TEMPERATURE DEPENDENCE OF OFF-AXIS CREEP RUPTURE BEHAVIOR OF A UNIDIRECTIONAL CARBON/EPOXY LAMINATE

Masamichi KAWAI* and Takahiko SAGAWA**
***Department of Engineering Mechanics and Energy, University of Tsukuba**
****Graduate School of Systems and Information Engineering, University of Tsukuba**

Keywords: *unidirectional composites, off-axis creep rupture, creep damage mechanics, Larson-Miller parameter, grand master creep rupture curve*

Abstract

Tensile creep rupture behavior of a unidirectional carbon/epoxy T800H/2500 laminate under off-axis loading conditions is examined at different temperatures of 60, 80 and 130ºC. Creep rupture tests are performed on plain coupon specimens with five kinds of fiber orientations θ = 0, 10, 30, 45 and 90°. Creep rupture of specimens takes place predominantly along the reinforcing fibers in a brittle manner, regardless of the fiber orientation and test temperature. The log-log plots of creep stress against time to rupture can approximately be represented by straight lines with negative slopes over the range of life up to 10 h for all fiber orientations and test temperatures. Two kinds of stress-time-temperature extrapolation methods for constructing a grand master rupture curve are then developed for the off-axis creep rupture data on the unidirectional composite over the range of temperature at different stress levels. Validities of the proposed grand master rupture curve approaches to off-axis creep life prediction are evaluated by comparing calculated and experimental results.

1. Introduction

For accurate determination of an allowable stress level for a long period of loading in designs of structural components made of polymer matrix composite (PMC) laminates, it is a prerequisite to quantify the creep strength of PMC laminates employed. Long-term creep rupture data on PMC laminates, however, are not readily available, and they cannot often be obtained by experiment, because of time and cost limitation. Therefore, it is demanded to establish an appropriate engineering method for extrapolating a limited amount of short-term stress rupture data on PMC laminates to the range of stress, time and temperature in service.

Matrix dominated creep rupture is the key to accurate evaluation of the durability of PMC laminates [1]. For understanding and modeling the matrix dominated creep rupture of PMC laminates, it is necessary to observe the off-axis creep rupture behavior of unidirectional PMC laminates for various fiber orientations over a range of stress and temperature. For a class of unidirectional PMC laminates, therefore, the off-axis creep rupture behavior has already been observed [2, 3]. In addition to these studies, we also examined the short-term off-axis creep rupture behavior of a unidirectional T800H/2500 carbon/epoxy laminate for various fiber orientations at 100°C [4]. It was confirmed that straight lines were well fitted to the off-axis creep rupture curves as plots of creep stress against time to failure on logarithmic scales over a range of creep life, regardless of the fiber orientation. The creep rupture time exhibited inverse dependence on the power of minimum creep rate for all the fiber orientations. The Monkman-Grant plots [5] of the off-axis creep rupture data did not fall in a single curve, but they were almost parallel with each other. The normalized master rupture curve approach developed in [4] was successful in coping with the fiber orientation dependence of the off-axis creep rupture data obtained from the short-term tests at the test temperature of 100°C.

To the best of the present authors' knowledge, however, no systematic data are available for the creep rupture behavior of unidirectional PMC laminates under off-axis loading conditions over a wide range of temperature. Thus, the temperature dependence of off-axis creep rupture behavior of unidirectional PMC laminates has not sufficiently been understood, and an efficient procedure for extrapolating the off-axis creep rupture data to a range of different temperatures and longer periods of lifetime has not been established. These facts suggest that further basic investigation on the matrix dominated creep fracture behavior of unidirectional PMC laminates is required with a view to developing an engineering creep rupture life prediction method that takes into account their temperature and fiber orientation dependence.

