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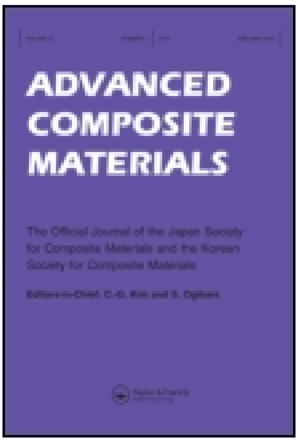

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Characterization of nonlinear behavior of carbon/epoxy unidirectional and angle-ply laminates

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Abstract—Nonlinear mechanical behavior of carbon/epoxy unidirectional and angle-ply laminates under uniaxial tensile loading is investigated experimentally. The generalized method of cells is applied to predict the nonlinear stress–strain relation of the unidirectional laminates under off-axis tensile loading. The one-parameter plasticity model is also used to characterize the nonlinear behavior of the unidirectional laminates. The mechanical behavior of the angle-ply laminates is predicted by using the one-parameter plasticity model of the unidirectional laminates.

Keywords: Carbon/epoxy; nonlinear stress–strain relation; plasticity; unidirectional laminate; angle-ply laminate.

1. INTRODUCTION

It is well known that fiber reinforced plastics exhibit nonlinear stress–strain response under off-axis loading. Nonlinear behavior of composites has been modeled by two approaches, i.e. macroscopic and microscopic. In the macroscopic approach, composites are considered as a homogeneous nonlinear elastic or plastic body. In the microscopic approach, attempts are made to describe the effective composite response using the properties of the fiber and matrix.

Hahn and Tsai [1] employed a complementary elastic energy density function which contained a biquadratic term for in-plane shear stress. The nonlinear stress–strain relation of unidirectional laminae under off-axis loading was pre-

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dicted. Sun and Chen [2] developed a one-parameter plasticity model to describe the nonlinear behavior of unidirectional composites based on a more general approach [3]. The approach is based on a quadratic plastic potential and the assumption that there is no plastic deformation in the fiber direction. Ogi and Takeda [4] proposed a model based on a fourth-order complementary elastic energy function and the one-parameter plastic potential in which an anisotropy parameter changes with plastic deformation. Tamuzs *et al.* [5] applied the Sun and Chen one-parameter plasticity model to the deformation of a composite with complex microstructure and found that the nonlinear response of the composite under creep and cyclic loading follow the associated flow rule with the one-parameter plastic potential function.

Aboudi [6, 7] constructed a cell model where fibers have rectangular cross-section. For resin matrix composites, a Ramberg-Osgood representation was employed for matrix nonlinear elasticity. Paley and Aboudi [8] developed the generalized method of cells (GMC) where an arbitrary number of cells can be used to model a composite unit cell. Pindera and Bednarcyk [9, 10] further reformulated the GMC to minimize computational effort. Dvorak and Bahei-el-Din developed a method to describe the elastic–plastic behavior of unidirectional composites [11] and multidirectional laminates [12] consisting of aligned, continuous elastic fibers and an elastic–plastic matrix. The composite is modeled as a continuum reinforced by cylindrical fibers of vanishingly small diameter which occupy a finite volume fraction of the aggregate. Sun and Chen [13, 14] developed a simple micromechanical model of elastic–plastic behavior of fibrous composites. In the model, the fiber is assumed to be linearly elastic and the matrix elastic–plastic following the J_2-flow rule. The micromechanical model is used to calculate stress–strain curves for off-axis boron/aluminum composites. These curves are used, in turn, to model a macromechanical orthotropic plasticity response [15].

In the present study, nonlinear mechanical behavior of carbon/epoxy unidirectional and angle-ply laminates under uniaxial tensile loading is investigated experimentally. The validity of the generalized method of cells for predicting the nonlinear stress–strain relation of the unidirectional laminates under off-axis tensile loading is discussed. The one-parameter plasticity model is applied to characterize the nonlinear behavior of the unidirectional laminates and to predict the stress–strain relation of angle-ply laminates.

2. EXPERIMENTAL PROCEDURE

The material system used is a T700S/2500 carbon/epoxy composite. The properties of T700S carbon fiber from the data sheet are listed in Table 1. The 2500 epoxy system is a 120°C cure conventional epoxy resin. Unidirectional (4 plies) and angle-ply ([$\pm\theta$]s) panels were fabricated by following the manufacturer's recommended cure cycle.

The unidirectional specimens were cut from the unidirectional panels. 0°, 15°, 30°, 45°, 60° and 90° specimens were prepared. The angle-ply panels, [$\pm\theta$]s,

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Table 1.
Mechanical properties of T700S carbon fiber

Young's modulus (GPa)	Tensile strength (GPa)	Failure strain (%)
230	4.9	2.1

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where $\theta = 15^\circ$, 30°, 45° and 60°, were also fabricated, from which the angle-ply specimens were cut. The specimen size for both unidirectional and angle-ply laminates was 150 mm long, 10 mm wide and 0.52 mm thick. 25 mm long GFRP tabs were glued on both ends of the specimens, which results in the specimen gage length of 100 mm. The fiber volume fraction for the composite was about 0.55. Resin specimens were also prepared. The size of the resin specimens was 100 mm long, 10 mm wide and 2.0 mm thick. No tabs were used for resin specimens and the grip length was 20 mm for each end so that the specimen gage length was 60 mm.

Tensile tests were performed on the unidirectional, angle-ply laminates and resin specimens at room temperature. The crosshead speed was 0.5 mm/min. The strain data was obtained by averaging the data from the strain gages attached on both sides of the specimens. At least three specimens were tested for each condition.

