AFRL-AFOSR-JP-TR-2019-0015

Statistical Creep Failure Time of Unidirectional CFRP under Compression Loading

Yasushi Miyano
KANAZAWA INSTITUTE OF TECHNOLOGY

08/20/2018
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 19-03-2019	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* 07 Jul 2016 to 06 Jul 2018

4. TITLE AND SUBTITLE
Statistical Creep Failure Time of Unidirectional CFRP under Compression Loading

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA2386-16-1-4088

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Yasushi Miyano, Masayuki Nakada

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
KANAZAWA INSTITUTE OF TECHNOLOGY
7-1 OHGIGAOKA, NONOICHI-MACHI ISHIKAWA-GUN
ISHIKAWA, 9218501 JP

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AOARD
UNIT 45002
APO AP 96338-5002

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR IOA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-JP-TR-2019-0015

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

. The compressive and tensile creep failure times of unidirectional CFRP were statistically predicted by substituting the compressive and tensile static strengths measured at various temperatures and viscoelastic behavior of matrix resin in our proposed formulation. Then the compressive and tensile creep failure times of unidirectional CFRP at a constant load and temperature were measured experimentally for comparison with the predicted ones. The characteristics of statistical compressive and tensile creep failure times of unidirectional CFRP were compared with each other from the difference of failure modes in the compression and tension loads.

15. SUBJECT TERMS
Creep, CFRP, Failure, Fatigue, Time-temperature superposition, Superposition, GFRP, Composite, Life prediction, Lifetime

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			KNOPP, JEREMY
Unclassified	Unclassified	Unclassified	SAR		**19b. TELEPHONE NUMBER** *(Include area code)* 315-227-7006

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AFRL-AFOSR-JP-TR-2019-0015
Grant No. FA2386-16-1-4088

STATISTICAL CREEP FAILURE TIME OF UNIDIRECTIONAL CFRP UNDER COMPRESSION LOADING

Yasushi Miyano[1] and Masayuki Nakada[2]

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

August 31, 2018

Final Report

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* *31-8-2018*	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* *From 07 July 2016 – To 06 July 2018*

4. TITLE AND SUBTITLE
Statistical Creep Failure Time of Unidirectional CFRP under Compression Loading

5a. CONTRACT NUMBER
FA2386-16-1-4088

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Yasushi Miyano and Masayuki Nakada

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Materials System Research Laboratory, Kanazawa Institute of Technology,
3-1 Yatsukaho Hakusan Ishikawa 924-0838 Japan

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Asian Office of Aerospace R&D
7-23-17 Roppongi Minato-ku Tokyo 160-0032 Japan

10. SPONSOR/MONITOR'S ACRONYM(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This paper is concerned with the statistical prediction of compressive creep failure time in the longitudinal direction of unidirectional CFRP based on the viscoelasticity of matrix resin. The compressive and tensile creep failure times of unidirectional CFRP were statistically predicted by substituting the compressive and tensile static strengths measured at various temperatures and viscoelastic behavior of matrix resin in our proposed formulation. Then the compressive and tensile creep failure times of unidirectional CFRP at a constant load and temperature were measured experimentally for comparison with the predicted ones. The characteristics of statistical compressive and tensile creep failure times of unidirectional CFRP were compared with each other from the difference of failure modes in the compression and tension loads.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER**	**19a. NAME OF RESPONSIBLE**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)

TABLE OF CONTENTS

List of Tables and Figures

1.0 Summary

The tensile strength along the longitudinal direction of unidirectional CFRP constitutes important and basic data for the reliable design of CFRP structures. Our most recent study undertook the prediction of statistical creep failure time under tension load along the longitudinal direction of unidirectional CFRP. The statistical creep failure time of unidirectional CFRP at a constant load and temperature was statistically predicted by substituting the statistical results of tensile static strengths of unidirectional CFRP measured at various temperatures and the viscoelastic behavior of matrix resin in our proposed formulation based on the accelerated testing methodology (ATM). The predicted results quantitatively agree well with the experimental results measured by the creep tests for unidirectional CFRP.

This paper is concerned with the statistical prediction of creep failure times under bending load as well as tension load in the longitudinal direction of unidirectional CFRP based on ATM. The creep failure times under tension and bending loads for unidirectional CFRP are predicted statistically using the tensile and flexural static strengths measured at various temperatures and viscoelastic behavior of matrix resin. Then the tensile and flexural creep failure times of unidirectional CFRP at a constant load and temperature are measured experimentally for comparison with the predicted ones.

The creep failure times of unidirectional CFRP under arbitrary constant tension and bending loads at a constant temperature were predicted based on our proposed ATM using the statistical tensile and flexural static strengths for CFRP strands and laminates measured at various temperatures and the viscoelasticity for matrix resin, respectively. And the predicted results were compared with the experimental data measured by the creep tests. As results, the predicted ones for both loads agree well with the experimental data for the corresponding load, respectively. Therefore, the long term tensile and flexural creep failure times can be statistically predicted by using the statistical tensile and flexural static strengths at various temperatures based on our methodology. Furthermore, it is cleared that the flexural creep strength decreases drastically with increasing time and temperature comparing with the tensile creep strength.

