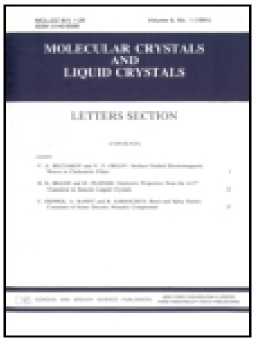

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Crack diffusion in failure process of composite materials

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ABSTRACT

We study the crack diffusion in composite materials subject to a local load-sharing fiber bundle model in two dimensions under an external load applied at a single point. By the use of the local load-sharing rule, the redistributed load remains localized along the boundary of the broken patch. We investigated the correlation function of the broken fibers. The results show that this magnitude decreases exponentially with time and it's characterized by a characteristic time which is inversely proportional to the diffusion coefficient of the localized crack. The results exhibit also that the crack correlation function in the failure process in composite materials decreases with both of applied load and temperature. We calculate then the diffusion coefficient of the localized crack. We have found that this diffusion coefficient increases by power law with the applied load and thermal noise.

KEYWORDS

the crack correlation function; Fiber bundle model; the crack diffusion coefficient, Thermal noise

I. Introduction

The fiber bundle models (FBM), with statistically distributed thresholds for the breakdown of the individual fibers, is the most interesting models of failure processes in composite materials. It's characterized by clear-cut rules for stress, caused by a failed element, which is redistributed in undamaged fibers. This model has been studied extensively since it can be analyzed to an extent that is not possible for more complex materials [1–6]. The statistical distribution of the magnitude of avalanche phenomenon in fiber bundles is well studied [7–9], and the failure dynamics under constant load has been investigated through recursion relations which appears in a phase transitions and associated critical behavior in this model [10].

However, there are two extreme rules which consider a bunch of fibers hanging from a rigid ceiling and a platform that is connected to the ends of these fibers and a load hangs from that plat form. Each fiber is characterized by a given limit or load-carrying threshold (usually taken randomly from some distribution functions), beyond which it fails. Completely different behaviors are observed when the elastic property of the lower platform changes. Two extreme cases arise when the platform is either absolutely rigid (global load-sharing (GLS) case) or absolutely soft (local load-sharing (LLS) case). For the GLS rule, the extra load of the broken is equally shared by all other remaining fibers, due to rigidity of the lower platform. Due to local deformation of the platform In the LLS rule, the load of the broken fiber is only to be carried by nearest surviving neighbors (stress concentration occurs around the failure or crack breaking).

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For an undamaged material with intact fibers on which we applied an external force *f*, the material resists to the applied load, but under a threshold time value t_r where the elongation of some fibers becomes greater than their critical ones, micro cracks appear in the system and grow rapidly in time until the final crack of the material through an avalanche process [2,3]

However, the situation differs totally if one creates the initial applied load localized at an arbitrarily chosen central site in a local load-sharing fiber bundle model. So, initially, no load is applied on any fiber except (for) the one at the central site. As the applied load increases beyond the failure threshold of this central fiber, it breaks and the load carried by it is redistributed among its nearest neighbors and so on. Hence, the applied load on central fiber gives rise to engenders a central crack which diffuse belong material and broken patch appears. In this investigation, we propose to calculate the diffusion coefficient of the boundary of the engendered damaged region by two different approaches.

The present paper is presented under form four sections. So, in the section 2, we discuss the adopted model and in the section 3, we report and discuss the finding results. Finally, we summarize summarized our results in the conclusion section (section 4).

II. The fiber bundle model: The lls rule

The fiber bundle model describes a collection of elastic fibers under load. The fibers fail individually when some threshold values of stretching is exceeded [11], and for each failure, the load distribution among the surviving fibers changes. Hence, this generates a feedback process that can produce the total failure of the system. Even though very simply, this model captures the essentials of failure processes in a large number of materials and settings. We present here a review of the fiber bundle model with different load redistribution mechanisms from the point of view of statistics and statistical physics rather than materials science, with a focus on concepts such as criticality, universality and fluctuations.

We consider a bundle of size L consisting of a large number $N = LxL$ of fibers clamped at both of ends. We study equal-load-sharing models in which the load previously carried by a failed fiber is shared equally by the nearest neighbor of undamaged fibers [12–15]. The bundle center is subject to a local constant external stress parallel to the fibers' direction. The load carried by that fiber is redistributed equally among its nearest surviving neighbor(s). In this way, the fibers which are newly exposed to the load, say seen, after an avalanche, have a relatively low load compared to the ones which are accumulating load shares from the earlier failures and are still surviving. In our work we assume that the initial local load f_0 is to be equal to the intact fibers which induce an initial elongation δl_0 given by the Hooke's law:

$$\delta l_0 = f_0/k \tag{1}$$

where k denotes the stiffness, which is assumed to be the same for all the fibers. The local elongation σ_i of fibers i have time-dependent fluctuations due to the presence of thermal noise load and to load transfer following breaking events given by:

$$\sigma_i = \gamma l_0 \sqrt{K_B} T \tag{2}$$

where l_0 is the initial length of fibers, K_B is the Boltzmann constant and γ is a coefficient of proportionality. The presence of the thermal noise will affect the lifetime for a constant applied stress controlled by the temperature T of the system [2,9].

