The 23rd International Conference on Composite Materials (ICCM-23)
July 30 – August 4, 2023, ICC, Belfast, Northern Ireland

Effect of Water Absorption on Time- and Temperature-Dependent Static Strength of Unidirectional CFRP Laminates

Masayuki Nakada, Yasushi Miyano, Yoko Morisawa

Materials System Research Laboratory,
Kanazawa Institute of Technology,
Japan

Background

The mechanical behavior of CFRP matrix resin exhibits time- and temperature-dependence, called viscoelastic behavior, not only above the glass transition temperature T_g, but also below T_g. Consequently, the mechanical behavior of CFRP presumably depends strongly on both time and temperature.

We have proposed an accelerated testing methodology (ATM) for predicting the life of CFRP from test data measured by short term testing under elevated temperatures based on the time-temperature superposition principle, which holds for the matrix resin viscoelasticity.

Our earlier report have proposed formulations of statistical static, creep, and fatigue strengths of CFRP based on matrix resin viscoelasticity.

Objective and approach

Objective:

The flexural static strength in the longitudinal direction of unidirectional CFRP laminates under Dry, Wet, and Wet + Dry conditions are evaluated by our developed ATM.

Approach:

First: CFRP specimens of three kinds, Dry, Wet and Wet + Dry are prepared by water absorption and re-drying after water absorption.

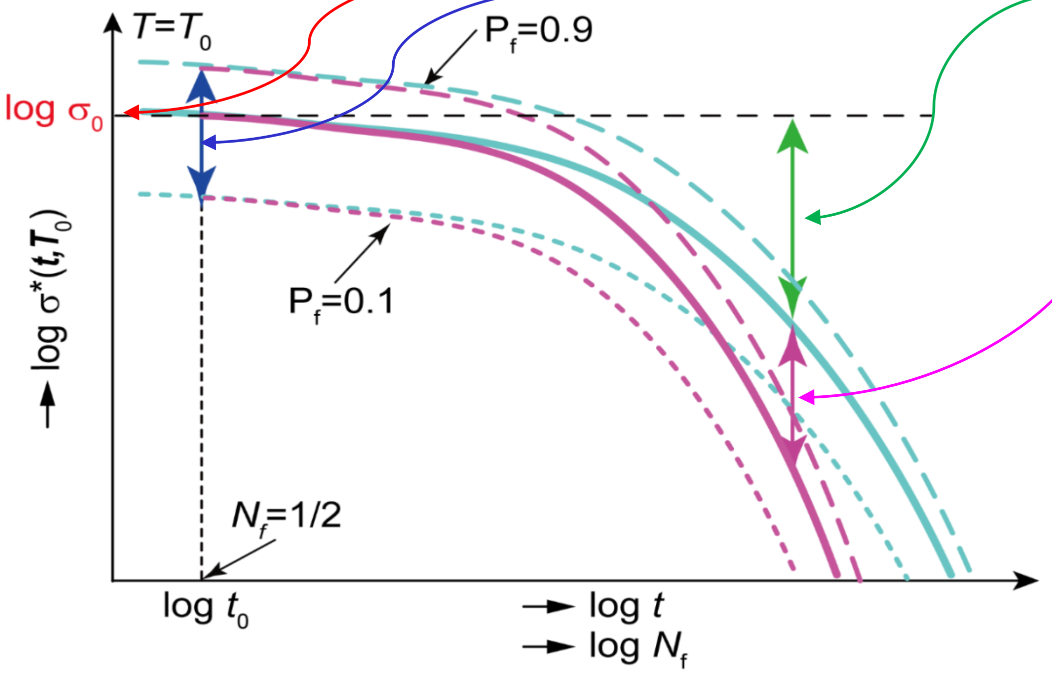
Second: The flexural static strength of CFRP and viscoelastic modulus of matrix resin are measured at several temperatures using three kinds of CFRP specimen and then the parameters in our ATM formulae are determined.

Third: The master curve of flexural static strength of CFRP under three kinds of conditions are expressed by using these parameters. The effect of water absorption on the static strength of CFRP is discussed.

