Creep damage and failure of polymer based composites : Nondestructive evaluation with ultrasonic waves and Acoustic emissions and modelling

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INTRODUCTION

The damage and fracture of materials are technologically of enormous interest due to their economic and human cost. Failure of composite systems is particularly important in naval, aeronautics and space industry. Despite considerable experimental [1, 2] and theoretical work [3] on fracture, many questions have not been answered yet. Recently, statistical physicists have shown the existence of a power law acceleration of acoustic emissions announcing the global failure of heterogeneous materials [1, 2], similar to the critical behavior of out-of-equilibrium phase transition [4], offering a way to predict material failure [1]. Creep is the progressive deformation of a material under constant load at a given temperature. Three creep regimes are usually observed. During the primary regime, the strain rate decays as a power law with time following the application of the stress (Andrade law) [5]. The secondary regime describes a quasi-constant low deformation rate, which evolves towards the tertiary creep regime, if the stress and the temperature are high enough, during which the strain rate accelerates up to rupture. This paper presents creep experiments on composite materials, which we explain using a simple model of representative elements, in the framework of fiber bundles models.

MATERIALS AND EXPERIMENTS

The experiments are carried out on cross ply glass/polyester composite materials [±62], [90/35] and on Sheet Moulding Compound (SMC) composites. All specimens are subjected to a constant stress and temperature (below the glass transition of the matrix) [6].

The creep tensile tests were performed using a servo-hydraulic mechanical testing system. Constant tensile load was applied and the resulting strain and acoustic emissions were recorded and ultrasonic velocity measurements were done in transmission mode through the thickness of the samples until final rupture. Acoustic emissions (AE) is a standard technique to monitor the evolution of damage in composites, due to matrix cracks, fiber matrix debounding, fiber breaks, and delaminations [7]. Normal primary creep transients followed by secondary and tertiary creep were observed for almost all samples, both for the strain rate (Fig. 1) and for the AE rate (Fig. 2). The decrease of the strain rate and EA rate in the primary creep regime can be described by Andrade's law [5] $de/dt \sim t^{-p}$, with an exponent p in the range 0.2 - 1.4 for the 15 samples tested [6]. The crossover for small times is probably due to the fact that the stress progressively increases up to about 10 sec after the start of the experiment. A quasi-constant strain rate (steady-state or secondary creep) is observed over an important part of the total creep time, followed by an increase of the creep rate up to failure in the tertiary creep regime.

The acceleration of the strain rate before failure is well fitted by a power-law singularity $de/dt \sim (t_c-t)^{-p'}$ with p' in the range 0.3 - 1.1 depending on the sample [6]. The critical time tc determined from the fit of the data with a power-law is close to the observed failure time. Our experiments confirm over large time scales covering up to four orders of magnitude in time previous announcement of power laws in the tertiary creep regime, which were established over more limited time scales [2]. We also obtain the same temporal evolution for the AE energy rate, with larger fluctuations for the energy rate than for the event rate due to the existence of a power-law distribution of AE energies. The values of p and p' are on average a little larger for the SMC than for the cross ply composites. Possibly due to the larger heterogeneity of the SMC. The Acoustic Emission was strongly correlated to the measured velocity through the thickness showing that microscopic damage mechanisms development are also very well correlated to the macroscopic loss of stiffness (figure 3).

There is a huge variability of the failure time from one sample to another one, for the same applied stress, as shown in Figure 4. This figure shows that the transition time t_m between the primary creep regime and the tertiary regime, measured by the minimum of the strain rate, is proportional to the rupture time $t_m \approx 2/3\ t_c$. This suggests a way to predict the failure time from the observation of the strain rate or AE rate during the primary and secondary creep regimes, before the acceleration of the damage leading to rupture.

MODELLING EFFORT

We view a composite system as made of a large set of representative elements (RE), each element comprising many fibers with their interstitial matrix. The applied load is shared democratically between all RE. This assumption has been shown to be a good approximation of the elastic load sharing for sufficiently heterogeneous materials [8]. Each RE is modelled as a non-linear Eyring dashpot [9] in parallel with a linear spring of stiffness E. A power law P(e) given by $P(e)=1-(e_{01}/(e+e_{02}))^{\mu}$, where e_{01} and e_{02} are two constants with $e_{01}<e_{02}$ while $\mu>1$ controls the heterogeneity of the system [6]. The equation controlling the deformation e(t) of each surviving RE is [6] :

$$\frac{de}{dt}=K\sinh\left(\beta\left(\frac{s}{(1-P(e))}-Ee\right)\right) \quad (1)$$

with the initial condition e(t=0)=0. the fraction of unbroken RE is 1-P(e) and s/(1-P(e)) is the stress applied on each unbroken RE.

In the primary regime, for weak values of e, the differential equation (1) has the simplified solution

$$\frac{de}{dt}\sim\frac{K}{c+t} \quad (2)$$

that predicts, if the stress is not too large, de/dt is of the Andrade form ~ t^{-p}, with an exponent $p=1$ at early times. In the tertiary creep regime, for large e, the linear term Ee is small compared with s/(1-P(e)). The solution of (1), to leading logarithmic order is :

$$\frac{de}{dt}=\frac{A}{\mu}\left[-\ln(t_c-t)\right]^{\frac{1}{\mu}-1}\frac{1}{t_c-t} \quad (3)$$

A is constant. This expression is consistent with our experimental observation showing that the acceleration toward failure is due to the positive feedback effect of broken RE, which increases the stress and strain on the unbroken RE leading to the global failure of the system.

CONCLUSION

In conclusion, we have shown that the interactions between the RE elements together with a large heterogeneity and a simple nonlinear rheology is sufficient to explain qualitatively and quasi-quantitatively our experiments. We have also shown that the AE could be a very efficient tool for damage charactization and rupture prediction.

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Figure1: Creep strain for a [±62] specimen. (a) linear time scale, (b) logarithmic time scale, (c) logarithmic time scale in tc-t test in the tertiary creep.

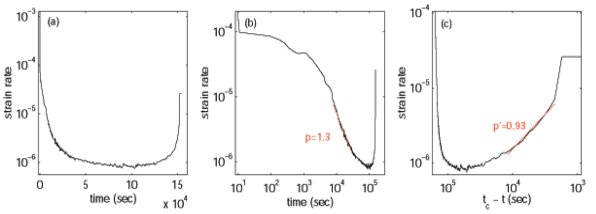

Figure 2 : Rate of AE events for a [±62] specimen. The three panels are as in Fig.1.

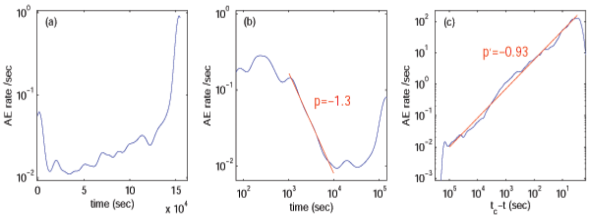

Figure 3 : Ultrasonic velocity variation and EA as function of time during the creep test for a [90/35] cross ply composite

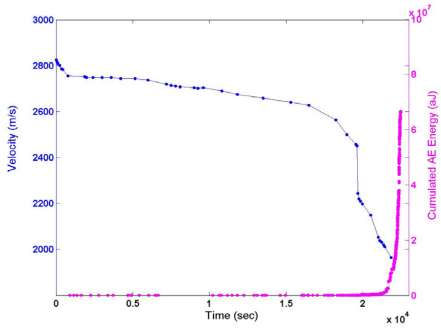

Figure 4: Relation between the time t_m of the minima of the strain rate and the rupture time t_C, for all samples