PREDICTION OF TENSILE CREEP FAILURE TIME FOR UNIDIRECTIONAL CFRP

Yoshiki Kobayashi[1], Masayuki Nakada[2] and Yasushi Miyano[3]

[1] Graduate School, Kanazawa Institute of Technology, Nonoichi, Ishikawa, Japan
Email: b6500229@planet.kanazawa-it.ac
[2,3]Materials System Research Laboratory, Kanazawa Institute of Technology, Yatsukaho, Hakusan, Japan
[2]Email: nakada@neptune.kanazawa-it.ac.jp
[3]Email: miyano@neptune.kanazawa-it.ac.jp

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Abstract
This paper is concerned with the statistical prediction of creep failure time under the tension loading along the longitudinal direction of unidirectional CFRP based on the viscoelasticity of matrix resin. The resin impregnated carbon fiber strands (CFRP strands) were used as the specimens for the static and creep tests of unidirectional CFRP. It was cleared for CFRP combined with high strength carbon fibers T300 and epoxy resin that the statistical creep failure time of unidirectional CFRP can be predicted by using the statistical static strengths at various temperatures and the viscoelasticity of matrix resin based on Christensen’s model of viscoelastic crack kinetics. Furthermore, the applicability of prediction method was discussed for CFRP combined with high modulus carbon fibers M40J and epoxy resin.

1. Introduction

Carbon fiber reinforced plastics (CFRP) has been used for the primary structures of airplanes, ships, automobiles and others, in which the high reliability should be kept during the long-term operation. Therefore, it is strongly expected that the accelerated testing methodology for the long-term life prediction of CFRP structures exposed under the actual environmental temperature, water and others will be established.

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. Thus, it can be presumed that the mechanical behavior of CFRP significantly depends on time and temperature [1-6]. We have proposed the formulation for the statistical static strength of CFRP based on the viscoelasticity of matrix resin in our previous papers [7, 8].

The tensile strength along the longitudinal direction of unidirectional CFRP is one of the important data for the reliable design of CFRP structures. The authors developed the test method for the creep and fatigue strengths as well as the static strength at elevated temperatures for the resin impregnated carbon fiber strand (CFRP strand) [9-11].

This paper is concerned with the prediction of statistical creep failure time under the tension loading along the longitudinal direction of unidirectional CFRP. CFRP strands combined with high strength carbon fiber T300 and epoxy resin are used for the static and creep tests of unidirectional CFRP in this

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paper. First, the static tests for CFRP strands are carried out at four levels of constant temperature by using 30 specimens for each temperature. Second, the statistical creep failure time at a constant load and a temperature is predicted using the statistical static strengths at four temperatures and the viscoelastic behavior of matrix resin based on Christensen's model of viscoelastic crack kinetics. Finally, the validity of predicted results is cleared by comparing with the experimental results obtained by the creep rupture tests for CFRP strands of 30 specimens. Furthermore, the applicability of prediction method was discussed for CFRP combined with high modulus carbon fibers M40J and epoxy resin.

2. Statistical Prediction of Creep Failure Time of Unidirectional 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 [8],

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

where, P_f is the failure probability, t is the failure time, t_0 is the reference time, T is the temperature, T_0 is the reference temperature, σ_0 and σ_s are the scale parameter and the shape parameter on Weibull distribution of static strength, n_R is the viscoelastic parameter, and D_c and D^* are 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 failure probability of unidirectional CFRP under creep load with a constant stress can be shown by the following equation.

$$P_f=1-\exp(-F),\ \log F=\alpha\log\left[\frac{\sigma_c}{\sigma_0}\right]+\alpha\ n_R\log\left[\frac{D_c(At/2,T_0)}{D_c(t_0,T_0)}\right] \tag{3}$$

Where the shifting amount log A determined by the slope of the static strength curve is shown by the following equation.

$$\log A=\log(1+1/k_R) \tag{4}$$

3. Experiments

3.1. Specimens

CFRP strand which consists of T300-3000 (Toray Industries Inc.) and a general purpose epoxy resin jER828 (Mitsubishi Chemical Corp.) was molded using filament winding method .The composition of epoxy resin and the cure condition of CFRP strand are shown in Table 1. As shown on this table, two kinds of curing conditions were selected in this paper. The diameter and the gage length of CFRP strands are approximately 1mm and 200mm, respectively. Figure 1 shows the CFRP strand specimen. The glass transition temperature T_g of the epoxy resin is approximately 150˚C. The fiber volume fraction of CFRP strand is approximately 55%. The tensile strength of the CFRP strand σ_s is defined by

$$\sigma_s=\frac{P_{max}}{t_e}\rho \tag{5}$$

where P_{max} is 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/1000m].

