STATISTICAL LIFE TIME PREDICTION FOR UNIDIRECTIONAL CARBON FIBER REINFORCED THERMOPLASTICS UNDER CREEP LOADING

Yoko Morisawa[1], Masayuki Nakada[2] and Yasushi Miyano[3]

[1,2,3]Materials System Research Laboratory, Kanazawa Institute of Technology,
3-1 Yatsukaho, Hakusan, Ishikawa 924-0838, Japan
[1]morisawa@neptune.kanazawa-it.ac.jp
[2]nakada@neptune.kanazawa-it.ac.jp
[3]miyano@neptune.kanazawa-it.asc.jp

Keywords: carbon fiber reinforced thermoplastics, creep failure time, statistical life time prediction, viscoelasticity

Abstract

The tensile strength along the longitudinal direction of unidirectional CFRP is one of the most important data for the reliable design of CFRP structures. Miyano et al developed the test method for the creep and fatigue strengths as well as the static strength at elevated temperatures by using the resin impregnated carbon fiber strand (CFRP strand) as the specimens for the longitudinal direction of unidirectional CFRP. The statistical creep failure time under tension loading for CFRP strands is successfully predicted by using the static strength of CFRP strands measured at various temperatures and the viscoelasticity of matrix resin based on our formulation developed in our previous paper. This paper is concerned with the prediction of statistical creep failure time under tension loading for unidirectional carbon fiber reinforced thermoplastics (CFRTP). First, the static tensile tests for CFRTP strands are carried out at several levels of constant temperature. Second, the statistical creep failure time at a constant load and temperature is predicted based on our formulation by using the statistical results of static tensile strengths for CFRTP strand and the viscoelastic behavior of thermoplastics as the matrices. Finally, the validity of predicted results is cleared by comparing with the experimental results obtained by the creep tests for CFRTP stands.

1. Introduction

Carbon fiber reinforced plastics (CFRP) have been used for the primary structures of airplanes, ships, automobiles and other vehicles for which high reliability must be maintained during long-term operation. Therefore, an accelerated testing methodology is strongly anticipated for the long-term life prediction of CFRP structures exposed to actual environmental temperatures, water, and other influences.

The mechanical behavior of matrix resin of CFRP exhibits time and temperature dependence, called viscoelastic behavior, not only above the glass transition temperature T_g, but also below T_g. Consequently, it can be presumed that the mechanical behavior of CFRP depends strongly on time and temperature [1–5]. Our previous papers have proposed the formulation of statistical static, creep, and fatigue strengths of CFRP based on the viscoelasticity of matrix resin [6–7].

The tensile strength along the longitudinal direction of unidirectional CFRP constitutes important and basic data for the reliable design of CFRP structures. The authors developed a test method for the creep and fatigue strengths as well as the static strength at elevated temperatures by using the resin-impregnated carbon fiber strands (CFRP strands) combined with T300-3000 and epoxy resin [8]. Our

Excerpt from ISBN 978-3-00-053387-7

most recent study undertook the prediction of statistical creep failure time under tension loading along the longitudinal direction of unidirectional CFRP performed using CFRP strands of T300-3000 and epoxy resin. The statistical creep failure time of CFRP strands at a constant load and temperature was predicted using statistical results of static tensile strengths of CFRP strands measured at various temperatures and the viscoelastic behavior of matrix resin. The predicted results quantitatively agree well with the experimentally obtained results measured using creep tests for CFRP strands [9].

As described herein, the proposed method of predicting the statistical creep failure time under the tension loading along the longitudinal direction of unidirectional CFRTP from the statistical static strengths of unidirectional CFRTP measured at various temperatures is clearly valid quantitatively. First, a method of predicting the statistical creep failure time of CFRTP from the statistical static strengths of CFRTP measured at various temperatures is explained briefly based on Christensen's model of viscoelastic crack kinetics [10]. Second, many CFRTP strands combined with T300-3000 and thermoplastic epoxy resin as the specimens for the longitudinal direction of unidirectional CFRTP are prepared using simultaneous molding to elicit stable and uniform mechanical and thermal properties. Third, the static strengths of unidirectional CFRTP are experimentally and statistically measured at various temperatures using these CFRTP strands. Then the creep failure time of unidirectional CFRTP is predicted statistically using the statistical static strengths at various temperatures based on the predicting method. Finally, the creep failure times of unidirectional CFRTP at a constant load and a temperature are measured experimentally and probabilistically using these CFRTP strands for comparison with the predicted ones.