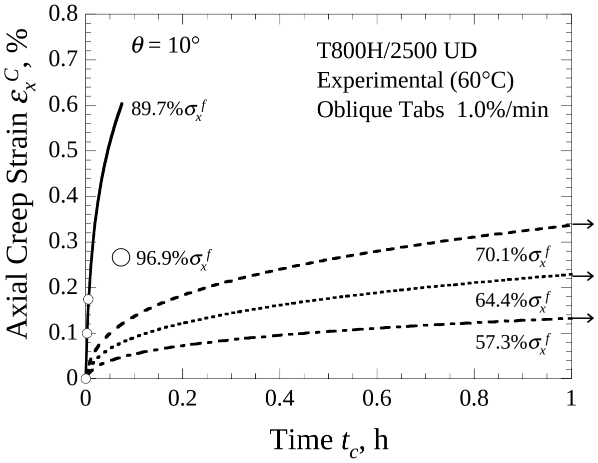
In the present study, the off-axis creep rupture behavior of the unidirectional carbon/epoxy laminate [4] is further examined for different test temperatures. Development of a phenomenological creep rupture model that takes into account the temperature and fiber orientation dependence of the off-axis creep rupture behavior of the unidirectional CFRP laminate is attempted. Two kinds of novel procedures for extrapolating short-term off-axis creep rupture data are formulated by means of the time-temperature extrapolation parameters based on the extended creep rupture model and the well-known Larson-Miller parameter [6]. Finally, validity of the proposed methods for predicting the off-axis creep rupture lives at low stress levels over a range of temperature is evaluated by comparing predicted and experimental results.

2. Material and Experimental Procedure

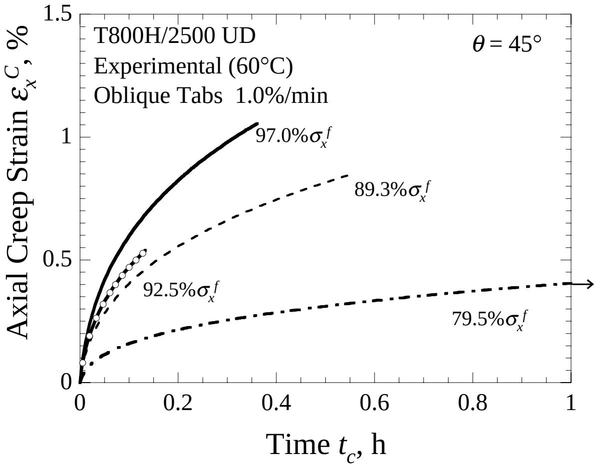
2.1 Material and specimen

Unidirectional carbon/epoxy laminates fabricated from the prepreg tape P2053-20 (T800H/2500, TORAY) were used in this study. The lay-up of virgin laminates is $[0]_{12}$, and they were cured in an autoclave at 130°C.

Five kinds of plain coupon specimens with different fiber orientations (θ = 0, 10, 30, 45, 90°) were cut from 400 mm by 400 mm unidirectional laminate panels; they are of the same batch used in the previous study [4]. The shape and dimensions of the off-axis specimens are based on the testing standards JIS K7073 and ASTM D3039; the specimen length L was 200 mm and the thickness t was 2.0 mm. The specimen width was 10 mm for θ = 0°, and 20 mm for the other off-axis angles. The oblique-shaped tabs [19] made of aluminum-alloy were attached on both ends of the specimens using epoxy adhesive (Araldite) in order to reduce the end-constraint effect, allowing the use of relatively short specimens. The thickness of the tabs was 1.0 mm.



(a) θ = 10°



(b) θ = 45°

Fig. 1 Off-axis creep deformation at 60°C

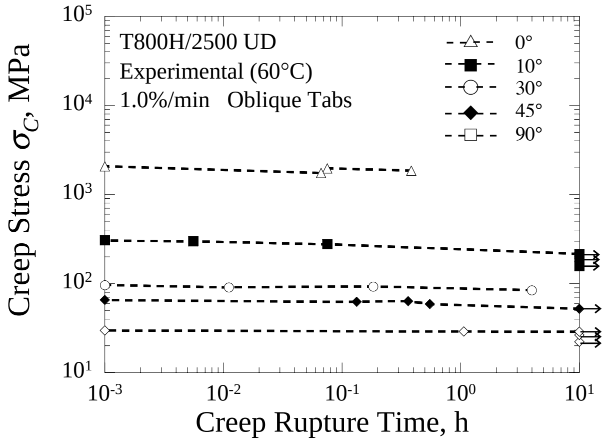
2.2 Creep rupture testing

Tensile creep rupture tests on off-axis coupon specimens were carried out at temperatures of 60, 80 and 130°C under load control, respectively, following the testing standards JIS K7087 and ASTM D2990. Creep rupture data at more than three different (nominal) stress levels were generated within the time range up to 10 h for each of the fiber orientations and test temperatures. The creep tests that last over the limit (10 h) of this study were terminated prior to fracture.

