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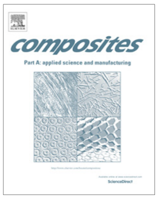

Compressive failure mechanism and strength of unidirectional thermoplastic composites based on modified kink band model

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ABSTRACT

A modified kink band model for compressive failure in fiber direction of fiber reinforced composite polymers was investigated and established in this study. Practically modifying the previous kink band model by logically applying a quadratic yield function combining transverse tensile and shear stress to the kinking instability, the modified model was able to determine the compressive strength along with the kink band failure angle theoretically. Especially in case of unidirectional carbon fiber reinforced thermoplastic composites, the compressive test procedure the authors have developed and its results revealed that the kink band failed in out-of-plane direction with each different inclined angle depending on temperature. From the correlation of the observed kink band failure angle and the evaluated compressive strength affected by temperature condition, the modified kink band failure formula was validated.

1. Introduction

Compressive failure mechanism of fiber reinforced composite polymers has been investigated by a lot of researchers, focusing on its variety and complexity of failure mode and considerably lower stress at failure than tensile. Above all, the compressive strength is almost independent of fiber tensile strength and frequently lower than expected. Such a problem requires attention for designing the reliability of materials and structures. The main failure mode under compressive loading is a shear buckling of fibers which is initiated by the fiber initial misalignment and depends a great deal on the matrix non-linearity [1–3]. Budiansky and Fleck [4], around the same time, established a kink band model which caused the shear buckling under compressive loading and derived a usable predicted formula for compressive strength based on Argon's [5] initial misalignment analysis. In the kink band model, the plastic shear properties including shear strain-hardening effect were actively utilized. In addition, the shear properties of fiber composites definitely have viscoelasticity, mainly affected by the matrix polymers. Schapery [6] derived a time dependent constitutive equation for shear stress-strain relationship and investigated creep failure time under constant compressive loading based on the kink band model.

The authors also focused on the polymer's viscosity and verified the temperature dependent compressive strength in fiber direction of carbon fiber reinforced polypropylene [7]. In the previous study, it was concluded that the kink band model by Budiansky and Fleck [4] could explain well the correlation between the temperature dependent compressive strength of thermoplastic composites and the viscoelastic plasticity of the polymers, by experimentally obtaining the elastic and plastic parameters of fiber-directional shear behavior at every designated temperature ranging from −30 °C to 80 °C. Through this verification, the fiber initial misalignment angle was detected by X-ray CT and defined as similar at every temperature.

However, even though it was found to be far from negligible that the kink band angle affects the compressive strength a lot as estimated by Budiansky [8], the kink band model the authors validated for temperature dependence was not able to predict different kink band angle depending on temperature. For an applicable determination of axial compressive strength of fiber composites, the kink band failure angle is strongly required to be predicted precisely, not detected as a result of compressive test.

In the other previous studies, several analyses and explanations for the kinking process and finally formed kink band angle at compressive failure were done before. Budiansky [8] indicated an equation predicting a range of the kink band angle depending on the wavelength of the assumed fiber initial imperfection. But, the proposed equation used the compressive strength in itself, so the assumption never derived a formula for quantifying kink band

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angle directly. The proposed model by Steif [9,10], making the connection between a fiber-tensile-breaking strain and a kink band formation, could not predict the kink band angle corresponding to the experimental results. Vogler and Kyriakides [11,12] observed kink band propagation and rotation of fibers in the band by a special shear and compressive loading experimental set-up, but could not demonstrate the failure phenomena under pure compression due to the presence of the shear stress by the proposed test set-up. Moran et al. [13] introduced a model predicting the compressive peak stress right after incipient kinking under steady-state conditions on which the width of kink band was broadening with the volume preserved. But, this model had a limited usability because the steady-state behavior was not always observed, especially never appeared in case of un-notched pure compressive test specimen as represented by the authors' previous test results [7].

This study focused on not how the kink band is propagated and inclined under compression loading but why the shear buckling breaks out at that very kinking angle. That mechanism could explain what the compressive failure stress is. Intrinsically, when the kink band angle is increased, the transverse tensile stress in the band is increased even though the shear stress stays unchanged, as expressed in a kink band kinematic equation constructed by Budiansky and Fleck [4].

From the other perspective, Hashin and Rotem [14] proposed a quadratic combined-stress function of transverse tension and shear as a failure criterion for fiber reinforced anisotropic materials and validated the criterion by experiments of off-axis lamina. Brewer and Lagace [15] applied the same failure criterion to examining the initiation of delamination of fiber reinforced laminates. Both researches proved that the proposed simple failure criterion (one for in-plane, the other for out-of-plane) was an excellent agreement with the failure behavior dominated by transverse tension and shear. After their accomplishments, many researchers verified the applicability of their quadratic stress functions, for example as referred by [16–18].