2.0 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 (ATM) 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 constitutes important and basic data for the reliable design of CFRP structures. Our most recent study undertook the prediction of statistical creep failure time under tension loading along the longitudinal direction of unidirectional CFRP. The statistical creep failure time of unidirectional CFRP at a constant load and temperature was statistically predicted by substituting the statistical results of tensile static strengths of unidirectional CFRP measured at various temperatures and the viscoelastic behavior of matrix resin in our proposed formulation based on ATM. The predicted results quantitatively agree well with the experimentally obtained results measured using creep tests for unidirectional CFRP [9].

This paper is concerned with the statistical prediction of flexural creep failure time as well as the tensile creep failure time in the longitudinal direction of unidirectional CFRP based on the viscoelasticity of matrix resin. The tensile and flexural creep failure times of unidirectional CFRP are statistically predicted by substituting the tensile and flexural static strengths measured at various temperatures and viscoelastic behavior of matrix resin in our proposed formulation. Then the tensile and flexural creep failure times of unidirectional CFRP at a constant load and temperature are measured experimentally and statistically using CFRP strands and CFRP laminates for comparison with the predicted ones, respectively. Finally, the characteristics of statistical tensile and flexural creep failure times of unidirectional CFRP were compared with each other from the difference of failure modes in the tension and bending loads.

3.0 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],

$$\log \sigma_{\mathrm{s}}(P_{\mathrm{f}}, t, T) = \log \sigma_0(t_0, T_0) + \frac{1}{\alpha} \log[-\ln(1 - P_{\mathrm{f}})] - n_{\mathrm{R}} \log\left[\frac{D^*(t, T)}{D_{\mathrm{c}}(t_0, T_0)}\right] \tag{1}$$

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 α are the scale and shape parameter on Weibull distribution of static strength at t_0 and T_0 respectively, n_R is the viscoelastic parameter determined through the relationship between the static strengths of CFRP and the viscoelastic compliance D^* of matrix resin at the same time and temperature. The viscoelastic compliance D^* of matrix resin to be defined by the compliance for a constant strain rate is shown by the following equation for the creep compliance D_c of matrix resin.

$$D^*\left(t, T\right) = D_{\mathrm{c}}(t/2, T) \tag{2}$$

The statistical creep strength σ_c can be determined by shifting the master curve of static strength with log A based on Christensen's theory for viscoelastic crack kinetics [10]. Therefore, the master curve of creep strength can be shown by the following equation,

$$\log \sigma_{\mathrm{c}}(P_{\mathrm{f}}, t, T) = \log \sigma_0(t_0, T_0) + \frac{1}{\alpha} \log[-\ln(1 - P_{\mathrm{f}})] - n_{\mathrm{R}} \log\left[\frac{D^*(At, T)}{D_{\mathrm{c}}(t_0, T_0)}\right] \tag{3}$$

where the shifting amount log A determined by the slope of the static strength–failure time curve is shown by the following equation.

$$\log A = \log(1 + 1/k_{\mathrm{R}}) \qquad k_{\mathrm{R}} = n_{\mathrm{R}} m_{\mathrm{R}} \tag{4}$$

where m_R is the slope of creep compliance of matrix resin against time. The failure probability of CFRP under creep load with a constant stress can be shown by the following equation from Equation 3.

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

4.0 Experimental Procedures

Unidirectional CFRP strands and laminates which consist~~s~~ of T800-12000 (Toray Industries Inc.) and a general purpose epoxy resin jER828 (Mitsubishi Chemical Corp.) was molded by the filament winding method. The fiber volume fraction V_f of CFRP laminates was approximately 59% and the V_f of CFRP strands were scattered from 50% to 60% and then the V_f of CFRP strands when the static and creep strengths were calculated was standardized to V_f = 59% which is the V_f of CFRP laminates. Molding condition of CFRP strands and laminates is shown in Table 1. The glass transition temperature T_g is 130°C for the epoxy resin used.

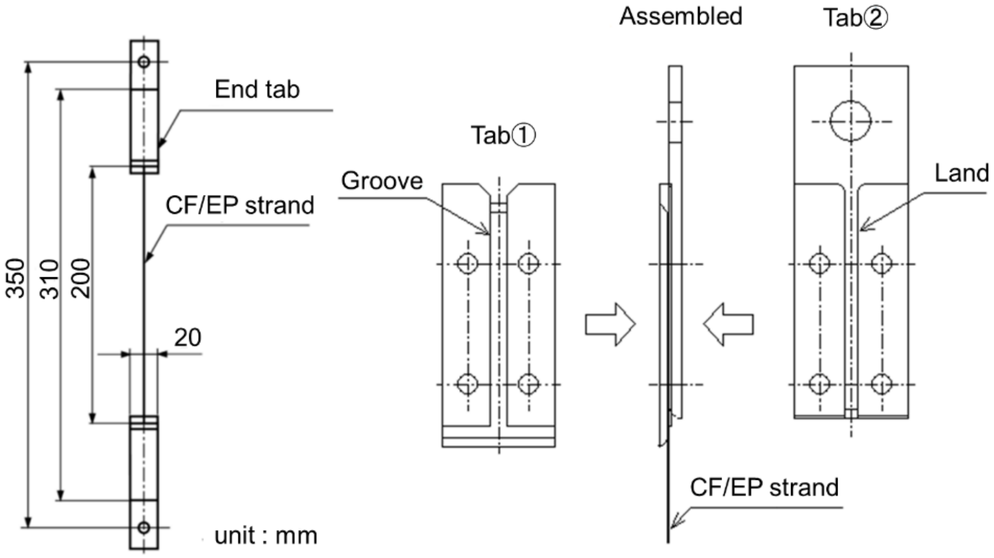
Table 1. Composition and cure schedule of CFRP laminates.