2. Satistical Prediction of Creep Failure Time of Unidirectional CFRTP

We have proposed the formulation for the statistical static strength σ_s of CFRTP based on the viscoelasticity of matrix resin, as shown in the following equation in our previous paper [7] as

$$\log\sigma_s(P_f,t,T)=\log\sigma_0(t_0,T_0)+\frac{1}{\alpha_s}\log[-\ln(1-P_f)]-n_R\log\left[\frac{D^*(t,T)}{D_c(t_0,T_0)}\right], \tag{1}$$

where P_f signifies the failure probability, t denotes the failure time, t_0 represents the reference time, T is the temperature, T_0 stands for the reference temperature, σ_0 and α_s respectively denote the scale parameter and the shape parameter on Weibull distribution of static strength, n_R is the viscoelastic parameter, and D_c and D^* respectively represent the creep and viscoelastic compliances of matrix resin. The viscoelastic compliance D^* for the static load with a constant strain rate is shown by the following equation.

$$D^*(t,T)=D_c(t/2,T) \tag{2}$$

The statistical static strength σ_s is shown by the following equation by substituting Equation (2) into Equation (1).

$$\log\sigma_s(P_f,t,T)=\log\sigma_0(t_0,T_0)+\frac{1}{\alpha_s}\log[-\ln(1-P_f)]-n_R\log\left[\frac{D_c(t/2,T)}{D_c(t_0,T_0)}\right] \tag{3}$$

The creep strength is obtainable by horizontally shifting the static strength by the amount log A. Therefore, the statistical creep strength σ_c is shown by the following equation.

$$\log\sigma_c(P_f,t,T)=\log\sigma_0(t_0,T_0)+\frac{1}{\alpha_s}\log[-\ln(1-P_f)]-n_R\log\left[\frac{D_c(At/2,T)}{D_c(t_0,T_0)}\right] \tag{4}$$

The failure probability of unidirectional CFRTP under a constant creep stress σ_{c0} can be shown by the following equation from Equation (4).

Excerpt from ISBN 978-3-00-053387-7

$$P_{\mathrm{f}} = 1 - \exp\left(-F\right),\ \log F = \alpha_{\mathrm{s}} \log\left[\frac{\sigma_{\mathrm{c}0}}{\sigma_0}\right] + \alpha_{\mathrm{s}} n_{\mathrm{R}} \log\left[\frac{D_{\mathrm{c}}(At/2, T_0)}{D_{\mathrm{c}}(t_0, T_0)}\right] \tag{5}$$

The shifting amount log A determined by the slope k_R of the logarismic static strength against the logarismic failure time is shown by the following equation.

$$\log A = \log(1 + 1/k_{\mathrm{R}}) \tag{6}$$

The slope k_R is obtainable from the following equation [10].

$$k_{\mathrm{R}} = n_{\mathrm{R}} m_{\mathrm{R}} \tag{7}$$

The parameter m_R is the slope of the logarismic creep compliance of matrix resin against the logarismic loading time.

3. Molding of CFRTP Strands

A CFRTP strand which consists of high strength type carbon fiber T300-3000 (Toray Industries Inc.) and a thermoplastic epoxy resin was molded using a filament winding system developed by the authors [8]. Actually, 200 specimens of CFRTP strands were molded at one time using this system. The composition of thermoplastic epoxy resin and the cure condition of CFRTP strand are presented in Table 1. The diameter and the gage length of CFRTP strands are approximately 1 mm and 200 mm, respectively. The glass transition temperatures T_g of the thermoplastic epoxy resin in CFRTP strand was 102°C determined from the peak of loss tangent against temperature at 1 Hz using the DMA.

Table 1. Composition and cure schedule of CFRTP strand T300/thermoplastic epoxy resin.