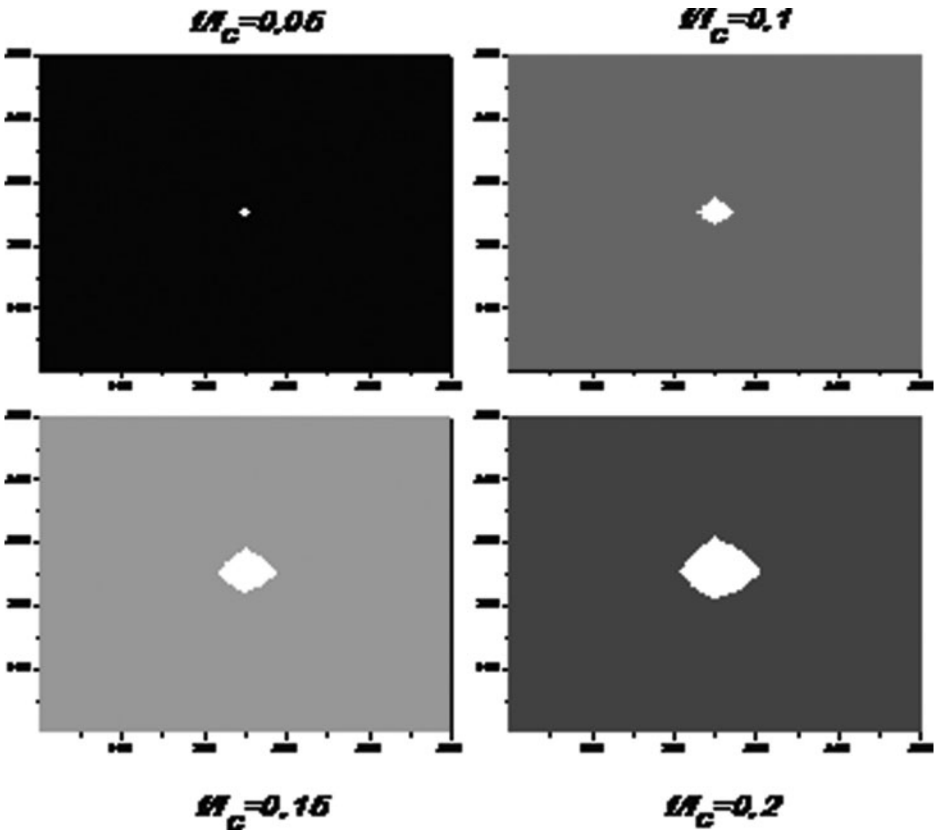

Figure 1. Image system calculated for different values of applied load and for system size of $L = 500$ and temperature value $T = 300$.

So, the actual stress arising δl_i of fiber i is written as:

$$\delta l_i = \delta l_0 + \sigma_i \tag{3}$$

The fibers have a finite strength characterized by a failure threshold δl_i^{th} which is, in general, a random variable. A fiber fails when the total elongation δl_i exceeds the corresponding threshold value δl_i^{th}. The fibers on the perimeter of the failed or damaged region, which are carrying the entire load together, increase quantitatively in number with time t.

We indicate the correlation function of broken fibers in the damaged region by:

$$G(\tau) = < \frac{dN_b}{dt}(t+\tau)\frac{dN_b}{dt}(t) > \tag{4}$$

where $N_b(t)$ represents the number of broken fibers at time t.

III. The results

III-1 The applied load behavior

We have investigated the crack correlation function in the failure process in the composite materials. Hence, we have calculated this parameter defined in equation (4). The basic idea is that there is a relation between the crack diffusion process and the adatom diffusion in

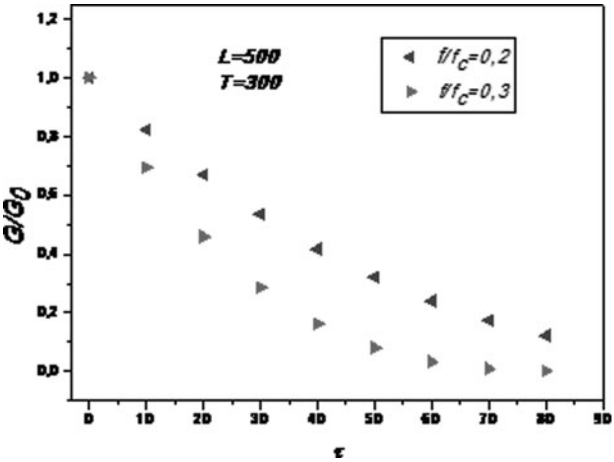

Figure 2. The time evolution of the crack correlation function for two different values of the applied load and for system of size $L = 500$.

