Off-Axis Creep Rupture of Unidirectional CFRP Laminates at Elevated Temperature

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Introduction

Polymers have strong tendencies for the significant time- and rate-dependent damage under a sustained stress over a wide range of temperature. This fact explains that the time-dependent fracture of polymer matrix composites (PMCs) and PMC structures under practical loading conditions should be appropriately considered for their reliable designs. The effect of load duration on the long-term performance and reliability of PMC structures cannot be always checked by experiment, because of time and cost limitation. Therefore, creep rupture modeling of PMCs is required to evaluate the lifetime and design stress of PMC structures for various loading conditions of practical interest.

However, information on creep fracture behavior and creep rupture modeling of PMCs are still limited in literature, especially for off-axis loading conditions. Regarding a problem of predicting the whole process of the creep deformation and creep fracture of unidirectional and multidirectional PMC laminates at high stresses and at high temperatures, very few studies have been reported.

Objectives

The off-axis creep rupture behavior of a unidirectional CFRP laminate is examined for various fiber orientations at high temperature.
A phenomenological creep rupture modeling is attempted for the creep deformation and rupture behaviors of the unidirectional CFRP.

- Experimental Observation:
  - Creep rupture life
  - Creep deformation

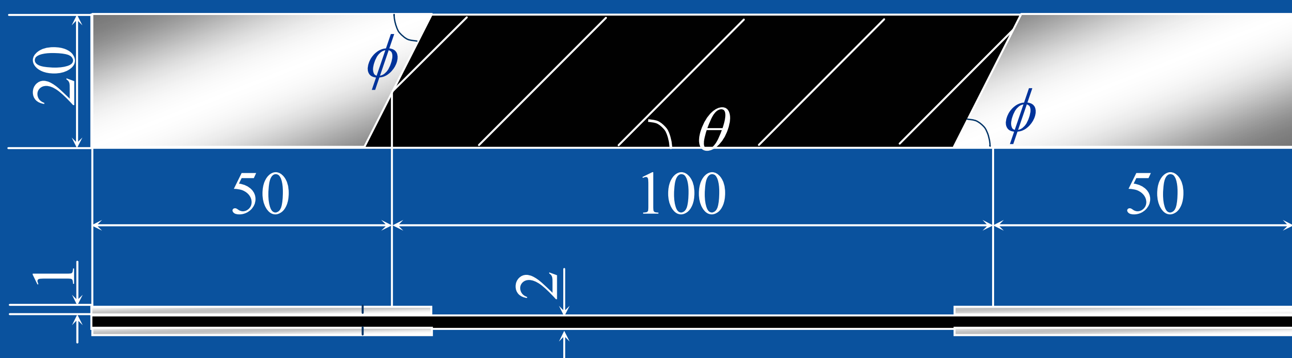
- Applicability of Creep Rupture Model:
  - Ply viscoplasticity model + Damage mechanics model

Material System and Specimens

T800H/Epoxy#2500
(Cure temperature: 130˚C)

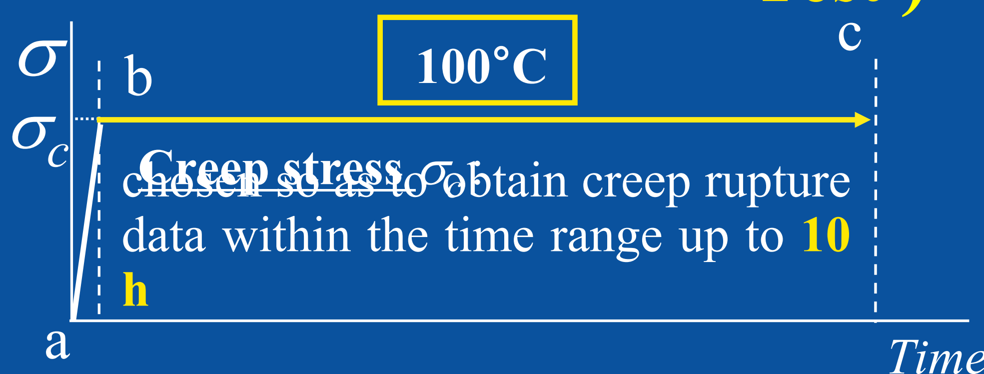
θ (deg)	0	10	30	45	90
ϕ (deg)	90.0	16.1	36.6	59.2	90.0

