ELASTIC STRESS OR STRAIN THRESHOLD FOR CARBON/EPOXY MATERIALS BEHAVIOUR

M. Castres[1,2,3], J. Berthe[1], M. Brieu[2,3], E. Deletombe[1]

[1]ONERA-The French Aerospace Lab, F-59014 Lille Cedex, France
Email : magali.castres,julien.berthe,eric.deletombe@onera.fr
[2]Univ Lille Nord de France, F-59000 Lille,France
[3]Centrale Lille, LML, F-59650 Villeneuve D'Ascq
Email : mathias.brieu@ec-lille.fr

Keywords: Polymer-matrix composite, Non linear behaviour, Mechanical properties, Strain rate and temperature dependency

Abstract

Composite materials are widely used in the aeronautical industry, in particular Composite Fibre Reinforced Polymers (CFRP). The behaviour of such materials can be splitted into two domains a first linear and a second non linear. The linear domain of the CFRP considered in this study, the T700GC/M21, has been already investigated by Berthe et al [1, 4]. The present study is dedicated to the analysis of the transition between the linear and the non linear domain. The first step consists in locating the transition between the linear and the non linear domain. For this purpose an experimental investigation on the T700GC/M21 [±45°] laminate at different strain rates and temperatures is used. A method based on a linearity deviation detection is proposed to characterize the elastic limit. This method is accurate, robust and can be used also with dynamic tests. Finally, the influence of strain rates and temperatures on this limit is reported.

1. Introduction

Composite materials are widely used in the transportation industry like aeronautics. The last aircraft of the Airbus family, the A350, accounts composite materials for more than 50% of its structural weight. Composites permit to reduce the weight, to avoid corrosion, and to build complex parts. The parts of the aircraft may be exposed to severe loadings at various temperatures. These loads cover a wide spectrum of strain rates, from low to high, and a wide range of temperatures, from 50°C to -50°C. However, the composite material behaviour is strain rate and temperature dependent [2, 3]. One of the issue of the aeronautical industry is to ensure safety. For this purpose, it is important to understand the composite behaviour and the influence of extreme conditions on this behaviour. The behaviour of the CFRP can be splitted into two domains, a first elastic linear domain and a second non linear [3]. The viscoelastic linear behaviour of CFRP T700GC/M21 has already been investigated with respect to the influence of strain rate and temperature on its apparent modulus by Berthe et al [1, 4]. The purpose of this work is to define a methodology in order to study the transition between the linear and the non linear behaviour. To the authors knowledge there is no clearly defined stress or strain criteria to obtain such an elastic limit. The methods actually used to define such thresholds are mostly inverse methods that are depending on a chosen model. In the literature there are various criteria which define different transitions in materials behaviour, for instance elastic limit for polymers [5–10] or failure criteria for composites [11, 12]. Like

Excerpt from ISBN 978-3-00-053387-7

in the case defined here, these criteria define an irreversible evolution of the material state. This transition is hereafter referred as the elastic limit. In the work presented here it is proposed to identify this elastic limit using only experimental data and not a model as often seen in the literature. For this purpose, an experimental investigation on the T700GC/M21 [±45°] laminate using an hydraulic jack and an environmental chamber has been used. The shear modulus is accurately determined thanks to this experimental investigation, then an original method is proposed to obtain the elastic limit. Finally, these observations are compared with other results reported in the literature.

2. Methodology and results

2.1. Material and tests

The studied material is a laminated composite constituted of four [±45°] plies of M21 epoxy resin and T700GC carbon fibres which has been cured with a typical cure cycle. The specimens shape is rectangular. Two strain gauges are glued on opposite faces of the specimens to measure the longitudinal and transverse strains. All tests are performed with a Schenck servo hydraulic jack with a ± 200 kN piezoelectric load cell, except for tests at 0.5 mm/min which are performed on a INSTRON 5887 machine with a maximum load capacity of 300 kN. Various upper holder speeds have been tested, six speeds at ambient temperature, between 0.5 mm/min and 2 m/s, three speeds at $-40°C$ and $-100°C$, between 50 mm/min and 0.5 m/s. For dynamic tests, a Kistler piezoelectric load cell is used for load measurements. Signals are recorded using a 1MHz data acquisition system. The shear stress-strain curves are plotted on figure 1. The shear behaviour clearly evolves with the strain rate and temperature. The material stiffness seems to be strain rate and temperature dependent. Indeed, the shear modulus increases with the increasing strain rate and with the decreasing temperature [1].