Carbon fiber	
T800HB-12000	
Matrix resin	
Composition	Weight ratio
Epoxy : jER828	100
Hardener : MHAC-P	103.6
Cure accelerator : 2-Ethyl-4-methylimidazol	1
Cure schedule	
100°C×5hr+150°C×4hr+190°C×2hr+(-0.5°C/min)	

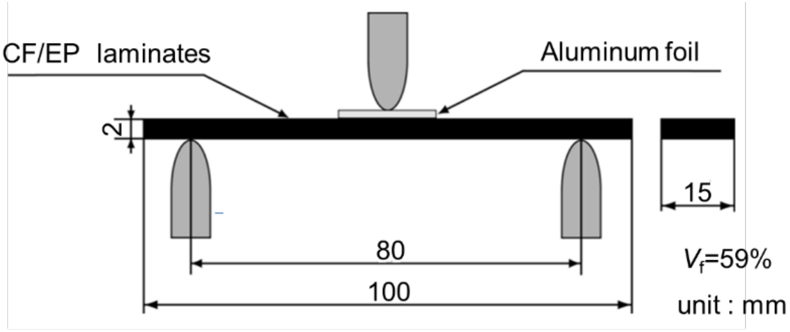
The tensile static and creep strengths for the fiber direction of unidirectional CFRP were conducted by our developed tension tests for CFRP strands [11]. The compressive static and creep strengths for the fiber direction of unidirectional CFRP were conducted by three-point bending tests according with ISO14125 for CFRP laminates because the failure occurs at the compression side of specimens. In the bending tests, cushion material made of aluminum foil was used to prevent localized destruction due to stress concentration at the loading point. Tension tests and three-point bending tests for static and creep loads are shown in Figure 1.

For the static tension tests, the test temperatures were 25°C, 120°C and 150°C, and cross-head speed was 1mm/min. For the creep failure tests, the test temperature was 120 °C, and the applied creep stress was 2,692MPa which is 82% of the scale parameter of static strength at 25°C. The fiber volume fraction V_f for CFRP strands were largely scattered as mentioned before, however the tex (weight per length) and density of carbon fiber strand was very stable and reliable. And then, the V_f of CFRP strands when the static and creep strengths were calculated was standardized to V_f = 59% which is the V_f of CFRP laminates.

For the static bending tests, the test temperatures were 25°C, 120°C, 135°C and 150°C, and cross-head speed was 2mm/min. For the creep failure tests, the test temperature was 120 ºC, and the applied creep stress was 791MPa which is 41% of the scale parameter of static strength at 25ºC.



(a) Tension



(b) Bending

Figure 1. Tension and bending specimen configurations and static and creep test methods.

5.0 Results and Discussion

5.1. Creep Compliance of Matrix Resin

Non dimensional creep compliance of matrix resin at 120ºC is shown in Figure 2. T_g is 130ºC for matrix resin. The creep compliance of matrix resin D_c was measured at various temperatures as shown by the left side of this figure and the smooth master curve of creep compliance at T = 120ºC is determined by shifting horizontally these curves at various temperatures based on the time-temperature superposition principle as shown by the right side of this figure. The viscoelastic compliance D^* under a constant strain rate loading can be obtained by shifting D_c horizontally in the amount of log 2 from Equation 2. The slope of creep compliance of matrix resin m_R can be obtained as shown in this figure.

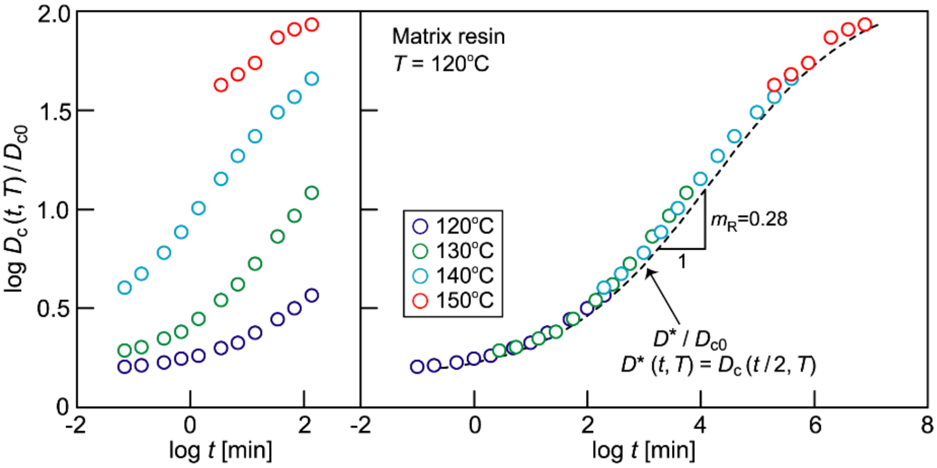


Figure 2. Dimensionless creep compliance of matrix resin at T=120°C.