*θ: Fiber orientation angle
*ϕ: Oblique tab angle



(Unit: mm)

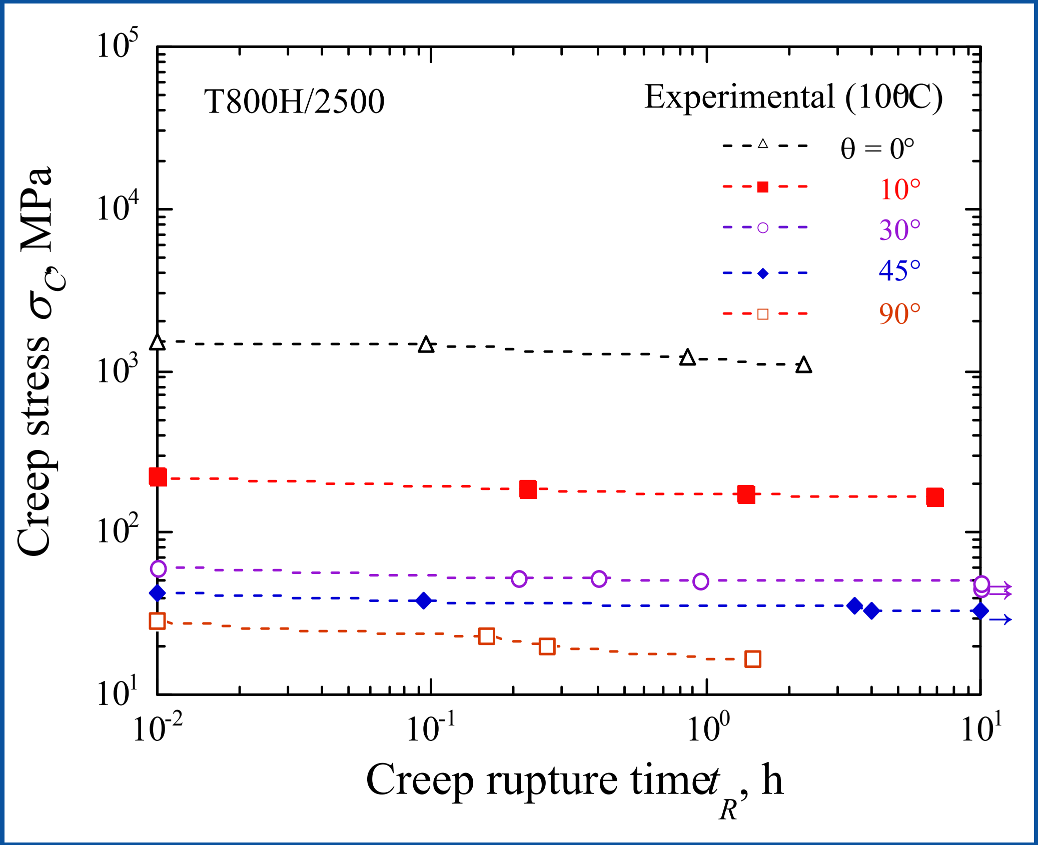
Experimental Procedure (Creep rupture Test)



Creep stress σ_c : chosen so as to obtain creep rupture data within the time range up to **10 h**

a-b : Loading
(1.0 mm/min; Stroke control)
b-c : Creep period
(within 10 h; Load control)

