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

Masayuki Nakada[1], Yoko Morisawa[2] , Yasushi Miyano[3] and Kiyoshi Uzawa[4]

[1,2,3,4]Materials System Research Laboratory, Kanazawa Institute of Technology,
3-1 Yatsukaho, Hakusan, Ishikawa 924-0838, Japan
[1]nakada@neptune.kanazawa-it.ac.jp, [2]morisawa@neptune.kanazawa-it.ac.jp,
[3]miyano@neptune.kanazawa-it.ac.jp, [4]uzawa@neptune.kanazawa-it.ac.jp,
[1,2,3,4]http://wwwr.kanazawa-it.ac.jp/MSRL/

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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. First, the test method for the creep strength as well as the static strength at elevated temperatures for the longitudinal direction of unidirectional CFRTP with thermoplastic epoxy resin as the matrix is developed by using the thermoplastic epoxy resin impregnated carbon fiber strand (CFRTP strand) as the specimens. Second, the static tensile strengths of CFRTP strands are statistically measured at various constant temperatures under a constant strain rate, and the statistical creep failure times under tension loading for CFRTP strands are predicted at a constant temperature by substituting the statistical static strengths into the formulation based on the viscoelasticity of matrix resin developed in our previous paper. Third, the validity of predicted results is cleared by comparing with the creep failure times measured statistically by the creep tests for CFRTP strands. Finally, the relationship between the failure probability and creep failure times at various load and temperature conditions were discussed by using the predicted results.

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 strand (CFRP strand) [8]. Our most recent study undertook the prediction of statistical creep failure time under tension loading along the longitudinal direction of unidirectional

CFRP performed using CFRP strand of T300-3000 and thermoset epoxy resin. The statistical creep failure time of CFRP strand at a constant load and temperature was predicted using statistical results of static tensile strengths of CFRP strand 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 strand [9].

In this paper, the prediction of the statistical creep failure time under the tension loading for CFRTP strand using thermoplastic epoxy as a matrix is performed. First, a method of predicting the statistical creep failure time of CFRP from the statistical static strengths of CFRP 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 as a matrix are prepared. Third, the static strengths of CFRP strand are experimentally and statistically measured at various temperatures. Then the creep failure time of CFRP strand is predicted statistically using the statistical static strengths at various temperatures based on the predicting method. Fourth, the creep failure times of CFRP strand at a constant load and a temperature are measured experimentally and probabilistically using these CFRP strands for comparison with the predicted ones. Finally, the relationship between the failure probability and creep failure times at various load and temperature conditions were discussed by using the predicted results.

2. Satistical Prediction of Creep Failure Time of CFRP

We have proposed the formulation for the statistical static strength σ_s of CFRP 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 of CFRP is shown by the following equation by substituting Eq.2 into Eq.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 of CFRP 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 CFRP under a constant creep stress σ_{c0} can be shown by the following equation from Eq.4.

$$P_f = 1 - \exp(-F),\ \log F = \alpha_s \log\left[\frac{\sigma_{c0}}{\sigma_0}\right] + \alpha_s n_R \log\left[\frac{D_c(At/2,T_0)}{D_c(t_0,T_0)}\right] \tag{5}$$

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

$$\log A = \log(1 + 1/k_R) \tag{6}$$

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

$$k_R = n_R m_R \tag{7}$$

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

3. Molding of CFRP Strand

A CFRP strand which consists of high strength type carbon fiber T300-3000 (Toray Industries Inc.) and a thermoplastic epoxy was molded by pultrusion method. For the comparison, we present the test results for the CFRP strand which consists of same carbon fiber T300-3000 and a thermoset epoxy. The composition of matrix epoxy and the cure condition for these two types of CFRP strand are presented in Table 1. The diameter and the gage length of CFRP strand are approximately 1 mm and 200 mm, respectively. The glass transition temperatures T_g of the thermoplastic epoxy was 102°C, and that for thermoset epoxy was 150°C respectively determined from the peak of loss tangent against temperature at 1 Hz using the DMA.

Table 1. Composition and cure schedule of CFRP strand.