5.2. Tensile and Flexural Static Strengths of Unidirectional CFRP

The tensile and flexural static strengths of unidirectional CFRP measured at various temperatures by using CFRP strands and laminates are shown in Figure 3, respectively. The tensile static strength decreases scarcely with increasing temperature, however the flexural static strength decreases remarkably with increasing temperature. The Weibull distributions of the static tensile and flexural strengths at various temperatures are shown in Figure 4. The shape parameter α_s and the scale parameter β_s on the Weibull distribution of both static strengths are shown in the table in this figure. It is cleared from this figure that the shape parameter keeps almost a constant for different temperatures for each of tensile and flexural strengths, and the decreasing of scale parameter with increasing temperature is very different for both strengths.

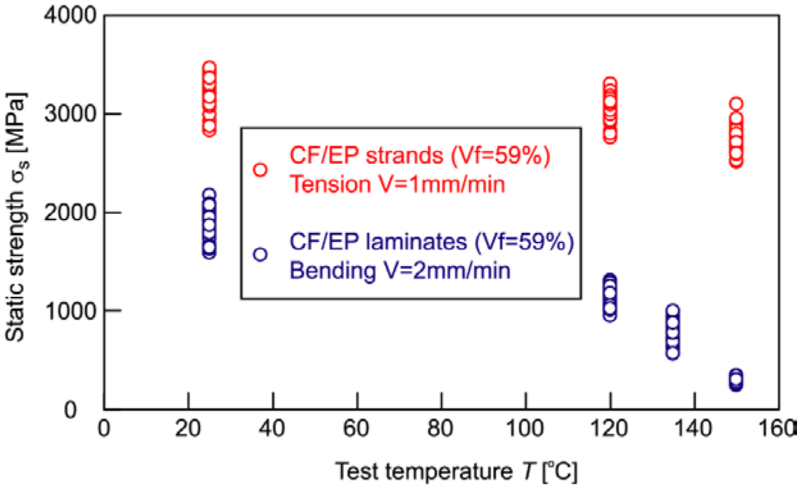


Figure 3. Tensile and flexural static strengths of unidirectional CFRP versus temperature.

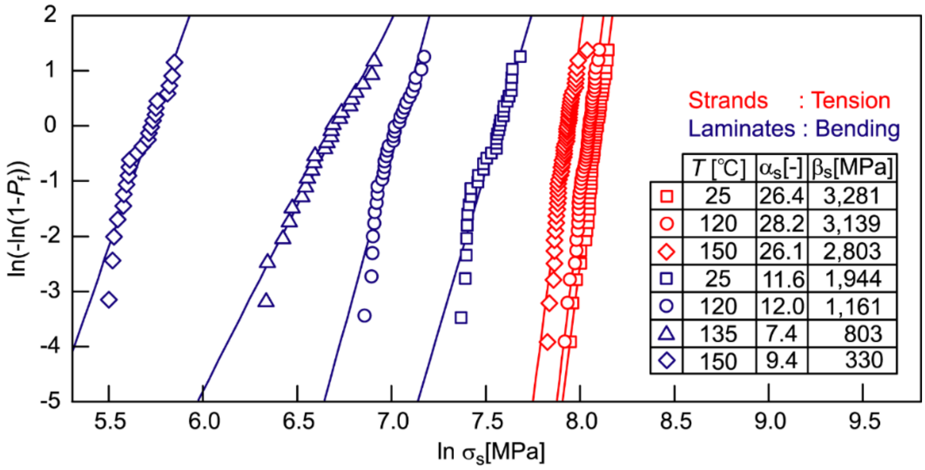


Figure 4. Weibull distributions of tensile and flexural static strengths of unidirectional CFRP at various temperatures.

5.3. Tensile and Flexural Static Strength of Unidirectional CFRP versus Viscoelastic Compliance of Matrix Resin

The tensile and flexural static strength of unidirectional CFRP σ_s/σ_0 versus the viscoelastic compliance of matrix resin D^*/D_{c0} at the corresponding condition of time and temperature is shown in Figure 5. The tensile and flexural static strengths of CFRP decreases with increasing the viscoelastic compliance of matrix resin although the slopes for both strengths are different each other. The viscoelastic parameter n_R can be determined by least square fitting. The slopes of fitting line, which is the viscoelastic parameter in Equation 1, are $n_R = 0.059$ for the tensile strength and $n_R = 0.652$ for the flexural strength, respectively.

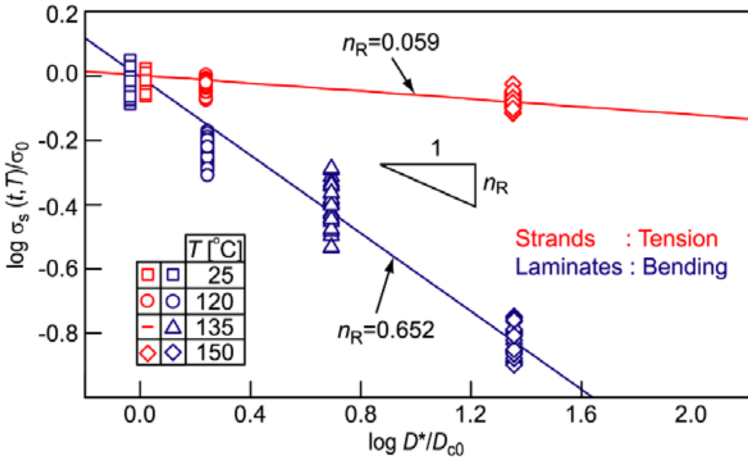


Figure 5. Statistical tensile and flexural static strengths of unidirectional CFRP against viscoelastic compliance of matrix resin at the same time and temperature.