General formulation for CFRP strength

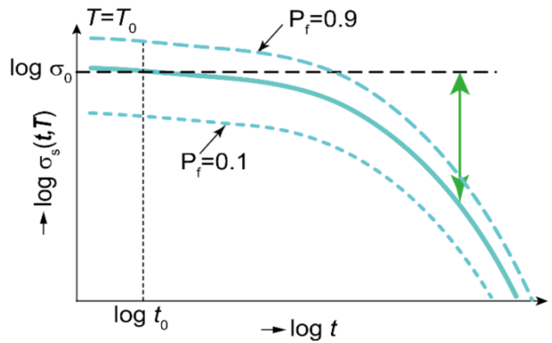
The CFRP strength for an arbitrary load direction and type is defined by the following formulation based on Christensen's viscoelastic crack kinetics.

$$\log\sigma^* = \log\sigma_0(t_0, T_0) + \frac{1}{\alpha}\log[-\ln(1 - P_f)] + n_R\log\left[\frac{E^*(t, T)}{E^*(t_0, T_0)}\right] + \log F_f(f, T, N_f)$$

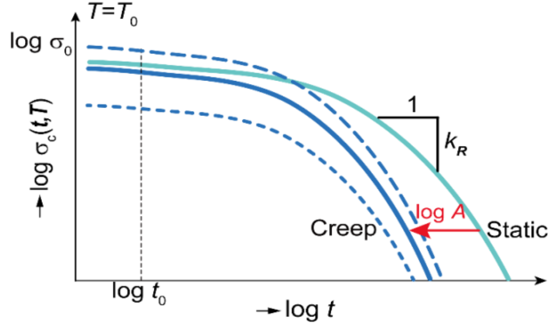


t : Failure time
t_0: Reference time
T: Temperature
T_0: Reference temperature
P_f : Failure probability
f: Frequency
N_f: Number of cycles to failure
σ_0 and α: Scale and shape parameters of static strength at t_0 and T_0
n_R: Viscoelastic parameter determined by failure mode
E^*: Viscoelastic modulus of matrix resin
F_f: Fatigue degradation parameter

Formulations of static and creep strengths of CFRP



Shifting log *A*



Static strength σ_s:

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

$$E_s(t,T) = E_r\ (t/2\,,T)$$

Creep strength σ_c:

$$\log\sigma_c(t,T) = \log\sigma_0(t_0,T_0) + \frac{1}{\alpha}\log[-\ln(1-P_f)] + n_R\log\left[\frac{E_c(t,T)}{E_c(t_0,T_0)}\right]$$

$$E_c(t,T) = E_s(At,T) = E_r\ (At/2\,,T)$$

$$\log E_c(t,T_0) = \log E_r(A_1 t_0/2,T_0) - \log\left[\left(\frac{A_1 t}{2t_0}\right)^{m_1} + \left(\frac{A_2 t}{2t_g}\right)^{m_2}\right]$$

Case of tension load to unidirectional CFRP (Rosen's model):

$$\log A_i = \log(1+1/k_{Ri}), \qquad k_{Ri} = m_i \times n_R, \qquad i = 1,2$$

Case of compression load to unidirectional CFRP (Micro-buckling):

