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Tensile creep deformation in unidirectional carbon/epoxy laminates under off-axis loading

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Due to the anisotropy of unidirectional composite laminates, the strength and stiffness of off-axis specimens are low compared to those in the fiber direction. Moreover, it is known that fiber composites exhibit nonlinear stress–strain response under off-axis loading [1–7]. In order to make good use of material properties, it is very important to understand the mechanical properties in off-axis direction accurately, because composite laminates are used as multidirectional laminates. On the other hand, it is reported that polymer matrix composites show creep behavior not only at higher temperatures but also at room temperature [2]. In the present study, tensile tests and creep tests of unidirectional laminates are performed at off-axis angles, 15°, 30°, 45°, 60°, 75°, and 90°. The purpose of this study is to describe the nonlinear behavior of a CFRP composite laminate under off-axis tension and to characterize the effect of the temperature and stress on the creep deformation of unidirectional laminates. The concept of effective stress and effective strain was used to generate master creep compliance curves based on the off-axis creep compliance curves. This model enables us to predict the creep compliance of the composite under the constant tensile loading.

A CFRP material used is T700S/2500 carbon/epoxy system. The laminate configuration is 5-ply unidirectional laminate. The specimens of tensile test and creep test cut from a panel in 15°, 30°, 45°, 60°, 75°, and 90° directions. The size of tensile and creep test specimens is 120 mm long, 10 mm wide, and 0.74 mm thick. GFRP tabs are glued on both edges of the specimens. Tensile and creep tests are performed on the specimens at room temperature (25 °C) and high temperature (65 °C). For the tensile test, the crosshead speed is 0.5 mm/min. The specimens are loaded until the final failure. For the creep test, constant tensile loads of 30 and 38 MPa are applied to off-axis specimens for 400 min. Biaxial strain gages are mounted at the center of the specimens to measure stress–strain curves and strain–time curves, for tensile test and creep test, respectively.

Fig. 1 shows the stress–strain curves of unidirectional laminates at room temperature (RT) and at high temperature (65 °C). The unidirectional composite showed nonlinear stress–strain relations at all angles. It is seen that the nonlinearity is larger at higher temperature.

To model the nonlinear stress–strain relation, the one-parameter plasticity model proposed by Sun and Chen is applied [1]. Following the procedure in reference [1], it is assumed that the strains can be divided into two parts, that is, linear elastic and nonlinear parts:

$$\varepsilon = \varepsilon^{\mathrm{e}} + \varepsilon^{\mathrm{p}}, \tag{1}$$

where superscripts e and p denote linear elasticity and nonlinearity, respectively.

It is also assumed that the nonlinear part comes from plasticity. In one-parameter plasticity model (Equations 2–4), we aim to obtain a parameter which leads to a master curve of the effective stress–effective plastic strain curve from the data of all angles. The effective stress and the effective plastic strain are obtained