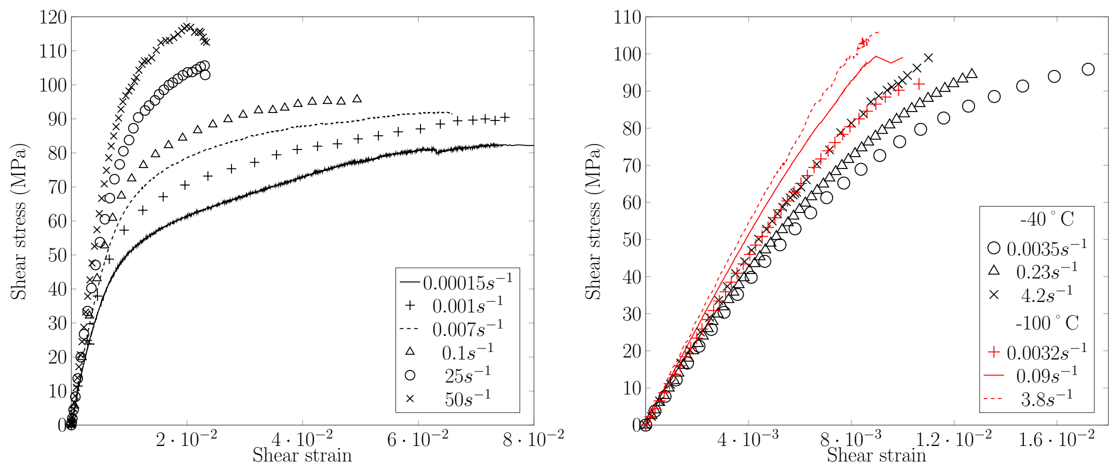

Figure 1. T700GC/M21 shear stress/strain at 20°C [4] (left) and shear stress/strain at -40°C and -100°C (right) [1]

As seen in CFRP behaviour by Delsart et al. [3], the shear behaviour can be splitted into a linear and a non linear behaviour. In this work, a method based on a linearity deviation detection is proposed to accurately identify the transition between linear and non linear domain, considered to be the material elastic limit.

Excerpt from ISBN 978-3-00-053387-7

2.2. Evaluation of the elastic limit

The method proposed in this work is based on a quantification of the linearity deviation. For this purpose, it is considered that behaviour is linear the material is elastic, and the elastic Hooke's law applies. Then, to quantify the linearity deviation the Hooke's law is used. For such a purpose, theoretical stress (σ_{theor}) and strain (ε_{theor}) are reconstructed as follows :

$$\sigma_{theor} = 2 * G_{12} * \varepsilon_{expe} \tag{1}$$

$$\varepsilon_{theor} = \frac{\sigma_{expe}}{2 * G_{12}} \tag{2}$$

G_{12} being the Hooke shear modulus evaluated accurately. Thanks to this modulus, theoretical strain and stress are evaluated and compared to experimental strain and stress (ε_{expe} and σ_{expe}). Then, the linearity deviation is quantified by calculating the distance between these two stresses, or strains, such as given in equations (3) and (4) :

$$d_1 = \frac{\left|\sigma_{expe} - \sigma_{theor}\right|}{\sigma_{expe}} \tag{3}$$

$$d_2 = \frac{\left|\varepsilon_{expe} - \varepsilon_{theor}\right|}{\varepsilon_{expe}} \tag{4}$$

In a first step, the rebuilt of theoretical stress and strain is compared to the experimental stress and strain. Then, the linearity deviation is evaluated thanks to the distance calculated in (3) and (4). Finally, the elastic limit is estimated for each tests at each strain rates and temperatures. In our case, the material is considered to be linear as long as d< 5%. This arbitrary value allows us to deal with experimental noise. So the proposed method evaluates the elastic limit with a a certain level of uncertainty which takes into account the experimental noise and the experimental dispersion. Moreover, the elastic limit is evaluated as well in terms of stress as of strain.

2.3. Elastic stress and strain limit : Application to T700GC/M21

In this section, the elastic stress and strain limits of the T700GC/M21 obtained with the proposed method at different strain rates and temperatures are calculated, and the influence of the strain rate and temperature variables are studied. For each parameter, at least three tests have been performed, except for the $10^{-4} s^{-1}$ strain rate where only two tests were performed due to the lack of specimens. The elastic stress and strain limits are strain rate and temperature dependent (see Figure 2 and Table 1).