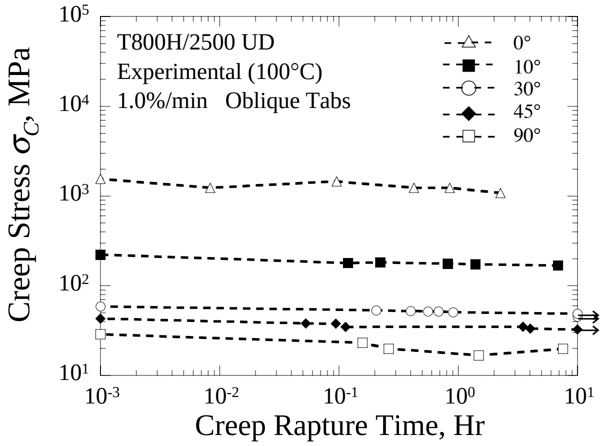
3. Experimental Results and Discussion

3.1 Creep deformation at different temperatures

The accumulation of creep strain with time at a given creep stress and a test temperature of 60°C is



(a) T = 60°C



(b) T = 100°C

Fig. 2 Off-axis creep rupture curves

shown in Figs. 1 (a), (b) for the fiber orientations θ = 10, 45°, respectively.

The off-axis creep rupture of the present material occurred without accompanying an appreciable tertiary creep stage, regardless of the fiber orientation and test temperature. In the off-axis creep deformation preceding the ultimate creep rupture, the secondary creep stage was not clearly identified either. These features of the off-axis creep deformation were observed in all kinds of strain measurements with strain gauges, LVDT and DVE. These observations suggest that the off-axis creep deformation of the unidirectional composite is characterized by the primary creep response over the range of lifetime for all the fiber orientations and test temperatures. The off-axis creep curves at the other test temperatures are omitted here, but the off-axis creep curves at 100°C can be find in the previous report [4].

3.2 Creep rupture curve

The off-axis creep rupture data obtained at the temperatures of 60, 100°C for all fiber orientations are shown in Figs. 2 (a), (b), respectively, as log-log plots of creep stress σ_C against rupture time t_R. The arrows in the figures indicate the data for specimens that were not fractured in 10 h, and those data points are simply plotted at the time of 10 h. The static tensile strengths are plotted by symbols on the vertical axis crossing at the rupture time $t_R = 10^{-3}$ h in theses figures, since the time to static tensile fracture at the constant displacement rate of 1.0 mm/min was in the order of 10^{-3} h for each test temperature.

It is obvious that the off-axis creep rupture strength becomes lower as the fiber orientation angle increases, demonstrating a strong fiber orientation dependence of the off-axis creep rupture time. All the off-axis creep rupture data for each fiber orientation approximately fall on a single straight line in the log-log plot over the range of creep rupture time up to 10 h, regardless of the test temperature. The straight lines fitted to the plotted data for different fiber orientations are almost parallel with each other. Therefore, the off-axis creep rupture data for a given fiber orientation can be described using a power-law relationship

$$\sigma_C{}^{q_1} t_R = C_1 \tag{1}$$

where the stress exponent q_1 and the coefficient C_1 stand for the slope and intercept of the straight line fitted to the log-log plot of creep rupture data, respectively.

3.3 Monkman-Grant relationship

The log-log plots of minimum creep rate against creep rupture time for all the fiber orientations are shown in Fig. 3 for the test temperature of 60°C. To a first approximation, it is seen that the creep rupture life is inversely proportional to the minimum creep rate. This proves that the Monkman-Grant relationship [5]

$$\dot{\varepsilon}_{\min}{}^{q_2} t_R = C_2 \tag{2}$$

is valid for the off-axis creep rupture behavior of the unidirectional CFRP laminate over the range of test temperature up to 130°C.