3. ANALYSIS

3.1. Generalized method of cells

The method of cells is a micromechanical model originally developed by Aboudi [6, 7]. The two-dimensional version of the generalized method of cells (GMC) was developed by Paley and Aboudi [8] to introduce an arbitrary number of subcells in a unit cell. A continuously reinforced composite is modeled as a periodic assemblage of the unit cells. The unit cell is divided into subcells, which are either fiber or matrix phase. Recently, Pindera and Bednarcyk [9, 10] reformulated the GMC to minimize computational effort. In this study, the reformulated version of the GMC is used to predict the mechanical behavior of unidirectional laminate under off-axis tension.

For the GMC analysis in this study, the fiber is assumed to be a transversely isotropic elastic material. The matrix is assumed to be a elastic–plastic material which obeys J_2-flow rule. The power-law type equivalent stress-equivalent plastic strain relation is assumed rather than the bilinear hardening relation because we did not observe a clear yield point in the tensile tests on resin. The classical incremental plasticity theory, reformulated in terms of strains, is employed in conjunction with Mendelson's iterative technique of successive approximations to calculate the subcell plastic strains at each load increment [16].

3.2. One-parameter plasticity model

The one-parameter plasticity model was developed by Sun and Chen [2] to model the nonlinear mechanical behavior of unidirectionally reinforced composite materials. Starting with a general 3-dimensional yield function, simplification is made by assuming that there is no plastic deformation in the fiber direction, which results in the yield function as

$$2f = \sigma_{22}^2 + 2a_{66}\sigma_{12}^2, \tag{1}$$

where a_{66} is a plastic parameter which should be determined from experiments. The parameter is chosen so that the effective stress-effective plastic strain curves from various off-axis tension data reduce to a single master curve. In this study, the one-parameter plasticity model is used to characterize the nonlinear behavior of the T700S/2500 carbon/epoxy unidirectional laminate. An attempt is made to predict the stress–strain behavior of the angle-ply laminates based on the one-parameter plasticity model of the unidirectional laminate.

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4. RESULTS AND DISCUSSION

Figure 1 shows the typical stress–strain curves for (a) unidirectional (0°, 15° and 30° specimens), (b) unidirectional (45°, 60° and 90° specimens), (c) angle-ply laminates ±15° and ±30° specimens), (d) angle-ply laminates ±45° and ±60° specimens) and (e) resin specimens. In the unidirectional laminates, the stress–strain relation is almost linear for 0° specimens. All the off-axis specimens and 90° specimens exhibit nonlinear stress–strain behavior. In the angle-ply laminates, only ±15° specimens show an almost linear relation between stress and strain. The ±45° specimens exhibit very high nonlinearity and large failure strain. The resin specimens show small nonlinearity as shown in Fig. 1e. To use this stress–strain relation in GMC as the effective stress-effective plastic strain curve, the data is fit by a power-law type relation as

$$\bar{\varepsilon}_m^p = \beta \bar{\sigma}_m^r, \tag{2}$$

where $\bar{\varepsilon}_m^p$ is effective plastic strain, $\bar{\sigma}_m$ is effective stress, β and r are material constants. The solid line in Fig. 1e is a fitting curve which uses the values of $\beta = 9.0 \times 10^{-9}$ (MPa^{-r}) and $r = 3.15$. As will be mentioned below, the GMC prediction of the stress–strain behavior of the unidirectional laminate under off-axis loading shows more enhanced nonlinearity than the experimental results when using these 'fit' values. An attempt is made to fit the experimentally obtained unidirectional laminate data by using modified parameters for the resin properties. The trial values are $\beta = 2.0 \times 10^{-9}$ (MPa^{-r}) and $r = 3.0$, which result in the resin properties as shown by the dotted line (denoted as 'modified') in Fig. 1e. This dotted line looks linear in this stress/strain range, but it exhibits nonlinearity at