CFRP strand	Carbon fiber strand	Composition of resin (weight ratio)	Cure schedule
T300/TS-EP	T300-3000	Epoxy resin (100) Hardener (104) Cure accelerator (1.0)	70°C×12h +150°C× 4h +190°C× 2h
T300/TP-EP	T300-3000	Thermoplastic epoxy resin (100) Cure accelerator (6.5)	150°C×0.5h

4. Creep Compliance of Matrix Resin and Static Strength of CFRP Strands

The dimensionless creep compliances D_c/D_{c0} measured at various temperatures for thermoset epoxy (TS-EP) and thermoplastic epoxy (TP-EP) are shown on the left of Fig.1. The long-term D_c/D_{c0} s at T=120°C for TS-EP and T= 70°C for TP-EP are respectively obtained by shifting horizontally those at various temperatures, as shown in the right of Fig.1. The reference temperature and time are selected as T_0=25°C and t_0=1 min. The creep compliance at reference temperature and reference time D_{c0} is 0.3 $(\mathrm{GPa})^{-1}$ for TS-EP and 0.31 $(\mathrm{GPa})^{-1}$ for TP-EP. The slope of the logarismic creep compliance of matrix resin against the logarismic loading time is m_R = 0.28 for TS-EP and m_R = 0.17 for TP-EP shown in Eq.7.

The static tension tests for CFRP strand were conducted at several constant temperatures with cross-head speed 2 mm/min. The tensile strength of the CFRP strand σ_s is obtained using the following equation.

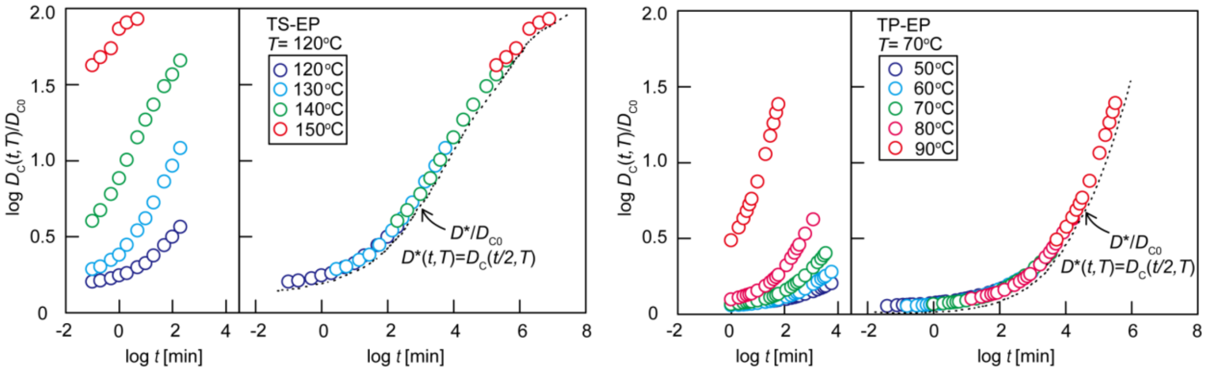
$$\sigma_s = \frac{P_{\max}}{t_e}\rho \tag{8}$$

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 CFRP strand. Although the scale parameter σ_0 decreases according to the temperature raise, the shape parameter α_s maintains almost a constant value for CFRP strands. σ_0 and α_s in Eqs.3, 4 and 5 were determined as shown on Table 2.

Figure 3 presents the dimensionless static strength of CFRP strand σ_s/σ_0 against the dimensionless viscoelastic compliance of matrix resin D^*/D_{c0}. 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 Eqs.3, 4 and 5. n_R is shown on Table 2.