5.4. Statistical Creep Failure Times under Tension and Bending Loads of Unidirectional CFRP

The upper and lower sides of Figure 6 shows the experimental and predicted results for the tensile creep strength against creep failure time and the failure probability at a constant creep stress σ_{c0} against creep failure time t at a constant temperature T, respectively. The predicted statistical creep failure time agrees well with the experimental data. The upper and lower sides of Figure 7 also shows the experimental and predicted results for the flexural creep strength and failure probability against creep failure time, respectively. The predicted statistical creep failure time agrees well with the experimental data with the exception of long time range. From Figures 6 and 7, it is cleared that the statistical creep failure time of unidirectional CFRP under tension and bending loads can be predicted by substituting the statistical static strength of CFRP measured at various temperatures and the viscoelastic compliance of matrix resin into Equations 3 and 5.

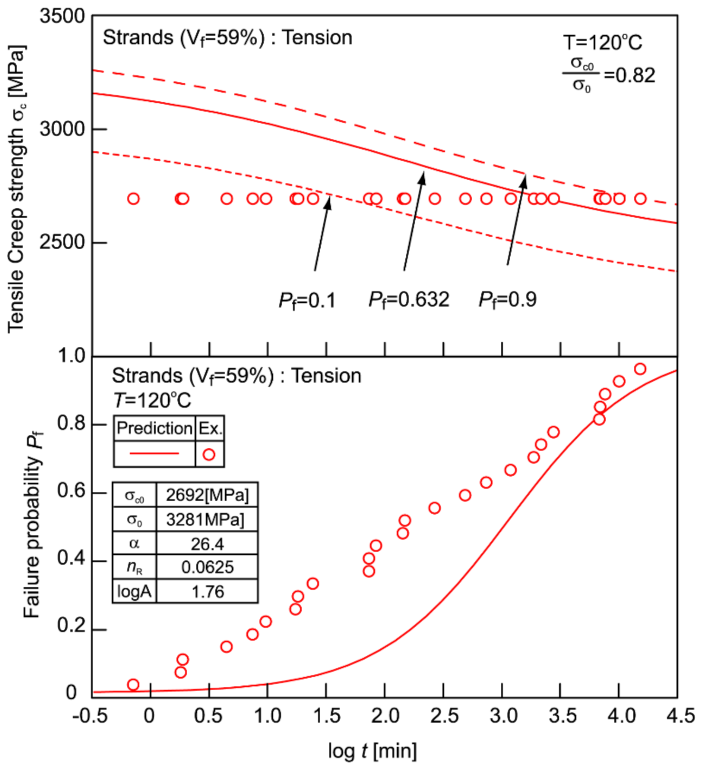


Figure 6. Tensile creep strength and failure probability against creep failure time.

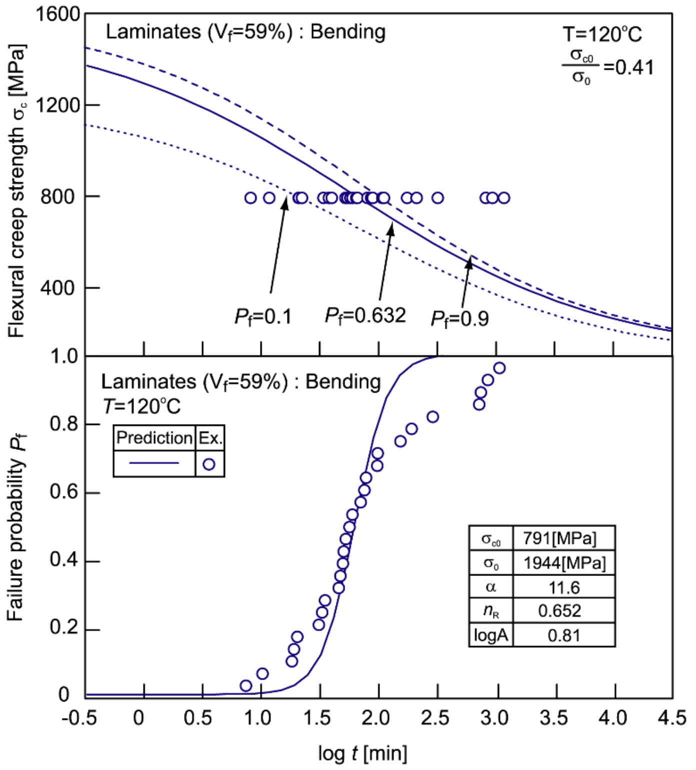
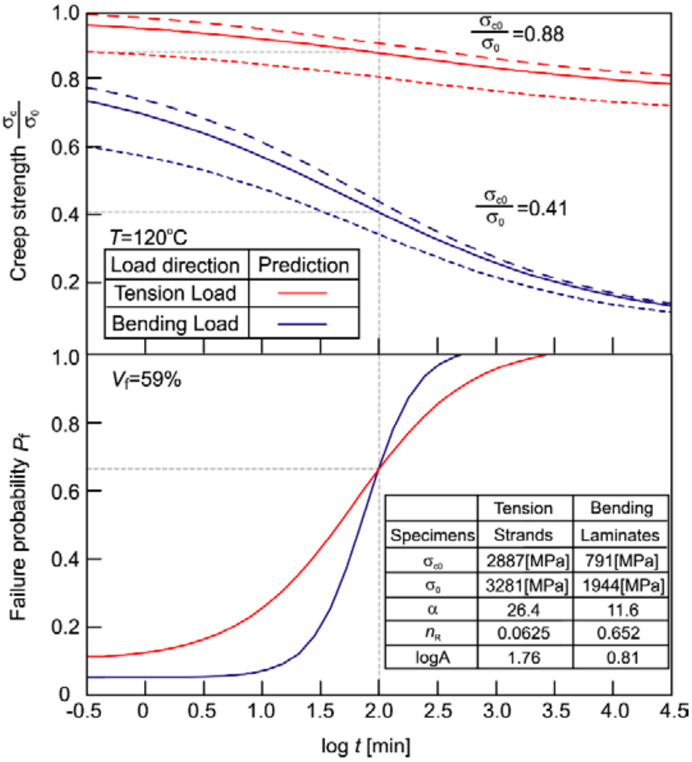