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Table 1. Composition and cure schedule of epoxy resin.

Matrix resin	
Composition	Weight ratio
Epoxy : jER 828	100
Hardener : MHAC-P	103.6
Cure accelerator : 2-Ethyl-4-methylimidazol	1
Cure schedule	
[A] 100℃×5hr+150℃×4hr+190℃×2hr+(-0.5℃/min)	
[B] 70°C×12hr+150°C×4hr+190°C×2hr+(-0.5°C/min)	

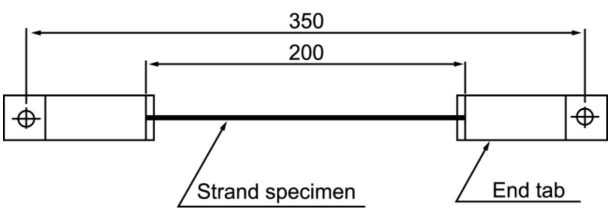

Figure 1. CFRP strand specimen.

3.2. Creep Compliance of Matrix Resin

The dimensionless creep compliance D_c/D_{c0} measured at various temperatures is shown in the left of Fig.2 and the long-term D_c/D_{c0} at T=120°C is obtained by shifting horizontally those at various temperatures as shown in the right of Fig.2. The reference temperature and time are selected as T_0=25 °C and t_0=1min in this study. Creep compliance at reference temperature and reference time D_{c0} is 0.33(GPa)$^{-1}$. The dashed curve is the dimensionless viscoelastic compliance D^* of matrix resin under the constant strain rate at T=120°C.

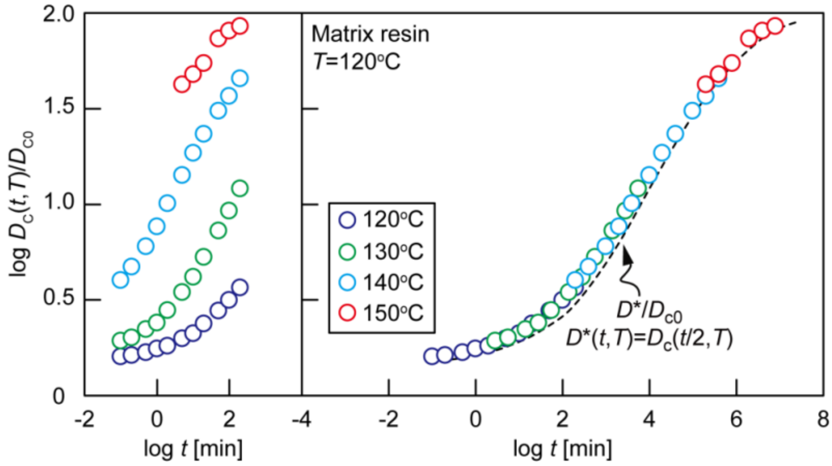

Figure 2. Dimensionless creep compliance of matrix resin at T=120°C.

3.3. Static Strength of CFRP Strand

The static strength tests for CFRP strand were conducted at 4 levels of temperature, 25°C, 120°C, 135°C and 150°C with cross-head speed 2mm/min. The Weibull distributions of the static strength of

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CFRP strand at four temperatures are shown in Fig.3. α_s is the shape parameter and β_s is the scale parameter of CFRP strand in this figure. While the scale parameter decreases according to the temperature raise, the shape parameter keeps almost a constant value. The α and σ_0 for two curing conditions in Equation (3) were selected from both values ar room temperature.

Figure 4 show the dimensionless static strength of CFRP strand σ_s/σ_0 against the dimensionless viscoelastic compliance of matrix resin D^*/D_{c0} at the same time and temperature. The solid lines are approximated lines of the experimental results. The n_R for two curing conditions in Equation (3) were determined, respectively.

All parameters in Equation (3) were obtained as shown on Table 2.