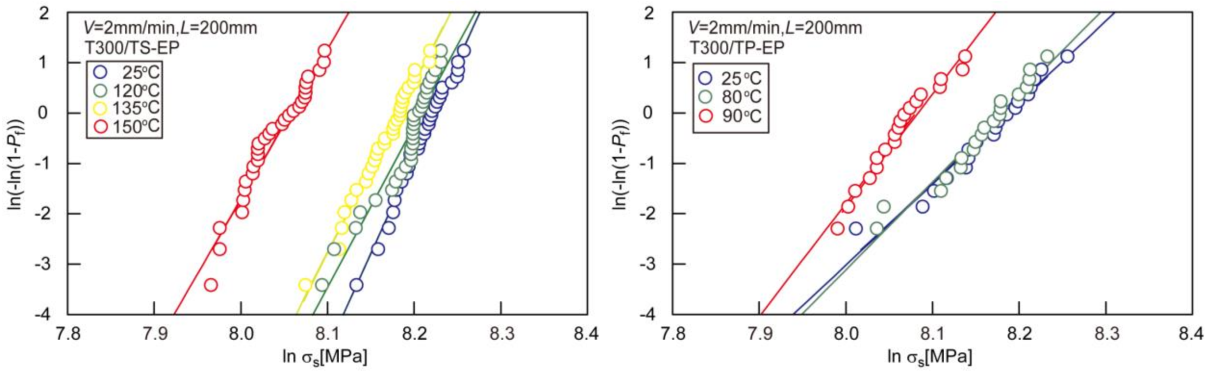
The tensile strength of CFRP strand at 25°C is almost same to that for carbon fiber itself. We have considered to develop the molding method of CFRP strand with unidirectional arignment of carbon fiber and with stable T_g of matrix resin. We have also considered to develop the tensile test method with special designed constant temperature chamber to keep the constant temperature in the cetral portion of CFRP strand specimen during testing [8]. Therefore, we can evaualte the tensile creep strength as well as tensile static strength of unidirectional CFRP under constatnt temperature condition by using CFRP strand specimen.



(a) Thermosett epoxy (TS-EP)

(b) Thermoplastic epoxy (TP-EP)

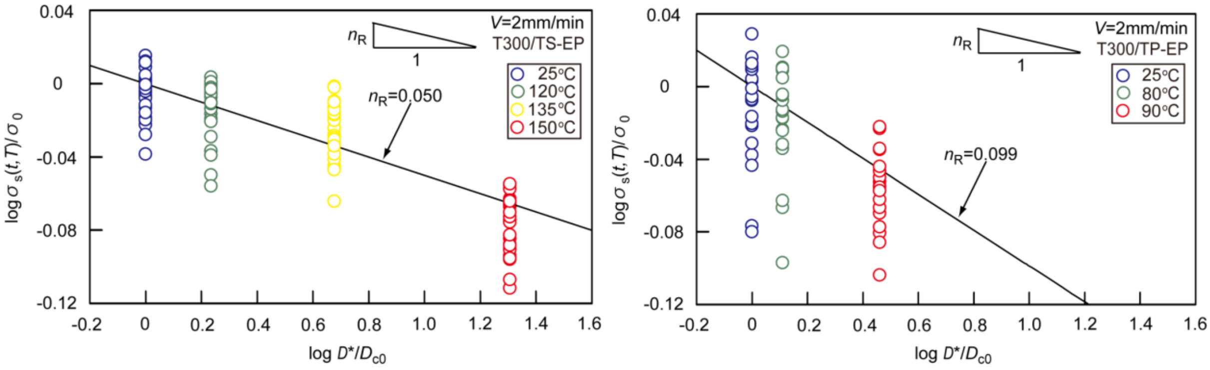
Figure 1. Dimensionless creep compliance of matrix resin.