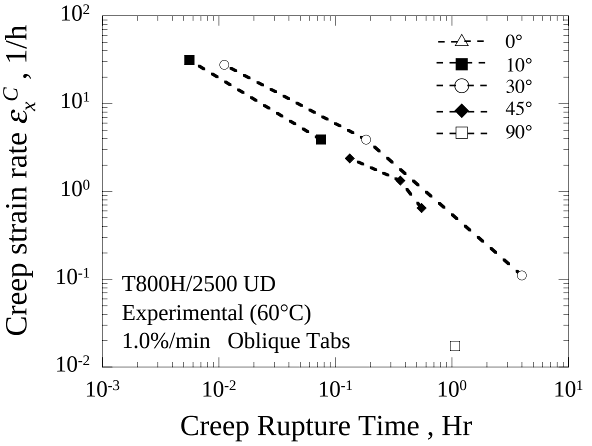
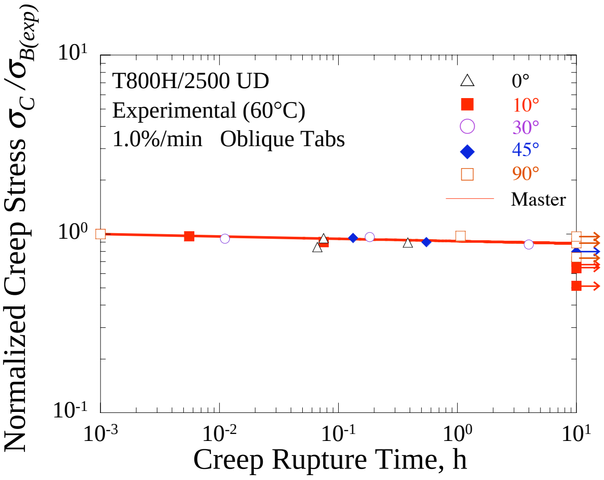


Fig. 3 Monkman-Grant relationship for the off-axis creep rupture behavior

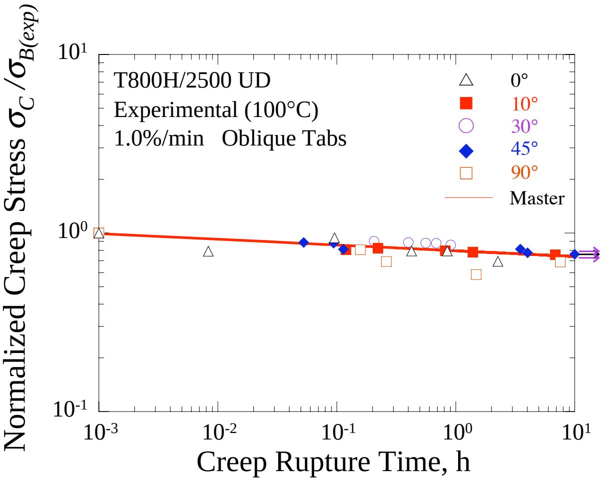
3.4 Normalized creep rupture curves at different temperatures

The creep stress levels corresponding to the rupture time $t_R = 10^{-3}$ h, which can be predicted by extrapolation using the straight lines fitted to the off-axis creep rupture data, almost agree with the static tensile strengths plotted by symbols on the vertical axis, regardless of the fiber orientation and test temperature. This fact implies that the fiber orientation dependence of the off-axis creep rupture strength is similar to that of the off-axis static strength at test temperature and that the temperature dependence of off-axis creep rupture strength is similar to that of the off-axis tensile strength.