Figure 7. Flexural creep strength and failure probability against creep failure time.



	Tension	Bending
Specimens	Strands	Laminates
σ_{c0}	2887[MPa]	791[MPa]
σ_0	3281[MPa]	1944[MPa]
α	26.4	11.6
n_R	0.0625	0.652
logA	1.76	0.81

Figure 8. Tensile and flexural creep strengths against failure time at a constant temperature andthese failure probabilities against failure time at a constant creep stress and temperature.

The upper side of Figure 8 shows the master curves for the dimensionless tensile and flexural creep strengths against creep failure time at a constant temperature T = 120°C and these curves were calculated by substituting the data shown in the table of this figure into Equations 3 and 4. This figure shows the flexural strength decreses remakably with increasing failure time, on the other hand the tensile strength decreases scarecely with increasing failure time. It can be presumed that this difference on the strength is due to the difference of viscoelastic parameter n_R and that the difference of n_R is due to the difference of failure modes in tension and bending loads. Actually, the failure mode for the tension load is clearly Rosen's shear lag mode and that for the bending load is the micro-buckling mode in the compression side of specimen.

The lower side of this figure shows the probabilities against failure time under tension and bending loads, respectively. Each of creep stresses for both of tension and bending loads were selected as the creep failure time t = 100 min when the failure probability is equal to 63.6%. As resutls, the creep stress for tension load is 88% of the scale parameter

σ_0 of reference static tensile stength and the creep stress for bending load keeps only 41% of the corresponding scale parameter. The creep life under bending load for the longitudinal direction of unidirectional CFRP is drastically sensitive comparing with the case under tension load.

On the other hand, the scatter of creep failure time under the tension load is clearly larger than that under bending load, although the scatter for the tensile strength is smaller than that for the flexural strength because the slope of tensile creep strength against time is smaller than that for the flexural creep strength.

6.0 Conclusions

The creep failure times of unidirectional CFRP under a constant tension and bending loads at a temperature were predicted based on our proposed methodology using the statistical tensile and flexural static strengths for unidirectional CFRP measured at various temperatures and the viscoelasticity for matrix resin and compared with the experimental data measured by creep tests. As results, the predicted ones agree well with the experimental data. Therefore, the long term tensile or flexural creep failure time can be statistically predicted by using the statistical tensile or flexural static strength at various temperatures based on the viscoelasticity of matrix resin. Furthermore, it is cleared that the flexural creep strength decreases drastically with increasing time and temperature comparing with the tensile creep strength.

7.0 Acknowledgements

The authors thank Asian Office of Aerospace Research & Development AFOSR for supporting this work through AOARD award with Dr. Scott Robertson and Dr. Jeremy Knopp. Our award, “Statistical Creep Failure Time of Unidirectional CFRP under Compression Loading” is numbered FA2386-16-1-4088.

8.0 References

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

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

[3] Y. Miyano, M. Kanemitsu, T. Kunio and H. Kuhn. Role of Matrix Resin on Fracture Strengths of Unidirectional CFRP. *Journal of Composite Materials,* 20:520–538, 1986.

[4] Y. Miyano, M. K. McMurray, J. Enyama and M. Nakada. Loading Rate and Temperature Dependence on Flexural Fatigue Behavior of a Satin Woven CFRP laminate. *Journal of Composite Materials,* 28:1250–1260, 1994.

[5] 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,* 31:619–638, 1997.

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

[7] 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,* 42:1897-1919, 2008.

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

[9] M. Nakada and Y. Miyano. Statistical Creep Failure Time of Unidirectional CFRP. Experimental Mechanic, 56:653-658, 2016.