Carbon fiber strand	Composition of resin (weight ratio)	Cure schedule
T300-3000	Thermoplastic epoxy resin: (100) Cure accelerator: (6.5)	100°C×0.5h

4. Creep Compliance of Matrix Pesin and Static Strength of CFRTP Strands

The dimensionless creep compliance D_c/D_{c0} measured at various temperatures is shown on the left of Figure 1. The long-term D_c/D_{c0} at T=85°C is obtained by shifting horizontally those at various temperatures, as shown in the right of Figure 1. The reference temperature and time are selected as T_0=23°C and t_0=1 min in this study. The creep compliance at reference temperature and reference time D_{c0} is 9.4 (GPa)$^{-1}$. The dashed curve is the dimensionless viscoelastic compliance D^* of matrix resin under the constant strain rate at T=85°C. The maximum slope in this figure is m_R = 0.67 shown in Equation (7).

The static tension tests for CFRTP strand were conducted at four temperature levels, 23°C, 80°C, 90°C, and 95°C with cross-head speed 2 mm/min. The tensile strength of the CFRTP strand σ_s is obtained using the following equation.

$$\sigma_{\mathrm{s}} = \frac{P_{\max}}{t_{\mathrm{e}}} \rho \tag{8}$$

Therein, $P_{\max}$ is the maximum load [N]. ρ and t_e are the density of the carbon fiber [kg/m^3] and the tex of the carbon fiber strand [g/1000 m].

Figure 2 shows the Weibull distributions of the static strength of CFRTP strand. α_s is the shape parameter and β_s is the scale parameter of CFRTP strand in this figure. Although the scale parameter

Excerpt from ISBN 978-3-00-053387-7

decreases according to the temperature raise, the shape parameter maintains almost a constant value for CFRTP strands. σ_0 and α_s in Equation (3), (4) and (5) were determined as shown on Table 2.

Figure 3 presents the dimensionless static strength of CFRTP strand σ_s/σ_0 against the dimensionless viscoelastic compliance of matrix resin D^*/D_{c0} for CFRTP strand. For CFRTP strand, the relation of σ_s/σ_0 against D^*/D_{c0} can be shown by the straight line with the slope of n_R which is the viscoelastic parameter in Equations (3), (4) and (5). n_R is shown on Table 2.

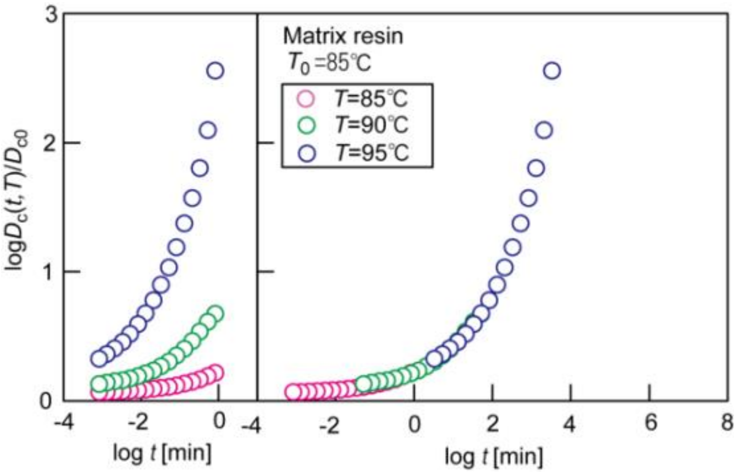
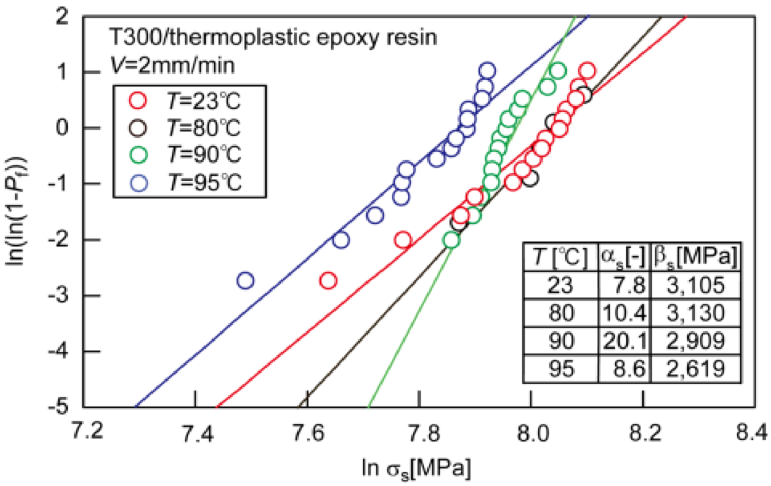


Figure 1. Dimensionless creep compliance of matrix resin at T=85°C.