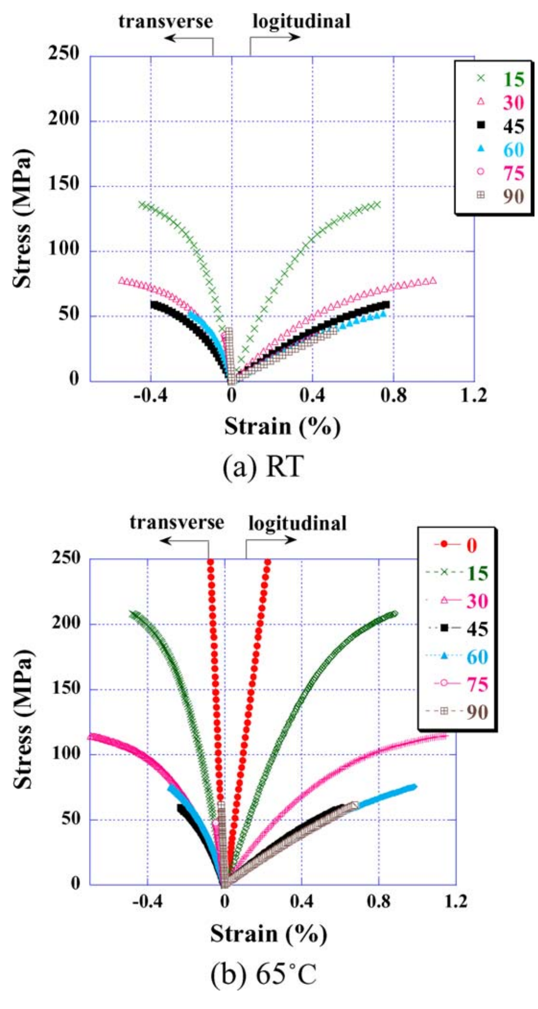

Figure 1 Stress–strain curves for unidirectional T700S/2500 laminates: (a) RT and (b) 65 °C.

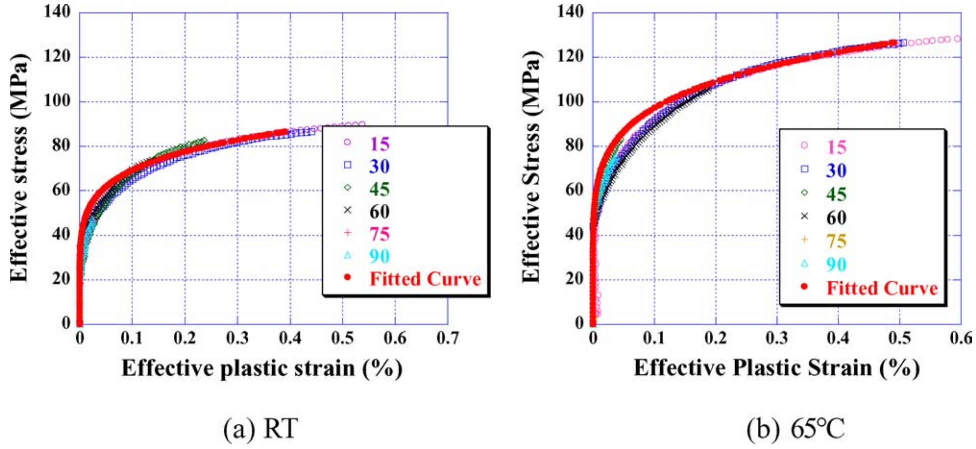

Figure 2 Effective stress–effective plastic strain curves for unidirectional T700S/2500: (a) RT and (b) 65 °C.