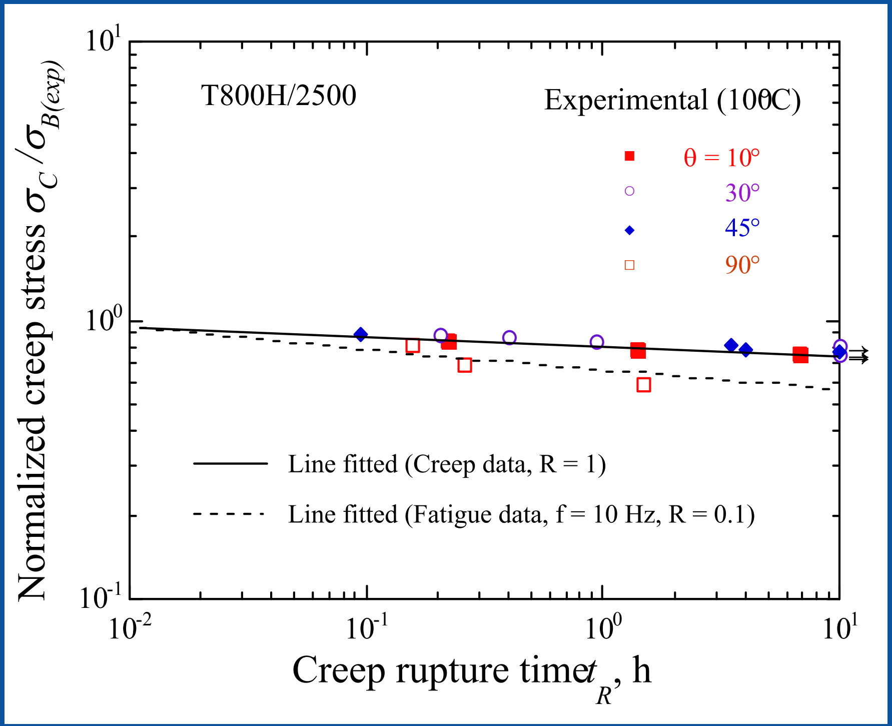
1.Off-Axis Creep Rupture Behavior

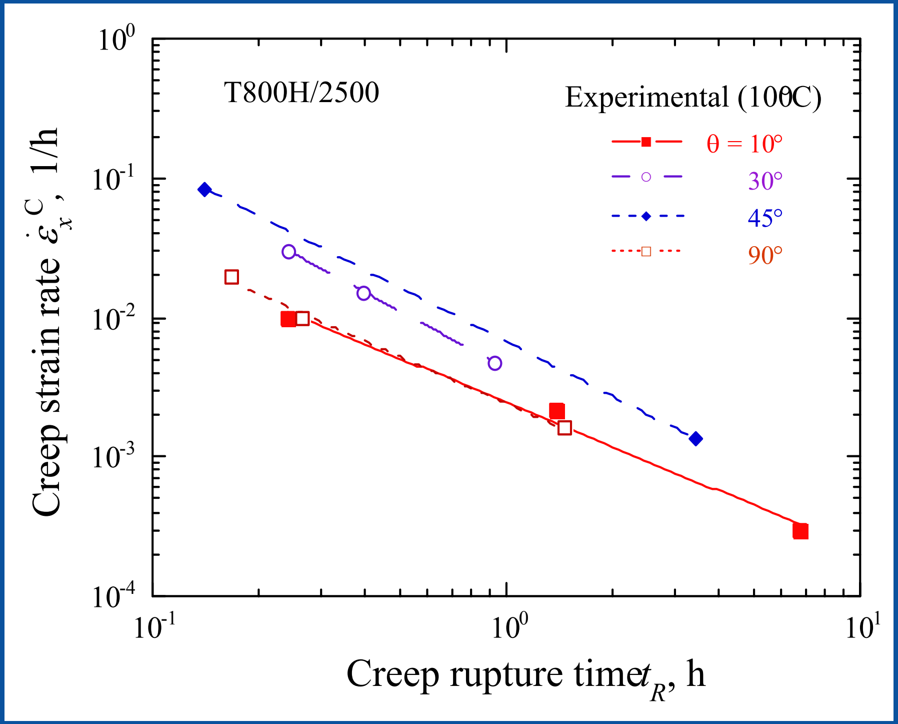


0° 10° 30° 45° 90°

- The off-axis creep rupture strength becomes lower as the fiber orientation angle increases, demonstrating a strong fiber orientation dependence of the creep rupture life.
- Straight lines can be fitted well to the log-log plots of the off-axis creep rupture data over the range of creep time up to 10 h, regardless of the fiber orientations.
- The macroscopic creep failure morphology is similar to the static tensile fai

2. Normalized Creep Rupture Behavior and the Monkman-Grant Relationship





- The fiber orientation dependence of the off-axis creep rupture strength is approximately removed using the normalized creep stress, and the creep strength ratio can be used as a creep strength measure for creep rupture modeling.
- The off-axis creep rupture data, which correspond to data at the stress ratio of $R = 1$, are distributed slightly above the off-axis fatigue data at $R = 0.1$.
- The creep rupture time exhibits an inverse dependence on the minimum creep rate, and the slope of the Monkman-Grant plot is almost identical for all the off-axis fiber

