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Development of a new constitutive model considering the shearing effect for anisotropic progressive damage in fiber-reinforced composites

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ABSTRACT

A corrected Linde's criterion considering the shearing effect for anisotropic progressive damage is developed to describe the elastic-brittle behavior of fiber-reinforced composites. Based on this criterion, a new three-dimensional (3D) nonlinear finite element model for static damage of unidirectional fiber-reinforced composites is proposed within a framework of continuum mechanics. The model is validated by taking 3D braided composites as example to study the relationship between the damage of materials and the effective elastic properties. The impregnated unidirectional composites are treated as homogeneous and transversely isotropic materials, whose properties are calculated by the Chamis' equations. The more accurate failure mechanisms of composites are revealed in the simulation process, and the effects of braided parameters on the uniaxial tensile behavior of 3D braided composites are investigated. Comparison of numerical results and experimental data is also carried out, which shows a better agreement than that of former study using the 3D Hashin's criterion.

1. Introduction

Fiber-reinforced composites have been widely used for load-bearing structures in many industries due to the advantages over conventional materials. Because of their benefits of mechanical performances, fiber-reinforced composites are particularly attractive for the aerospace industrial applications [1–4]. Damage in fiber-reinforced composites plays a significant role in the analysis of the mechanical properties of materials, which can never be entirely avoided. The progressive damage behavior of fiber-reinforced composites must be investigated to ensure the reliability of structures [5]. Therefore, it will be of great significance to develop an effective approach to assess the damage effect on the reduction of mechanical properties for fiber-reinforced composites.

Since the early work by Kachanov for creep rupture [6,7], many damage models have been developed within the framework of continuum mechanics and used to simulate material damage by multitudinous scholars [8–11]. For unidirectional fiber-reinforced composites, an assumption was made by Tsai [12] that the mathematical form of failure criterion of materials is the same as the yield criterion postulated by Hill [13]. Hoffman [14] proposed a phenomenological fracture condition for orthotropic brittle materials, which contained nine material parameters. And further the widely differing tensile and compressive strengths in various directions could be explained. Tsai and Wu [15] developed an operationally simple strength criterion for anisotropic materials from a scalar function of two strength tensors, which was an improvement over most existing quadratic approximations of the yield surface. Based on the Hashin's criteria [16,17], Matzenmiller et al. [18] proposed a damage model to describe the elastic-brittle behavior of fiber-reinforced composites. Five damage variables are utilized to control the reduction of elastic moduli in the damage model. Zhou et al. [19] formed a formal-unified 3D Hashin-type criterion, with shear nonlinearity considered in the stiffness matrix of unidirectional composites, to investigate the progressive damage behaviors of 2D plain weave composites under various uniaxial and biaxial loadings. Maimi et al. [20] proposed a continuum damage model for the fiber-reinforced plastic laminates to predict the damage onset and structural collapse of structures, which was established by LaRC04 criterion [21]. A set of internal

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variables is used to determine the reduction of elastic moduli. Linde et al. [22] developed a criterion for progressive damage of fiber metal laminates, which is based on a strain-based continuum damage formulation with different criteria for fiber and matrix failure, respectively. Recently, based on the Linde's criterion, the 3D damage evolution model is proposed to predict the mechanical properties of 3D braided composites [23,24]. However, since the contribution of shearing effect on the damage in the fiber direction is not considered in Linde's criterion, the results obtained are not consistent with the actual situation.

In this paper, we develop a corrected Linde's criterion considering the shearing effect for anisotropic progressive damage in fiber-reinforced composites subjected to tensile loads, and propose a new 3D nonlinear finite element model for static damage of unidirectional fiber-reinforced composites within the framework of continuum mechanics. Section 2 describes the failure mechanisms in fiber-reinforced composites. A viscous regularization scheme is utilized in Section 3 to improve the convergence of nonlinear numerical calculation in the softening regime. Section 4 gives the numerical implementation to solve the resulting system of nonlinear equations. Then the experimental data of two types of textile carbon fiber-reinforced composites are utilized to validate the proposed constitutive model. The effects of braided parameters on the uniaxial tensile behavior of 3D braided composites are also investigated in Section 5. The valuable conclusions are presented in Section 6.

2. Failure mechanisms in fiber-reinforced composites

2.1. Fiber/matrix failure in unidirectional composites

The damage plays a significant role in the analysis of the mechanical properties of fiber-reinforced composites. To investigate the relationship between the damage of materials and the effective elastic properties, a reasonable criterion should be established, which can describe the elastic-brittle behavior of fiber-reinforced composites.

The 2D failure criterion is firstly proposed by Linde [22] to simulate the damage failure behavior of fiber-metal laminates, which does not consider the contribution of shearing effect on the damage in the fiber direction. However, for the composites with complex meso-geometry structures, the influence of shearing effect on the damage in the fiber direction can't be ignored. In this study, based on a strain-based continuum damage formulation, a corrected Linde's criterion considering the shearing effect for anisotropic progressive damage is developed for fiber-reinforced composites. The corresponding relationships between the failure modes in unidirectional composites and the damage initiation criterions can be written as follows.