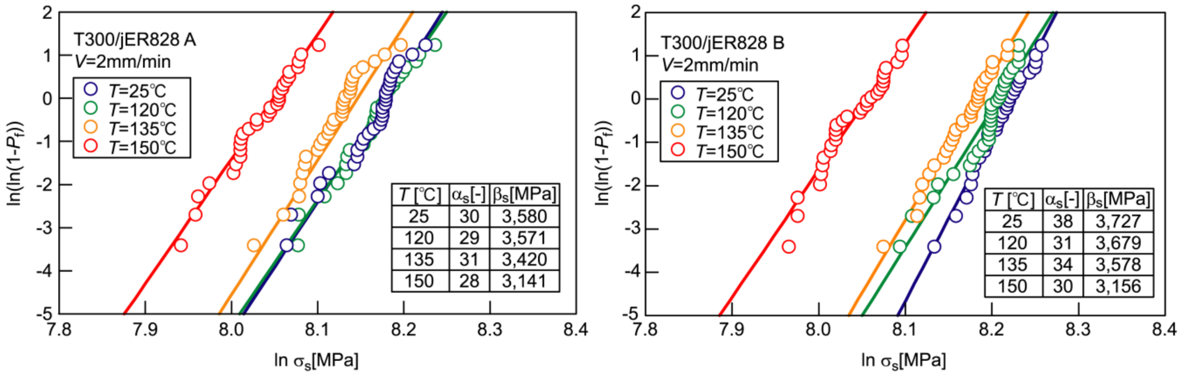

Figure 3. Weibull distribution of tensile strength for CFRP strands.

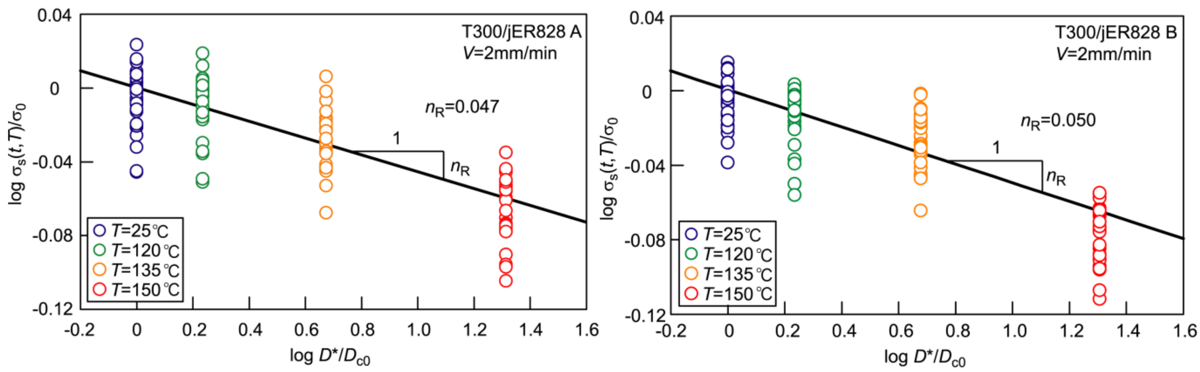

Figure 4. Tensile strength ratio of CFRP strands versus viscoelastic compliance of matrix resin.

Table 2. Parameters for statistical static and creep master curves of CFRP strand.

	[A]	[B]
Scale parameter of static strength of CFRP strand at reference time and temp. : σ_{s0}	3,580 MPa	3,730 MPa
Shape parameter of static strength of CFRP strand at reference time and temp. : α_{s0}	30	38
Slope of static strength of CFRP strand: k_R	0.013	0.014
Logarithmic time shifting factor: log A	1.87	1.86

3.4. Creep Failure Tests of CFRP Strand

Creep failure tests of T300 CFRP stands were conducted by using the specially designed creep failure testing machine. The test condition is shown in Table 3. The results of the creep failure tests are shown in Fig.6. Test temperature is 120°C. σ_{c0} and σ_0 represents the scale parameter of the static strength at 25°C and the tensile creep stress. Tensile creep stress was 84% of the scale parameter of the static strength at 25°C.

Table 3. Creep test condition.

	Temperature	σ_{co}	σ_o	σ_{co}/σ_o	Number of specimens
A	120° C	3,007 MPa	3,580 MPa	84%	30
B	120° C	3,131 MPa	3,727 MPa	84%	30

3.5. Statistical Prediction of Creep Failure Time of CFRP Strand

As shown in Fig.5, the statistical creep failure time were obtained by substituting the parameters on Table 3 in Equations (3). The predicted statistical creep failure time agrees well with the experimental data.