The off-axis creep rupture data re-plotted using the normalized creep stress level $\sigma_C / \sigma^f_{\mathrm{exp}}$ with respect to the static tensile strength σ^f_{exp} are shown in Figs. 4 (a), (b) for the test temperatures of 60, 100°C, respectively. It is clearly observed that the normalized off-axis creep rupture data at a specified test temperature are distributed within a narrow range for all the fiber orientations, and they are approximately represented by a single straight line over the range of rupture time. This feature is common to the normalized plots of the creep rupture data for all test temperatures. This observation demonstrates that the fiber orientation dependence of the off-axis creep rupture strength can approximately be removed using the normalized creep stress level, regardless of the test temperature, and the use of the normalized creep stress level allows construction of a master rupture curve (MRC) for the off-axis creep data that is independent of off-axis fiber orientation at each of the test temperatures. These facts justify that the normalized creep stress level become a useful measure to cope with the anisotropic creep rupture behavior of the unidirectional CFRP laminate over the range of test temperature below 130°C.



(a) T = 60°C



(b) T = 100°C

Fig. 4 Normalized off-axis creep rupture curves

The straight line fitted to the normalized creep rupture data at a test temperature, which represents the master creep rupture curve that is independent of the off-axis fiber orientation, can be described by the following formula:

$$\left(\frac{\sigma_C}{\sigma_{B(\mathrm{exp})}} \right)^n t_R = t_R^0 \tag{3}$$

where the stress exponent n stands for the slope of the fitted straight line, and t_R^0 is a reference time associated with the condition $\sigma_C = \sigma_{B(\mathrm{exp})}$.

4. Damage mechanics approach to creep life prediction at different temperatures

4.1 Non-dimensional effective stress

A non-dimensional effective stress σ^* [8] based on the Tsai-Hill static failure criterion is introduced. For the case of plane stress, it can be expressed as

$$\sigma^* = \sqrt{\left(\frac{\sigma_{11}}{X}\right)^2 - \frac{\sigma_{11}\sigma_{22}}{X^2} + \left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2} \qquad (4)$$

where the stress components involved are taken with respect to the in-plane principal axes of material anisotropy, and X and Y represent the longitudinal and transverse strengths and S denotes the shear strength regarding the principal fiber coordinate system.

4.2 A simple law for creep damage evolution

The brittle-natured off-axis creep failure observed in the present study can be modeled by means of the damage mechanics approach. A single scalar damage variable approach [30] is adopted, and the evolution of the scalar damage variable ω is specified using the non-dimensional effective stress as

$$\frac{d\omega}{dt} = K(T)\left(\sigma_C^*\right)^{n(T)}\left(\frac{1}{1-\omega}\right)^{k(T)} \qquad (5)$$

where K, k, and n are assumed to be functions of temperature in general.

By integration of Eq. (5), we can derive the following completely normalized formula for creep rupture time:

$$\sigma_C^* = \left[\frac{t_R^0}{t_R}\right]^{1/n} \qquad (6)$$

where t_R^0 denotes a reference time associated with fictitious creep loading to the level of tensile strength and it is related with the material parameters and expressed as

$$t_R^0 = t_R\big|_{\sigma^*=1} = \frac{1}{[1+k]K} \qquad (7)$$

Note that the formula given by Eq. (6) represents the theoretical master rupture curve (MRC) for off-axis creep that is independent of the fiber orientation of specimens at a specified test temperature.

4.3 A time-temperature extrapolation parameter

Temperature dependence of the slope of the normalized creep rupture curve is approximately represented using the power function

$$\frac{1}{n(T)} = AT^m \qquad (8)$$

where A and m are material constants. A combination of the creep rupture equation [Eq. (6)] and the temperature dependent stress exponent yields a mathematical expression

$$AT^m \log\frac{t_R}{t_R^0} + \log\sigma_C^* = 0 \qquad (9)$$

Obviously, this equation prescribes a grand master rupture curve (GMRC) for off-axis creep that is independent of fiber orientation and test temperature.