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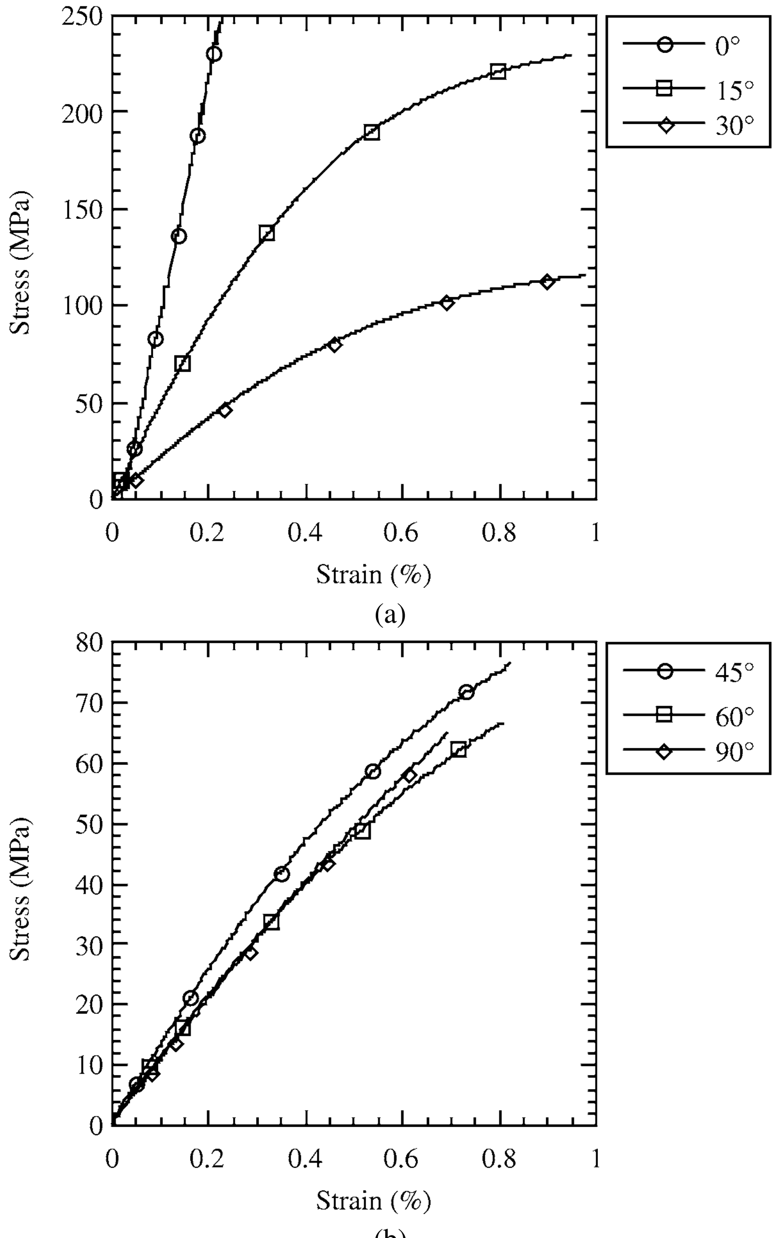
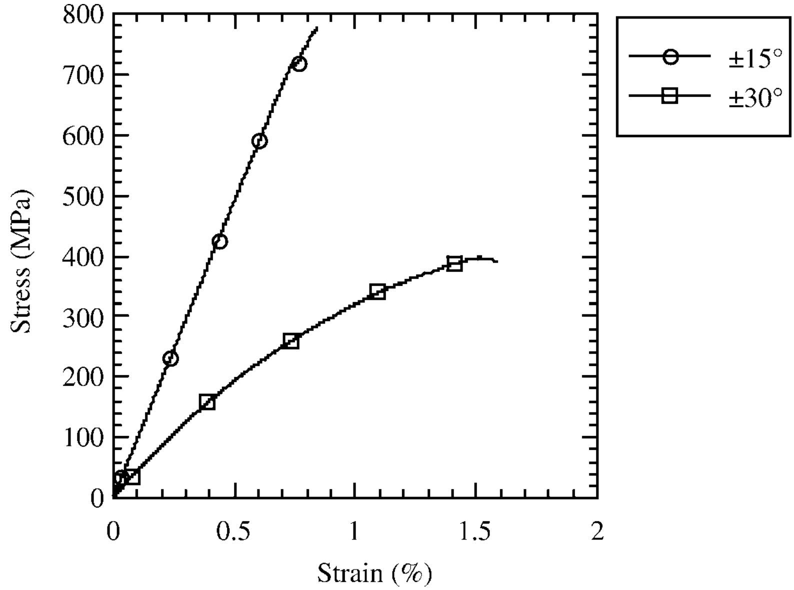
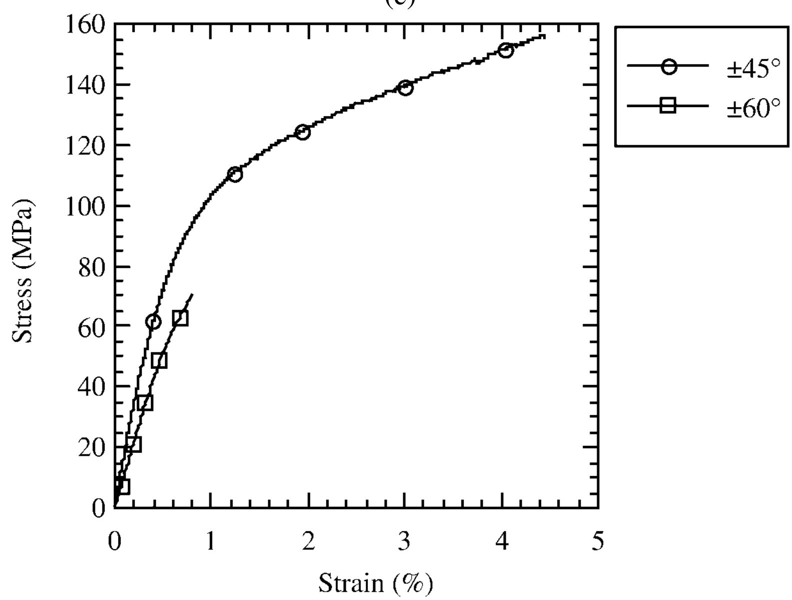


Figure 1. Typical stress-strain curves for (a) unidirectional laminates (0°, 15° and 30°), (b) unidirectional laminates (45°, 60° and 90°), (c) angle-ply laminates (±15° and ±30°), (d) angle-ply laminates (±45° and ±60°) and (e) resin with fitting curves.



(c)



(d)

Figure 1. (Continued).

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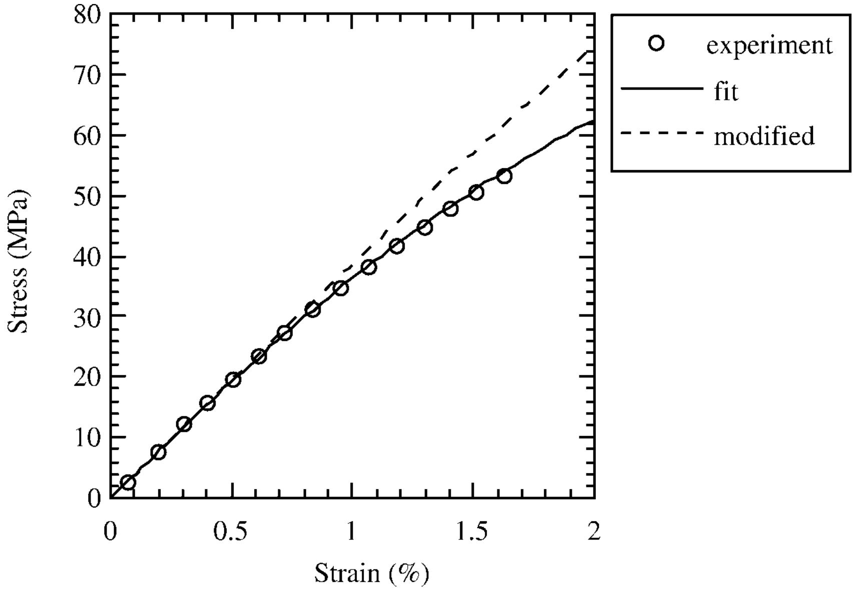
higher stress–strain levels, although it cannot be confirmed by experiments on the neat resin.