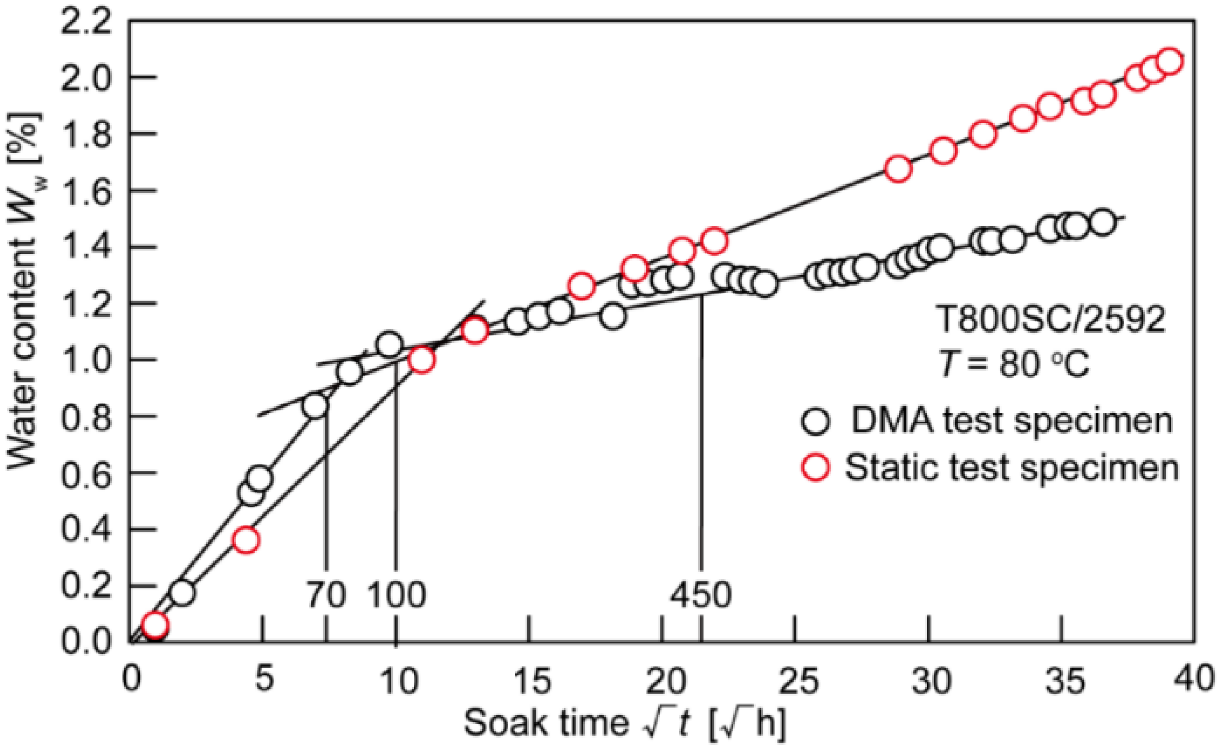
$$\log A = \log 2$$

All parameters in the formulations of static and creep strengths of CFRP can be determined through the static tests at a constant strain rate and various temperatures for CFRP and the viscoelastic tests for matrix resin. The creep tests are not necessary for getting these parameters.

Unidirectional CFRP laminates employed in this study

Fiber/Resin of prepreg (Torayca prepreg)	T800SC/2592
Thickness of prepreg	0.125 mm
Stacking sequence	$[0_8]$
Laminate thickness	2.0 mm
Plate size	200 mm × 200 mm
Curing method	Autoclave
Curing temperature	130 ^{o}C
Curing pressure	0.3 MPa
Curing time	2 hours

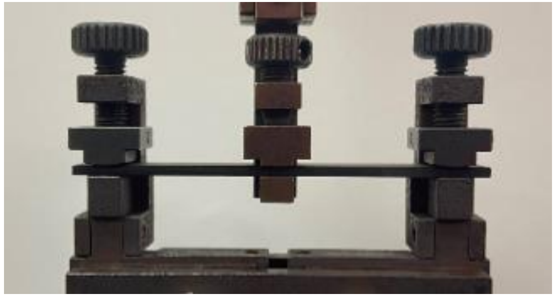
Water absorption of CFRP laminates



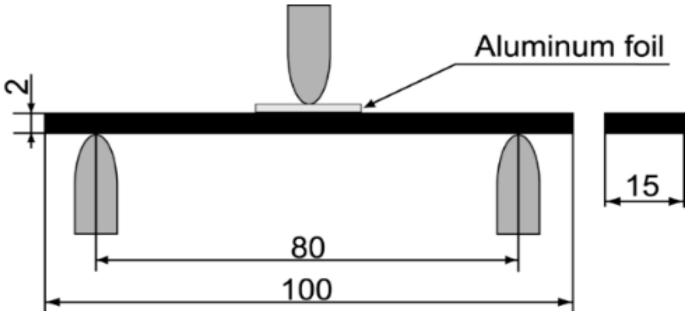
The water content increases with increasing soak time. The relationship between water content and square root of soak time is almost linear until 100 hours under T= 80 ºC. We selected 70 hours, 100 hours and 450 hours as the soak time conditions.