3.Creep Deformation-Rupture Modeling

Viscoplasticity Model

Effective viscoplastic strain rate:

$(K, m : Material\ constants)$

$$\dot{p} = \left\langle \frac{U - r}{K} \right\rangle^{1/m} \qquad \left(U = \sqrt{\frac{3}{2}\left[\sigma_{22}^2 + 2a_{66}\sigma_{12}^2\right]} \right)$$

Evolution equation of internal hardening variable :

$(Q_i, b_i : Material\ constants)$

$$\dot{r} = \left(\frac{1}{1-\omega}\right)^{1+1/m} \sum_i b_i (Q_i - r_i)\, \dot{p}$$

Viscoplastic strain rate in individual plies:

$(a_{66} : Material\ constant)$

$$\begin{Bmatrix} \dot{\varepsilon}_{11}^{p} \\ \dot{\varepsilon}_{22}^{p} \\ \dot{\gamma}_{12}^{p} \end{Bmatrix} = \frac{3}{2}\left(\frac{1}{1-\omega}\right)^{1+1/m} \frac{\dot{p}}{U} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2a_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix}$$

Damage Mechanics Model

Damage evolution equation:

$(N, k, n : Material\ constants,$

$\sigma_L^* : Creep\ limit)$

$$\dot{\omega} = N\left[\frac{1}{(1-\sigma^*)-\omega}\right]^k \left\langle \sigma^* - \sigma_L^* \right\rangle$$

Non-dimensional effective stress:

$(X = \sigma^f_{\theta=0^\circ}, Y = \sigma^f_{\theta=90^\circ},$

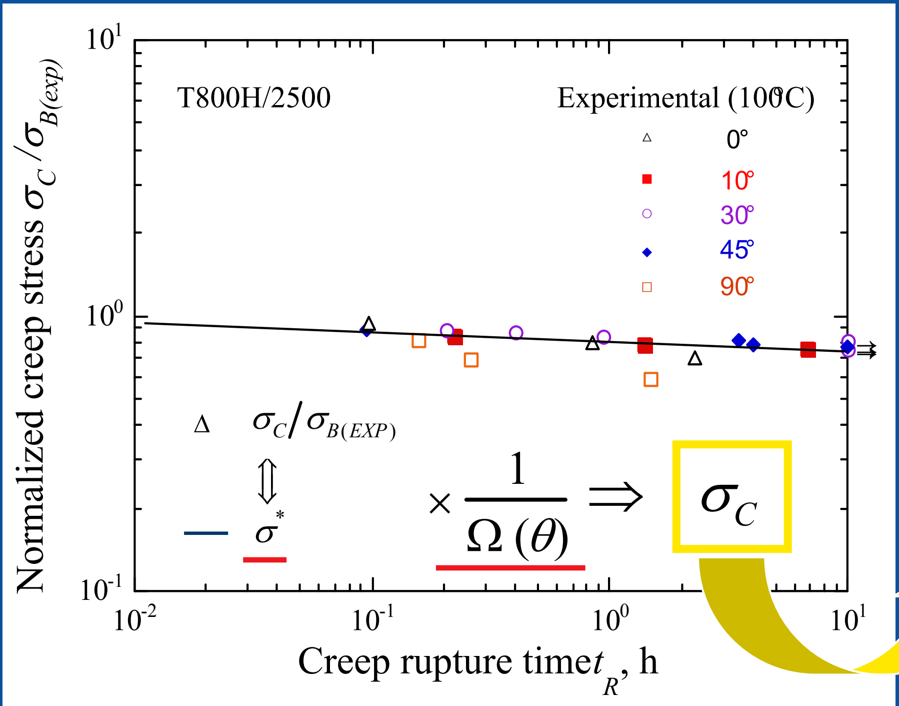
$S = \sigma^f_{\theta=10^\circ}\cos 10^\circ \sin 10^\circ)$