When the temperature decreases, the elastic limit increases and when the strain rate increases the elastic limit increases too. This trend has already been noticed by Berthe when the T700GC/M21 viscoelastic shear modulus was studied [1, 4]. On the right hand side in Figure 2, the elastic strain limit at $25 s^{-1}$ is lower than the elastic limit at $0.1 s^{-1}$. This gap can be due to perturbations owed to experimental tests like rate variations, temporal reconstruction, or real physical reasons. The proposed method allows to obtain elastic stress and strain limits at different strain rates and temperatures. This method is robust and can be used with dynamic tests. It is not disturbed by the experimental perturbations owed to dynamics.

Beside these results, works realised by Huchette on T700GC/M21 quasi static tests [13] revealed a damage initiation around 25 MPa for a $4.10^{-5} s^{-1}$ strain rate. This point is reported in figure 2 (blue cross). There is a good correlation between this observation and the ones obtained with the non linear deviation method. In this work, elastic stress and strain limits are obtained. These two values can be associated to

Excerpt from ISBN 978-3-00-053387-7

T(°C)	$\dot{\varepsilon}(s^{-1})$	$\varepsilon_a(10^{-3})$	$\sigma_a(MPa)$
20	1.10^{-4}	2.5±6%	19.75±4%
	1.10^{-3}	2.7±7%	25±7%
	7.10^{-3}	3.3±6%	30±6%
	0.1	3.6±8%	35±8%
	25	3.4±9%	37.5±9%
	50	5.25±5%	65.5±4%
-40	$3.5.10^{-3}$	3.85±4%	37.25±3%
	0.23	4.45±3%	46±2%
	4.2	5.0±4%	56±12%
-100	$3.2.10^{-3}$	4.65±5%	50.5±3%
	0.09	5.65±3%	68.5±2%
	3.8	6.75±1%	79±10%

Table 1. T700/M21 elastic shear stress-strain threshold

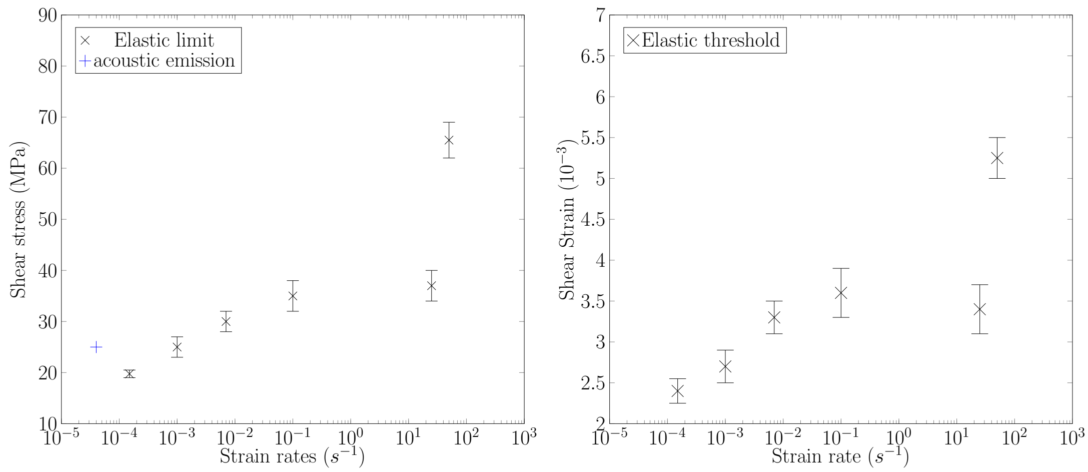

Figure 2. Elastic shear stress and strain limit at ambient temperature for T700/M21

form an elastic limit couple (σ_a; ε_a). The question is to know if this criterion is a dual one. To verify that, the Hooke's law is used to estimate a theoretical elastic stress limit σ_a^* thanks to the shear modulus and the elastic strain limit obtained experimentally as follows :

$$\sigma_a^* = 2 * G_{12} * \varepsilon_a \tag{5}$$

Then this σ_a^* is compared to σ_a obtained with the previous method. σ_a^* and σ_a are plotted in Figure 3. σ_a^* quite well corresponds to σ_a. The proposed threshold indicators then seem to be dual for tests at 20°C.

This study was also conducted on tests at 20°C and −100°C. The same conclusion was obtained.

