STUDY ON STRENGTH DEGRADATION IN UNIDIRECTIONAL COMPOSITES, DUE TO TIME-DEPENDENT DAMAGE ACCUMULATION

Fumio OGAWA*, Jun KOYANAGI, Hiroyuki KAWADA*****
[Fumio OGAWA]: f.ogawa@akane.waseda.jp
***Graduate School of Waseda University**
****Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency**
*****Department of Mechanical Engineering, Waseda University**
Keywords: *Unidirectional Composites, Fiber breakage, interfacial debonding, Time-dependence*

1 Introduction

Mechanical properties of unidirectional composites are important for design and reliability of composite structures, since unidirectional ply bears most of load subjected to composite laminates and its properties are used to estimate that of laminates. As is known, strength and lifetime of unidirectional composites is considerably governed by mechanical properties of fiber, matrix and fiber/matrix interface. So, understanding relationship between damage evolution and properties of constituents and developing methods for estimation of strength or lifetime are needed for reliability and durability of composite structures.

It is found strength degradation with time, due to time-dependent accumulation of micro-damages e.g. fiber breakage or interfacial debonding, occurs in unidirectional composites. Interfacial creep and/or time-dependent debonding propagation are causes for such a phenomena. Time-dependent debonding propagation increases the stress recovery length, and is thought to be one of the dominant mechanisms in strength degradation. Authors investigated time-dependent debonding propagation in single fiber composite (SFC) specimen and its mechanism [1]. In this paper, methods for prediction of strength degradation in unidirectional composites due to time-dependent debonding propagation is proposed and validity of the model compared to experimental results are discussed.

2 Formulation of debonding length

Measurement and formulation of time-dependent debonding propagation were performed in past studies of authors [1]. In this section, mechanism for debonding propagation is briefly discussed and debonding length is reformulated for convenience in analysis of strength degradation in unidirectional composites.

Study on time-dependent debonding propagation in SFC composites revealed that debonding propagation is controlled by both of relaxation in frictional stress within the debonding region and interfacial shear creep within bonded region. However, relaxation in frictional stress is the most dominant factor and interfacial creep has less effect on debonding propagation in short-term [1]. So, we here neglect the effect of interfacial creep, i.e. change in stress recovery length due to interfacial creep.

Debonding length is formulated as equation. (1), since fiber strain must be recover to constant value within debonding region.

$$L_d(t) = \frac{\varepsilon_d E_f r_f}{2\tau_d(t)} \tag{1}$$

Here, $\tau_d(t)$ is frictional stress within debonding region and is formulated as follow.

$$\tau_d(t) = -\mu\sigma_r(t) \tag{2}$$

In equation (2), coulomb friction is assumed and $\sigma_r(t)$ is radial stress on interface. $\sigma_r(t)$ is formulated as follows in consideration of thermal residual stress.

$$\sigma_r(t) = \frac{\nu_f \varepsilon_d - \nu_m \sigma_m(t) J(t) + (\alpha_m - \alpha_f)\Delta T}{\frac{1-\nu_f}{E_f} + (1+\nu_m) J(t)} \tag{3}$$

Here, $J(t)$ and $\sigma_m(t)$ are creep compliance and tensile stress in matrix. $\sigma_m(t)$ was determined in analytical way, independently.

3 Analysis of time-dependent strength degradation

3.1 Formulation of time-dependent failure strain

Here, we formulate strength degradation in unidirectional composites. In Global Load Sharing (GLS) rule neglecting stress concentration on intact fiber, average stress in fibers is formulated as equation (4), considering debonding propagation.

$$\bar{\sigma}_f = E_f \varepsilon \left\{1-\left(\frac{\varepsilon_b}{\varepsilon}+\frac{L_d(t)}{L_d(t)+L_b}\right)\left(\frac{L_d(t)+L_b}{L_0}\right)\left(\frac{E_f \varepsilon}{\sigma_0}\right)^m\right\} \quad (4)$$