T [℃]	α_s[-]	β_s[MPa]
23	7.8	3,105
80	10.4	3,130
90	20.1	2,909
95	8.6	2,619

Figure 2. Weibull distributions of static tensile strength of CFRTP strand.

Excerpt from ISBN 978-3-00-053387-7

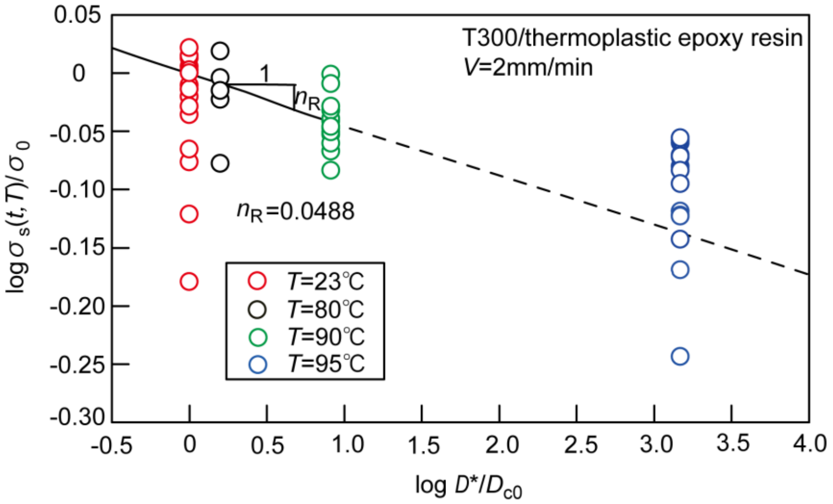


Figure 3. Statistical static strength of CFRTP strand against viscoelastic compliance of matrix resin.

5. Creep Failure Time of CFRTP Strands

Creep failure tests of CFRTP strands were conducted using the specially designed creep failure testing machine [10]. The applied creep stress σ_{c0} was 2,510MPa (80% of scale parameter of static strength at 23°C). Test temperature was 85°C. Number of specimens was 20. Results of the creep failure tests are presented in Figure 4.

The predicted creep failure probability against failure time calculated by substituting the parameters on Table 2 in Equations (5), (6), and (7) is also shown in Figure 4. The predicted statistical creep failure time agrees with the experimental data. This fact clarified that the statistical creep failure time of unidirectional CFRTP can be predicted quantitatively from the statistical static strengths of unidirectional CFRTP and the creep compliances of matrix resin at various temperatures.

6. Effect of Load Ratio and Temperature on Creep Failure Time

The effects of load ratio and temperature on the statistical creep failure time of CFRTP strand were discussed by substituting the parameters of Table 2 in Equation 5. The load ratio σ_{c0}/σ_0 is the ratio of applied creep stress against the scale parameter of static strength at 23°C. Figure 5(a) shows the cases of various load ratio σ_{c0}/σ_0 for the failure probability against creep failure time for CFRTP strand at T = 85 °C and Figure 5(b) shows the cases of various temperatures at the load ratio σ_{c0}/σ_0 = 0.80. The upper figure indicates the faiture time scarcely changes with decreasing the load ratio although the failure probability decreases, and the lower figure indicates the failure time remarkably increases with decreasing temperature.

Table 2. Parameters for statistical creep failure time prediction for CFRTP strand.