Figure 2 shows the unit cell geometries used in the GMC analysis of this study. Two cases of unit cell geometry are considered. One uses 4 $\times$ 4 subcells as shown



(e)

Figure 1. (Continued).

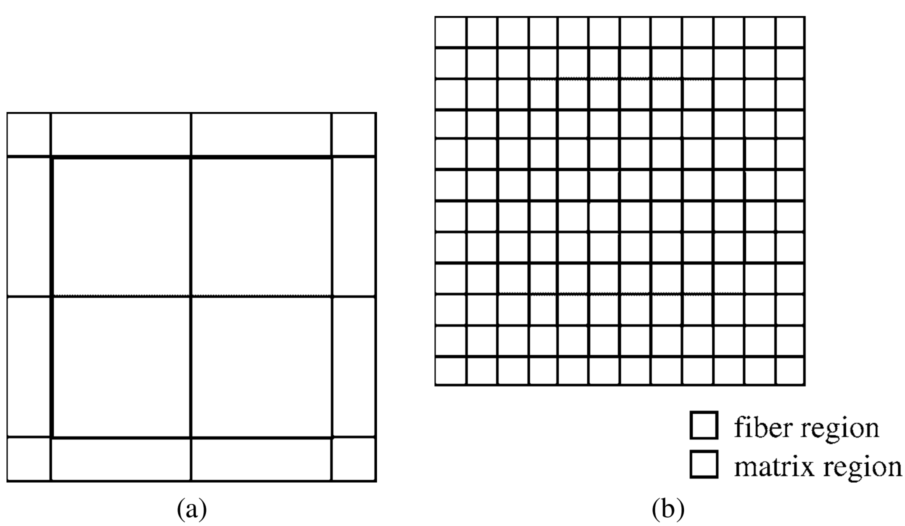


Figure 2. GMC unit cell geometry (fiber volume fraction is 55%) (a) 4 × 4 subcells, (b) 12 × 12 subcells.

in Fig. 2a and another 12 × 12 as shown in Fig. 2b. The fiber volume fraction is 0.55 for each geometry. It should be noted that both geometries assume the square fiber array. The material properties used in the GMC analysis are listed in Table 2. The fiber is assumed to be a transversely isotropic material. The matrix is assumed to be a isotropic elastic–plastic material whose effective stress-

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Table 2.
Material properties used in GMC micromechanics

	Fiber	Matrix
E_A (GPa)	230	3.90
E_T (GPa)	25	3.90
G_A (GPa)	30	1.40
G_T (GPa)	9.3	1.40
ν_A	0.2	0.39
ν_T	0.35	0.39
β (fit) (MPa^{-r})	—	9.0×10^{-9}
r (fit)	—	3.15
β (modified) (MPa^{-r})	—	2.0×10^{-9}
r (modified)	—	3.0

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effective plastic strain relation is expressed by equation (2). For the fiber, the only available data is the axial Young's modulus, E_A, and the other values are assumed to fit the initial linear part of the experimentally obtained stress–strain relations of the unidirectional laminates. Figure 3 shows the comparison between the experimental results and GMC predictions of the stress–strain relations of unidirectional laminates under uniaxial tensile loading ((a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60° and (f) 90° specimens). The initial slope of the stress–strain curve is well fitted by the GMC micromechanics by using the assumed fiber properties. When using the plastic parameters which fit well the resin tension data, the GMC predicts more enhanced nonlinearity of stress–strain relations of the unidirectional laminates than the experimental results. A similar difficulty in predicting the unidirectional composite behavior using the experimentally obtained matrix properties is also encountered by Sun and Chen [13]. This is not improved very much by using larger number of subcells in a unit cell. Instead, by using the modified values for the resin plastic parameters, the agreement is better, but there is still some discrepancy at the higher stress–strain levels which are near to the final fracture of the specimens. In these regions, we can expect damage, such as fiber–matrix interfacial debonding, matrix cracking and fiber breaks, which are not considered in the present analysis. Considering the uncertainty of the fiber properties and damage at higher stress–strain levels, the GMC prediction gives a generally good correlation with the experimental results with 'modified' matrix properties, which implies that there is a possibility that GMC will be a useful tool for predicting the stress–strain behavior of unidirectional laminates. With the 'modified' matrix properties, it will be possible to do parametric studies of composite behavior for different fibers. At the present stage, we do not have a clear answer to the problem why the 'fit' parameters cannot explain the nonlinear behavior of unidirectional composite. To explain this, further studies involving detailed observation of microscopic deformation may be necessary.

