A normalization method for life-time prediction of composite materials

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The objective of this study is to predict the rupture of specimens of composite materials. During a creep experiment, with traction method, the specimens have different time of rupture (130 seconds, 159 seconds, 539 seconds...). The acoustic activity during the test involves three phases (phase 1, phase 2 and phase 3). When we apply our normalization method (cumulative acoustic emission vs. time), we can notice that all tests look very similar, and we can see that there is a proportionality relation between the transition time t_m (phase 1 -> phase 2) and the time of rupture t_r. The technique works significantly better than other recent works. To validate this technique we have achieved a K-cross validation, on 7 specimens. The proportionality between t_m and t_r of the 7-cross validations had a mean value of 0.1218 and a standard deviation of 0.0018. The mean errors that we got is about 8.58 % (± 4.65). It is a very important result in life-time prediction.

1 Introduction

Industrials are increasingly using more composite materials in various fields particularly in aviation and automobiles fields. Their great advantage is their strength and stiffness associated with their lightness. However, more studies are needed to ensure the correct use of these materials (types of damage, lifetime prediction, type of materials to use ...). Acoustic emission (AE), which represents the generation of transient ultrasonic waves in a material under load, is a useful tool that can be used in situ for structural health monitoring.

The knowledge of the behaviour of these materials under heavy loads over long duration requires additional information on behaviour. Accurate knowledge of the creep behaviour becomes essential. In this field, non-destructive testing such as ultrasound and acoustic emission are little used in particular in terms of creep rupture prediction.

Recent work has proposed an approach that involves studying the break through phenomena of phase transitions in creep [8, 9, 10]. In this perspective Nechad et al [9, 10] analysed the evolution of strain rate and the rate of acoustic emission in the primary and tertiary creep phase on polyester matrix composites reinforced with fiberglass. They have established a relationship between the transition time primary / secondary corresponding to the minimum strain rate and time to material failure. Our contribution was to improve this relation by using a two dimensional normalization technique. The first part of the article details the materials and tests. The second part concerns the data that were collected. The third part deals with the methods that were used. The next part concerns the results and the discussion. Finally, the conclusion and the perspectives are given.

2 Materials and test

2.1 Materials

The studied materials were manufactured by moulding composite cross vacuum at the Acoustic Laboratory of the University of Maine, Le Mans, France. They were laminated by stacking up 8 plies, reinforced by unidirectional glass UDG with mass flux 300 (g/m^2) and epoxy resin SR 1500 / SD 2505. These components are manufactured by the company SICOMIN. The plies were laminated and impregnated at room temperature, then placed empty with a depression of 30 kPa vacuum for 8 hours between the mold and the mold cons, followed by polymerization of 8 hours at 80°C in an electric oven [1]. The cuts were made using a diamond blade saw.

2.2 Creep experiment

To determine the lifetime of the tensile specimens, a set of tensile tests were performed. The specimen dimensions reached 2 x 20 x 300 mm. Tests were conducted on an INSTRON type machine equipped with a cell load of 100 KN and controlled by computer (Figure-1). A two channels EPA Acoustic Emission device was used. AE (acoustic emission) measurements were achieved by the means of two resonant Micro-80 sensors with a frequency band 100 kHz - 1 MHz and a peak of resonance around 300 kHz, coupled on the faces of the specimens with silicone gel. The calibration of each test used a pencil lead break procedure in order to generate repeatable AE signals. Several time-based descriptors were calculated by the acquisition system for each AE event: amplitude, energy, duration, rise time, number of times the amplitude of the event goes beyond the given amplitude threshold (called counts)... These parameters were used as input descriptors in the proposed classification method. Traction test was applied on the specimens with 30 kN of strength. However creep method was based, in first time, on traction method by applying 90% of strength and then waiting until fracture (figure 1).

