a numerical method to approximate the solution is proposed. The method used herein is the multivariable Newton-Raphson method.

The adhesive behavior is clearly affected by modifying any parameter in the equations. Figure 3 shows a comparison varying several parameters (for damage, plastic strain rate and hardening). The blue curves indicate the reference plots and the red curves indicate the parameter modification plots in order to do the comparison.



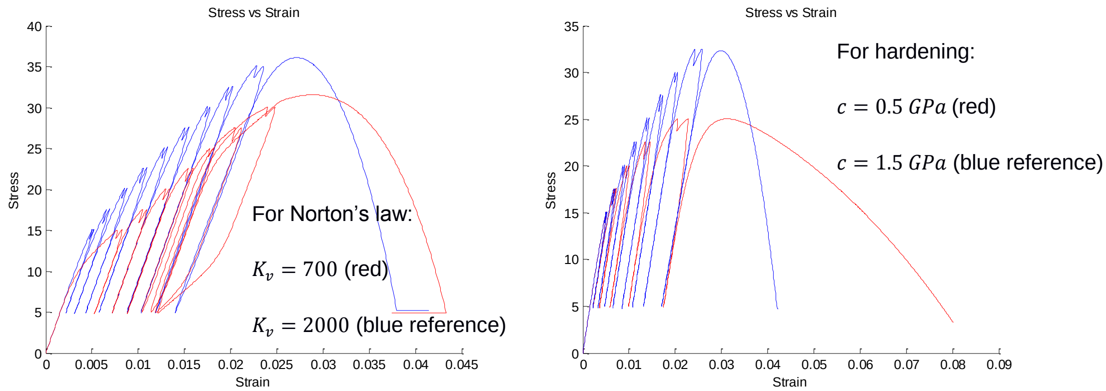


Figure 3. Effect of parameters variation on the predicted mechanical response.

The 1D model provides information of the behavior of adhesives. Plotting the stress-strain due to the damage, viscoplasticity and hardening. Figure 4 shows a comparison between the experimental data and simulation data for a cyclic loading. Figure 4 shows that the simulation (right side) approximates the behavior of a cyclic load test (left side) by programing damage, viscoplasticity and hardening.

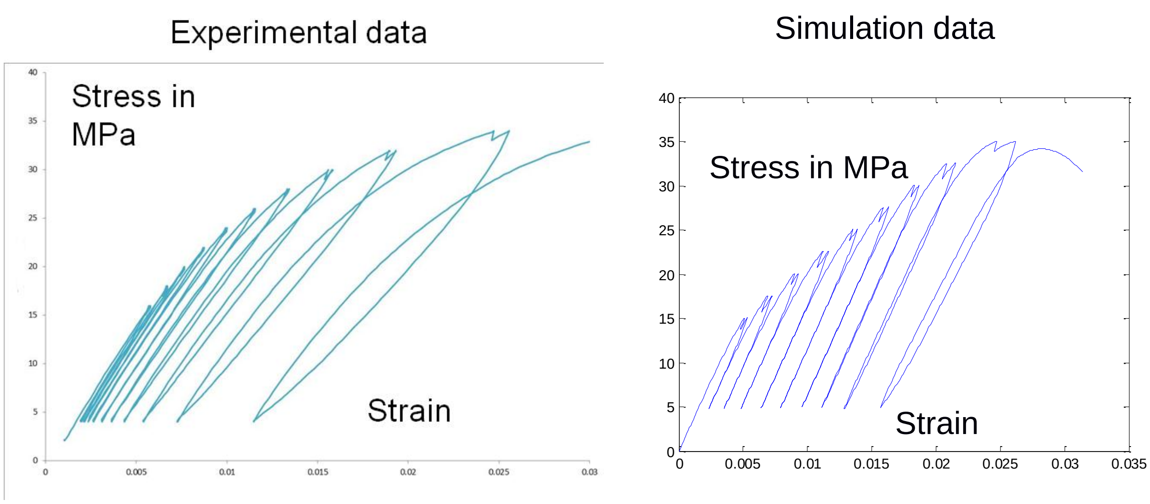


Figure 4. Comparison between the experimental data (left) and the simulation (right).

Conclusions

The ensemble of equations (1), (2), (3) and (4) in MATLAB provides a more general solution for the non-linear behavior of an adhesive bulk sample for 1D tests. When the adhesive riches the plastic zone, the non-linear problem variables are activated. Experimental data confirms the influence of several phenomena related with the non-linear behavior in the adhesive such as: damage, plastic strain rate dependence, viscoplasticity and hardening. This last part is the main reason to give a more general solution adding more variables and more equations to the problem improving it and making it more accurate.

Perspective

As shown in figure 4 the simulation (right side) is not exactly the experimental curve (left side). That gives the next perspective:

- Improve the 1D model in order to fit as more as possible the experimental data curve.

- Use the 1D model to design experimental tests.

- Apply the 1D model results in a more general model (3D model).

References:

[1] Lemaitre J, Chaboche J.L. Mechanics of solid materials. Cambridge University Press. 253-345. 2002.

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[3] J.Y. Cognard, P. Davies, L. Sohier, R. Créac'hcadec. A study of the non-linear behavior of adhesively-bonded composite assemblies. 2006. Composite Structures. Mechanics of Naval and Offshore Structures, ENSIETA, 2 rue F. Verny, 29806 Brest, France. Materials and Structures group, IFREMER Brest Centre, 29280 Plouzané, France. Laboratoire d'Inge´nierie Me´canique et Electrique, UBO, 29285 BREST Cedex, France.