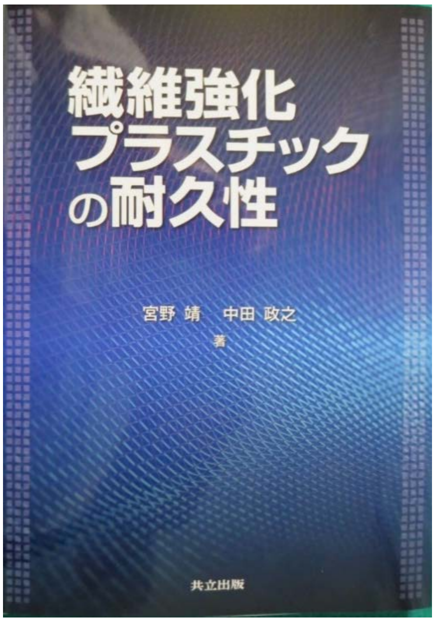
[10] R. Christensen and Y. Miyano. Stress Intensity Controlled Kinetic Crack Growth and Stress History Dependent Life Prediction with Statistical Variability. *International Journal of Fracture*, 137:77-87, 2006.

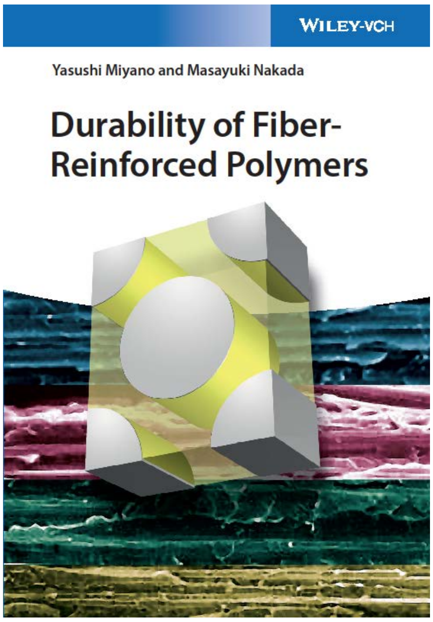
[11] T. Okuya, M. Nakada and Y. Miyano. Reliable test method for tensile strength in longitudinal direction of unidirectional carbon fiber-reinforced plastics. *Journal of Reinforced Plastics and Composites,* 32:1579-1585, 2013.

Appendix A: Publications and Presentations

Books

1. Y. Miyano, M. Nakada, “Durability of Fiber-Reinforced Plastics (Japanese)”, Kyoritsu Shuppan Co. Ltd., ISBN: 9784320082168 (June 2017: Soft Cover)
2. Y. Miyano, M. Nakada, “Durability of Fiber -Reinforced Polymers”, Wiley-VCH Verlag GmbH & Co. KGaA, ISBN: 9783527343560 (Nov. 2017: Hard Cover)





Book Chapters

1. Miyano, Y. and Nakada, M. “Statistical Long-Term Creep Failure Time of Unidirectional CFRP”, Chapter of “Durability of Composites in a Marine Environment 2”, Editors Peter Davies and Yapa D.S. Rajapakse, Springer (2018).
2. Y. Miyano and M. Nakada, “Temperature Dependence of Statistical Static Strengths for Unidirectional CFRP with Various Carbon Fibers”, Chapter of “Challenge in Mechanics of Time Dependent Materials, Volume 2”, Editors: Antoun, B., Arzoumanidis, A., Qi, H.J., Silberstein, M., Amirkhizi, A., Furmanski, J., Lu, H. Springer (2018).

Journal Papers

1. Nakada, M. and Miyano, Y., “Statistical Creep Failure Time of Unidirectional CFRP”, Experimental Mechanics, 56, (2016), pp.653-658.

2. Nakada, M. and Miyano, Y., “Multiscale modeling for long-term life prediction of CFRP structures under cyclic loading”, Multiscale and Multidisciplinary Modeling, Experiments and Design, Published online: 13 November 2017, DOI 10.1007/s41939-017-0003-7.

Conference Presentations

1. Nakada, M., Morisawa, Y., Kobayashi, Y. and Miyano, M., “Statistical Prediction of Tensile Cree1.p Failure Time for Various Unidirectional CFRP”, US-Japan Conference on Composite Materials, August 1-2, 2016, Hokkaido University, Sapporo, Japan.
2. Nakada, M. and Miyano, Y., “Statistical Life Time Prediction for Unidirectional CFRP under Tensile Creep Loading”, The XVIIth International Congress on Rheology, August 8-13, 2016, Kyoto Terrsa, Kyoto, Japan.
3. Nakada, M. and Miyano, Y., “Influence of Water Absorption on Long-term Strengths in Various Directions of Unidirectional CFRP for Marine Use”, Asia-Pacific Conference on Fracture and Strength 2016, September 19-22, 2016, Toyama International Convention Center, Toyama, Japan.
4. Nakada, M. and Miyano, Y., “Influences of Temperature and Water Absorption on Static Strength of Unidirectional CFRP for Marine Use”, The 10th Asian - Australasian Conference on Composite Materials, October 16-19, 2016, Bexco in Busan, Korea.
5. Enma, Y., Nakada, M. and Miyano, Y., “Prediction of Flexural Creep Failure Time for Unidirectional CFRP”, Conference & Exposition on Experimental and Applied Mechanics, June 12-15, 2017, Hyatt Regency Indianapolis, Indianapolis, Indiana, USA.
6. Nakada, M., Morisawa, Y. and Miyano, Y., “Statistical Life Time Prediction under Tension Loading for Unidirectional CFRP with Thermoplastics as Matrices”, Conference & Exposition on Experimental and Applied Mechanics, June 12-15, 2017, Hyatt Regency Indianapolis, Indianapolis, Indiana, USA.
7. Miyano, Y., Kobayashi, Y. and Nakada, M., “Time and Temperature Dependence on Tensile Strength of Unidirectional CFRP with Various Carbon Fibers”, Conference & Exposition on Experimental and Applied Mechanics, June 12-15, 2017, Hyatt Regency Indianapolis, Indianapolis, Indiana, USA.
8. Enma, Y., Nakada, M. and Miyano, Y., “Prediction of Flexural Creep Failure Time for Unidirectional CFRP Laminates”, 12th International Symposium on Advanced Science and Technology in Experimental Mechanics, 1-4 November, 2017, Kanazawa, Japan.