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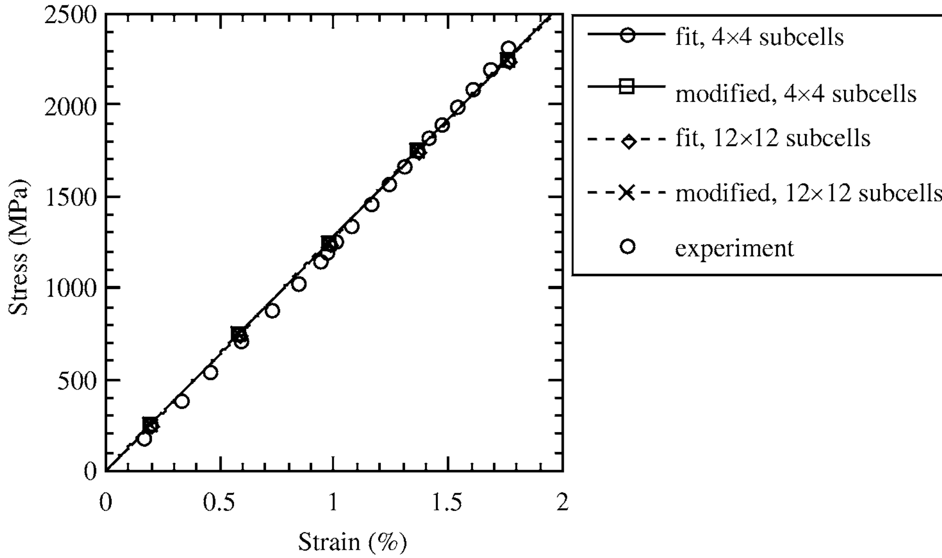
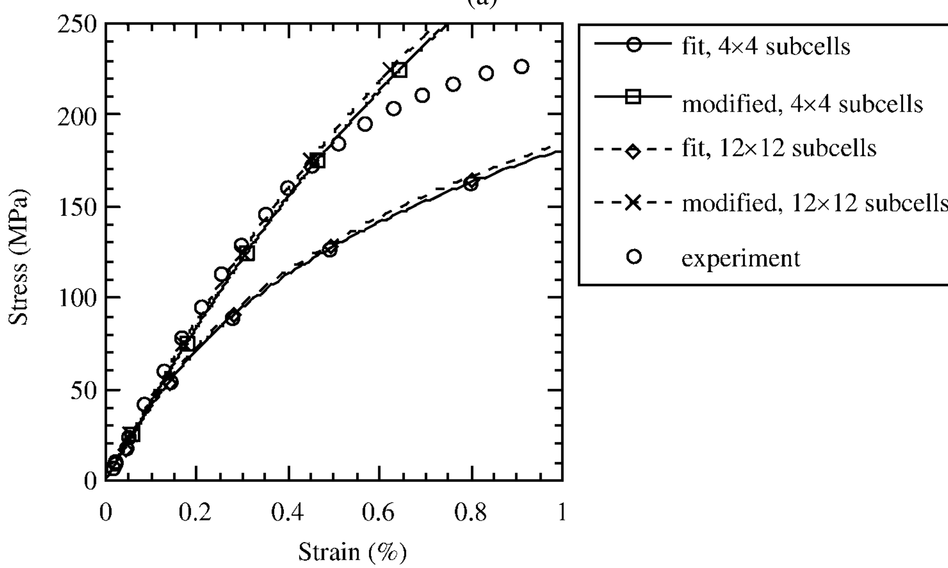


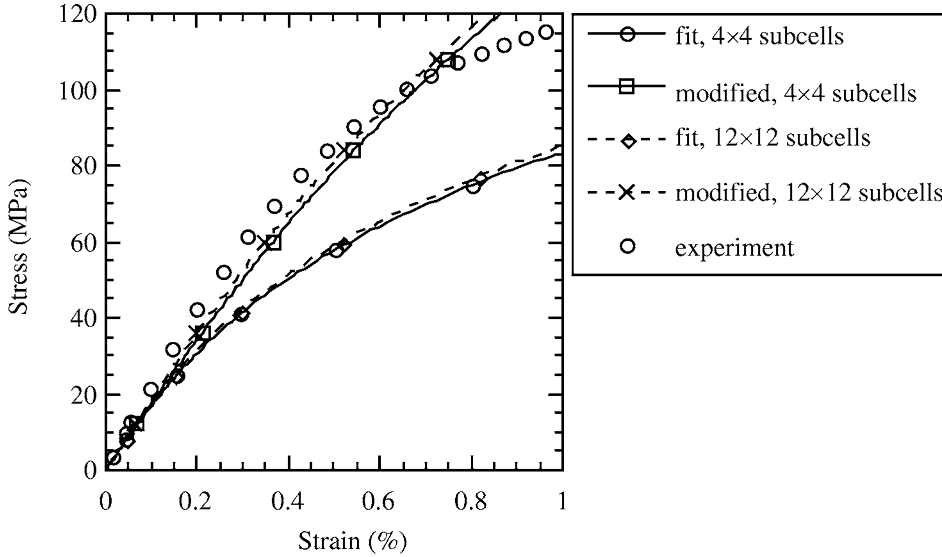
(a)



(b)

Figure 3. Comparison between the experimental results and the GMC analytical predictions of the stress–strain curves for the unidirectional laminates ((a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60° and (f) 90°).

In the present study, the one-parameter plasticity model is also used to characterize the unidirectional stress–strain behavior. It is assumed that the total strain at a certain stress level is decomposed into a linear elastic part and nonlinear part and that the nonlinear part is plastic strain. The linear elastic part is calculated by



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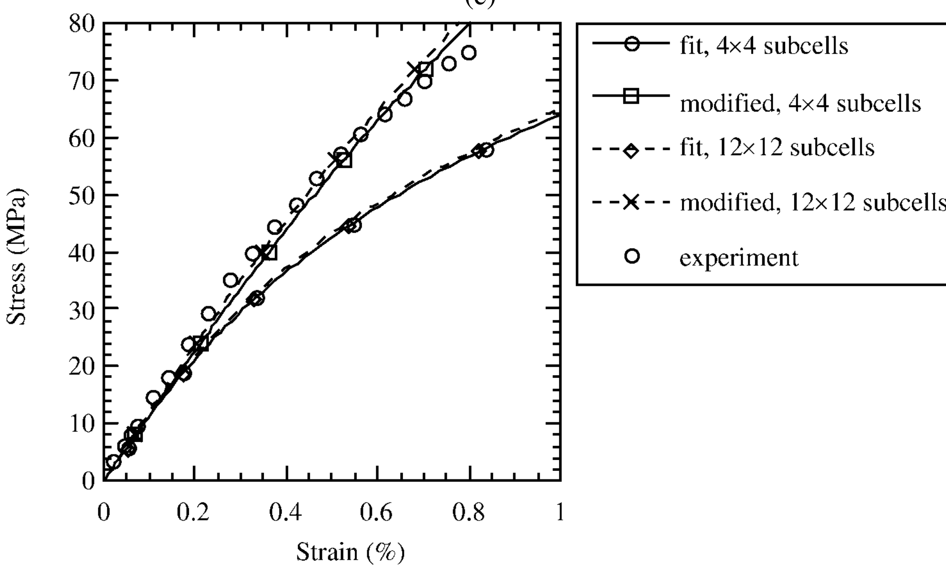

(d)

Figure 3. (Continued).

