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ICM11

## Strain fluctuations from DIC technique applied on paper under fatigue or creep

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### Abstract

We study the evolution of deformation on a quasi 2D paper sample during fatigue and creep experiments. Paper is a fibrous material, sensitive to various parameters (humidity, temperature, history effect). As for many materials, the lifetime varies a lot. Basquin's law claims that the number of cycles at break in fracture tests has a power-law dependence on the external load amplitude; Monkman-Grant relationship predicts that lifetime is proportional to the minimum strain rate during creep. The main question is therefore: is it possible to predict the time-dependent rupture? We perform creep and cyclic tests on paper samples. The main tools of investigation are acoustic emission (AE) - based analysis and digital image correlation (DIC). Via the AE, one can follow the damage evolution in samples, like microcrack formation that releases elastic energy. The DIC instead works well as a tool to measure at great accuracy both global and local deformation fields. From these, local strain rates can be derived, which then can be used to understand the microscopic dynamics that lie behind a certain rheology or sample response. The issue is to predict the break by looking at the sample-to-sample variation and by comparing experiments.

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*Keywords:* Creep and fatigue, heterogenous material, strain from DIC, acoustic emissions

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### 1. Introduction

Paper is a viscoelastic material consisting of cellulose fibers. This disordered material is sensitive to lot of parameters like temperature or humidity [1], as cellulose fibers made from wood are hydrophilic. Paper is inhomogeneous and is effectively a two-phase composite due to the pore space inside the fiber network, but its properties are largely dependent on the fibers network. The fracture of paper is as in all common materials and continuum fracture mechanics is an important concept, but reaching a critical value for the external applied load is not the only condition for rupture. The load history plays also an important role [1-5]. In this work, we consider fracture from creep and fatigue in the low-cycle limit, and in particular we overview our experiments where the main emphasis is on the issue to predict the failure of individual

samples. For materials under creep, the Monkman-Grant relationship shows that the lifetime of a material is related to the minimum creep strain rate [6-7]. In case of fatigue, one of the most important scaling laws of time dependent fracture is the empirical Basquin's law, which states that the lifetime of samples increases as a power law when the external load amplitude decreases [8-9]. This simple law is however an average and sample-to-sample variation may be quite important.

In our work, we have studied various aspects of fatigue and creep fracture, with an eye on prediction. To reach this goal we used diverse experimental methods like digital image correlation (DIC) and acoustic emission recording. The acoustic emission (AE) technique is widely used to study the fracture of paper [10-13] and other materials [14]. In this article we will first review the mechanical tests performed on paper samples and the experimental techniques used. In the second part, we will present the experimental data collected about deformation and strain rate, as well as results from acoustic emission, and discuss their changes with time and/or number of cycles. Finally we will conclude that those diverse values and their evolution during first cycle or successive ones can give useful indications to predict the final break.

## 2. Experiments

### 2.1. Experimental set-up and samples

We used 10x5cm<sup>2</sup> samples from normal copy machine paper. In order to improve the grey scale contrast needed for the digital image correlation technique, samples are hatched with a drawing pencil and therefore the sample presents shadings on the side which is in front of the camera. The paper is stretched vertically in the cross-direction of paper, which is the direction perpendicular to the travel of the paper sheet in papermaking machine. As the cellulose of the wood fibers is hydrophilic, paper is sensitive to humidity [1, 3]; therefore the experimental set-up is enclosed in a chamber where temperature and humidity are stabilized ( $T = 21.6^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$ ,  $\text{RH} = 50.5\% \pm 0.7\%$ ).

The experimental setup includes a fixed frame made of aluminum and a hook fixed to the top crosshead. The sample is fixed between two steel clamps. Both clamps can move in translation, but can not turn as they are inserted in the rabbit of the lateral frame, that allows them only translate in vertical direction. The upper clamp holds on to the hook and so has a fixed height. The lower clamp is gripped onto the paper sample and holds a weight of 6,3kg, which applies a constant tensile force by hanging during loading phases. The lower clamp rests on two pistons during unloading. These pistons are moved by a system of compressed air controlled by computer and translate vertically on a run of 4cm. A LED lamp is used to illuminate the sample. The test procedure consists of one creep load or successive loading and unloading phases of 30s each. The bottom clamp has a slow translation speed (5mm/s), in order to obtain a smooth stress application. The actual time under load is only 22s per cycle in fatigue case.