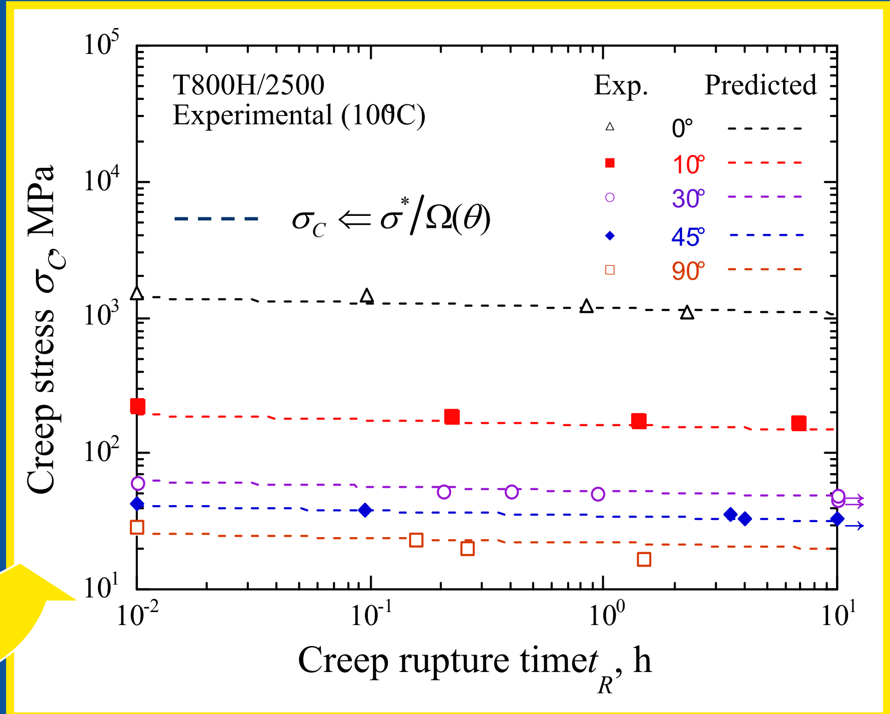
$$\sigma^* = \sqrt{\left(\frac{\sigma_{11}}{X}\right)^2 - \frac{\sigma_{11}\sigma_{22}}{X^2} + \left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2}$$

Failure criterion:

$$\omega = 1 - \sigma^*$$

4.Predictions of Off-Axis Creep Rupture Behavior





Creep rupture time:

$$t_R = \frac{1}{(1+k)N}\frac{(1-\sigma^*)^{k+1}}{\langle \sigma^* - \sigma_L^* \rangle^n}$$

$(n = 38.2,\ N = 1483,\ k = -0.9,\ \sigma_L^* = 0)$

Orientation factor: $(m = \cos\theta,\ \ n = \sin\theta)$

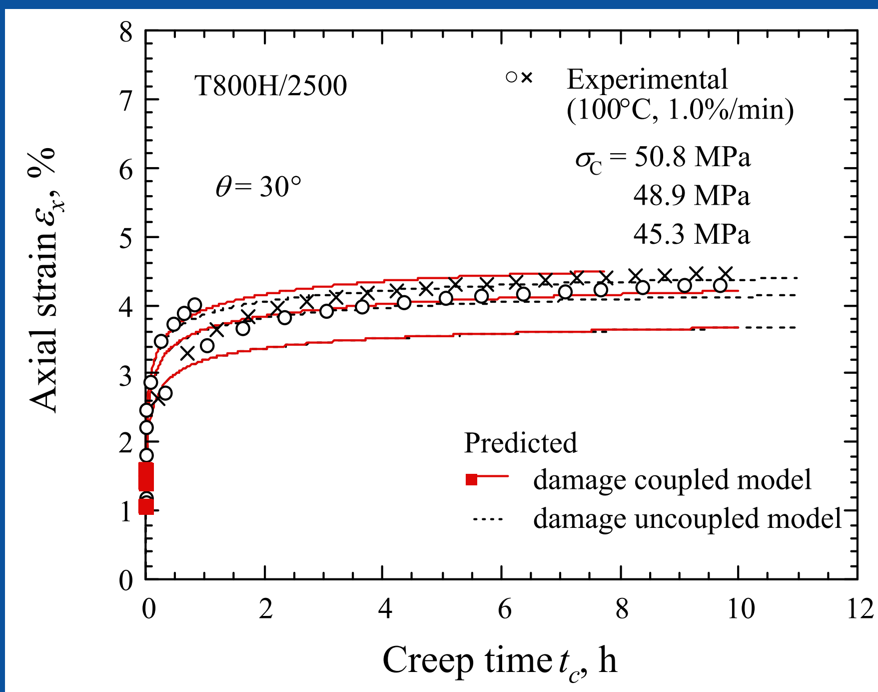
$$\Omega(\theta) = \frac{1}{\sigma_{B(Pred)}} = \sqrt{\frac{m^4}{X^2} - \frac{m^2 n^2}{X^2} + \frac{n^4}{Y^2} + \frac{m^2 n^2}{S^2}}$$