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dividing the stress by the initial Young's modulus of the laminate. By subtracting the linear elastic part from the total strain, the relation between the stress and the plastic strain is obtained, as shown in Fig. 4a. In the one-parameter plasticity analysis, the curves are converted to effective stress-effective plastic strain curves using

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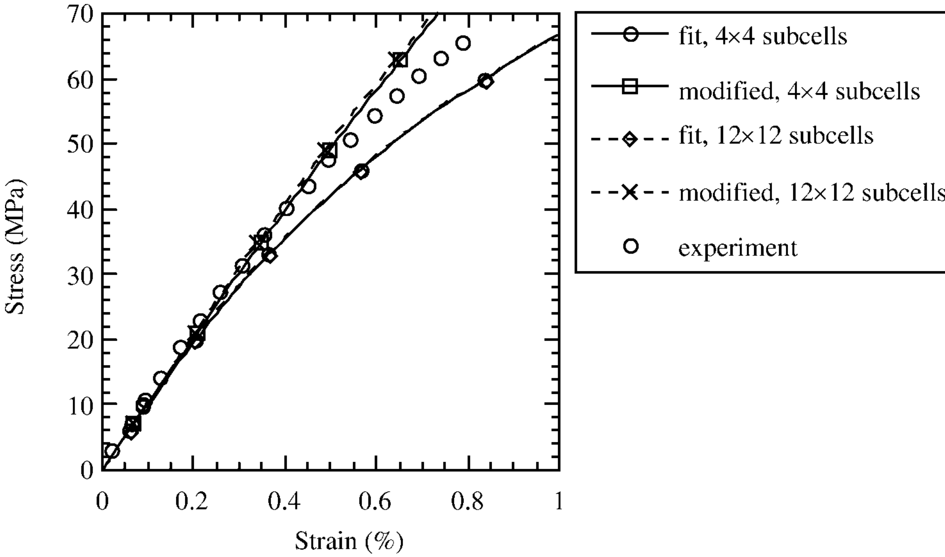
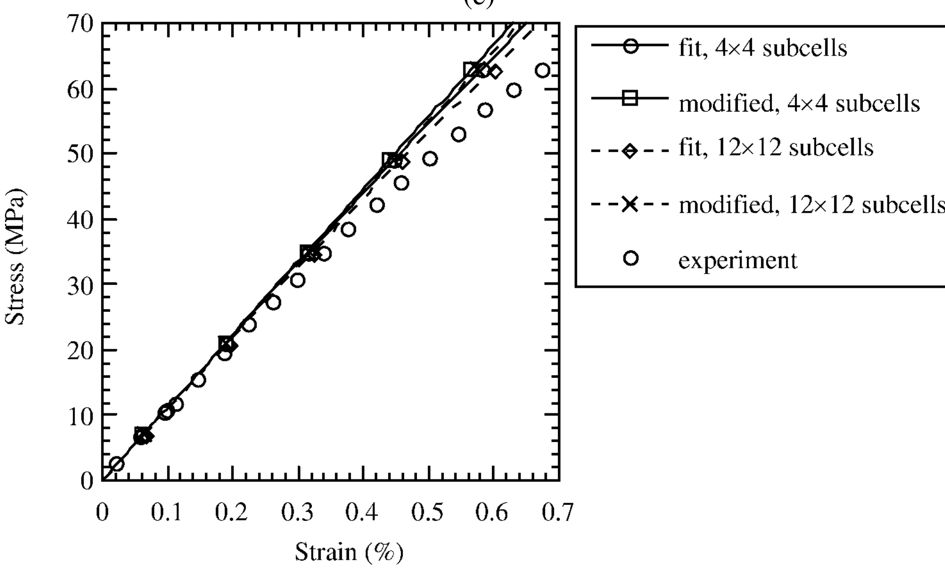


(e)



(f)

Figure 3. (Continued).

an assumed value of the parameter a_{66}. The following relations are used.

$$\left.\begin{aligned} \bar{\sigma} &= h(\theta)\sigma_x \\ \bar{\varepsilon}^p &= \varepsilon_x^p / h(\theta) \\ h(\theta) &= \left\{\frac{3}{2}\left(\sin^4\theta + 2a_{66}\sin^2\theta\cos^4\theta\right)\right\}^{1/2} \end{aligned}\right\}, \tag{3}$$