### 2.2. Acquisition and treatment of experimental data: deformation and acoustic emissions

The deformation of the sample is obtained by use of the digital image correlation technique [15-16]. A camera takes pictures of the sample each 2 s during the test, 1 pixel corresponding to 109 $\mu\text{m}$ . Pictures are then cropped to keep only a view on the internal part of the sample and their final size is thus around 420x730 pixels<sup>2</sup>, 1 pixel corresponding to 0.11 $\mu\text{m}$ . A reference picture is chosen as being from the beginning of the first load when the paper sample is firstly totally spread out and slightly stretched. The digital image correlation is the task of finding a deformation function, mapping coordinates from the reference picture to coordinates in the test image at time "t". Then the deformation function is presented as cubic splines, where knots are defined in an evenly spaced grid, with knot spacing 32x32 pixels (crate). The exact algorithm of elastic image registration that we used can be found in [16] for more details. The

vertical strain of a square with coordinates (i,j) is:  $\epsilon_{i,j+1}=(\Delta y_{i,j+1}-\Delta y_{i,j})/(y_{i,j+1}-y_{i,j})$  where  $\Delta y$  and  $y$  are respectively vertical displacement and position. Average vertical strain on the whole sample surface and its standard deviation are also studied. In addition, strain rate is calculated by two methods: from the slope of a local fit over few points of the time-strain curve and also by dividing the strain computed between two successive pictures by the time interval. In addition, DIC lets us focus on local deformation field and spatial and temporal fluctuations.

AE from the micro-fracturing of a paper sample is recorded by a physical acoustics piezoelectric transducer, attached to the upper clamp and gently pressed to the sample. While the transducers are generally fairly sensitive, direct contact to the paper was required to avoid need for excessive amplification. The acquisition chain contains a piezoelectric transducer, an amplifier, a 12-bit A/D-converter and a computer with a four channel sample-and-hold type data acquisition hardware. In order to detect the high frequency AE events, high sampling rate is required. We used 312.5 kHz, which was the maximum supported by the A/D-converter. The first step towards analyzing the AE signal is to detect and extract the actual events from the signal. This is done with a threshold algorithm which filters out any signal weaker than a specified limit. Acoustic emission energy is then calculated as the square integral of an event and AE time series consists of pairs of time and energy ( $t_i, E_i$ ). We are then interested in the distributions of energy and waiting times between two successive events.

### 3. Results

#### 3.1. Strain and strain rate fields and their fluctuations

We realized 26 creep tests and 40 fatigue experiments. Lifetimes spread from 48s to 1447s for creep experiments and deformation before break are of  $0.9-4.5 \cdot 10^{-2}$ , with fluctuations from  $3.1 \cdot 10^{-4}$  to  $4.5 \cdot 10^{-3}$ . Fatigue experiments last from 60s to 750s under load for samples breaking after 2 to 36 cycles; strain and fluctuation maximal values are respectively found of  $1.7-2.8 \cdot 10^{-2}$  and  $1.8-4.7 \cdot 10^{-3}$ . The average deformation increases with time, and with number of cycles for fatigue, but recovery happens [17] during unloading phases for cyclic tests (no data represented during unloadings, fig.1). In fatigue curves of deformation against time gets flatter and flatter during successive loads and each load strain fit rather well with a logarithmic law but, especially for samples which break after a short number of cycles, a power law seems to be more adapted, particularly for the first cycle. Before break at the end of tests, the strain increases faster. This observation is similar to the evolution of deformation during single creep tests that presents three steps [7]: the primary creep at the beginning described by a power law  $\epsilon(t) = k \cdot t^p$ , where  $p$  between 0 and 1 and with a special Andrade's value of 1/3, then a secondary creep phase presenting a logarithmic increase of strain, and finally the tertiary creep starting when the strain rate begins to rise again. The values of the exponent  $p$  are found to spread from 0.36 to 0.71 for all the cyclic experiments and between 0.16 and 0.58 in creep tests. Table 1 summarizes the values of the fitting parameters.

All the  $\epsilon(t)$  creep curves were then fitted with a logarithmic law  $A \cdot \log(t)+B$ : the slope  $A$  from logarithmic fits decreases with the number of cycles and the slope during first cycle is clearly higher for tests in which the rupture of the sample occurs after a small number of cycles. Moreover by just comparing the first cycles for different tests, it seems that the strain is bigger for short tests and much smaller in a sample where the lifetime is important. Similarly, the initial slope of the creep strain(time) curve is greater for short lifetime samples and shows an important initial strain increase for long creeps.

