EXPERIMENTAL CHARACTERISATION AND MODELLING OF RTM-6 VISCO-ELASTIC BEHAVIOUR AT HIGH STRAIN RATES IN TENSION

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Abstract. To accurately predict the response of Carbon Fibre Reinforced Polymers (CFRP) structures subjected to high speed loading such as crash and impact, the visco-elastic behaviour of the material should be taken into account. An approach to study the dependency of CFRP material is to study the strain-rate dependency of the resin material. In this study tensile characterisation tests have been performed on RTM-6 resin using a servo-hydraulic jack. Tests have been performed at strain-rates between $1{\cdot}10^{-2}$ s^{-1} and 60 s^{-1}. Significant increases of the Young modulus and of the yield stress have been observed between these strain-rates. A spectral visco-elastic model has been identified using these tests results.

1 Introduction

To increase the performances of vehicles and to face greening challenges, organic matrix composite materials are widely used today in transportation industry. For the new aircraft generation, more than 50% of the structural design is made of composite materials. During the aircraft life cycle, primary structure parts are facing various kinds of mechanical loadings, from low to high strain-rates. The mechanical behaviour of Carbon Fibre Reinforced Polymers (CFRP) have been proved to be rate dependent [1]. To accurately predict the behaviour of CFRP structural parts under various mechanical loadings, models must be able to deal with this dependency. For CFRP, this dependency is generally attributed to the visco-elastic, visco-plastic behaviour of the matrix. An approach to model the behaviour of CFRP is to study the behaviour of the resin. In the literature this dependency is mainly studied in compression for very high strain rates using split Hopkinson pressure bars. A noticeable exception is Gerlach et al. [2] who perform an intensive characterisation of this material both in tension and compression. However the main focus of their study was on the post-yield behaviour.

2 Experimental devices used

The testing device used is a servo-hydraulic jack which permits to test the specimens from a quasi-static stroke-rate of 6 mm/min, corresponding to an approximate strain-rate of 10^{-3} s^{-1}, to high-stroke rate of 6 m/s which correspond approximately to strain-rate in the order of 100 s^{-1} depending on the specimen geometry.

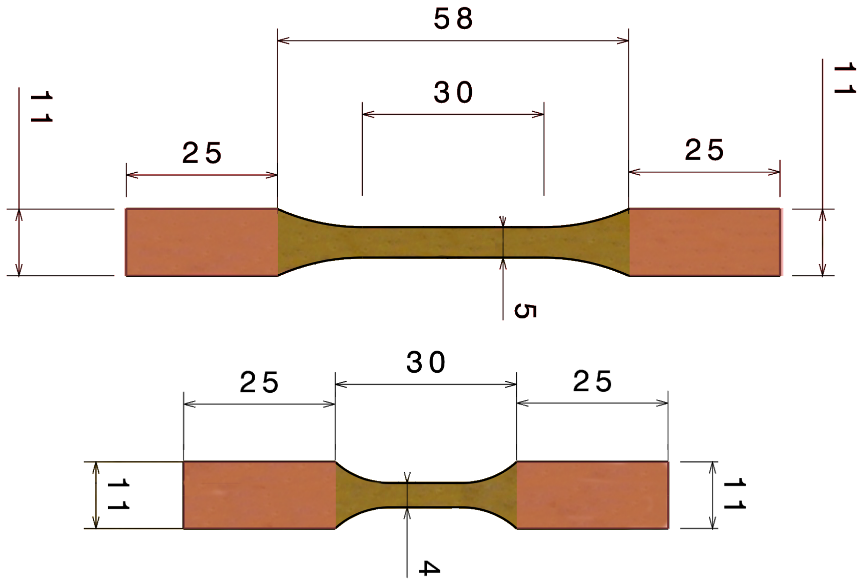

Figure 1: Specimen geometries tested, the long one is in agreement with ISO-527-2 standard. The red area is where the specimens are clamped. Dimensions are in mm.