Experiments for prediction of creep life of CFRP laminates

Viscoelastic tests (DMA) for matrix resin

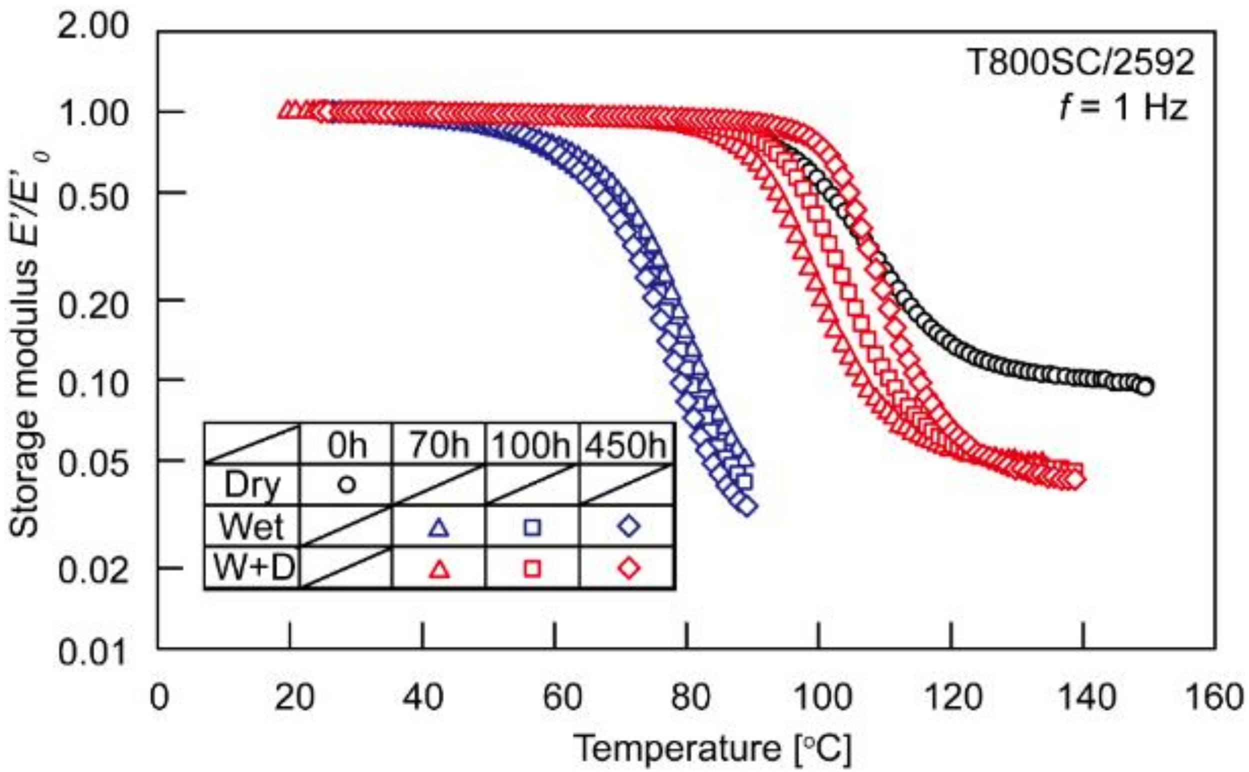


Static strength tests for CFRP laminates



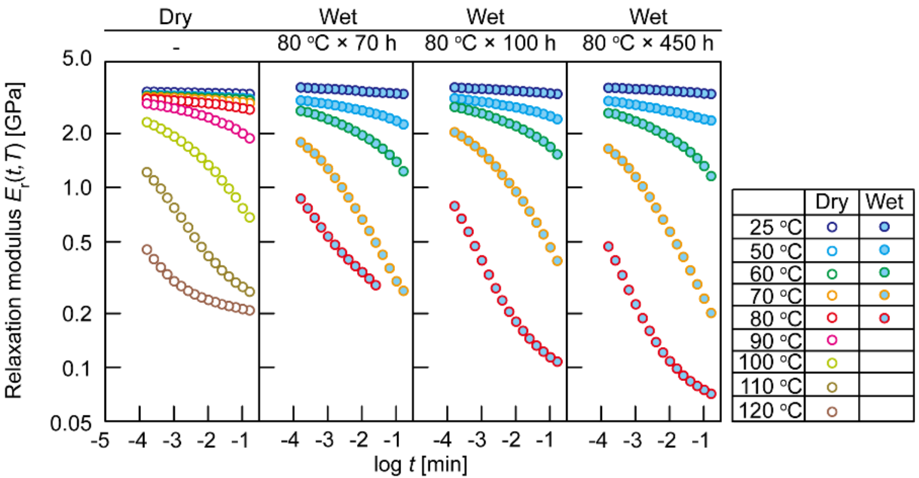
		Viscoelastic test		Static strength tests	
		Frequency [Hz]	Temperature [ºC]	Deflection rate [mm/min]	Temperature [ºC]
Dry		0.01 - 10	25 - 120	2	25 - 120
Wet	80 ºC × 70 h		25 - 80		25 - 70