An other interesting feature can be seen by looking at the standard deviation of the vertical strain, which corresponds to fluctuations of the strain around its averaged value. Like the averaged deformation, these fluctuations increase with the time and number of cycles, and a sharper growth is observed at the end of the test, a short time before that sample breaks. Moreover we calculated the value of ratio

“standard deviation/average strain” in percentage, and then averaged it for each creep phase in fatigue case. This ratio shows the strain fluctuations. This ratio decreases first with time and number of cycles, but rises strongly before the break, in creep as well as in cyclic experiments. In addition, in case of fatigue, this ratio is higher for short lifetime samples, which means that the paper sample will break more rapidly when the amplitude of strain fluctuation is large.

Averaged strain rate decreases clearly with time for the first cycle, and then seems to be almost constant during each other cycle in fatigue. Strain rate decreases firstly with the number of cycles or with time for creep, but again this quantity presents an increase before the rupture for every test. This is all the more visible when considering the average strain rate for each fatigue cycle. A Monkman-Grant [6] type relationship exists between the time of minimum strain rate and the lifetime:  $t_{\min} = 0.826 \cdot t_{\text{break}}$  for fatigue tests and  $t_{\min} = 0.830 \cdot t_{\text{break}}$ . We should notice that the acoustic emission occurs after this  $t_{\min}$ . The lifetime and time of minimum strain rate are calculated only during loading parts for cyclic tests. But even if time including unloading phases is used, the same relationship is obtained. The ratio  $t_{\min}/t_{\text{break}}$  is actually between 0.72 and 0.98 with an averaged value of 0.846 and a standard deviation of 10% for creep tests and ratio  $t_{\min}/t_{\text{break}}$  is from 0.72 to 0.98 with an averaged value of  $0.846 \pm 16\%$  for fatigue tests; this ratio is low for long lifetime samples and higher for samples with a short lifetime.

DIC technique allows us to study the spatial aspects of strain over the sample. Before final failure, significant deformations are confined near the location where the final crack will propagate from. Spatial fluctuations in strain are also observed and localization appears with successive loading cycles. At the beginning of a test, during the first load phases, strain fluctuations are spread rather homogeneously on the whole sample area, but localization is seen with further cycling. Moreover, a correlation between fluctuations and lifetime seems to emerge: samples which break quickly present large strain fluctuations and the fluctuation amplitude could be more than two times smaller for long lifetime samples. Additionally the fluctuations are localized only close to the final crack for short lifetime sample. Just a few locations with higher fluctuations are seen for samples breaking after around 10 cycles while in contrast, for samples with a longer lifetime, large fluctuations are widely present over the sample.

### 3.2. Acoustic emissions: indication of an imminent rupture

In general, acoustic emission events recorded in experiments were sparse but consistent. In all the different experiments, AE occurs only few seconds before the finale failure. The power/energy of acoustic emission events as well as their density increases towards the time of final rupture. We studied in the usual vein the distributions of waiting times between successive events and the distribution of AE energy. Both exhibit a power law form  $P(t) = A \cdot t^{-\alpha}$  and  $P(E) = B \cdot E^{-\beta}$ , respectively. This is independent of the lifetime of the particular sample. We found exponents  $\alpha = 1.5 \pm 0.2$ ,  $\beta = 1.4 \pm 0.3$  for all the cyclic creep experiments. These results are also slightly higher than the values  $\alpha = 1.20 \pm 0.01$  and  $\beta = 1.33 \pm 0.03$  obtained in simple creep tests on paper sample in cross direction. These power laws of the distributions appear to be universal features in fracture as it can be seen in lot of different materials [18] or at different scales [19] and in particular in other tests on paper [10-13].  $\alpha$  and  $\beta$ , respectively for inter-event times and energies, are close to  $\alpha = 1.40 \pm 0.1$  and  $\beta = 1.3 \pm 0.2$  found in [11] for tensile experiments on paper samples, with an initial notch on one side, stretched in cross direction. For same kind of experiments than [11] (initial notched samples) but stretched in machine direction [13], the values are found in bit smaller:  $\alpha = 1.25 \pm 0.1$  and  $\beta = 1.0 \pm 0.1$ .

Acoustic emissions are yet an early warning sign of break. Indeed acoustic activity takes place mostly in the very last part of experiment, before the final rupture happens. The time during which acoustic emissions occur is very short and represents less than 10% of the sample lifetime. As in [19], figure 2

presents the repartition of AE energy against the change in time relatively to time of break:  $((t_c - t)/t_c)$  where  $t_c$  is the lifetime. The relationship found here between cumulative energy and relative time is somewhat reminiscent of a power law with an exponent between -1.0 to -1.2. In figure 2, close to the rupture time, a divergence of the experimental data from this power law is observed. This figure shows too that most of AE energy is released during a very short time before failure. For example,  $E = 10^9$  (a.u.) when  $((t_c - t)/t_c) = 10^{-2}$  and the maximum energy released is  $10^{12}$  (a.u.) mean that in a duration of only 1% of the lifetime, 99.9% of the total acoustic energy is released. Therefore acoustic emissions themselves indicate that rupture will occur in a very short time after they start. This observation is obviously consistent with the fact that strain and strain rate increase before break and are localized.