2.1 Instrumentation

A KISTLER 60 kN piezo-electrical load cell is fixed on the inferior part of the clamping device. Its signal is amplified with a KISTLER 5007 amplifier. The specimen strains are measured using TML QFLA-2-350-11 (350 Ω) strain gauges bonded on the specimen. These high impedance gauges permit to reduce the signal noise. One gauge has been used along the length of the specimen and one perpendicular to the length to measure the Poisson ratio. For the synchronous acquisition of the data a SIRIUS STG8 system has been used. It has a maximal sampling frequency of 1 MHz for each input and a resolution of 24 bits.

2.2 Specimen geometry

Several specimen geometries are used in the literature to study polymers. The goal of this study was mainly to investigate the dependency of the elastic properties of the material to strain-rates. Dog-bone shape plane specimens have been chosen, two geometries are used. The first one is in agreement with ISO-527-2 standard [3], and a second one is shorter to reach higher strain-rates for the same stroke-rates. It is known that plane specimens are not adapted to study the failure of RTM-6, which exhibit a brittle failure [4, 5]. To control the hygrometry rate the specimen where heated at 100 ^{o}C during 72 hours and stocked in a desiccator up to the test. Figure 1 shows the two specimen geometries used in this study.

3 Test results

A progression of stroke-rates has been used from the low limit of the testing device (6 mm/min) to the limit of exploitation of these tests, that was found around 5 m/s. The lowest stroke-rates

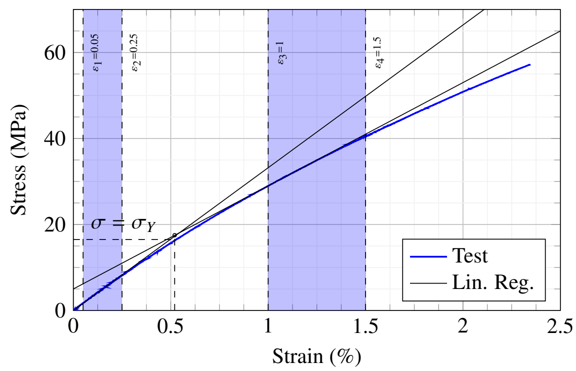

Figure 2: Stress-strain curve for a quasi-static test at $1{\cdot}10^{-3}$ s^{-1} of a standard specimen.

tests have been performed on the standard specimens. For this specimen geometry a minimum of three specimens have been tested for each stroke-rates. The test results have been found quite reproducible. However for the highest stroke-rates on the shortest specimens the clamping device needed ajustements and only a few valid tests could be performed. It has been verified that at the same low strain-rate ($1{\cdot}10^{-2}$ s^{-1}) both the specimen geometries gives the same results. The analysis of these tests consist mainly in the comparison of the stress-strain curves according to ISO-527-2 [3] standard.

3.1 Analysis of the tensile tests

Figure 2 presents the stress-strain curve for a quasi-static test. It can be seen that this curve is initially linear then non-linearity start to appear at approximately 0.5% of strain. The final failure of the specimen occurs at low levels of stress and strain compared to those reported in the literature for the same material (approximately 10% of strain in tension reported by Gerlach et al. [2]). In their study using cylindrical specimen a strong non-lineraity is observed in traction on this material. Such strong non-linearity is not observed in these tests because the geometry of the specimen lead to its premature rupture. This issue has already been reported in the literature [4, 5]. However since the main focus of this study is on visco-elasticity, this is not a major problem.

The elastic properties are determined in the strain interval [$\varepsilon = 0.05\%$, $\varepsilon = 0.25\%$] in agreement with the standard ISO-527-2. The Young modulus, Poisson ratios and strain-rate are obtained using a linear regression in this interval. For polymers, the definition of the yield stress depends on the model. So in this study, a linear regression is done in the arbitrary interval [$\varepsilon = 1\%$, $\varepsilon = 1.5\%$]. The yield stress is defined as the intersection between the two linear regressions as illustrated in Figure 2. This yield stress is only computed indicatively to determine if an evolution is observed in these tests.

The mean values of the mechanical parameters of interest : Young modulus E, Poisson coefficient ν and the yield stress σ_Y are summarised in Table 1. The maximal stress and strain recorded are also summarised however these plane specimens do not permit to study the behaviour of RTM-6 up to the failure. The strain-rate in the non-linear part of the test are also

Table 1: Mean values of the mechanical properties for all stroke-rates and for the different specimen geometries.

