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The avalanche process of the fiber bundle model with defect in local loading sharing

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HIGHLIGHTS

- The short-range correlation mechanism is introduced to the fiber bundle model with defect.
- The defect has a significant impact on the mechanical properties in the fracture process.
- The statistical properties of the model are significantly influenced by the defect.

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ABSTRACT

The fiber bundle model with defect is an extended model based on the classical fiber bundle model to describe the impact of the defect size and the defect density on the failure process in actual materials with defect. In order to explore the dynamic properties of the breakdown of materials with defect in short-range correlation, the model in local load sharing condition is numerically studied in detail in both uniform and Weibull threshold distribution cases. The simulation results show that both the defect size and the defect density have diverse impacts on the macroscopic mechanical properties and the statistical nature. From macroscopic view, the model parameters mainly impact the macroscopic fracture stage of the stretch process, while the initial tensile stage of the constitutive curves are almost not affected by the defect size and defect density. In the microscopic scale, the avalanche size distributions have no universality and are significantly influenced by the defect size and defect density.

1. Introduction

Due to the inherent nonuniformity and disorder, the failure process of structure and materials are quite complicated and often cannot be described by a simple kinetic equation. As a result, in the physics community, the theoretical research of the material fracture process and its microscopic mechanism often rely on the statistical physics. At the same time, the fluctuation will play a key role in description of the fracture based on the average properties [1]. In order to simulate the actual breakdown process of disordered materials, the fiber bundle model (FBM) which is a bundle consisting of a large number of parallel massless elastic fibers is introduced. In most cases, the model can correctly capture the collective static and dynamic properties of fracture failure in loaded materials [2,3]. In addition, the algorithm of FBM is so simple that it is relatively easy to obtain the fracture properties analytically or numerically.

In general, the FBM is assumed to be composed of a set of fibers whose breaking strength is assumed to comply with a certain statistical law, such as uniform or Weibull distribution. Under stress-controlled loading condition, the bundle is

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loaded parallel to the fiber direction quasi-statically, i.e. after each step of stretching, only the weakest fiber will breakdown. Then, the load carried by the failed fiber is redistributed among the intact fibers, which can lead to a series of avalanches. The avalanche can either stop after a certain number of consecutive failures, keeping the integrity of the bundle, or can be catastrophic, resulting in the macroscopic failure of the entire system. In the model, the mechanism of the stress redistributed among the intact fibers play a key role in the rupture process and can be classified into several types, such as the global load sharing(GLS), the local load sharing(LLS), and so on [4].

In the initial stage of the quasi-statistically loading process, the stress increases monotonically with the strain. Before the catastrophic failure of the whole system, there exists a critical stress σ_c which reflects the strength of the system. On the other hand, the size distribution of the burst avalanches can intuitively describe the statistical properties of the failure process and can be monitored experimentally by acoustic emission techniques [5–7]. 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 $-5/2$ [8–10]. While in some local stress redistribution cases, such as the LLS, the avalanche size distribution is more complicated, depending on the specific form of the threshold distribution and the tensile fracture property of a single fiber [11,12].

The classical FBM only considers brittle linear elastic fibers and simple global or local load sharing condition, however, the internal structure of actual materials and the stretching conditions are quite complicated. So, some extended FBM are constructed from the following two perspectives: the form of stress redistribution and the tensile fracture property of a single fiber [13]. In the first case, Hidalgo et al. [14] introduced an interpolation form between 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-rang correlation was obtained in the fracture properties of FBM. In this regard, the relevant works include the soft membrane fiber bundle [15], the soft clamp fiber bundle model [16–18]. In the other hand, some complicated tensile fracture properties were introduced instead of the simple brittle fracture to describe numerous non-brittle fracture process of various biological materials. For instance, the continuous damage FBM [19], the continuous damage FBM with strong disorder [20], the FBM with stick–slip dynamics [21–23], and the multilinear FBM [24]. In addition, Some mixed FBM were also introduced to describe a lot of heterogeneous materials. For example, Divakaran et al. [25,26] studied two kinds of FBM with mixed fibers, the one is the mixed fiber bundle with uniform distribution thresholds which can be regarded as the limitation case of random fiber bundle with many discontinuities in the threshold distribution [27,28]; the other is the FBM with two different Weibull distribution [26]. Bosia et al. [29] developed a hierarchical FBM consisting of a certain percentage of brittle fibers and elastic–plastic fibers to simulate the hierarchical structure of some biological materials such as spider silk.

As the research on the microstructure properties of materials, there is a universal paradox that the experimental strength will be smaller than the theoretical strength in actual materials, especially in brittle materials. One important reason is the existence of defects in actual materials which play a crucial role in the mechanical behavior of materials under stress, such as the nucleation and propagation of fracture. According to the very different stress–strain response and fracture properties, materials are broadly classified into three types: brittle, quasi-brittle, and ductile. In microscopic scale, the guiding factors behind these different macroscopic fracture properties are the defects and their kinetics. Furthermore, for the common crystalline materials, the defects can be classified into point defects, line defects and planar defects from the geometric scale, which include vacancy, interstitial, impurity, dislocation, microcrack and so on in actual materials [1]. Recently, we have constructed an extended FBM with defect in GLS case [30]. In the model, the size and density of defects are the two critical parameters. By analysis and numerical simulation, we reveal that the presence of defects in materials can lead to nontrivial effects on the tensile fracture process.

Compared to GLS case, the other limit case, i.e. the LLS may better describe the stress redistribution in some actual heterogeneous materials. In the LLS case, the previous fracture process can bring prominent damage localization and stress concentration near the crack front, which will trigger more significant brittleness of the system. At the same time, the LLS mechanism can introduce local spatial correlation, which makes it difficult to perform analytical calculation. Therefore, in this paper, we employ LLS for the stress redistribution in FBM with defect. By numerical simulation, we reveal the constitutive relationship, the critical stress, the max avalanche size, the avalanche size distribution and the step number of the external load increasing as a function of the defect size and the defect density.

2. The avalanche process of the FBM with defects in LLS

The FBM with defect in LLS case is constructed based on the one in GLS case [30]. The only difference is the stress redistribution form, i.e. the stress redistribution in this model is the local load sharing. At first, we assume that the model consists of N parallel fibers, all with an identical Young modulus $E_f = 1$ initially, which are arranged in parallel in one dimension. The fibers are generally assumed to crack irreversibly when the stress exceeds a certain threshold. The thresholds of each fiber are initially assumed to be σ_i, where $i = 1, 2, \ldots, N$. The thresholds σ_i of individual fibers are independent, identically distributed, random variable with a probability density p, and a cumulative probability distribution

$$P(\sigma_i) = \int_0^{\sigma_i} p(x)dx. \tag{1}$$

In the classical fiber bundle model and various extended fiber bundle models, the fracture thresholds of fibers are often assumed to conform to the uniform distribution or the Weibull distribution. The uniform distribution is undoubtedly the