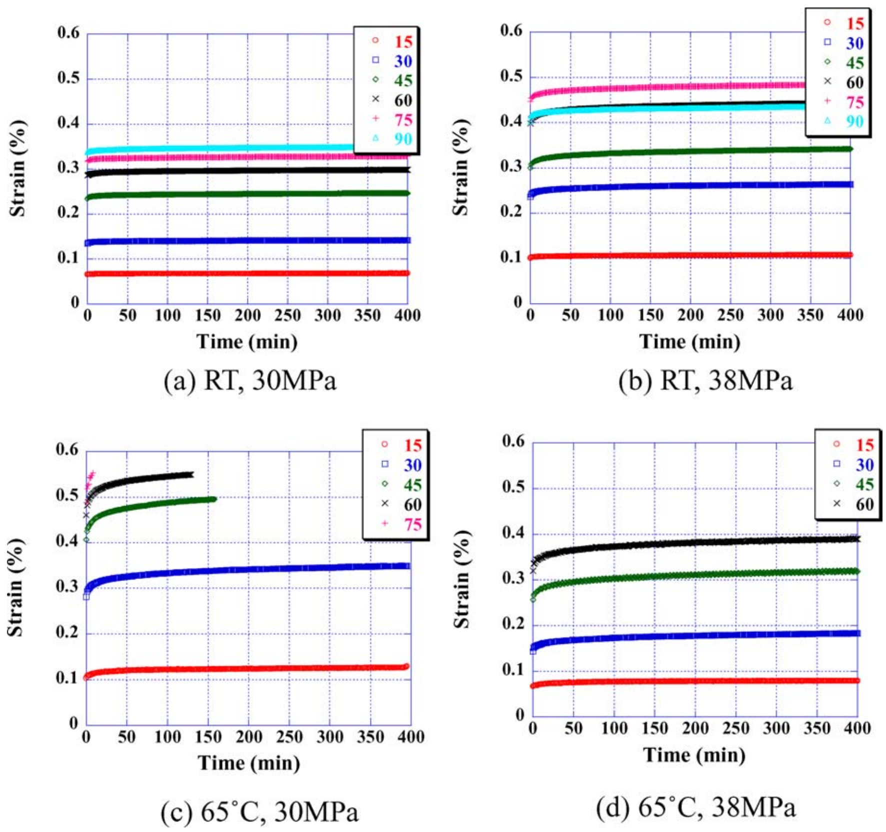

Figure 3 Strain–time curve for unidirectional T700S/2500: (a) RT, 30 MPa; (b) RT, 38 MPa; (c) 65 °C, 30 MPa; and (d) 65 °C, 38 MPa.

from the axial tensile stress and the axial nonlinear strain by using the following equations:

$$\bar{\sigma} = h(\theta)\sigma_x \tag{2}$$

$$\bar{\varepsilon}^p = \varepsilon^p / h(\theta), \tag{3}$$

where

$$h(\theta) = \left[\frac{3}{2}\{\sin^4\theta + 2a_{66}\sin^2\theta\cos^2\theta\}\right]^{1/2}. \tag{4}$$

Fig. 2 shows the effective stress–effective plastic strain curves for unidirectional laminate at RT and 65 °C. It is seen that the curves from all off-axis angles gather on a single curve at each temperature. Initial longitudinal Young's moduli for all angles are listed in Table I. The initial Young's moduli were used to determine the linear elastic strain. The plastic parameters obtained are shown in Table II. We could show that, independent of off-axis angles, a

TABLE I Initial longitudinal Young's modulus at RT and 65 °C

θ		0	15	30	45	60	75	90
Young's modulus	RT	110	41	20	13	11	9.8	9.8
(GPa)	65 °C	–	35	15	12	9.3	9	8.3