9. Koma, A., Nakada, M. and Miyano, Y., “Prediction of Tensile Creep Failure Time for Unidirectional CFRP”, 12th International Symposium on Advanced Science and Technology in Experimental Mechanics, 1-4 November, 2017, Kanazawa, Japan.
10. Yamanaka, S., Nakada, M., Miyano, Y. and Matsumoto, T., “Evaluation of Fatigue Strength of Interlaminar Toughened CFRP Laminates Using Benzoxazine Resin as Matrix”, 12th International Symposium on Advanced Science and Technology in Experimental Mechanics, 1-4 November, 2017, Kanazawa, Japan.
11. Miyano, Y. and Nakada, M., “Temperature Dependence of Statistical Static Strengths for Unidirectional CFRP with Various Carbon Fibers” 2018 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, June 4-7, 2018, Hyatt Regency Greenville, South Carolina USA,
12. Koma, A., Nakada, M. and Miyano, Y., “Temperature Dependence of Static Strengths for Unidirectional CFRP with Various Carbon Fibers”, 18th European Conference on Composite Materials, June 24 – 28, 2018, Athens Greece
13. Miyano, Y. and Nakada, M., “Prediction of Statistical Creep Failure Time for Unidirectional CFRP”, 18th European Conference on Composite Materials, June 24 – 28, 2018, Athens Greece.
14. Nakada, M., Morisawa, Y., Miyano, Y. and Uzawa, K., ”Prediction of Statistical Life Time for Unidirectional Carbon Fiber Reinforced Thermoplastics Under Creep Loading”, 18th European Conference on Composite Materials, June 24 – 28, 2018, Athens Greece
15. Yamanaka, S., Nakada, M., Miyano, Y. and Matsumoto T., “Open Hole Tensile and Compressive Failure Strengths of Interlaminar Toughened CFRP Lamainates Using Benzoxazine Matrix”. 18th European Conference on Composite Materials, June 24 – 28, 2018, Athens Greece

Appendix B: Abstracts

This paper is concerned with the statistical prediction of tensile and flexural creep failure times in the longitudinal direction of unidirectional CFRP based on the viscoelasticity of matrix resin. The tensile and flexural creep failure time of unidirectional CFRP was statistically predicted by substituting the tensile and flexural static strengths measured at various temperatures and viscoelastic behavior of matrix resin in our proposed formulation. Then the tensile and flexural creep failure times of unidirectional CFRP at a constant load and temperature were measured experimentally for comparison with the predicted ones. The characteristics of statistical tensile and flexural creep failure times of unidirectional CFRP were compared with each other from the difference of failure modes in the tension and bending loads.

Appendix C: Window on Science Program

Visitor Trip Report by Yasushi Miyano Date: June 26, 2017

WOS Number: 172106
Visitor Name/Organization: Yasushi Miyano/Kanazawa Institute of Technology
Host Name/Organization: Craig Przybyla/AFRL/RXCCP
Program Officer: Scott Robertson

Purpose**:** Polymer Composites Technical Interchange Meeting

Outcome/Discussion for Visit;

I visited to Materials and Manufacturing Directorate in WPAFB on June 16, 2017 hosted by Dr. Craig Przybyla with Professor Masayuki Nakada who is one of my co-researchers.

Prof. Nakada presented our research work as a seminar at Materials and Manufacturing Directorate in WPAFB. Furthermore, we joined to laboratory tour and some personal meetings with researchers in Materials and Manufacturing Directorate in WPAFB.

This visit was very useful for our future research work about the durability of polymer matrix composites and structures.

Action Items/ Future Plan:

1. Seminar

   Prof. Nakada presented our research work titled "Statistical life time prediction for unidirectional CFRP" at a seminar at Materials and Manufacturing Directorate in WPAFB. More than 20 researchers in Materials and Manufacturing Directorate were attended. There are many useful questions and comments from researchers to our presentation.
2. Laboratory tour

   I and Prof. Nakada joined to laboratory tour in Materials and Manufacturing Directorate by the guide of Dr. Allan Katz and Dr. Flores. We obtained useful information through the laboratory tour.
3. Personal meetings

   I and Prof. Miyano had personal meetings with Dr. David Mollenhauer, Dr. Dhriti Nepal, Dr. Richard Hall and Dr. Craig Przybyla about their recent research works. We had useful discussion for their recent research works.