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Crossover behavior in the avalanche process of the fiber bundle model in local load sharing

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HIGHLIGHTS

- The fiber bundle model is simulated by dividing the tensile process into several segments.
- The crossover behaviors in avalanche size distribution near the catastrophic failure are illustrated.
- The evolution of fracture parameters with tensile process is well fitted by some simple function relationship.

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ABSTRACT

The crossover behavior near the catastrophic failure in the avalanche process of fiber bundle model in local load sharing condition is numerically investigated by dividing the tensile stretching process into several segments. In every segment of the tensile process, the fracture parameters, such as the number of fracture fibers, the energy emission, the avalanche size and its distribution, are calculated respectively. The results illustrate that the evolution of the fracture process from the initial tensile stage to the final fracture can be well described by a power law relationship or a simple quadratic polynomial. In the vicinity of the catastrophic failure, the avalanche size distribution appear crossover behavior with two different power law exponents, which provides a possible route for theoretically predicting the catastrophic fracture of materials.

1. Introduction

As the basis of assessing the stability and predicting the catastrophic failure of materials, the statistical properties and its microscopic mechanism of the rupture process have attracted much theoretical and technological interests. Due to the inherent nonuniformity and disorder in actual materials, the theoretical approach of statistical physics is widely used to investigate the statistical properties [1]. Specifically, most of the statistical investigations on the rupture of disordered materials rely on a so-called fiber bundle model (FBM), which was first introduced by Peirce nearly a century ago [2]. Despite of its simple algorithm, in most cases, the FBM can capture correctly the collective static and dynamic properties of fracture failure in loaded materials [3,4].

The FBM consists of a series of elastic fibers mounted in parallel between two hard clamps. Each fiber is linearly elastic up to a threshold load, after which it fails irreversibly. Under stress-controlled loading condition, after each fiber failures, the load carried by the broken fiber is redistributed among the intact fibers. The subsequent load redistribution can lead to an entire avalanche of breakages, which can either stop after a certain number of consecutive failures, keeping the integrity

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of the bundle, or can be catastrophic, resulting in the macroscopic failure of the entire system. According to the strength of transverse association in the rupture process, the redistribution mechanism of the extra stress released from broken fibers can be classified into several types. The most common one is global load sharing (GLS), that is, after each fiber failures, the released load is equally redistributed among all the intact fibers. The FBM in GLS case assumes the interaction among the fibers with a mean field approximation and can often be solved analytically. On the other hand, The extreme case of the short-range interaction is the local load sharing (LLS) maintaining stress concentration around the broken fibers. In this case, the extra load released from failing fibers is transferred to their nearest intact neighbors. Due to the nontrivial localized spatial correlation, the analytical solution of LLS bundles becomes quite difficult [5]. In most cases, LLS models can only be studied through computer simulation or determination of asymptotic behaviors. In fact, some researches show that stress redistribution in actual heterogeneous materials should fall in many intermediate load sharing forms, such as the power law redistribution rules [6].

On the macroscopic scale, the various stretching and fracture natures of actual materials can be described visually by the stress–strain relationship, by which, different fracture properties of materials can be intuitively divided into brittle, semi-brittle, plastic and so on. As the applied load increases quasi-statically, there exists a critical stress σ_c, beyond which the catastrophic failure of the whole system takes place. While for the microscopic fracture mechanism, the most important characteristic of the model is the size distribution of the burst avalanches, which can be monitored experimentally by acoustic emission technique [7–9]. In the GLS case, the avalanche size distributions of the classical FBM with various fracture threshold distributions follow a power law with a universal exponent $-5/2$ [10–12]. While in the LLS limit, the avalanche size distributions show more complicated properties, depending on the specific fracture mechanism of the single fiber [13,14]. In general, current studies on FBM mainly involve the describing of the constitutive relationship, the determination of the critical stress σ_c, and the investigation of the statistical property of the avalanche process.

In order to obtain a more realistic description for a wide range of composites, a series of deformation models based on the classical FBM have been introduced. In the respect of stress distribution, Hidalgo et al. [15] introduced an interpolation form between the two limit case of load redistribution, i.e. the global and the local load sharing schemes. By varying the correlation strength between an intact element and the rupture point, the crossover behavior from mean-field approach to short-range correlation was obtained in the properties of the FBM. In order to describe numerous non-brittle fracture process of various biological materials, some complicated tensile fracture properties were introduced to a single fiber instead of the simple brittle fracture. For instance, the continuous damage FBM [16], or continuous damage FBM with strong disorder [17], the FBM with stick–slip dynamics [18,19], and the multilinear FBM [20]. Some FBM with mixed fibers were also introduced to describe a lot of heterogeneous materials. For example, Divakaran et al. [21,22] studied FBM with mixed fibers, whose threshold strength was randomly chosen from two uniform or Weibull distributions; Bosia et al. [23] developed a hierarchical FBM consists of a certain percentage of fragile fibers and plastic fibers, which can simulate the hierarchical structures of some biological materials, such as spider silk; Hidalgo [24] introduced the FBM with strong heterogeneities which is composed of classical brittle fibers and unbreakable fibers. In addition to study the avalanche process, the FBM has also been used to investigate some slow damage process of materials, such as creep process [25].

In order to investigate the dynamic critical behavior before the fixed point in the failure process, Pradhan et al. [26] introduced the FBM with a low cutoff which is assumed to has a low cutoff in the strength threshold distribution. In the following papers [14,27–29], the crossover behaviors in the failure avalanche process, such as avalanche size distribution and step of load increase, were studied not only in GLS or LLS case, but also in a general LLS case which is an interpolation model between GLS and LLS. In addition, Pradhan et al. [30,31] also investigated the energy burst distribution in the GLS model and the prediction of the collapse point of the overloaded materials by the breaking-rate minimum. Recently, based on the above research works on the loaded FBM with a low cutoff, Pradhan [32] given the crossover behavior and the critical phenomenon in the vicinity of the macroscopic failure point. Then, the predict method of the final failure point was constructed in various loading conditions.

Compared to GLS case, the other limit case, i.e. the LLS can better describe the stress redistribution in some actual heterogeneous materials. Therefore, it is of great significance to study the fracture evolution in the tensile process of the FBM in LLS case. Although the FBM with a low cutoff threshold has achieved huge success in the study of the crossover behavior in the avalanche process of FBM in GLS case, it is not suitable to use the same model to simulate the crossover behavior of FBM in LLS case. The reason is that, in LLS case, the previous fracture process will bring prominent damage localization and stress concentration near the crack front, which hinder the simulating of the previous fracture process by the low cutoff of fracture threshold. In this paper, the tensile fracture process is divided into several subsections, in which some parameters, such as the maximum avalanche size, the mean energy burst, are recorded and averaged. Then, the fracture evolution in the tensile process and the crossover behavior near the catastrophic failure, which can provide a possible route for theoretically predicting the macroscopic fracture, are exhibited and discussed.

2. The crossover behavior of the avalanche process of the FBM in LLS

In this paper, we utilize a classical FBM in LLS case, the specific arithmetic can be described as follows: the bundle consists of N parallel fibers, all with an identical Young modulus $E_f = 1$, but with random failure thresholds σ_i, $i = 1, 2, \ldots, N$. The fibers are assembled on a one-dimensional lattice of length L. The failure strength of individual fibers is an independent,