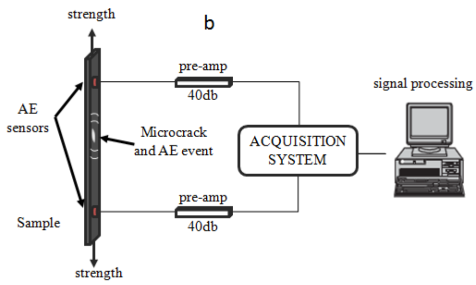

Figure 1: system schematic

2.3 Acoustic Emission Activity

The acoustic emission is a phenomenon of liberation of elastic energy in the form of transient elastic waves in a material with dynamic processes of deformation [2]. When subjected to external stresses, composite materials undergo various types of degradation resulting from local damage at the matrix, fiber and fiber-matrix interface. Generally, these mechanisms occur simultaneously, thereby reducing the mechanical properties of composite material. Degradation mechanisms are developed according to the nature of materials and mechanical stress conditions imposed. In a composite material, the stress redistribution, and consequently the rupture process resulting, depends principally on the fiber's crack characteristic, the ability of the matrix to absorb the released

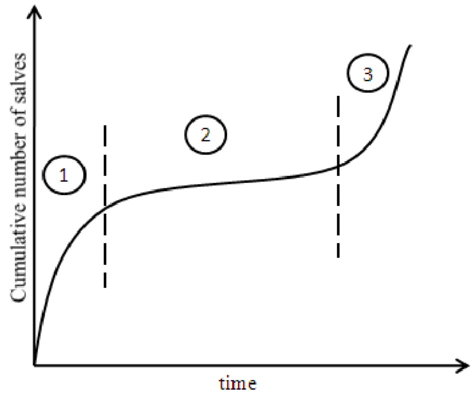

Figure 2: Typical form of creep curve

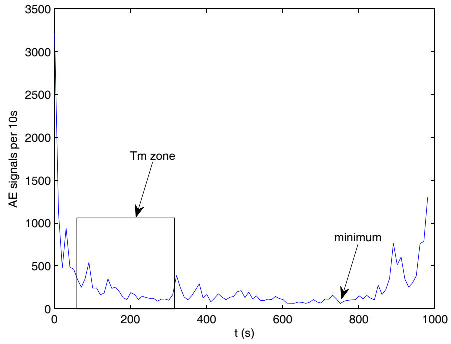

Figure 3: Tm selection refers to [Nechad et al.] and [Berbaoui et al.]

energy, the interface properties of fiber-matrix, the fraction volume of fiber, and the conditions of mechanical stress imposed.

3 Lifetime prediction

In this section, we show the effect of creep test on composite materials, and we explain the method used to predict the rupture.

3.1 State of the art

Little works has been done on the lifetime prediction on composite materials. These works indicate a relation between a transition time and the rupture time [9, 10].

Creep reflects the ability of certain materials to deform over time under the action of mechanical stress at a constant temperature [3]. The creep test shows very clearly the viscoelastic behaviour of composite materials polymer based. Figure 2 illustrates the typical evolution of the deformation in a creep test on polymer composites. The results obtained show that the acoustic activity during the creep tests has three phases:

Phase I: The application of the stress at time t = 0 causes an elastic instantaneous deformation, followed by a time-dependent deformation (concave down), it is the primary or transient creep. This phenomenon was explained by Shen et al. [4] as follows: initially, the connections of the macromolecular network are not oriented, so there is little movement which explains that the primary creep rate is important. Then there is a reorganization of the material (fiber alignment and orientation of the molecular structure of the matrix) which has the effect of increasing the creep resistance causing a decrease in strain rate.

Phase II: The area is very spread out over time and therefore the most dominant throughout the creep test, called the phase of secondary or stationary creep [5]. The deformation varies linearly with time, in other words the strain rate is constant. It is also established that the damage mechanisms that occur in this area control the flow [6].

Phase III: is characterized by a sudden acceleration and continues to strain rate (convex curve down). It is associated with the occurrence of damage growing up to ruin the material (figure 2).

Thummen [11] and Godin [12] showed that t_m is between the secondary and the tertiary creep regimes (determined with a geometrical method), this work has been improved by Nechad et al. [9, 10]. They have showed that the transition time t_m is between the primary and the tertiary creep regimes (determined as the position of the minimum of the strain rate). The correlation between the transition time t_m and the rupture time t_r: tT_m is found about $\frac{2}{3}$ of the rupture time t_r. This method is imprecise and not reproducible on all samples. Berbaoui [8] showed that the transition time t_m corresponds to a moment between the end of the primary phase and the beginnings of secondary phase. In this work t_m was detected by accumulating the AE signals in a lapse of 10 seconds, and then picking the minimum which corresponds to t_m. The minimum we got (figure 3) does not match with the transition time (phase 1,2) shown by the AE curve in figure 2. As shown in figure 3, t_m should be in "Tm zone" where we can find many minimums and it is difficult to choose one.