Geometry	stroke-rate	$\dot{\varepsilon}$ (s^{-1})	E (GPa)	σ_{max} (MPa)	ε_{max} (%)	ν	σ_Y (MPa)	$\dot{\varepsilon_Y}$ (s^{-1})
Standard	6 mm/min	$1.3{\cdot}10^{-3}$	3.2	57.9	2.47	0.37	19.5	$2.1{\cdot}10^{-3}$
	60 mm/min	$1.52{\cdot}10^{-2}$	3.06	53.43	2.21	0.34	19.17	$2.0{\cdot}10^{-2}$
	600 mm/min	$1.47{\cdot}10^{-1}$	3.30	43.30	1.67	0.37	19.2	0.19
	0.1 m/s	1.86	3.24	44.83	1.60	0.37	20.67	2.15
	1 m/s	19.2	4.02	52.47	1.82	0.34	19.8	27.5
Short	24 mm/min	$1.15{\cdot}10^{-2}$	3.24	47.5	1.77	0.36	19.3	$1.2{\cdot}10^{-2}$
	1 m/s	19.4	4.17	52.9	1.80	0.29	23.7	72
	3 m/s	34.5	4.86	60.4	1.75	0.30	29.5	156
	5 m/s	60	5.37	61.4	1.72	0.34	33	195

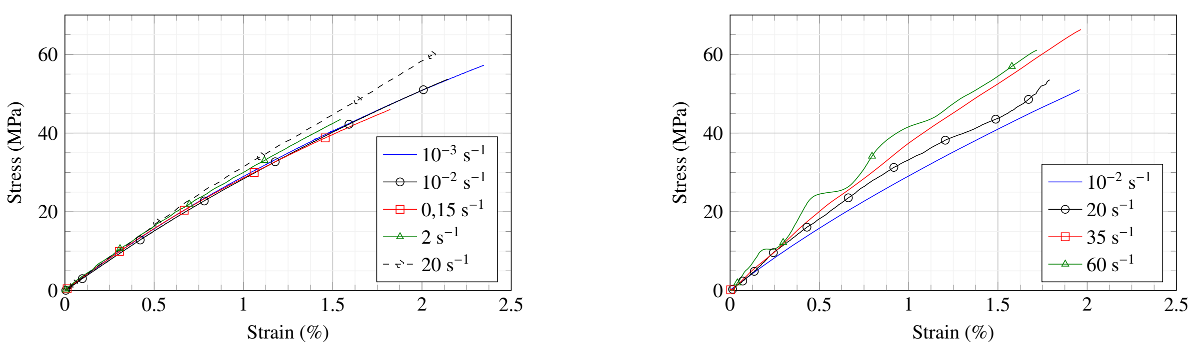

Figure 3: stress-strain curve for a quasi-static in function of the strain rate for the standard specimen geometry (left) and the short one (right).

summarised, they are noted $\dot{\varepsilon_Y}$.

3.2 Strain-rate dependency of the mechanical properties

Figure 3 shows the evolution of the stress-strain curves with strain-rates for the two specimen geometries. An increase in the rigidity is observed with the increase of the strain-rates. The curve at 60 s^{-1} show the resonance phenomena that occurs for high stroke-rate tests.

Figure 4 shows the dependency of the Young modulus, Poisson coefficient, yield stress as a function of the strain-rates. A significant increase of the Young modulus can be observed for strain-rates higher than 10 s^{-1}. The last point at 60 s^{-1} is plotted indicatively as it seems coherent with the other strain rates, however it corresponds to large oscillations of the load cell. Concerning the Poisson ratio, no strain-rate effect superior to the experimental scatter are observed. However for the yield stress a significant increase seems to be observed for strain-rates over 10 s^{-1}. However this tendency is only observed for the shorter specimen geometry and unfortunately only few repetitions are available at these strain-rates.