3. Conclusion

The aim of this work was to evaluate the transition between the linear and the non linear behaviour of the T700GC/M21 material. This transition is considered to be the elastic limit of the material. The proposed criterion defines a lost of linearity using only experimental data and the Hooke's law. This

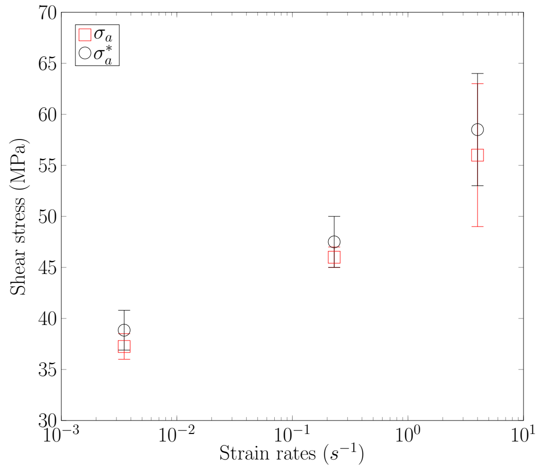

Figure 3. Comparison of σ_a^* and σ_a for T700/M21 at -40°C

method is robust, accurate and allows to obtain the elastic limit for a large range of temperatures and strain rates. It can also be used with dynamic tests, because it is not disturbed by the experimental noise owed to dynamic. The influence of the temperature and strain rate variables are reported : the elastic limit increases with the increasing strain rate and with the decreasing temperature. The accuracy of this elastic limit has been assessed with an acoustic emission analysis which located the first acoustic activities at $20°C$ and 5 mm/min at the same load level than this elastic limit.

Références

[1] J. Berthe, M. Brieu, E. Deletombe, and Gerald Portemont. Temperature effects on the time dependent viscoelastic behaviour of carbon/epoxy composite materials : Application to T700GC/M21. *Materials and Design*, 62 :241–246, 2014.

[2] A.T. Nettles and E.J. Biss. Low temperature mechanical testing of carbon-fiber/epoxy-resin composite materials. Technical report, NASA/Marshall Space Flight Center Center/MSFC,Alabama, 1996.

[3] E. Deletombe and D. Delsart. Composite helicopter structural crashworthiness ONERA/DLR Cooperation II-1st year progress report. Technical Report TP 1999-72, ONERA, 1999.

[4] J. Berthe. *Comportement thermo-visco-élastique des composites CMO-De la statique à la dynamique grande vitesse*. PhD thesis, ONERA/Laboratoire Mécanique de Lille/ EDSPI 072, 2013.

[5] J. Richeton, S. Ahzi, L. Daridon, and Y. Rémond. A formulation of the cooperative model for the yield stress of amorphous polymers for a wide range of strain rates and temperatures. *Polymer*, 46(16) :6035–6043, 2005.

[6] J. Richeton, S. Ahzi, K.S. Vecchio, F.C. Jiang, and R.R. Adharapurapu. Influence of temperature and strain rate on the mechanical behavior of three amorphous polymers : Characterization and modeling of the compressive yield stress. *International Journal of Solids and Structures*, 43(7-8) :2318–2335, 2006.

[7] J. Richeton, S. Ahzi, L. Daridon, and Y. Rémond. Modeling of strain rates and temperature effects on the yield behavior of amorphous polymers. *J. Phys. IV France*, 110 :39–44, 2003.

Excerpt from ISBN 978-3-00-053387-7

[8] R. Matadi Boumbimba, K. Wang, N. Bahlouli, S. Ahzi, Y. Rémond, and F. Addiego. Experimental investigation and micromechanical modeling of high strain rate compressive yield stress of a melt mixing polypropylene organoclay nanocomposites. *Mechanics of Materials*, 52 :58–68, 2012.

[9] Jennifer L. Jordan, Jason R. Foley, and Clive R. Siviour. Mechanical properties of epon 826/dea epoxy. *Mechanics of Time-Dependent Materials*, 12(3) :249–272, 2008.

[10] R. Gerlach, C.R Siviour, N. Petrinic, and J. Wiegand. Experimental characterisation and constitutive modelling of RTM-6 resin under impact loading. *Polymer*, 49 :2728–2737, 2008.

[11] Isaac M. Daniel, Jyi-Jiin Luo, Patrick M. Schubel, and Brian T. Werner. Interfiber/interlaminar failure of composites under multi-axial states of stress. *Composites Science and Technology*, 69(6) :764 –771, 2009.

[12] I.M. Daniel, B.T. Werner, and J.S. Fenner. Strain-rate-dependent failure criteria for composites. *Composites Science and Technology*, 71(3) :357–364, 2011.

[13] C. Huchette. *Sur la complémentarité des approches expérimentales et numériques pour la modélisation des mécanismes d'endommagement des composites stratifiés*. PhD thesis, Université Paris VI, 2005.

Excerpt from ISBN 978-3-00-053387-7