We studied fits with a power law of the distributions of waiting times and AE energy for each sample. The exponents of distributions fits vary slightly for the different samples and a slight effect of the lifetime is observable, but no clear tendency with lifetime can be concluded, indicating that microscopic fracture accumulation is the same in all the experiments.

#### 4. Conclusion

We have analyzed fatigue – or cyclic creep – and creep experiments on paper using digital image correlation and acoustic emission records. The AE shows usual complexity indicated by the power law behavior of event energy and waiting times; AE occurs predominantly right before break, during a time that is less than 10% of the lifetime, thus damage accumulation starts only during last loads.

Similar acceleration is seen in the strain, the strain rate and their fluctuations which grow sharply just before failure in creep as in fatigue tests. Significant localizations in these both fields appear since there is a high strain concentration near the location where final crack will propagate from. Thus one observes two different subsequent behaviors in a test: as in primary creep, first a sample effectively exhibits strain hardening, which in the last phase changes to strain softening. Both of these exhibit interesting statistical fracture/deformation signatures.

We have shown furthermore that, in fatigue, looking at the evolution of various data during first load cycle only could already give interesting indications to predict the lifetime of the sample. The deformation during first creep tends to be larger for short lifetime samples and first cycle behavior reflects the final lifetime. Second, short lifetime samples show strain fluctuations which are greater and more localized than in samples which last a longer time before rupture. It is unclear to us whether these features arise e.g. because of the intrinsic sample-to-sample variation, or since the random variations early during the strain hardening –like behavior have a deterministic effect on the later developments, including the sample lifetime. The strain and strain rate features of the initial cycles in fatigue are reminiscent of what is seen in creep experiments with some differences. These may ensue for at least two reasons: either the actual loading level applied here is actually not similar to what has been used in creep experiments, or it is the fundamental effect of sample relaxation.

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**Annexes: figures and table**

Table 1: Averaged values, and dispersion in %, of parameters (factor k and exponent p) and correlation coefficient R<sup>2</sup> (least mean square) from fits with a power law of the strain and fluctuations against time, during the 1<sup>st</sup> load or first 10% of total creep time

Experiment	10 <sup>3</sup> .k for strain(t)	p for strain(t)	R <sup>2</sup> for strain(t)	10 <sup>4</sup> .k for fluctuation(t)	p for fluctuation(t)	R <sup>2</sup> for fluctuation(t)
Creep	4.9±73%	0.35±31%	0.96±1.4%	2.5±88%	0.33±38%	0.96±1.4%
Fatigue	3.4.±47%	0.32±13%	0.94±5.5%	5.4.±62%	0.29±24%	0.92±6.3%

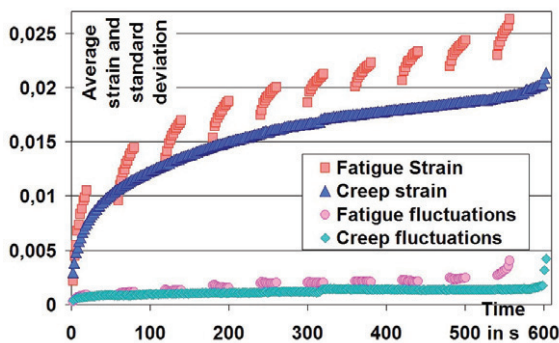


Fig. 1: Averaged vertical strain and its standard deviation vs. time for examples of single creep and cyclic test;

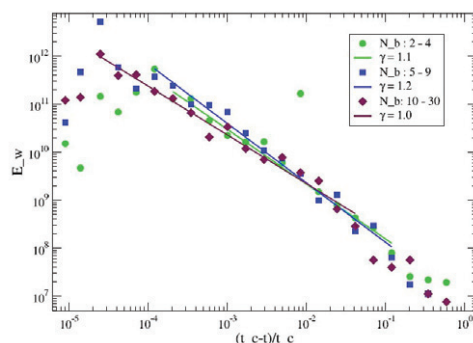


Fig. 2: AE energy vs. time normalized by lifetime, average for tests with different lifetime ranges.