Scale parameter of static strength of CFRTP strand at 23°C: σ_0	3,105 MPa
Shape parameter of static strength of CFRTP strand: α_s	11.7
Viscoelastic parameter of matrix resin: n_R	0.0488
Slope of viscoelastic compliance of matrix resin: m_R	0.673
Slope of static strength of CFRTP strand against failure time: k_R	0.0328
Logarithmic time shifting factor: log$A$	1.498

Excerpt from ISBN 978-3-00-053387-7

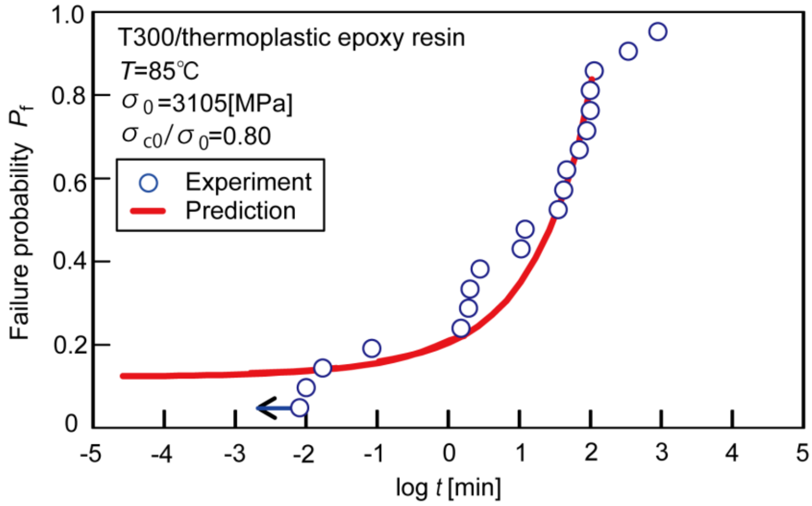
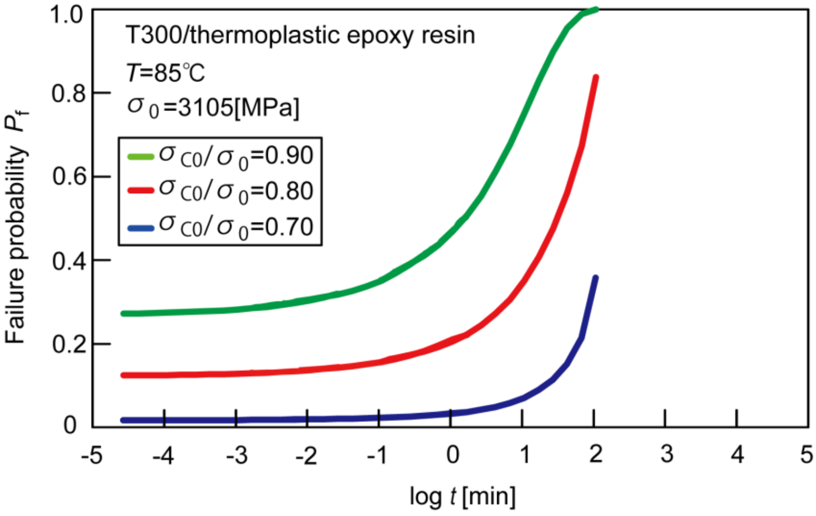
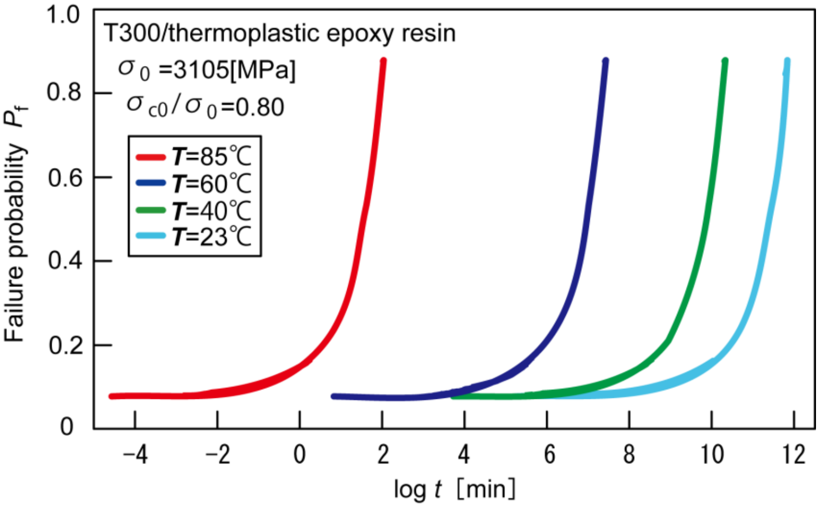


Figure 4. Failure probability against creep failure time for CFRTP strand.