Defining a new time-temperature extrapolation parameter as

$$P^* = T^m \log\frac{t_R}{t_R^0} \qquad (10)$$

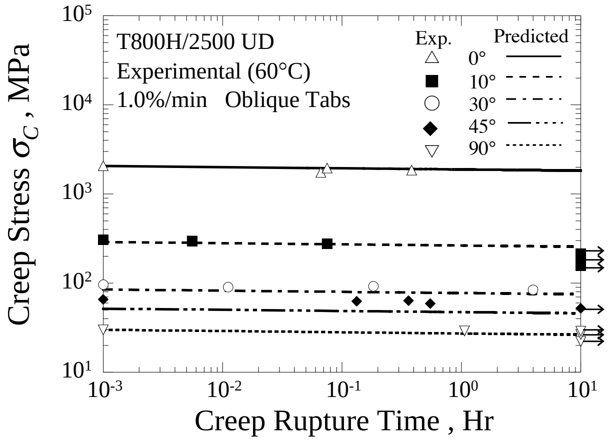
we can describe the grand master creep rupture curve using the following compact formula:

$$\log\sigma_C^* = -AP^* \qquad (11)$$

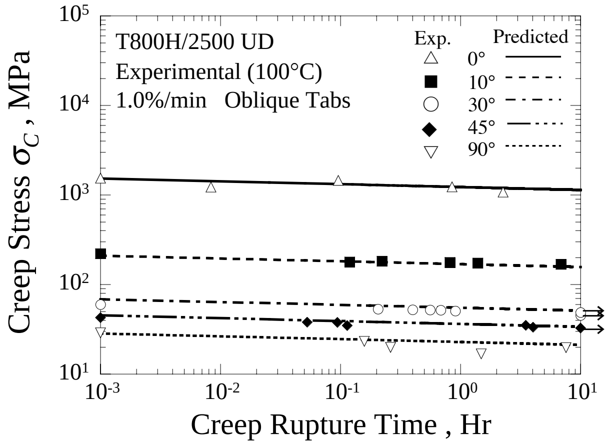
4.4 Comparison with experimental results

The theoretical master creep rupture curve [Eq. (6)] can be identified with the experimental master creep rupture curve plotted using the experimental creep strength ratio, and it is approximated by Eq. (3). Temperature dependence of the stress exponent is determined by fitting Eq. (8) to the stress exponent versus temperature plot. As a result of this procedure, the following approximation was obtained:

$$\frac{1}{n(T)} = 7.2\times10^{-22}T^{7.64} \qquad (12)$$



(a) T = 60°C



(b) T = 100°C

Fig. 5 Comparisons between predicted and observed off-axis creep rupture curves using a damage mechanics model

where T is temperature in K.

In Figs. 5 (a), (b), the off-axis creep rupture curves predicted following this procedure are compared with those observed in experiments at 60, 100°C, respectively. It is seen that the stress dependence and fiber orientation dependence of the off-axis creep rupture strength have been well described using the proposed method. For the other test temperatures, the predictions agreed well with experimental results. Therefore, it may be concluded that the proposed damage mechanics based creep rupture prediction method can adequately predict the off-axis creep rupture life for different fiber orientations over the range of temperature from RT to 130°C.

5. Creep rupture life extrapolation method based on Larson-Miller parameter

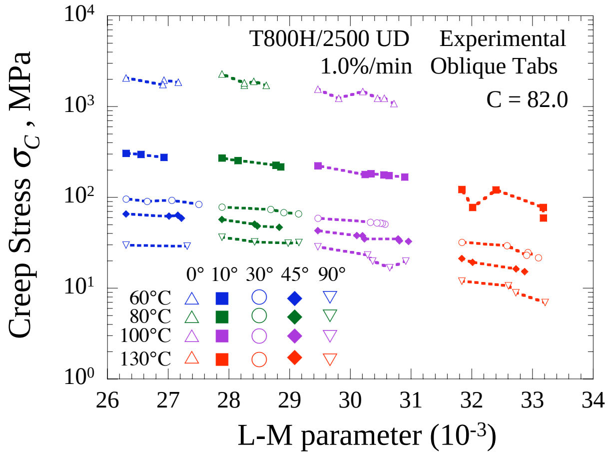


Fig. 6 Larson-Miller plots of the off-axis creep rupture data obtained at different temperatures

5.1 Larson-Miller parameter

In order to build a grand master curve for off-axis creep rupture data at different temperatures, a time-temperature extrapolation parameter is required. One of the commonly used time-temperature parameters (TTPs) is the Larson-Miller (L-M) parameter [6] defined as

$$P_{LM} = T(C + \log t_R) \tag{13}$$

where T is test temperature in K, t_R is time to rupture in hours, and C is a material constant called the Larson-Miller constant.

