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Simulation study on the avalanche process of the mixed brittle–plastic fiber bundle model

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HIGHLIGHTS

- The mixed brittle–plastic fiber bundle model in local load sharing is simulated.
- The impacts of plastic fibers on the fracture properties are investigated.
- The introduction of plastic fibers will hinder the brittle fracture process.

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ABSTRACT

The mixed brittle–plastic fiber bundle model is an extension model based on the classical fiber bundle model to describe the nonbrittle failure process of some hierarchical structure materials such as spider silk. In order to explore the breaking dynamic properties of the hierarchical structure materials in short-range correlation, the mixed brittle–plastic fiber bundle model in local load sharing condition is detailed and numerically studied. The impacts of the proportion of plastic fibers and the plastic strength of a single plastic fiber on the macroscopic constitutive behavior, the avalanche size distribution and the step number of the external load increasing are investigated, respectively. The numerical results show that the insert of plastic fibers will hinder the brittle fracture process; as a result, both the macroscopic mechanical natures and the statistical properties of fracture are significantly influenced.

1. Introduction

Due to the inherent nonuniformity and disorder in actual materials, the statistical physics approach is a popular theoretical way to investigate the macroscopic fracture properties and its microscopic mechanism in the physics community [1]. In theoretical work, most of the statistical investigations on the rupture of disordered materials rely on a so-called fiber bundle model (FBM), which was firstly introduced by Peirce in 1926 [2]. Although the algorithm of FBM is relatively simple, in most cases, the model can still correctly capture the collective static and dynamic properties of failure process [3,4].

The classical FBM is assumed to be a bundle of parallel elastic fibers, which will fail irreversibly when the load exceeds some threshold value. The stretching form of the bundle can be divided into two forms: the strain-controlled loading and the stress-controlled loading. To simulate the avalanche process of various materials, in the stress-controlled loading condition, the applied load increases quasi-statically, i.e. after each step of load increasing, only the weakest intact fiber will break. Then, the released load from the broken fiber will redistribute among the intact fibers following some redistribution mechanism. The most common one is the global load sharing (GLS), which means that all the intact fibers will averagely borne the

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released load. With a mean field approximation, the model can be solved analytically. On the other hand, the extreme case of the short-range interaction is the local load sharing (LLS) which reflects the stress concentration around the breaking fibers. In detail, the extra load released from the failing fibers is transferred to their nearest intact neighbors. Due to the nontrivial localized spatial correlation, the analytical solution of the LLS model becomes quite difficult [5]. The possible solution method is the numerical simulation. In addition, some intermediate load sharing forms, such as the power law redistribution rule, are also used to imitate the intricate stress redistribution in actual heterogeneous materials [6].

Utilizing FBM, the macroscopic mechanical properties and the statistical mechanism of fracture process can be well explained. On the macroscopic scale, the various stretching and fracture natures of actual materials can be described visually by the stress–strain relationship; at the same time, different fracture properties of materials can be intuitively divided into brittle, semi-brittle, plastic and so on. In the tensile fracture process, there exists a critical stress σ_c, after which the catastrophic failure of the whole system takes place. For statistical properties, the most important characteristic of the model is the avalanche size distribution, which can be monitored by acoustic emission technique in experiment [7–9]. In GLS case, the avalanche size distributions of various FBM with different fracture threshold distributions follow a power law relationship with a universal exponent $-5/2$ [10–12]. In LLS case, the avalanche size distributions show more complicated properties, depending on the specific fracture mechanism of a single fiber [13,14].

Based on the classical FBM, a series of deformation models have been introduced to better describe a wide range of composites. In the aspect of stress redistribution, 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], the continuous damage FBM with strong disorder [17], the FBM with stick–slip dynamics [18,19], and the multilinear FBM [20]. In addition, Some mixed FBM were also introduced to describe a lot of heterogeneous materials. For example, Divakaran et al. [21,22] 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 [23,24]; the other is the FBM with two different Weibull distributions whose threshold strength is randomly chosen from Weibull distributions with two different index parameters. On the other hand, Pradhan et al. [25] built a FBM with an interpolation form of stress redistribution and numerically simulated the crossover behavior between GLS and LLS. Recently, Biswas et al. [26] studied the crossover behavior by a heterogeneous load sharing fiber bundle model in one and two dimensions.

By constructing a plastic fiber, Raischel et al. [27] explained that the finite load baring capacity of broken fibers has a substantial effect on the failure process of the bundle of plastic fibers. Recently, Bosia et al. [28] 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. In GLS condition, the strength and specific energy absorption values were calculated and compared with the experimental observation results. Compared to GLS case, the other limit case i.e. the LLS can 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 impossible to perform analytical calculation. So in this paper, we employ LLS for the stress redistribution in the mixed brittle–plastic FBM. In theory, the model have two independent parameters, i.e. the ratio of plastic fibers α and the plastic elongation ε_p. Based on numerical simulation, we explore the constitutive behaviors, the critical stress, the maximum avalanche size, the avalanche size distribution, and the step number of the external load increasing as a function of the two parameters.

2. The avalanche process of the mixed brittle–plastic FBM in LLS

Referring to the research of the mixed brittle–plastic FBM in GLS case, in this paper, the specific arithmetic of the model in LLS case can be described as follows: the bundle consists of N parallel fibers, which are assembled on a one-dimensional lattice. The bundle is assumed to be composed of two subsets of fibers with obviously different breaking characters: a proportion α of fibers have a perfect plastic state after the linear elastic stage, while the remaining fibers of $1-\alpha$ fraction have normal brittle fracture property. The normal brittle fibers are considered to be linearly elastic until its brittle rupture with an identical Young modulus $E_f = 1$, but random failure thresholds $\sigma_i,\ i = 1, 2, \ldots, N$. The failure strength of individual fibers is an independent, identically distributed, random variable with a probability density p, and a cumulative probability distribution

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

In the following simulation it is instructive to consider two different strength distributions for the fracture thresholds, namely a uniform distribution between 0 and 1, and a Weibull distribution with the cumulative distribution function

$$P(\sigma) = 1 - \exp[-(\sigma/\lambda)^m] \tag{2}$$