	80 ºC × 100 h				
	80 ºC × 450 h				
Wet + Dry	80 ºC × 70 h		25 - 120		25 -100
	80 ºC × 100 h				
	80 ºC × 450 h				

Storage modulus in the transverse direction of unidirectional CFRP laminates under Dry, Wet, and Wet + Dry conditions

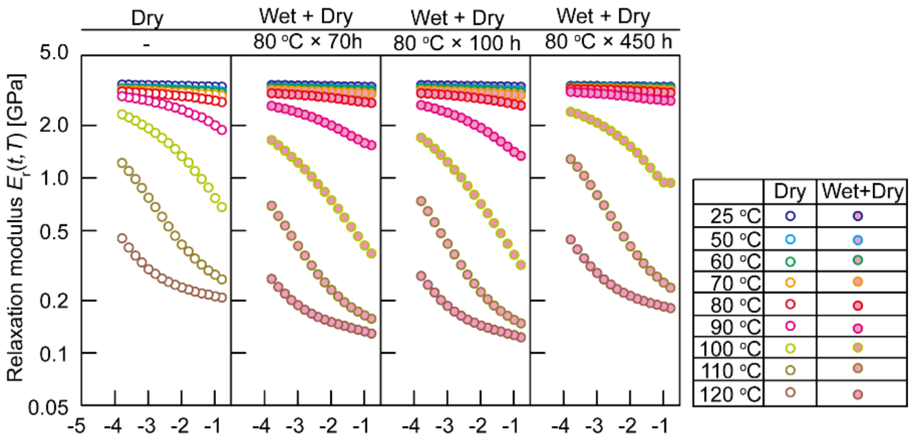


The temperature at which the storage modulus drops sharply decreases with water absorption, but it returns to the original value after re-drying.