- A good agreement between the predicted and observed results has been achieved regarding the fiber orientation dependence of the creep rupture time.

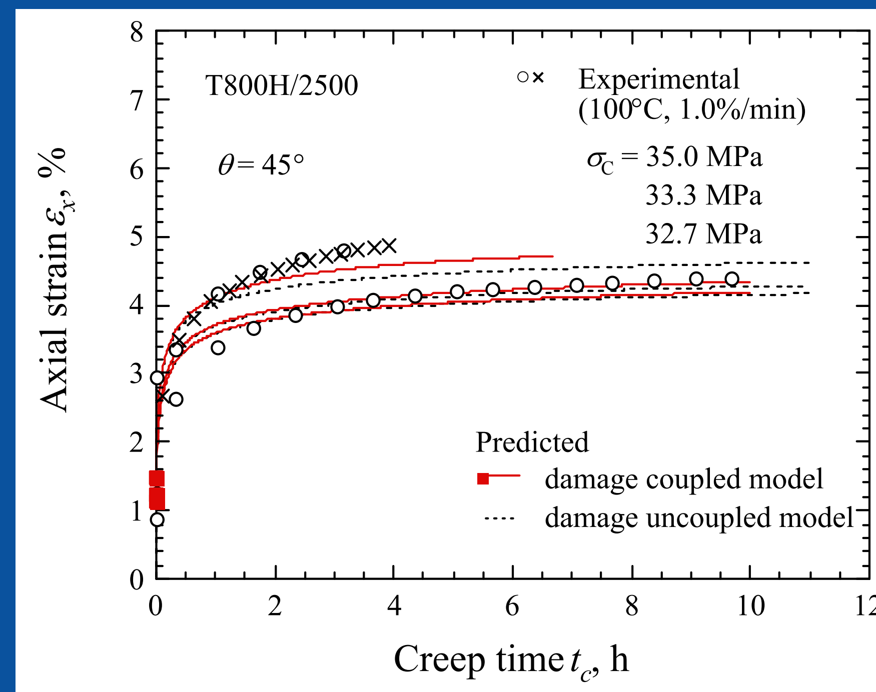
5.Coupled Creep Deformation-Rupture Analysis

Material Constants:

a_{66} = 1.3	K = 78 MPa$^{m}\cdot$min^{m}	X = 2146 MPa
Q_1 = 100 MPa	m = 0.24	Y = 32.4 MPa
Q_2 = 7 MPa	n = 38.2	S = 36.4 MPa
b_1 = 10	N = 1483	$\sigma^{*}_{\square}$ = 0 MPa
b_2 = 3000	k = -0.90	



$\theta = 30°$



$\theta = 45°$

- The end points of these solid lines correspond to creep fracture.
- The overall features of off-axis creep behavior have been qualitatively described using the proposed model.

Conclusions

Off-axis creep rupture behavior of a unidirectional T800H/Epoxy laminate under constant load conditions at 100°C is studied.

Applicability of the proposed model is evaluated by comparing with experimental results.

- The off-axis creep rupture strength decreases with increasing fiber orientation angle. The creep rupture time becomes shorter as the creep stress increases, regardless of the fiber orientations.

- The fiber orientation dependence of the off-axis creep rupture strength can be almost eliminated using the creep strength ratio. This suggests that the non-dimensional effective stress becomes a good creep strength measure to cope with the fiber orientation effect.

- The proposed model can moderately describe the salient features of the creep deformation and rupture behaviors of the unidirectional CFRP laminate. Applicability and accuracy of the model should be further examined on the basis of more extensive creep rupture testing on unidirectional and multidirectional laminates at different temperatures.