the scaling tunneling microscopy (STM) one [18–19]. In the figure 1, we present an image of our system calculated for different values of the applied load. So the created damaged region increases with the applied load and this process ensures an advancing interfacial fracture. In the figure 2 we have plotted the time variation of the normalized crack correlation function for two different values of the applied load. So, the corresponding results exhibit that the correlation function G decreases exponentially with time as: $G(\tau) = G_0 \exp(-\tau/\tau_r)$ where τ_r is the characteristic time of the correlation function which also represents the time between a two consecutive cracks. This variation law of G is also observed in [18–20].

In order to check the effect of the applied load on the correlation cracks, we have calculated the correlation function G versus applied load for system of size $L = 500$. The corresponding results are represented in figure 3. We indicate that this magnitude decreases with applied load. However, we have calculated the effective diffusion coefficient of the created crack by using the following expression $D_{eff} = 1/\tau_r$ which has been used in the fluctuations adsorbed surfaces in the STM treatment. The corresponding results are plotted in figure 4. We remark that the

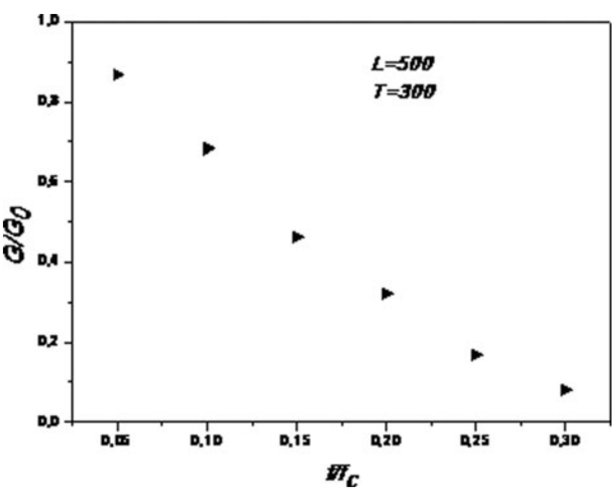

Figure 3. The normalized crack correlation function versus applied load for system of size $L = 500$.

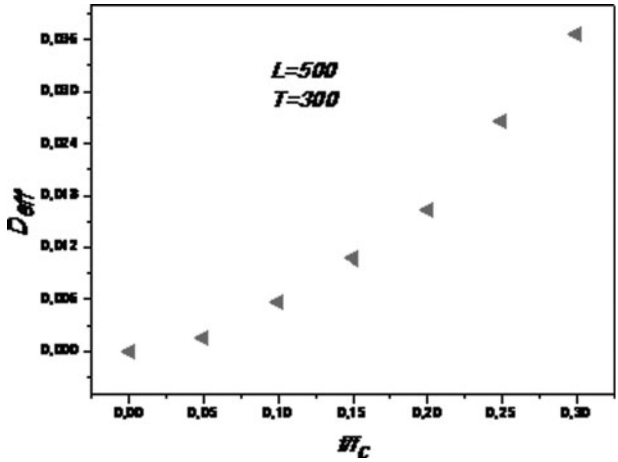

Figure 4. The variation of the effective diffusion coefficient of the created crack versus applied load for system of size $L = 500$ and temperature value $T = 300$.

effective diffusion coefficient of the created single crack in the composite materials increases with the applied load and exhibits a following power law $D_{eff} \propto (f/f_c)^{7/4}$ independently to the temperature value, which proves this universal law.

III-2. The temperature behavior

Thermal quenched noise disorder in the form of defects, flaws, or microcracks gives rise to strong sample-to-sample fluctuations of the fracture strength and the yield stress of materials. These macroscopic characteristics show also a strong size effect; i.e. their average values decrease with increasing sample size, which is of a high importance in applications and it is extensively exploited by industrial design [21]. So in order to make in evidence this point, we have investigated the time evolution of the crack correlation function for system size of $L = 500$ subject to the load value $f/f_c = 0.2$and for a two different values of temperature. The corresponding results are plotted in figure 5. We indicate that the correlation process