For the fiber damage initiation (considering the shearing effect):

$$f_f = \sqrt{\frac{\varepsilon_L^{f,t}}{\varepsilon_L^{f,c}}(\varepsilon_{11})^2 + \left(\varepsilon_L^{f,t} - \frac{\left(\varepsilon_L^{f,t}\right)^2}{\varepsilon_L^{f,c}}\right)\varepsilon_{11} + \left(\frac{\varepsilon_L^{f,t}}{\varepsilon_{LT}^{f,s}}\right)^2 (\varepsilon_{12'})^2} > \varepsilon_L^{f,t} \tag{1}$$

where $\varepsilon_L^{f,t} = \sigma_L^{f,t}/C_{11}$ and $\varepsilon_L^{f,c} = \sigma_L^{f,c}/C_{11}$ are the tensile and compressive failure strains in the fiber direction, respectively; The direction 1 (shown in Fig. 1) is along the fiber direction; $\varepsilon_{LT}^{f,s} = \sigma_{LT}^{f,s}/C_{44}$ is the failure strain for shear; $\sigma_L^{f,c}$ and $\sigma_L^{f,t}$ are the compressive and tensile strengths of unidirectional composites in the fiber direction, respectively; C_{11} and C_{44} are the moduli of unidirectional composites in the fiber direction and modulus of unidirectional composites for shear, respectively; $\sigma_{LT}^{f,s}$ is the shear strength of unidirectional composites.

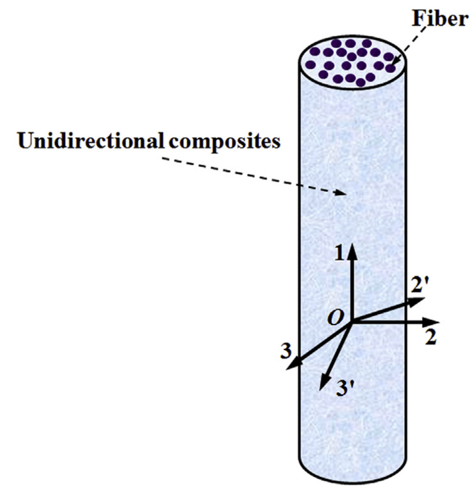

Fig. 1. The coordinate systems of a unidirectional composite.

For the damage initiation in matrix, the criterion is defined as:

$$f_m = \sqrt{\frac{\varepsilon_T^{f,t}}{\varepsilon_T^{f,c}}(\varepsilon_{2'2'})^2 + \left(\varepsilon_T^{f,t} - \frac{\left(\varepsilon_T^{f,t}\right)^2}{\varepsilon_T^{f,c}}\right)\varepsilon_{2'2'} + \left(\frac{\varepsilon_T^{f,t}}{\varepsilon_{LT}^{f,s}}\right)^2 (\varepsilon_{12'})^2} > \varepsilon_T^{f,t} \tag{2}$$

where $\varepsilon_T^{f,c} = \sigma_T^{f,c}/C_{22}$ and $\varepsilon_T^{f,t} = \sigma_T^{f,t}/C_{22}$ are the compressive and tensile failure strains perpendicular to the fiber direction, respectively; The direction 2′ (shown in Fig. 1) is a transverse direction; $\sigma_T^{f,c}$ and $\sigma_T^{f,t}$ are the compressive and tensile strengths of unidirectional composites perpendicular to the fiber direction, respectively; C_{22} is the modulus of unidirectional composites perpendicular to the fiber direction.

Here, it is assumed that the gradual degradation of material properties is under the control of the individual fracture energies of fiber and matrix, respectively. Once f_f exceeds its threshold value $\varepsilon_L^{f,t}$, the fiber damage occurs. A damage parameter, d_f, is introduced to describe the damage failure process of fiber:

$$d_f = 1 - \frac{\varepsilon_L^{f,t}}{f_f} e^{-C_{11}\varepsilon_L^{f,t}\left(f_f - \varepsilon_L^{f,t}\right)\frac{L^*}{G_f}} \tag{3}$$

where G_f is the fracture energy of fiber, and L^* is the characteristic length related to the elements.

To describe the damage failure process of matrix, a damage parameter, d_m, is defined as follows:

$$d_m = 1 - \frac{\varepsilon_T^{f,t}}{f_m} e^{-C_{22}\varepsilon_T^{f,t}\left(f_m - \varepsilon_T^{f,t}\right)\frac{L^*}{G_m}} \tag{4}$$

where G_m is the fracture energy of matrix.

Here, the properties of unidirectional composites are counted as transversely isotropic. The equivalent stiffness tensor of the undamaged unidirectional composites in the local-coordinate system $O-12'3'$ (as shown in Fig. 1) equals that in the coordinate system O-123, i.e.

$$C'_{ij} = C_{ij}, \quad (i,j = 1,2,\ldots 6) \tag{5}$$

After appearing of the damage initiation in composites, the damage gradually accumulates with loading increasing. The