(a) Cases of various load ratio σ_{c0}/σ_0



(b) Cases of various temperatures

Figure 5. Prediction of failure probability against creep failure time for CFRTP strand.

Excerpt from ISBN 978-3-00-053387-7

7. Conclusion

The prediction method for statistical creep failure time under tension loading along the longitudinal direction of unidirectional CFRP using the statistical static tensile strength of CFRP strand and the viscoelasticity of matrix resin based on Christensen's model for viscoelastic crack kinetics were applied to the case of unidirectional CFRTP with a thermoplastic epoxy resin as the matrix. The applicability of the prediction method was confirmed using the following steps.

1. Static strengths at various temperatures under tension loading along the longitudinal direction of unidirectional CFRTP were measured experimentally and statistically using many CFRTP strands.
2. The creep failure times of unidirectional CFRTP were predicted probabilistically using statistical static strengths at various temperatures based on the prediction method.
3. The creep failure times of unidirectional CFRTP at a constant load and a temperature are measured experimentally and statistically using many CFRTP strands for comparison with the predicted ones.

Results show that the statistical creep failure time of unidirectional CFRTP can be predicted using the statistical static strengths of unidirectional CFRTP because the experimental creep failure times agree well quantitatively with the predicted ones.

Acknowledgments

This research was promoted by COI program "Construction of next-generation infrastructure using innovative materials ~Realization of a safe and secure society that can coexist with the Earth for centuries~ supported by MEXT and JST.

References

[1] J. Aboudi and G. Cederbaum, Analysis of Viscoelastic Laminated Composite Plates, *Composite Structures*, **12**, 1989, pp.243–256.

[2] J. Sullivan, Creep and Physical Aging of Composites, *Composites Science and Technology*, **39**, 1990, pp.207–232.

[3] T. Gates, Experimental Characterization of Nonlinear, Rate Dependent Behavior in Advanced Polymer Matrix Composites, *Experimental Mechanics*, **32**, 1992, pp.68–73.

[4] Y. Miyano, M. Nakada, M.K. McMurray and R. Muki, Prediction of Flexural Fatigue Strength of CFRP Composites under Arbitrary Frequency, Stress Ratio and Temperature, *Journal of Composite Materials*, **31**, 1997, pp.619–638.

[5] M. Kawai, Y. Yagihashi, H. Hoshi and Y. Iwahori, Anisomorphic constant fatigue life diagrams for quasi-isotropic woven fabric carbon/epoxy laminates under different hygro-thermal environments, *Advanced Composite Materials*, **22**, 2013, pp.79–98.

[6] Y. Miyano, M. Nakada, and H. Cai, Formulation of Long-term Creep and Fatigue Strengths of Polymer Composites Based on Accelerated Testing Methodology, *Journal of Composite Materials*, **42**, 2008, pp.1897–1919.

[7] M. Nakada and Y. Miyano, Advanced Accelerated Testing Methodology for Long-Term Life Prediction of CFRP Laminates, *Journal of Composite Materials*, **49**, 2015, pp.163-175. DOI: 10.1177/0021998313515019.

[8] Y. Miyano, M. Nakada, H. Kudoh and R. Muki, Prediction of Tensile Fatigue Life under Temperature Environment for Unidirectional CFRP, *Advanced Composite Materials*, **8**, 1999, pp.235–246.

[9] M. Nakada and Y. Miyano, Statistical Creep Failure Time of Unidirectional CFRP, *Experimental Mechanics*, Published online: 05 June 2015, DOI 10.1007/s11340-015-0049-6.

[10] R. Christensen and Y. Miyano, Stress Intensity Controlled Kinetic Crack Growth and Stress History Dependent Life Prediction with Statistical Variability, *International Journal of Fracture*, **137**, 2006, pp.77–87.

Excerpt from ISBN 978-3-00-053387-7