In Fig. 6, the creep stress levels of those off-axis creep rupture data at different test temperatures are plotted against the Larson-Miller parameter. The value of the Larson-Miller constant C was assumed to be 82 in these plots. It is seen that a single curve can approximately be fitted to the plots of creep stress versus Larson-Miller parameter for the off-axis creep rupture data over the range of test temperature, regardless of the fiber orientation. Therefore, the Larson-Miller parameter can be used for time-temperature extrapolation of the off-axis creep rupture data for the unidirectional CFRP laminate over the range of temperature.

5.2 A grand master rupture curve approach based on σ^* and P_{LM}

Another efficient engineering method for building a grand master rupture curve for off-axis creep is formulated by means of the non-

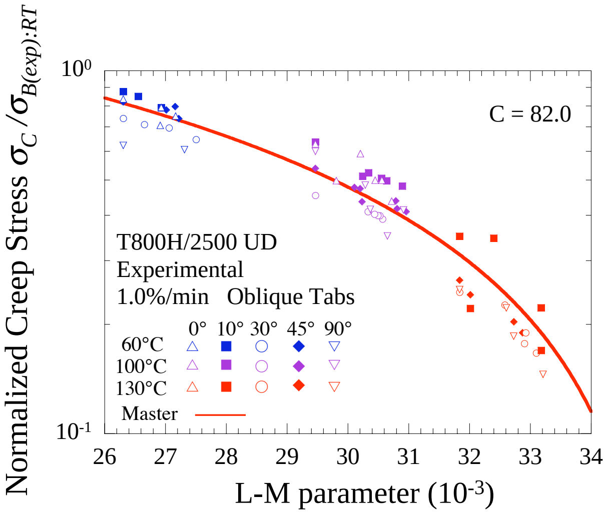


Fig. 7 Normalized creep stress level versus Larson-Miller parameter plots of the off-axis creep rupture data obtained at 60, 100, 130°C

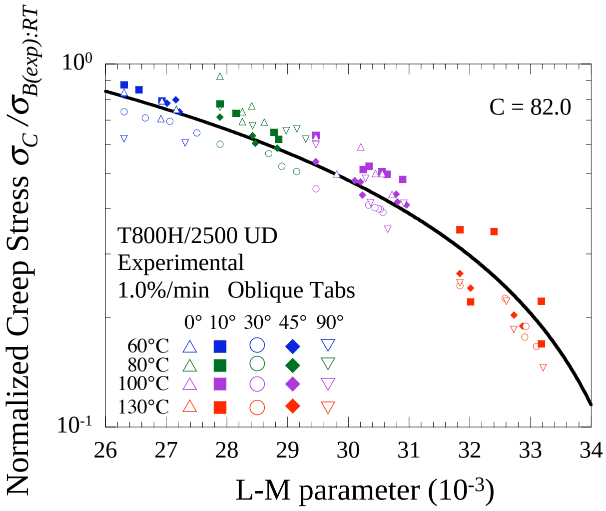


Fig. 8 $\sigma^* - P_{LM}$ plots for all the test temperatures (T = 60, 80, 100, 130°C)

dimensional effective stress and the Larson-Miller parameter in the functional form

$$\sigma_C^* = f(P_{LM}) \tag{14}$$

where the non-dimensional effective stress plays a role to remove the fiber orientation dependence of the off-axis creep rupture data. As a particular form of the functional, a linear approximation

$$\sigma_C^* = a + bP_{LM} \tag{15}$$

is considered in the present study.

The Larson-Miller constant C is determined so that the formula given by Eq. (15) is well fitted to the normalized creep stress level versus Larson-Miller parameter plots, as shown in Fig. 7. In the present case, the material constants involved by the formula were determined as $a = 3.210$, $b = -0.091$ (Kh)$^{-1}$, and C = 82 h. The solid line in Fig. 7 indicates the grand master creep rupture curve identified following the proposed procedure. A good agreement between the theoretical and experimental grand master creep rupture curves has been achieved.

