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BURSTS IN A FIBER BUNDLE MODEL OF CREEP RUPTURE

Zs. Danku and F. Kun

Department of Theoretical Physics, University of Debrecen,
H-4010 Debrecen, P. O. Box: 5, Hungary

Abstract

We present a theoretical study of the creep rupture of heterogeneous materials based on a fiber bundle model where material elements fail either due to immediate breaking or to a damage accumulation process. We studied the time evolution of single bursts and found that they are composed of sub-avalanches which lead to a non-trivial temporal shape. The pulse shape proved to be sensitive to the range of load sharing: for long range interaction the average pulse shape is symmetric, however, short range interaction leads to right handed asymmetry.

I. Introduction

Creep rupture processes occurring under constant sub-critical external loads are often responsible for the failure of constructions and can lead to natural catastrophes such as snow and stone avalanches, earthquakes. In order to prevent accidents and catastrophes acoustic emission monitoring techniques are indispensable. Here we study the time evolution of single acoustic outbreaks to determine features which may be utilized for non-destructive materials testing.

II. Fiber bundle model

We studied creep rupture by computer simulations with an extended version of the fiber bundle model [1, 2, 3]. In this model the heterogeneous material is described as a set of parallel fibers arranged on a square lattice. Fibers have identical elastic properties, but randomly distributed failure thresholds. Two physical mechanisms could lead to the failure of fibers: fibers have a brittle response so that they break immediately when the local load on them exceeds their fracture strength σ_{th} which is a random variable. Furthermore, loaded intact fibers undergo an aging process in which they accumulate damage in the form of micro-cracks. We assume that the rate of damage accumulation Δc depends on the local load as a power law $\Delta c(t) = a\sigma^{\gamma}(t)\Delta t$, where a is a constant and the exponent γ controls the time scale of the damage accumulation process [1, 2]. Fibers break when $c(t)$ exceeds their local damage threshold c_{th}. Breaking thresholds c_{th} and σ_{th} of fibers are uniformly distributed random variables between 0 and 1 and they are treated independent of each other. When a fiber breaks intact fibers have to take over the load of the broken one. Through the load redistribution we can control the range of interaction between fibers. We performed computer simulations in the two extreme cases of the load redistribution: in the equal load sharing limit (ELS) the load of the broken fiber is equally redistributed over all the remaining intact fibers which results in a homogeneous stress field. However, in the local load sharing limit (LLS) only the closest intact neighbors take over the load which leads to an inhomogeneous stress field since around failed fibers the stress concentration is higher.

III. Time evolution on the microscopic level

The fiber bundle is subject to a constant external load σ_0 below the fracture strength σ_c of the system. As the load has been set, weak fibers immediately break. After these initial immediate breakings slow damaging starts to control the time evolution. These damage breakings gradually increase the local load on intact fibers till its level gets high enough to trigger a burst of immediate breakings. Consequently, on the microscopic level the time evolution of creep rupture occurs as a series of bursts corresponding

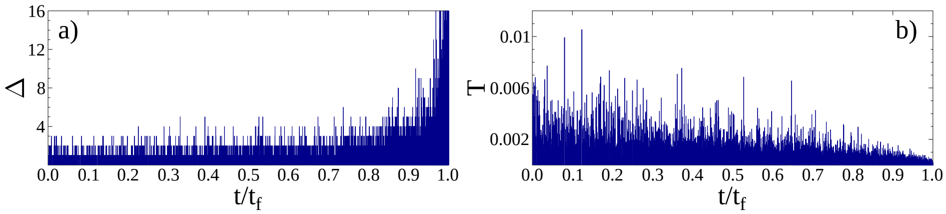

Figure 1: (a) The burst size Δ as a function of time t. (b) The waiting time T elapsed between consecutive bursts in (a). Both quantities strongly fluctuate during the fracture process.

to the nucleation and propagation of cracks, separated by silent periods of slow damage sequences. Figure 1(a) and 1(b) presents the burst size Δ (number of fibers breaking in a burst) and the waiting time T between consecutive bursts as a function of time t, where t_f is the lifetime of the system defined by the instant of macroscopic failure. Both quantities have strong fluctuations, however, the average burst size increases, while the waiting times decrease towards macroscopic failure. In our model bursts of immediate breakings are analogous to acoustic outbreaks of experiments which can be recorded by sensitive microphones.