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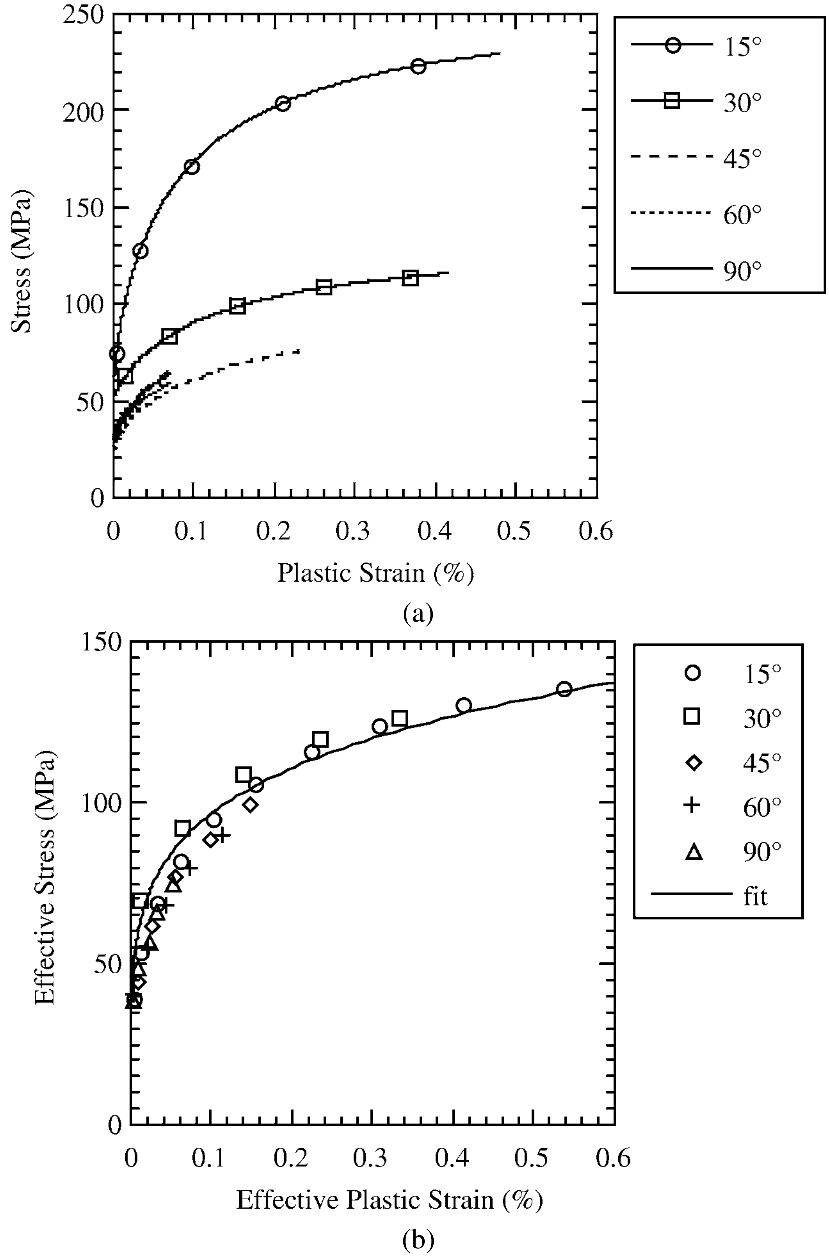

Figure 4. Relations between (a) stress and plastic strain and between (b) effective stress and effective plastic strain using $a_{66} = 2.0$ with fitting curve, for T700S/2500 unidirectional laminates.

where σ_x is the uniaxial stress in the tensile direction, ε_x^p is the plastic strain in the tensile direction and θ is the off-axis fiber angle. Our task is to find the value of a_{66} that makes the curves of various off-axis data gather on a master curve. We obtain a value of $a_{66} = 2.0$ and resulting master curve is shown in Fig. 4b. The master curve

Table 3.
Elastic properties and one-parameter plasticity parameters for T700S/2500 unidirectional composite

E_1 (GPa)	121
E_2 (GPa)	10.4
ν_{12}	0.31
G_{12} (GPa)	4.80
a_{66}	2.0
α (MPa^{-n})	7.5×10^{-14}
n	5.1

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is fitted in the form

$$\bar{\varepsilon}^p = \alpha \bar{\sigma}^n, \tag{4}$$

where α and n are constants. The values we obtained are $\alpha = 7.5 \times 10^{-14}$ (MPa^{-n}) and $n = 5.1$. The experimentally obtained mechanical properties of the T700S/2500 carbon/epoxy unidirectional laminate are summarized in Table 3. By using these data we can predict the stress–strain curve at any off-axis angle.

In this paper, an attempt is made to predict the nonlinear behavior of angle-ply laminates under an assumption that the nonlinear behavior of the unidirectional composite is known, that is, the nonlinear behavior of unidirectional laminate can be described by the Sun and Chen one-parameter plasticity model. We perform a classical lamination analysis using the one-parameter plasticity model.

The total strain increments are assumed to be the sum of the elastic strain increments and the plastic strain increments. The elastic strain increments obey the orthotropic stress–strain relations. The total incremental stress–strain relations for the elastic–plastic composite can be expressed in the form

$$\begin{Bmatrix} d\varepsilon_{11} \\ d\varepsilon_{22} \\ d\gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{16} \\ S_{21} & S_{22} & S_{26} \\ S_{61} & S_{62} & S_{66} \end{bmatrix} \begin{Bmatrix} d\sigma_{11} \\ d\sigma_{22} \\ d\sigma_{12} \end{Bmatrix}, \tag{5}$$

where

$$\left.\begin{aligned} S_{11} &= \frac{1}{E_1}, \quad S_{12} = S_{21} = -\frac{\nu_{12}}{E_1} \\ S_{16} &= S_{61} = 0, \quad S_{22} = \frac{1}{E_2} + \Omega\sigma_{22}^2 \\ S_{26} &= S_{62} = 2a_{66}\Omega\sigma_{12}\sigma_{22} \\ S_{66} &= \frac{1}{G_{12}} + 4a_{66}^2\Omega\sigma_{12}^2 \\ \Omega &= \frac{4}{9}\alpha n \bar{\sigma}^{n-3} \end{aligned}\right\}. \tag{6}$$

Now a multidirectional laminate under in-plane loading is considered. The total incremental stress–strain relations for the kth lamina in the laminate can be expressed in the form (from (5)) in the material (local) coordinate system

$$\{d\varepsilon^k\} = [S(\sigma^k)]\{d\sigma^k\}, \tag{7}$$

where superscript k denotes kth lamina. In the global coordinate system,

$$\{d\tilde{\varepsilon}^k\} = [\tilde{S}(\sigma^k)]\{d\tilde{\sigma}^k\}, \tag{8}$$

where

$$\left.\begin{aligned} \{d\varepsilon^k\} &= [T_\varepsilon]\{d\tilde{\varepsilon}^k\} \\ \{d\sigma^k\} &= [T_\sigma]\{d\tilde{\sigma}^k\} \\ [\tilde{S}(\sigma^k)] &= [T_\varepsilon]^{-1}[S(\sigma^k)][T_\sigma] \end{aligned}\right\}, \tag{9}$$