Fig. 8 includes the off-axis creep rupture data at 80°C which were not used for identification of the grand master rupture curve. It is clearly seen that these additional data fall on the grand master creep rupture curve. The grand master creep rupture curve for a given fiber orientation can be reduced by multiplying the normalized stress level and the static strength at a reference temperature. Specifying a temperature further, we can rescale the time axis to extract the off-axis creep rupture curve for the given fiber orientation and temperature.

6. Conclusion

Short-term creep rupture behavior of a unidirectional carbon/epoxy laminate was examined in terms of fiber orientation and temperature dependence. To prediction of the off-axis creep rupture lives of the unidirectional composite over a range of temperature, two kinds of grand master rupture curve approaches were developed. Validities of the proposed methods were estimated by comparing calculated and experimental results. The results obtained can be summarized as follows:

The fiber orientation dependence of the off-axis creep rupture strength at each test temperature can successfully be eliminated using normalized creep stress levels within the time range up to 10 h. This justifies that the non-dimensional effective stress, a theoretical counterpart of the normalized creep stress level, becomes a useful measure to cope with the fiber orientation dependence of the off-axis creep rupture data over the range of test temperature.

The effect of temperature on the off-axis creep rupture behavior of the unidirectional composite can be quantified by means of the change in slope of the normalized master creep rupture curve. The fiber orientation and temperature dependence of the off-axis creep rupture life of the unidirectional CFRP laminate at high temperatures were modeled by means of the framework of the continuum damage mechanics. The proposed model for off-axis creep rupture life prediction was validated over the range of temperature by comparing predicted and experimental results.

A new time-temperature parameter derived on the basis of the damage mechanics approach can successfully be used to define a grand master creep rupture curve that is independent of fiber orientation and test temperature within the range from room temperature to 130°C.

Another simple formula to describe the grand master curve for off-axis creep rupture was devised using the Larson-Miller parameter and the non-dimensional effective stress. This grand master rupture curve approach is also successful in adequately extrapolating the off-axis creep rupture data for the unidirectional composite in the range of temperature from RT to 130°C.

References

[1] Brinson H.F. “Matrix dominated time dependent failure predictions in polymer matrix composites”. *Composite Structures*, Vol. 47, pp 445-456, 1999.

[2] Dillard D.A., Morris D.H. and Brinson H.F. “Predicting Viscoelastic response and delayed failures in general laminated composites”. *Composite Materials: Testing and Design* (Sixth Conference), Ed. I.M. Daniel, ASTM STP 787, pp. 357-370, 1982.

[3] Raghavan J. and Meshii M. “Creep rupture of polymer composites”. *Composites Science and Technology*, Vol. 57, pp 375-388, 1997.

[4] Kawai M., Masuko Y. and Sagawa T. “Off-axis tensile creep rupture of unidirectional CFRP laminates at elevated temperature”. *Composites Part A*, Vol. 37, pp 257-269, 2006.

[5] Monkman F.C. and Grant N.J. “An empirical relationship between rupture life and minimum creep rate in creep-rupture test”. *Proc. ASTM*, Vol. 56, pp 593-620, 1956.

[6] Larson F.R. and Miller A. “A time temperature relationship for rupture and creep stresses”. *Transactions of the ASME*, Vol. 74, pp 765-771, 1952.

[7] Sun C.T. and Chung I. “An oblique end-tab design for testing off-axis composite specimens”. *Composites*, Vol. 24, pp 619-623, 1993.

[8] Kawai M. “Damage mechanics model for off-axis fatigue behavior of unidirectional carbon fiber-reinforced composites at room and high temperatures”. In: Massard, T. and Vautrin, A. (eds.), *Proc. of 12th Int. Conf. on Composite Materials* (ICCM12), Paris, France, July 5-9, p 322, 1999.

[9] Kawai M., Yajima S., Hachinohe A. and Takano Y. “Off-axis fatigue behavior of unidirectional carbon fiber-reinforced composites at room and high temperatures”. *Journal of Composite Materials*, Vol. 35, No. 76, pp 545-576, 2001.