3.2 Normalization technique

Data normalization eliminates differences in norms of variables. In fact, variables with large values can have a greater influence than variables with small values, without being more significant [7]. The result of this linear normalization on all observations provides a distribution of the variable such as having properties to limit the variable values between [0, 1].

In this work, seven tensile specimens have been tested with creep experiment. We got seven different rupture times (539 s, 159 s, 3362 s, 1831 s, 992 s, 145 s and 845 s). Each test conducted to obtain thousands of salves. The normalization was applied in two directions : on the cumulative number of acoustic emission (CS) and on their time of occurrence (t). An attribute is normalized by scaling its values so that they fall within a small-specified range [0 to 1].

$$CS' = CS/SN \text{ and } t' = t/tr.$$

SN: total signals number, tr: rupture time.

The result of normalization is shown in figure 4, we can see clearly that the samples have a similar appearance even if they do not have the same lifetime.

3.3 Polynomial reconstruction

To analyse the data, we need an analytical model to reconstruct the acoustic phenomenon. A polynomial function is the most adapted function that represents the characteristics form of AE with a minimum square error. The best function that represents the form of the normalized AE with

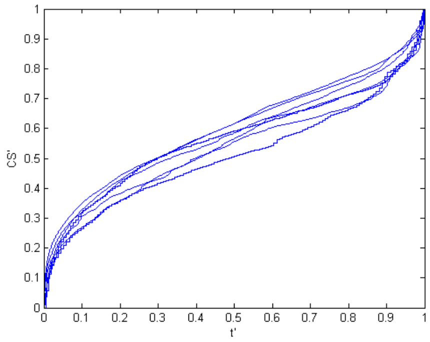

Figure 4: all samples normalized

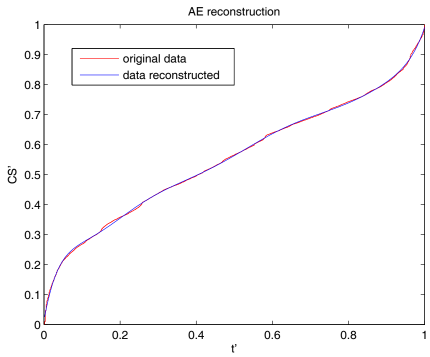

Figure 5: AE modelization

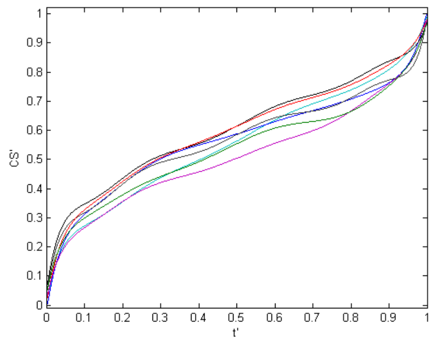

Figure 6: reconstruction of all samples

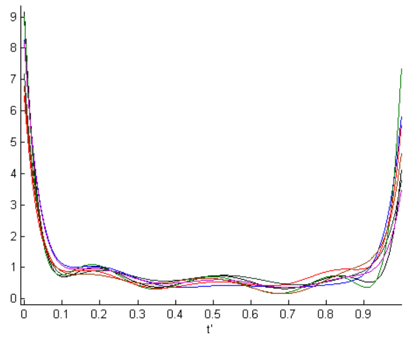

Figure 7: derivative of all curves

a creep test on materials and that minimize the error was a 9 degree polynomial:

$$f(t) = a_0 + a_1\,t + a_2\,t^2 + a_3\,t^3 + a_4\,t^4 + a_5\,t^5 + a_6\,t^6 + a_7\,t^7 + a_8\,t^8 + a_9\,t^9 \quad (1)$$

Figure 5 shows the original data and the data reconstructed.