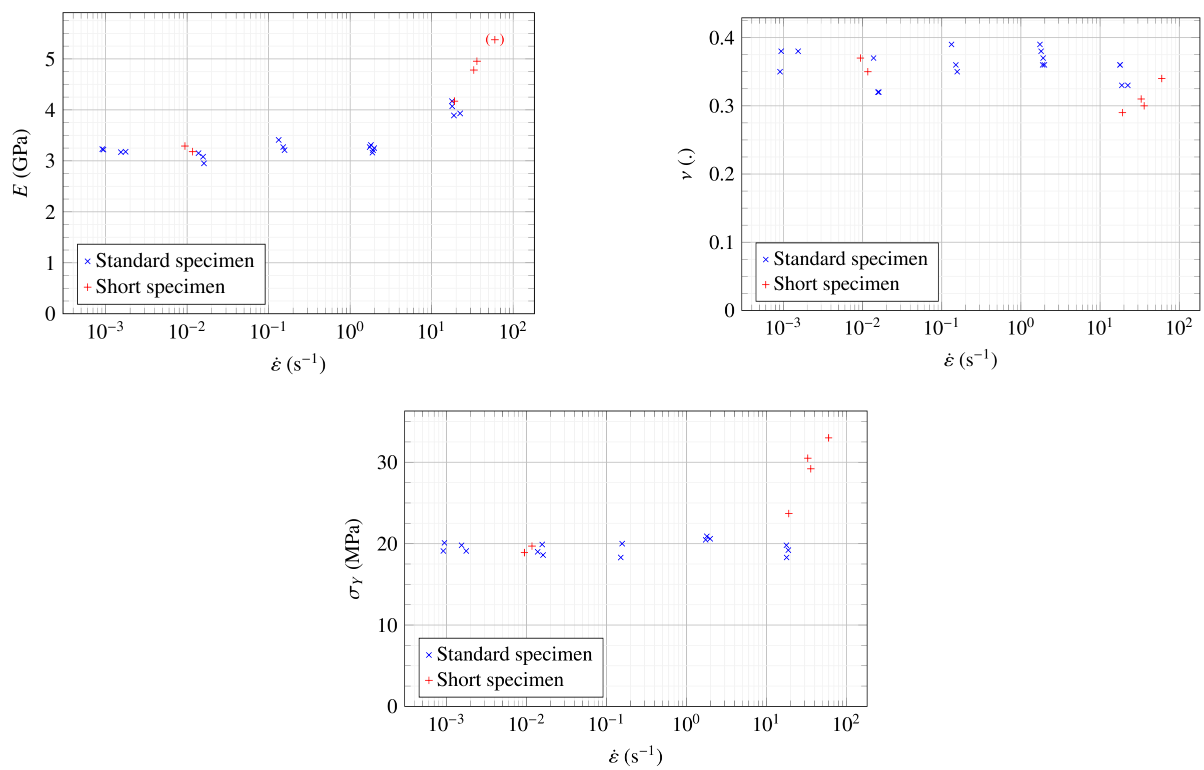

Figure 4: Young modulus, Poisson ratio and yield stress as a function of the strain-rate for the RTM-6 resin.

4 Visco-elastic model identification

The behaviour of RTM-6 resin is modelled using a spectral visco-elastic model such as in [6]. This model is based on the assumption that the visco-elastic behaviour can be seen as the sum of elementary viscous mechanisms. Each elementary viscous mechanism is defined by its weight and relaxation time. All the weights and relaxation times define the spectral distribution of the model which is supposed to be a Gaussian distribution. Figure 5 illustrates the Gaussian distribution, it is defined by two parameters n_c and n_0. The model is fully presented in [7]. Other parameters of the model are: γ and n the coefficient of the non-linear function and β the coefficient of the viscous effect.

The identification is performed using a test at $1{\cdot}10^{-2}$ s^{-1}, 1.80 s^{-1}, 17.9 s^{-1} and 60 s^{-1} using the *lsqcurvefit* tool of Matlab. The input is the experimental strain and the computed stresses are compared to the experimental ones. Figure 6 compares the prevision of the visco-elastic model identified to the experimental results. The overall agreement between the prediction of the model and the experimental results is good.

5 Conclusion

An experimental campaign has been performed on RTM-6 resin in tension at intermediate strain-rates : $1{\cdot}10^{-3}$ s^{-1} to 60 s^{-1}. Clear increases of the Young modulus and yield stress have been observed on these tests. A spectral visco-elastic model has been identified using these experimental results. It describe satisfactorily the experimental data.