,where L_b, length of recovery length in bonded region was determined independently by stress analysis assuming hexagonal fiber packing. And ε_b and σ_0, m, L_0 are fiber strain which recovers within L_b and Weibull parameters for fiber strength. Change in failure strain with time, strength degradation in unidirectional composites is formulated from maximum value of $\bar{\sigma}_f$, as follows

$$\varepsilon_{rup}(t)=\frac{\sigma_0}{E_f}\left\{(m+1)\frac{L_d(t)+L_b}{L_0}\left(\frac{\varepsilon_b}{\varepsilon}+\frac{L_d(t)}{L_d(t)+L_b}\right)\right\}^{-1/m} \quad (5)$$

Equation (5) can't be solved analytically and failure strain was determined computationally.

3.2 Simulation based on local load sharing rule

To investigate the effect of stress concentration on strength degradation, Monte Carlo simulation based on Local Load Sharing (LLS) rule was performed. The simulation model was based on 3D shear-lag model proposed by Okabe et.al [2] and relaxation of frictional stress and interfacial debonding propagation were incorporated into the model, using equations (1)-(3).

4 Evaluation in strength degradation in multi-fiber composite specimen

Strength degradation in unidirectional composites was investigated using multi-fiber composite (MFC) specimen shown in Figure1.

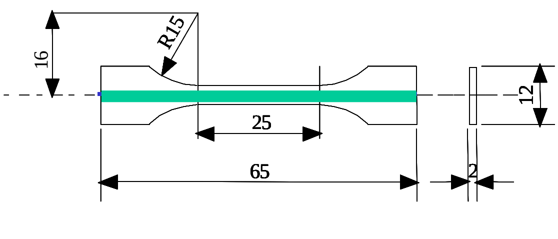

Fig.1 Geometry of multi-fiber composite specimen

In MFC specimen, a bundle composed of 6000 carbon fibers was embedded in vinyl-ester resin and its fiber volume fraction is approximately 3.9%. MFC specimen was statically stretched till certain displacement and then displacement was constrained to the value for certain period. After the passage of the period, specimen was statically stretched again and failure strain i.e. residual strength of the specimen was measured.

5 Discussion

Shown in Figure2 are experimental results of residual strength test and strength analysis. Plots in Figure 2 are rupture strain of MFC specimen constrained to 0.92% strain for 0, 100, 200hours. Solid line and dashed line indicate theoretical line obtained from equation (5) and Monte Carlo simulation.

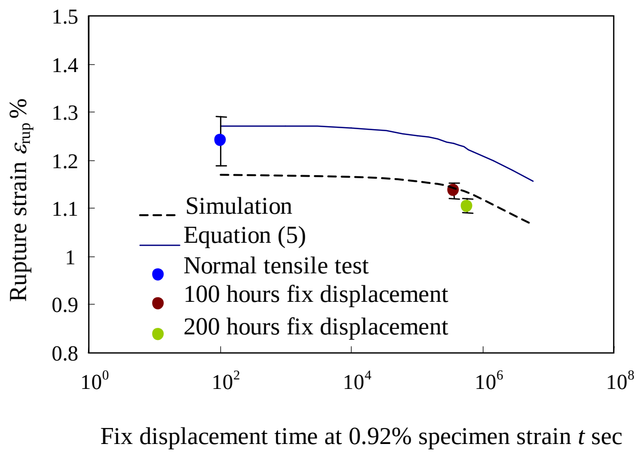

Fig. 2 Relationship between rupture strain and fix displacement time at 0.92% specimen strain

In Figure2, theoretical result from Monte Carlo simulation, considering stress concentration is more close to experimental results. Damage accumulation process due to debonding propagation and stress concentration will be examined in detail in near future.

References

[1] Koyanagi J., Ogawa F. and Kawada H. "Long-term creep rupture prediction in unidirectional composites". *16th European Conference on Fracture* in CD-ROM, 2006

[2] Okabe T., Takeda N., Kamoshida Y., Shimizu M. and Curtin W. A. "A 3D shear-lag model considering micro-damage and statistical strength prediction of unidirectional fiber-reinforced composites". *Composites Science and Technology*, Vol. 61, No. 12, pp. 1773-1787, 2001