TABLE II Plasticity parameter for unidirectional T700S/2500 at RT and 65 °C

	a_{66}	A (MPa^{-n})	n
RT	2.0	6.0×10^{-13}	6.0
65 °C	2.0	1.2×10^{-13}	6.1

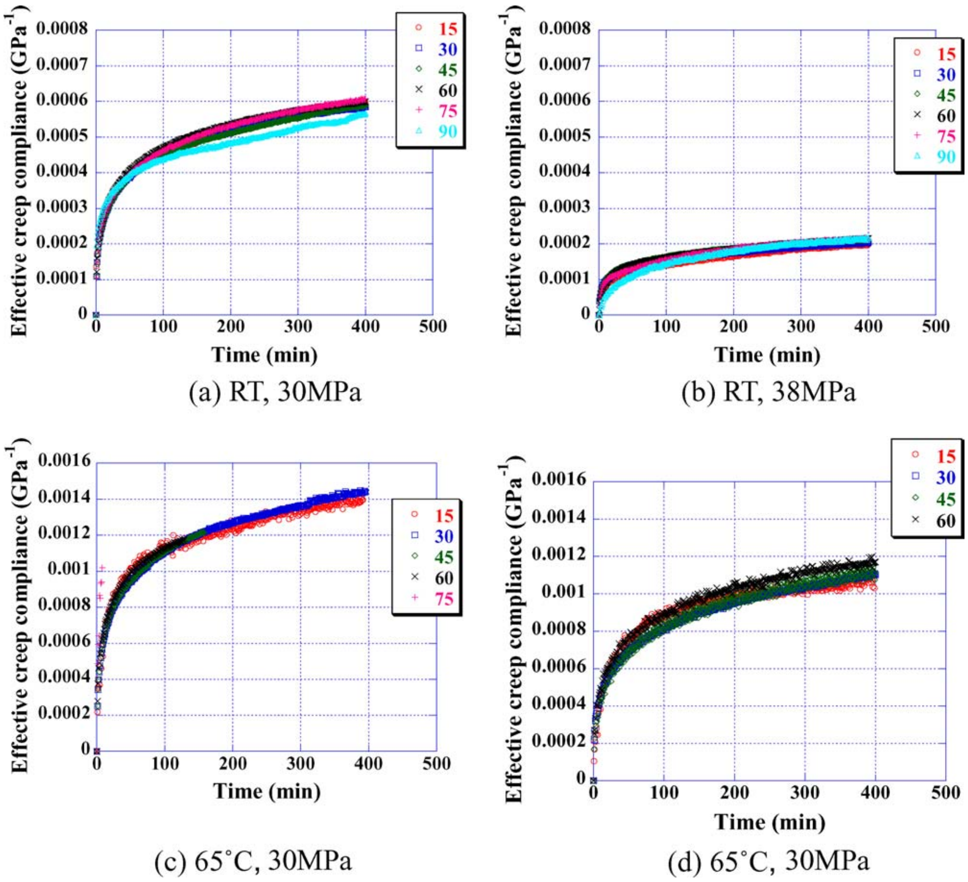

Figure 4 Relation between effective creep compliance and time: (a) RT, 30 MPa; (b) RT, 38 MPa; (c) 65 °C, 30 MPa; and (d) 65 °C, 38 MPa.

master curve is obtained; nonlinear behaviors for unidirectional CFRP laminate are described by a one-parameter plasticity model. Table III shows the tensile strength of the unidirectional laminate as a function of off-axis angle.

Fig. 3 shows time–strain relations obtained by the creep tests for (a) RT, 30 MPa; (b) RT, 38 MPa; (c) 65 °C, 30 MPa; and (d) 65 °C, 38 MPa. It is seen that the CFRP unidirectional laminate used in the present study shows tensile creep behavior at both RT and 65 °C.

To model the creep behavior observed, the creep compliance model is used [4]. Following the procedure used in reference [4], we assumed that the strain can be divided into initial strain and creep strain as

$$\varepsilon = \varepsilon^{\mathrm{i}} + \varepsilon^{\mathrm{c}}. \tag{5}$$

The creep compliance was obtained from the creep strain by subtracting the initial strain. Creep compliance is defined as the value which is the creep strain divided by the constant stress applied.

Now we assume that creep potential has the same form as the one-parameter plasticity model. The relation between the effective creep compliance and the creep compliance can be written as

$$\bar{S}^{\mathrm{c}} = \frac{\bar{\varepsilon}^{\mathrm{c}}(t)}{\bar{\sigma}} = \frac{\varepsilon_{\mathrm{x}}^{\mathrm{c}}(t)}{\sigma_{\mathrm{x}}}\frac{1}{h_{\mathrm{c}}^{2}(\theta)} = \frac{S_{\mathrm{x}}^{\mathrm{c}}(t)}{h_{\mathrm{c}}^{2}(\theta)}, \tag{6}$$

where

$$h_{\mathrm{c}}(\theta) = \left[\frac{3}{2}\left(\sin^{4}\theta + 2a_{66}^{\mathrm{c}}\sin^{2}\theta\cos^{2}\theta\right)\right]^{1/2}. \tag{7}$$

Fig. 4 shows the resulting effective creep compliance–time curves for the unidirectional laminates. It is found that the strain–time behavior in unidirectional laminate can be described by the effective creep compliance model.

TABLE III Tensile strength at RT and 65 °C

θ		0	15	30	45	60	75	90
Tensile strength	RT	–	208	115	81	75	47	62
(MPa)	65 °C	–	137	78	61	53	37	39

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