3.4 Transition time detection

Behaviour is observed with three phases of acoustic activity. The first corresponds to the increased load, the number of signals that appear is important but this number is decreasing which leads to a decrease in change rate. Then we have the quiet phase two where evolution of the AE is slow. The transition time t_m between phase 1 and phase 2 is characterized by the passage of change rate through a minimum. We can detect the transition time between phases one and two by the location of the minimum of rate change.

The rate of change in the number of acoustic emission is given through the mathematical derivative form of the cumulative number function. The derivative function is given from:

$$f'(t) = a_1 + 2\,a_2\,t + 3\,a_3\,t^2 + 4\,a_4\,t^3 + 5\,a_5\,t^4 + 6\,a_6\,t^5 + 7\,a_7\,t^6 + 8\,a_8\,t^7 + 9\,a_9\,t^8 \quad (2)$$

Figure 6 and figure 7 represent respectively the polynomial reconstruction of all samples and their corresponding derivative.

The derivative graph shows several minimums, the 1^{st} minimum correspond to t_m the transition time between phases 1 and 2. The physical explication of this phenomenon is that the rate of appearance of acoustic signals decreases at the end of the first phase and reaches a minimum value, this corresponds to t_m. Figure 8 shows clearly the position of the minimum.

3.5 Results and discussion

In this section we created a model to establish a correlation between the primary creep and the rupture time. The exploitation of characteristics for seven specimens allowed us to determine the relative time of transition (t_r) between phases 1 and 2. The following table shows the results t_m/t_r obtained and their corresponding model. In order to increase the statistical estimation, a K-fold cross-validation was applied. to validate the method on the 7 samples that we have,

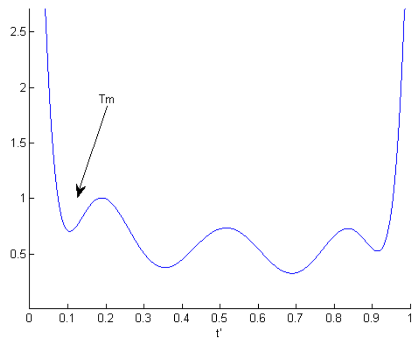

Figure 8: t_m detection

we applied 7 cross-validations. The results are presented in table 1. The variable $m = \overline{t_m/t_r}$, represents the mean value of t_m/t_r of 6 samples not marked as (*). The sample marked as (*) means that he has not been selected to create the model. Also t_r is the rupture time of sample (*), and t_{re} is the rupture time estimated of the same sample calculated by $t_{re} = t_{m*}/m$, where t_{m*} represent the transition time of the sample tested (*). The error is calculated by: $error = |(t_r - t_{re})/t_r|$.

Table 1: *K*-cross validation results

Sample	m	t_r	t_{re}	error
1, 2, 3, 4, 5, 6, *	0.12	992	1149	15%
1, 2, 3, 4, 5, *, 7	0.123	134	131	2.2%
1, 2, 3, 4, *, 6, 7	0.122	845	900	6.5%
1, 2, 3, *, 5, 6, 7	0.123	1832	1790	2%
1, 2, *, 4, 5, 6, 7	0.125	3362	3060	9%
1, *, 3, 4, 5, 6, 7	0.12	155	168	8.3%
*, 2, 3, 4, 5, 6, 7	0.12	525	480	8.5%

Table 2: Descriptive statistics of the results

	Min.	Max.	Mean	St. deviation
m	0.12	0.125	0.1218	0.0018
error	2%	15%	8.58%	4.65

The present study shows that a normalization method can predict the time occurrence of composite material rupture. The variable m ($\overline{t_m/t_r}$), on a 7-cross validation, is around 0.1218 (± 0.0018) it's near to be identical in all samples. The error we reached is 8.58 % (± 4.65). This error could have been lower (mean=6.1 % ± 2.9) if the prediction on the last specimen were more precise. This remark claims for a significant increase of the specimens number in the future.

4 Conclusion

This study has taken a significant step in the direction of creep material rupture prediction. We have proposed a normalization method that can predict the time of composite material rupture occurrences. We can predict the rupture of the samples from a moment about 12.18 % of the rupture time. The error we reach, on a 7-cross validation, is about 8.58 % (± 4.65).

Further research in this field could focus on the power of generality of this approach: could this method be applied on other material?

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