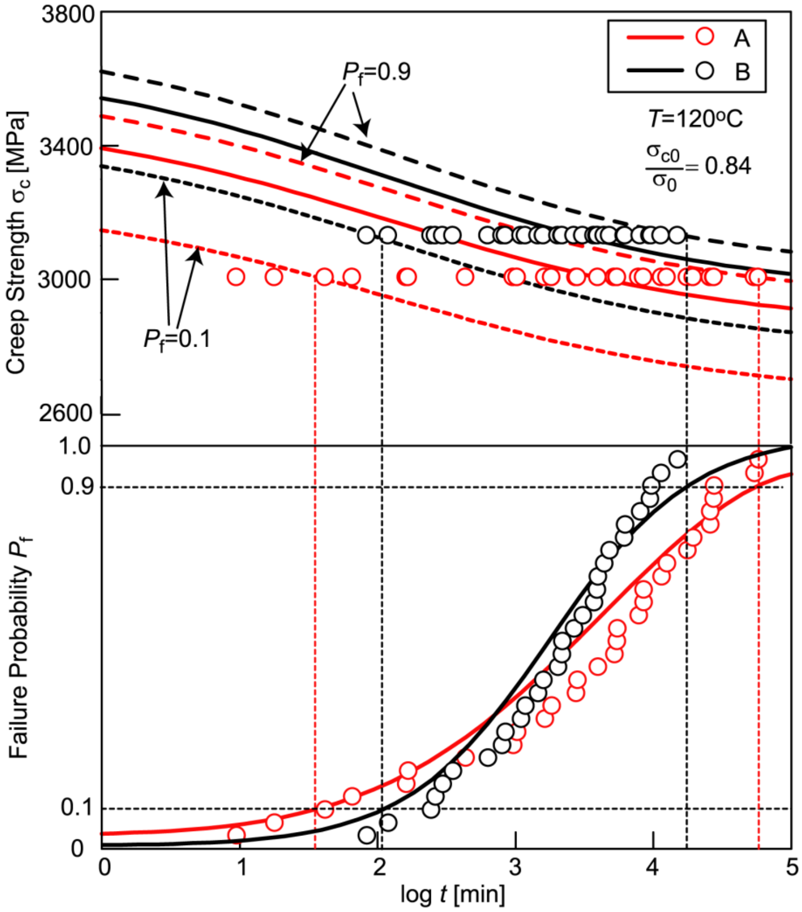

Figure 5. Probability of creep failure time of CFRP strand.

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4. Discussion

CFRP strand with high modulus carbon fiber M40J and epoxy resin were employed for comparing with T300 CFRP strand cured by condition [B]. Figure 6 shows Weibull distributions of static strengths at various temperatures in which the scale parameter α_s as well as the shape parameters β_s of M40J CFRP strand does not show temperature dependent. Therefore, the n_R of M40J CFRP strand is equal to zero as shown Fig.7.

Figure 8 shows the master curves and the failure probabilities against creep failure time for two kinds of CFRP strands of which the carbon fibers are T300[B] and M40J. Creep test condition of M40J is shown in Table 4. Figure 8 shows theoretically and experimentally that M40J CFRP strand does not occur the creep failure although T300 CFRP strand clearly occurs the creep failure. Concreatly, the failure probability P_f is predicted to be only 0.32% theoretically in the case of σ_{c0}/σ_0 = 0.84 and it is confirmed experimentally that loaded ten specimens do not fails for long period as shown in the lower portion in Fig.8.

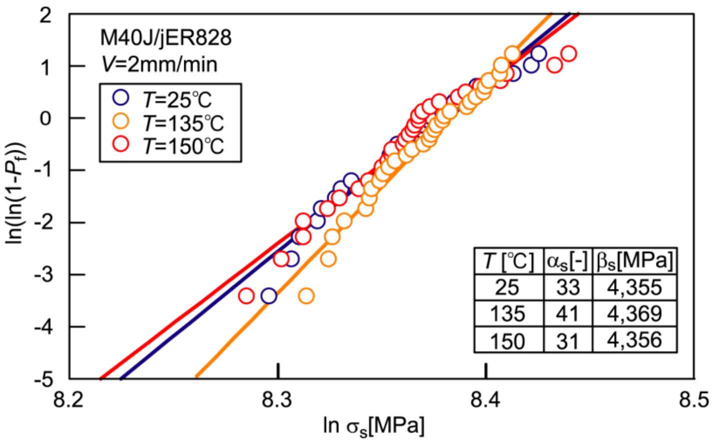

Figure 6. Weibull distribution of tensile strength for M40J CFRP strands.