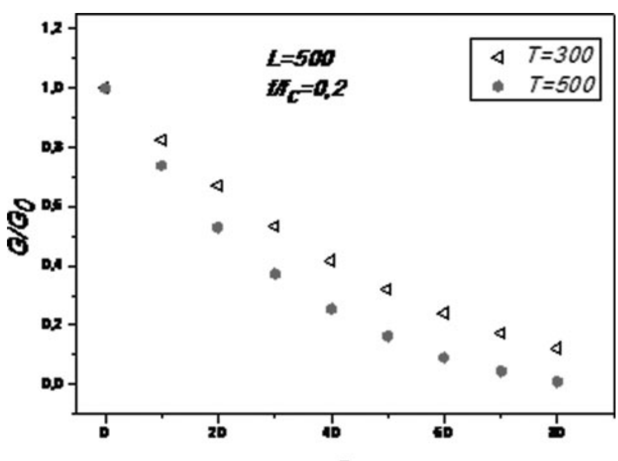

Figure 5. The time evolution of the normalized crack correlation function for system of size $L = 500$ and for two different values of temperature.

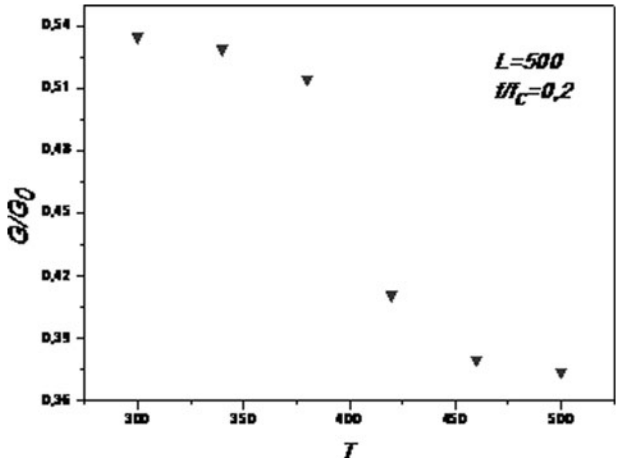

Figure 6. The normalized crack correlation function versus temperature for system of size $L = 500$.

is characterized by characteristic time $\tau_r$which decreases with temperature. So, this later leads to minimize the time between a two consecutive cracks. However the calculation of the crack correlation function in the failure process in composite materials exhibits an avalanche decrease with temperature near a temperature value $T = 400$ (see figure 6). This avalanche phenomenon is also observed in the breaking process of the composite materials subject not only to a single load but to its all intact fibers [2,3,9].

We have also calculated the effective diffusion coefficient D_{eff} with temperature. The corresponding results are plotted in figure 7 . So the diffusion of the created single load in the material increases with temperature and exhibits a height increase due to the avalanche breaking of the fibers. We indicate that the crack correlation process and the diffusion one present an opposite behavior (see figures 6 and 7). These results are also observed in the precedent paragraph (figures 3 and 4)

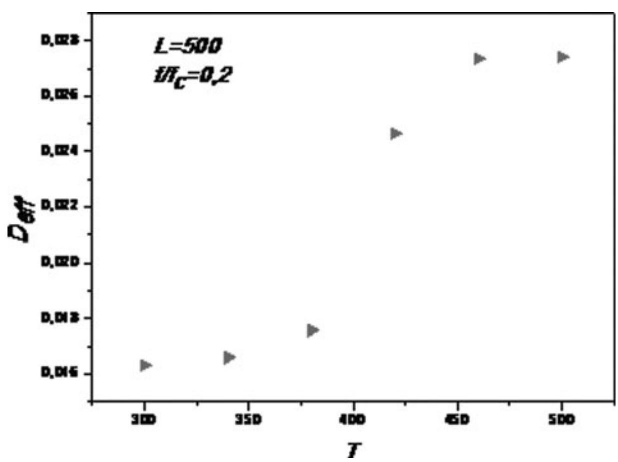

Figure 7. The variation of the effective diffusion coefficient of the created crack versus temperature for system of size $L = 500$.

IV. Conclusion

In summary, we have investigated the crack diffusion process in composite materials subject to a local load-sharing fiber bundle model in two dimensions under an external load applied at a single point. So we have calculated the crack correlation function. The results show that this correlation process decreases exponentially with time and the correlation function is described by a characteristic time which decreases with both of applied load and thermal noise. However, the crack correlation function presents an avalanche decrease with the temperature. Based on the method used in the fluctuation process of the adsorbed surfaces in the STM experiments, we have calculated the effective diffusion coefficient which inversely proportional to the characteristic time of the crack correlation function. The corresponding results show that the diffusion process of the created crack in the composite materials increases with both applied load and thermal noise. We note also that the crack correlation process and the diffusion one of the created crack present an opposite behavior in the two cases by varying the temperature and the applied load.

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