Relaxation modulus of matrix resin under Dry, Wet, and Wet + Dry conditions



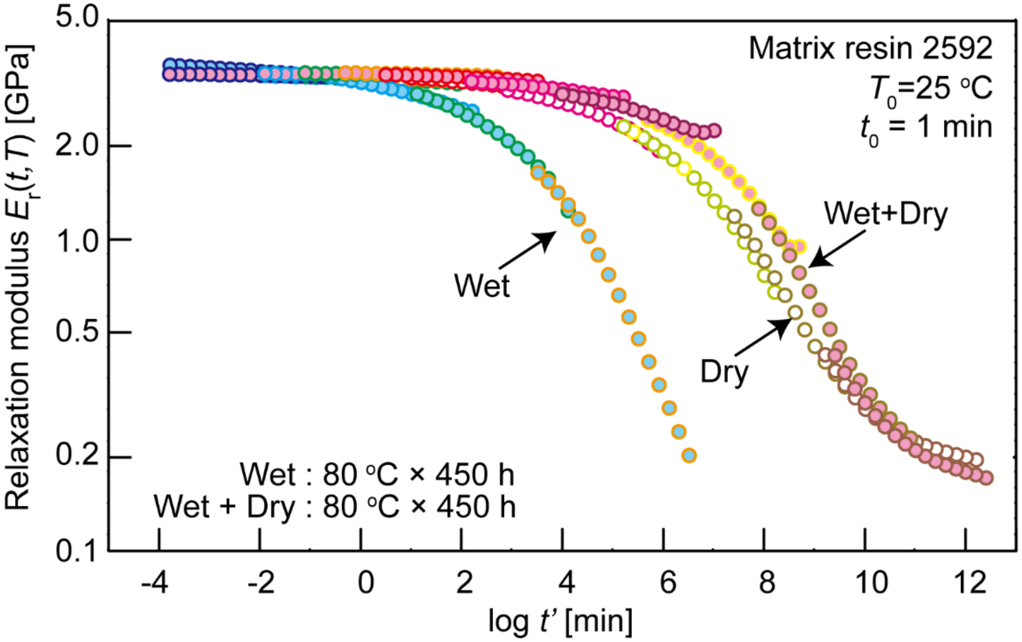
Dry and Wet conditions



Dry and Wet + Dry conditions

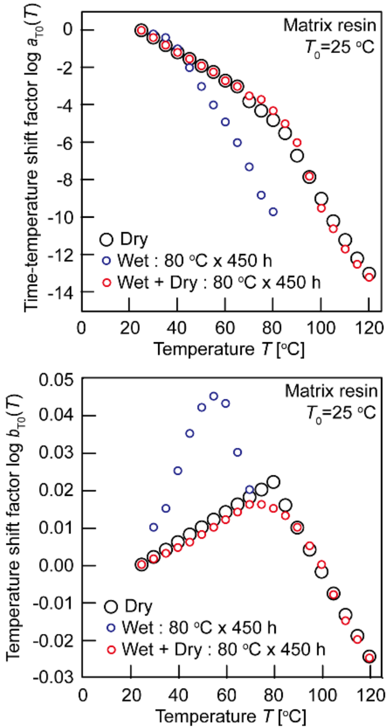
The relaxation modulus of matrix resin cab be obtained from storage modulus in the transverse direction of unidirectional CFRP laminates based on the linear viscoelasticity and Chamis' rule of mixture.

Master curves of relaxation modulus of matrix resin under Dry, Wet, and Wet + Dry conditions



Master curves of relaxation modulus

	Dry	Wet	Wet+Dry
25 °C	○	●	●
50 °C	○	●	●
60 °C	○	●	●
70 °C	○	●	●
80 °C	○		●
90 °C	○		●
100 °C	○		●
110 °C	○		●
120 °C	○		●



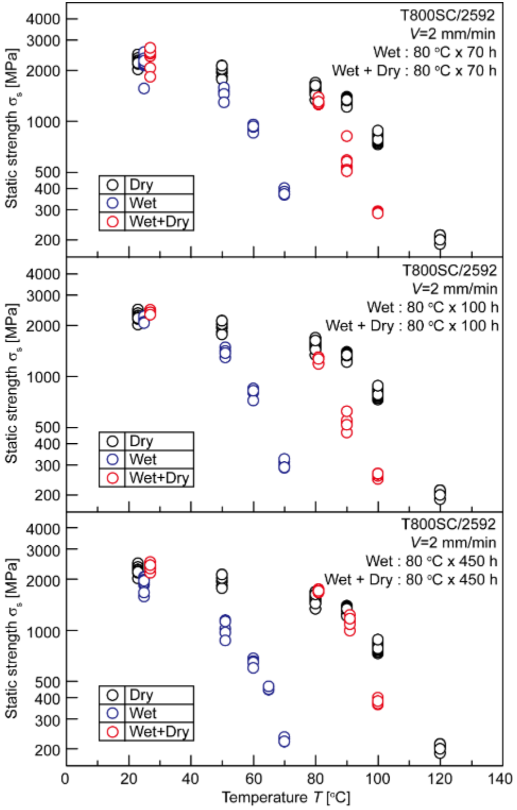
Shift factors

The time-temperature superposition principle holds for relaxation modulus of matrix resin under Dry, Wet, and Wet + Dry conditions, respectively.