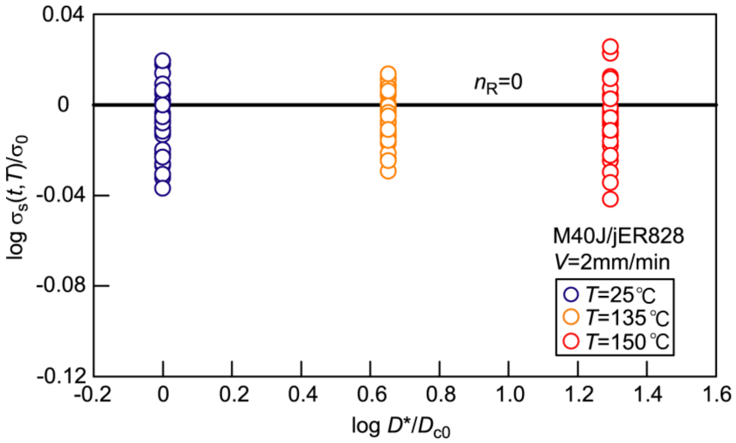

Figure 7. Tensile strength ratio of CFRP strands versus viscoelastic compliance of matrix resin.

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Table 4. Creep test condition.

Temperature	σ_{c0}	σ_0	σ_{c0}/σ_0	Number of specimens
120°C	3,658MPa	4,355MPa	84%	10

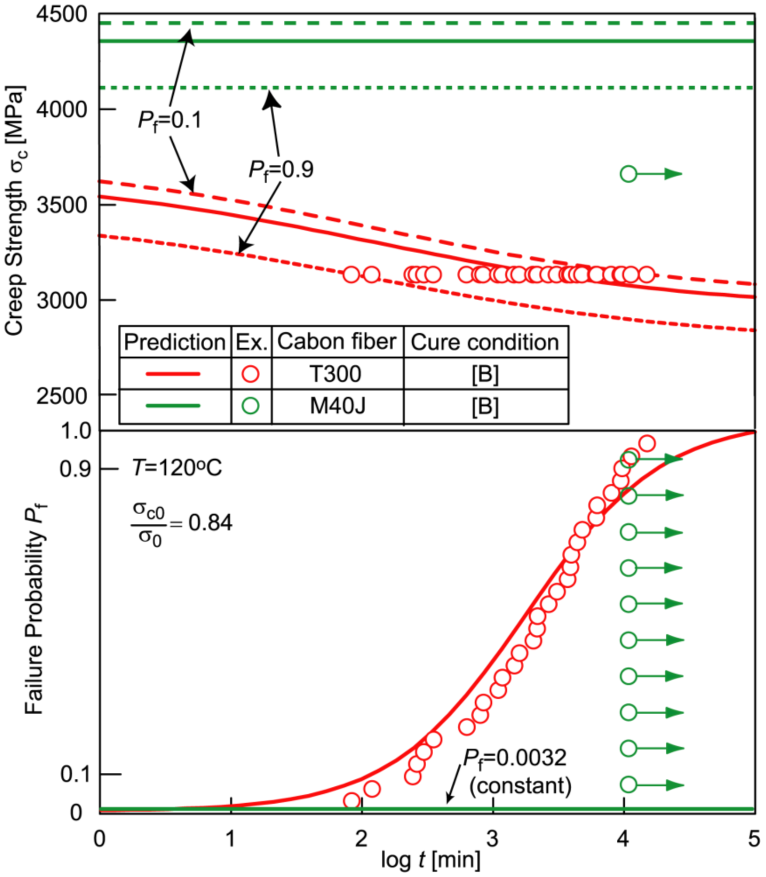

Figure 8. Probability of creep failure time of T300 and M40J CFRP strands.

5. Conclusion

We proposed the prediction method for statistical creep failure time under the tension loading along the longitudinal direction of unidirectional CFRP using the statistical static tensile strengths of CFRP strand and the viscoelasticity of matrix resin based and Christensen's model for viscoelastic crack kinetics. The applicability of prediction method can be confirmed through the following steps.

1. The statistical static strength of high strength T300 CFRP strand shows Weibull distribution based on Christensen's model of viscoelastic crack kinetics. While the scale parameter decreases according to the temperature raise, the shape parameter keeps almost a constant value.
2. The statistical creep failure time at a constant load and temperature predicted using the statistical static tensile strengths of T300 CFRP strand and the viscoelasticity of matrix resin based on Christensen's model for viscoelastic crack kinetics agrees with the experimental results obtained by the creep rupture tests for T300 CFRP stands.
3. The statistical static strength of high modulus M40J CFRP strand does not change with temperature and M40J CFRP strand does not occur the creep failure.

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