(a) T300/TS-EP

(b) T300/TP-EP

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



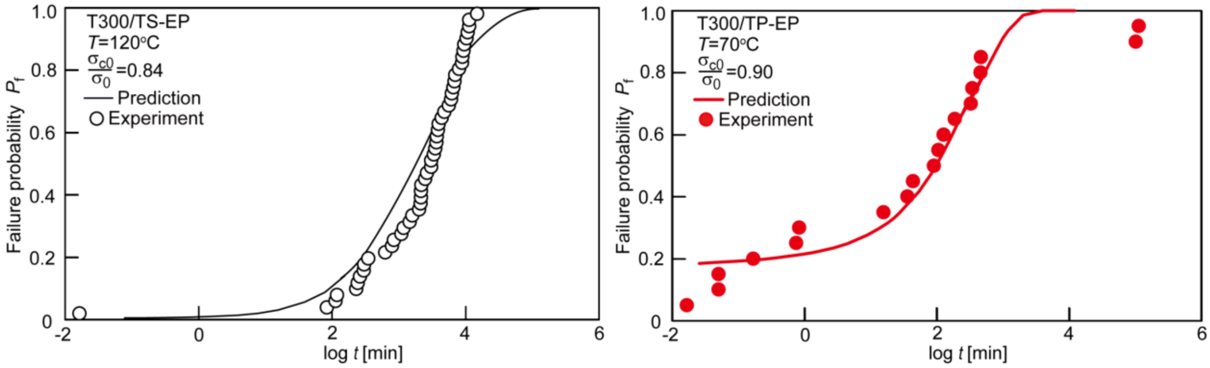
(a) T300/TS-EP (b) T300/TP-EP

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

5. Creep Failure Time of CFRP Strands

Creep failure tests of CFRP strands were conducted using the specially designed creep failure testing machine [9]. The applied creep stress σ_{c0} was 3,127MPa (84% of scale parameter of static strength at 25°C) for T300/TS-EP and 3,227MPa (90% of scale parameter of static strength at 25°C) for T300/TP-EP. Test temperature was 120°C for T300/TS-EP and 70°C for T300/TP-EP. Results of the creep failure tests are presented in Fig.4.

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



(a) T300/TS-EP (b) T300/TP-EP

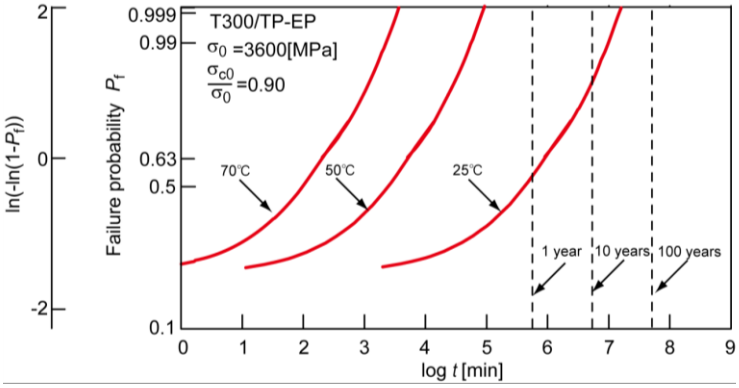
Figure 4. Failure probability against creep failure time for CFRP strand.

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

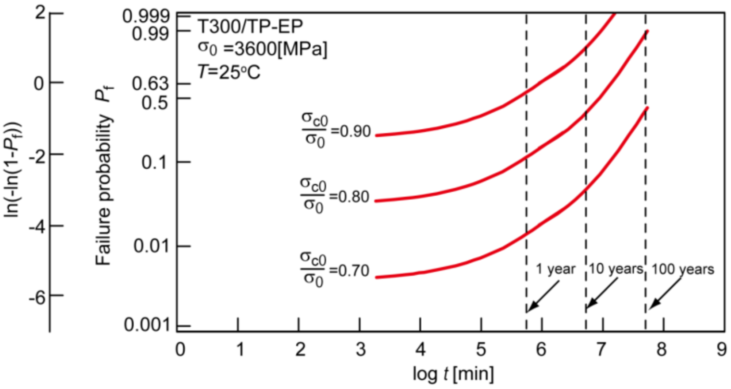
	T300/TS-EP	T300/TP-EP
Scale parameter of static strength of CFRP strand at 25°C: σ_0	3723	3600
Shape parameter of static strength of CFRP strand: α_s	33	16
Viscoelastic parameter of matrix resin: n_R	0.050	0.099
Slope of viscoelastic compliance of matrix resin: m_R	0.28	0.17
Slope of static strength of CFRP strand against failure time: k_R	0.014	0.017
Logarithmic time shifting factor: log$A$	1.86	1.79

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

The effects of temperature and load ratio on the statistical creep failure time of CFRP strand were discussed by substituting the parameters of Table 2 in Eq. 5. The load ratio σ_{c0}/σ_0 is the ratio of applied creep stress against the scale parameter of static strength at 25°C. Figure 5 shows the failure probability against creep failure time of CFRP strand for the cases of various temperatures at the load ratio σ_{c0}/σ_0 = 0.90 and for the cases of various load ratios σ_{c0}/σ_0 at T = 25 °C. These results indicate that the failure time remarkably increases with decreasing temperature and that the faiture time scarcely changes with decreasing the load ratio although the failure probability remarkably decreases.



(a) Cases of various temperatures



(b) Cases of various load ratios σ_{c0}/σ_0

Figure 5. Prediction of failure probability against creep failure time for T300/TP-EP.

7. Conclusions

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 as a matrix. 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. Finally, the relationship between the failure probability and creep failure times at various load and temperature conditions were cleared by using the predicted results.

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