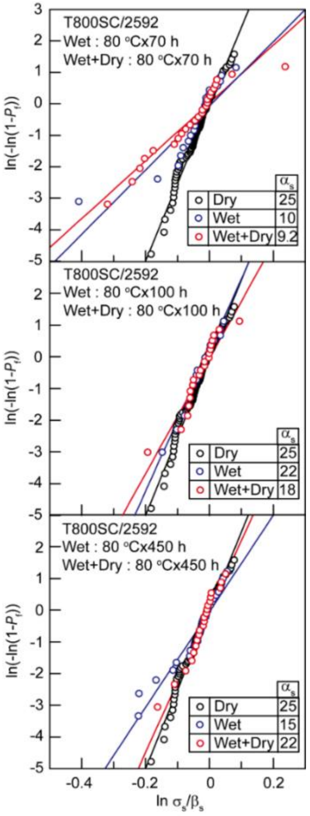
Kanazawa Institute of Technology

Determination of parameters in ATM formulae

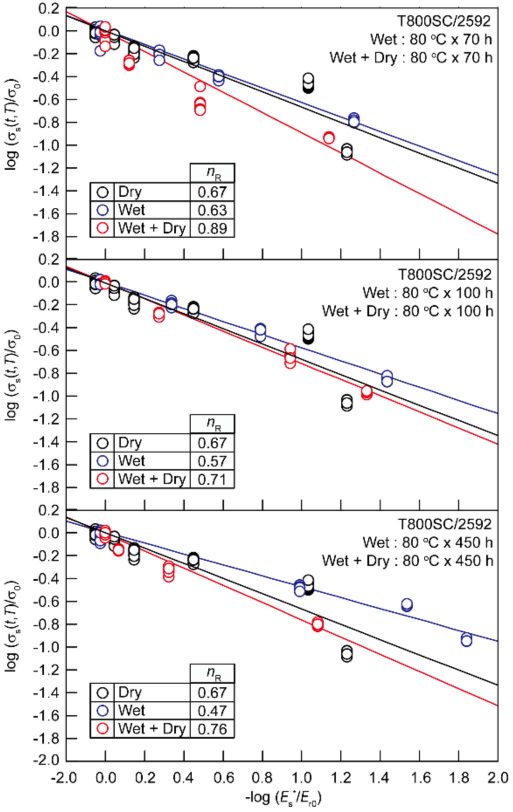
Materials System Research Laboratory



Determination of scale and shape parameters

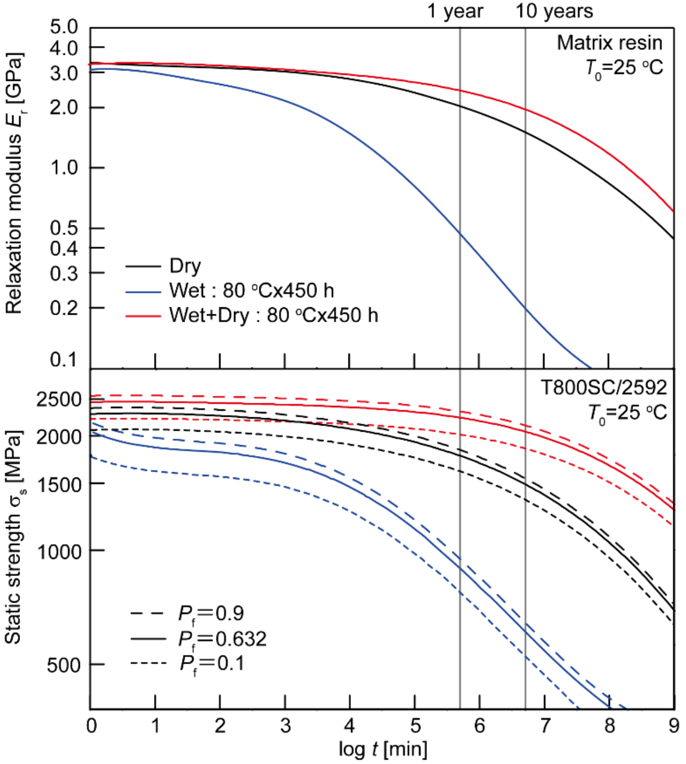


Determination of viscoelastic parameter



The scale and shape parameters of static strength and viscoelastic parameter can be determined under Dry, Wet, and Wet + Dry conditions, respectively.