IV. Results

In acoustic emission measurements even the evolution of single breaking events can be captured by sensors with high precision. The pulse shape of the voltage signals of sensors may provide valuable information on how cracks evolve in the system. Our model allows for a detailed investigation of the temporal dynamics of bursts. A burst is triggered by the last damage breaking in a damage sequence. The redistribution of the load of the broken fiber leads to a few immediate breakings which may then trigger further breaking events, as well. Hence, bursts evolve through sub-avalanches and stop when all of the intact fibers at their perimeter are able to hold the elevated local load on them. The duration of bursts W can be defined as the number of sub-avalanches, while the temporal profile is characterized by the size of sub-avalanches $\Delta_s(u)$ as a function of the internal time u, where

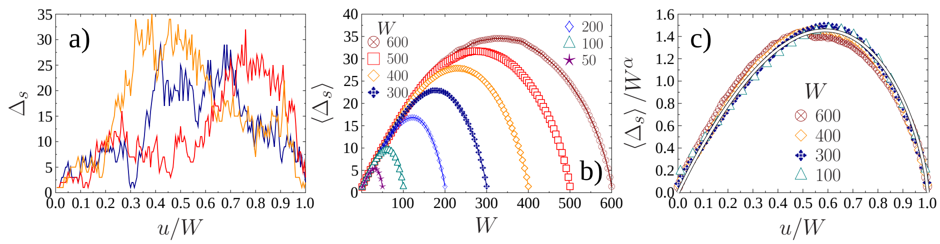

Figure 2: (a) Temporal profile of single bursts of the same duration $W = 200$. (b) Average pulse shapes of bursts for different durations W. (c) Scaled average pulse shapes where the scaling exponent is $\alpha = 0.7$. Fit parameters of the scaling function $f(x)$: $B = 4.6$, $\beta = 0.7$.

$1 \leq u \leq W$ holds. Figure 2(a) shows the temporal profile of avalanches of the same duration W as a function of the normalized time u/W. A complex stochastic evolution of bursts can be observed. The temporal profiles $\Delta_s(u)$ of bursts obtained from our simulations are analogous to the pulse shape of acoustic signals measured in experiments. To unveil the information encoded in the shape of pulses we determined the average temporal profile for fixed durations $\langle \Delta_s(u, W) \rangle$. Fig. 2(b) presents the average pulses for localized load sharing where a parabolic shape can be observed with a right handed asymmetry. With increasing duration W the functional form of the curves remains the same but the maximum of the profiles increases. Figure 2(c) shows that the average pulses can be collapsed on each other as a function of u/W by rescaling $\langle \Delta_s(u, W) \rangle$ with an appropriate power α of the duration W. The good quality of the collapse implies the scaling form

$$\langle \Delta_s(u, W) \rangle \propto W^{\alpha} f(u/W), \tag{1}$$

where the scaling function is

$$f(x) = Bx(1 - x)^{\beta}. \tag{2}$$

The right handed asymmetry demonstrates that an avalanche starts slowly, then it accelerates and stops suddenly by reaching stronger material regions. However, in the case of homogeneous stress fields a symmetric parabola can be obtained for the average pulse shapes due to the dominance of structural disorder. Our results shows that the temporal evolution of single acoustic outbreaks carries information about the range of interaction of material elements.

IV. Conclusions

In this paper we used a fiber bundle model of damage enhanced creep of heterogeneous materials to investigate the time evolution of single bursts. Computer simulations showed that the temporal profile of bursts is analogous to the pulse shape of acoustic outbreaks in the voltage signal of sensors. For short range interaction a right handed asymmetry of pulse shapes was found as bursts start slowly, accelerate and stop suddenly when the crack gets pinned. However, in the case of homogeneous stress fields a symmetric pulse shape emerges as the structural disorder dominates.

Acknowledgment

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