$[T_\sigma]$ and $[T_\varepsilon]$ are coordinate transformation matrix for stress and strain, respectively. The relations between laminate stress and strain and the ply stress and strain in the global coordinate system are

$$\{\varepsilon^{LAM}\} = \{\tilde{\varepsilon}^k\}, \tag{10}$$

$$\{\sigma^{LAM}\} = \frac{\Sigma t_k\{\tilde{\sigma}^k\}}{\Sigma t_k}, \tag{11}$$

where the superscript *LAM* represents the multidirectional laminate and t_k is the thickness of the kth ply. Considering the above relations, the stress–strain behavior of a multidirectional laminate under in-plane loading can be obtained in a step by step manner.

Figure 5 shows the comparison between the experimental results and the analytical predictions for stress–strain curves of the angle-ply laminates. A good agreement is obtained which implies the validity of the combination of the one-parameter plasticity model and the classical lamination theory. It may be possible to predict the stress–strain behavior of general multidirectional laminates by using the one-parameter plasticity model.

5. CONCLUSION

Nonlinear mechanical behavior of carbon/epoxy unidirectional and angle-ply laminates under uniaxial tensile loading is investigated experimentally. With the generalized method of cells, the nonlinear stress–strain relation of the unidirectional laminates under off-axis tensile loading can be predicted reasonably well with 'modified' matrix properties. The one-parameter plasticity model is also used to characterize the nonlinear behavior of the unidirectional laminates. By combining the one-parameter plasticity model with the classical lamination theory, the mechanical behavior of the angle-ply laminates is predicted and good agreement with the

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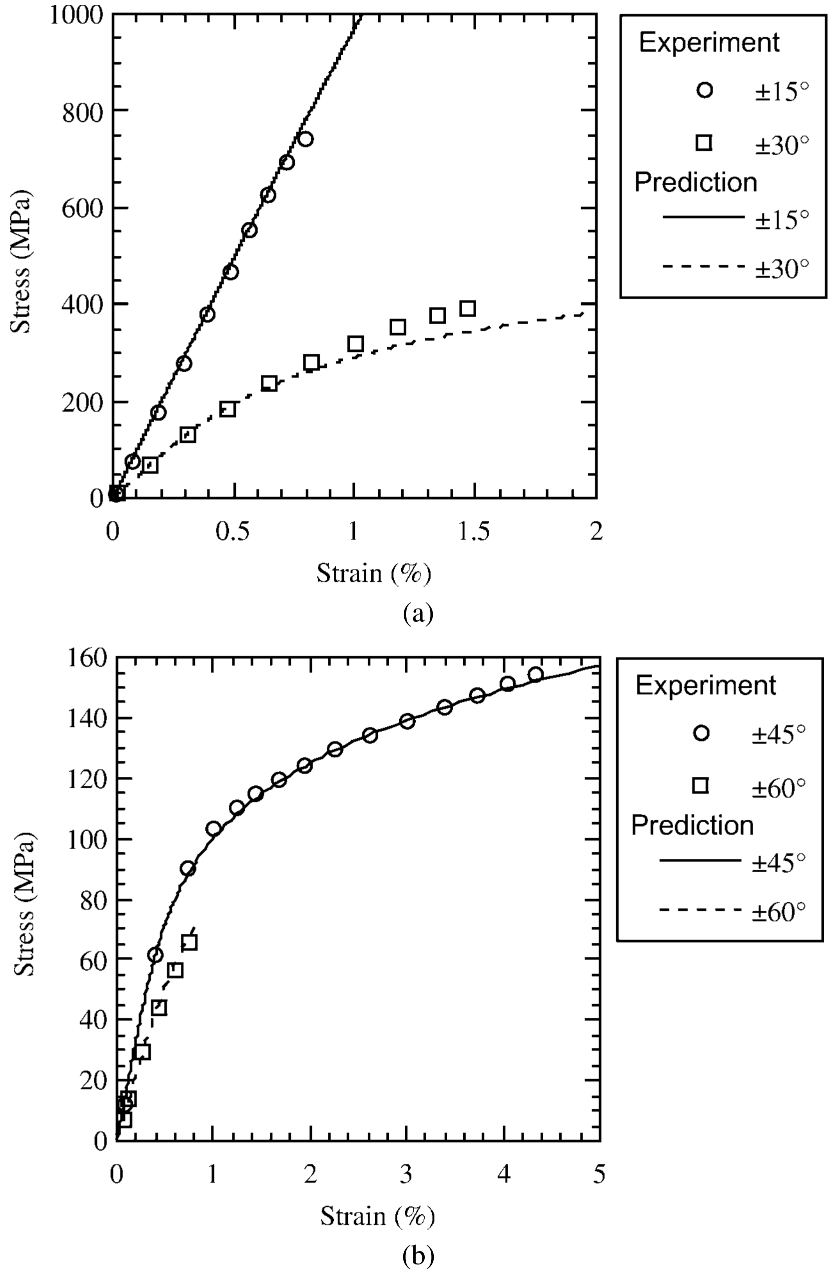

Figure 5. Comparison between the experimental results and the analytical prediction using the classical lamination theory and the one-parameter plasticity model for the stress–strain curves of T700S/2500 angle-ply laminates. (a) ±15° and ±30°; (b) ±45° and ±60°.

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experimental results is obtained. As a lamina-level macroscopic approach, the one-parameter plasticity model will be useful to predict the mechanical behavior of multidirectional laminates.

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