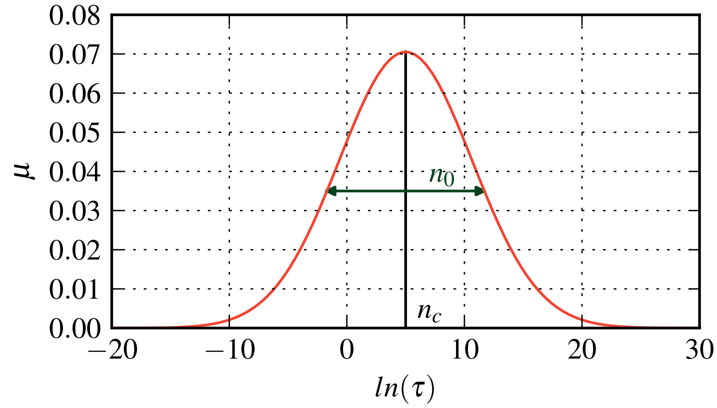

Figure 5: Illustration of the spectrum of the viscus mechanism in the spectral visco-elastic model.

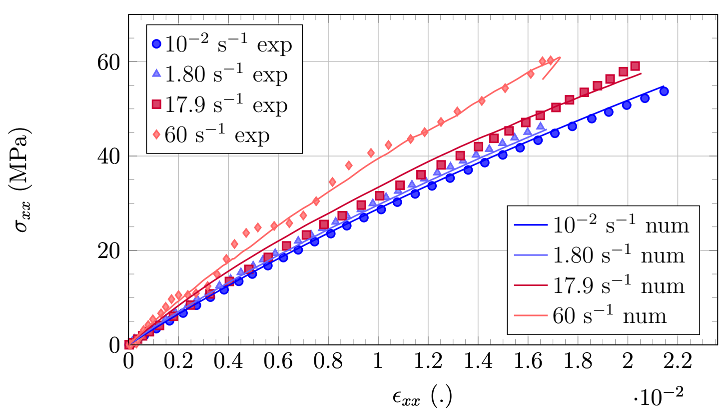

Figure 6: Stress-strain curves predicted by the visco-elastic model compared to the experimental results.

Table 2: Numerical values identified for the visco-elastic model for RTM-6.

E (MPa)	n_c	n_0	β	γ	n
6227	-9,73	2,92	0,82	0,60	0,82

REFERENCES

[1] H Koerber, J Xavier, and PP Camanho. High strain rate characterisation of unidirectional carbon-epoxy IM7-8552 in transverse compression and in-plane shear using digital image correlation. *Mechanics of Materials*, 42(11):1004–1019, 2010.

[2] Robert Gerlach, Clive R Siviour, Nik Petrinic, and Jens Wiegand. Experimental characterisation and constitutive modelling of rtm-6 resin under impact loading. *Polymer*, 49(11):2728–2737, 2008.

[3] NF EN ISO 527-2:2012:04. Plastiques - détermination des propriétés en traction - partie 2 : Conditions d'essai des plastiques pour moulage et extrusion, 2012.

[4] Amos Gilat, Robert K Goldberg, and Gary D Roberts. Strain rate sensitivity of epoxy resin in tensile and shear loading. *Journal of Aerospace Engineering*, 20(2):75–89, 2007.

[5] C Paul Buckley, J Harding, JP Hou, C Ruiz, and A Trojanowski. Deformation of thermosetting resins at impact rates of strain. part i: Experimental study. *Journal of the Mechanics and Physics of Solids*, 49(7):1517–1538, 2001.

[6] Julien Berthe, Mathias Brieu, and Eric Deletombe. Thermo-viscoelastic modelling of organic matrix composite behaviour–application to T700gc/M21. *Mechanics of Materials*, 81:18–24, 2015.

[7] Anne Schieffer. *Modélisation multiéchelle du comportement mécanique des composites à matrice organique et effets du vieillissement thermique*. PhD thesis, Université de Technologie de Troyes, 2003.