So, this study presumed that the kink band failure was developed by transverse tensile failure as well as shear yield and plastic deformation. Actually, the previous kink band model by Budiansky and Fleck [4] used a combined-stress yield condition considering transverse tension and shear for deriving an effective shear stress and substituted it into the predicted formula for compressive strength. But through their calculated presumption, for details, at the step when assuming that the square of the ratio of transverse tensile yield stress to shear yield stress was constantly equal to the ratio of their elastic moduli, transverse tensile to shear, the quadratic combined-stress criterion had no meaning in their constructed formula, which not emphasizing that the transverse tensile failure stress was a key factor for kink band failure.

Such an impractical assumption was taken off in this study. And instead of that, a different kinking failure mechanism was devised, taking advantages of the quadratic combined-stress function. The main concept of the mechanism is that the kink band inclining followed by an increment of the transverse tensile stress is simply bound by the transverse tensile allowable stress on the yield ellipse formulated by the quadratic combined-stress function. Not adopting an effective stress by combining transverse tensile stress with shear stress, the yield ellipse is expanded by the plastic straining in the kink band. Here, the most remarkable different point is that the limited kinking angle is mainly defined by the transverse tensile bounded stress. As a fact supporting this point, the fiber-directional shear stress-strain curve examined in the authors' previous study indicated no breaking along with a stress drop even at much extension after yield [7]. On the other hand, it is easy to imagine that the pure transverse tensile breaking occurs at considerably smaller strain than the pure shear failure, whether or not using thermoplastic matrix. So, the idea that the kinking failure angle is dominated by the transverse tensile failure rather than the shear failure is reasonable.

From this mechanical insight, the authors proposed a theoretical model determining the finally-formed kink band angle as a function of parameters obtained from transverse tensile tests and fiber-directional shear tests. That model was introduced to the conventional kink band model and the predicted formula for axial compressive strength was modified. And through experimental verification including axial compressive test, it was validated whether the prediction by the modified kink band model agreed well with the actual measured compressive strength and the observed kink band angle on any temperature condition.

2. Theoretical analysis

2.1. Kink band failure model

In this section, even referring to the previous kink band model and analysis [4], a slightly different approach deriving a predicted formula for the compressive strength is explained. Here, it is not necessary to use a combined-stress function for an effective stress related to transverse tension and shear, because the compressive failure caused by the shear buckling in the kink band could be derived only from instability of the kinking equilibrium. The approach is described as below.

Based on the kink band model shown in Fig. 1, the kinking equilibrium is expressed by the following equation [4]:

$$\sigma^{\infty} = \frac{\tau + \sigma_T \cdot \tan\beta}{\gamma + \phi_0}. \tag{1}$$

Here, the symbols represent externally applied compressive stress as σ^{∞}, initial misalignment angle of fibers as ϕ_0, additional shear strain followed by the kink band rotation as γ, shear stress and transverse tensile stress in the kink band as τ and σ_T, and the kink band angle as β, respectively.

Additionally, the kinking kinematics, introducing the strain rate tensor in the band, derives the following simple relationship for plastic strain as well as elastic strain, for details, referring to [4]:

$$e_T = \gamma \cdot \tan\beta. \tag{2}$$

Here, e_T is the transverse tensile strain. As far as elastic deformation, applying the relations that $\sigma_T = E_T \cdot e_T$ and $\tau = G \cdot \gamma$, where E_T is the transverse tensile elastic modulus and G is the shear elastic modulus in fiber direction, Eq. (2) can be transformed into the following equation:

$$\frac{\sigma_T}{\tau} = \frac{E_T}{G} \cdot \tan\beta. \tag{3}$$

This relationship can be expanded homogeneously to the plastic strain region, assuming that both of transverse tension and shear are influenced mainly by the matrix elasto-plasticity based on

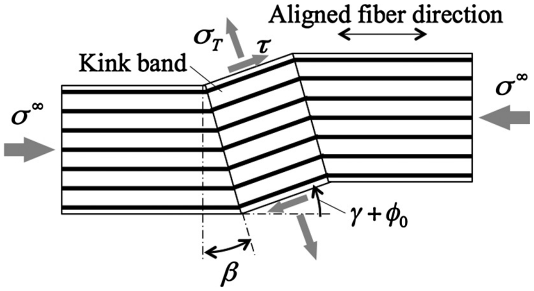

Fig. 1. Kink band model.