Master curves of flexural static strength of CFRP laminates

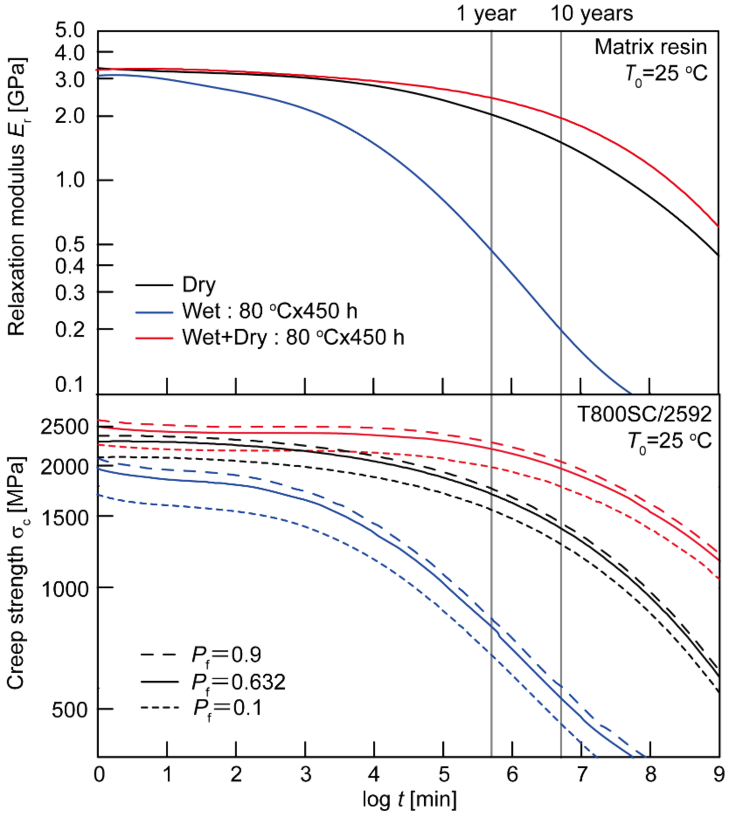


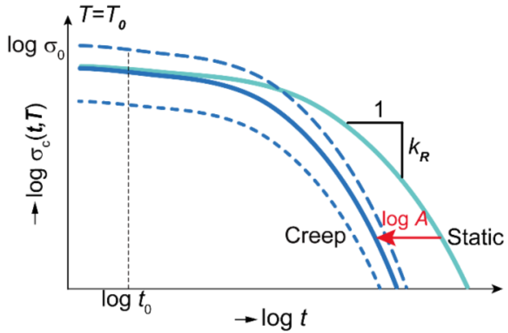
$$\log\sigma_s(t,T) = \log\sigma_0(t_0,T_0) + \frac{1}{\alpha}\log[-\ln(1-P_f)] + n_R\log\left[\frac{E_s(t,T)}{E_s(t_0,T_0)}\right]$$

		σ_0 [MPa]	α	n_R
Dry		2,300	25	0.67
Wet	80 °C × 70 h	2,340	10	0.63
	80 °C × 100 h	2,180	22	0.57
	80 °C × 450 h	1,960	15	0.47
Wet + Dry	80 °C × 70 h	2,510	8.2	0.89
	80 °C × 100 h	2,420	18	0.71
	80 °C × 450 h	2,420	22	0.76

The flexural static strength of CFRP decreases drastically with increasing time with similar behavior of the relaxation modulus of matrix resin. The static strength degradation of CFRP with increased elapsed time is accelerated with water absorption. It returns to the original state or is further suppressed with re-drying.

Prediction of long-term creep life of CFRP laminates





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

$$E_s(t,T) = E_r\ (t/2\,,T)$$

Case of compression load: $\log A = \log 2$

$$\log\sigma_c(t,T) = \log\sigma_0(t_0,T_0) + \frac{1}{\alpha}\log[-\ln(1-P_f)] + n_R\log\left[\frac{E_c(t,T)}{E_c(t_0,T_0)}\right]$$

$$E_c(t,T) = E_s(At,T) = E_r\ (At/2\,,T)$$

The long-term flexural creep strength of CFRP can be predicted by shifting flexural static strength along with the log-scale of failure time based on our ATM.

Conclusion

The flexural static strength in the longitudinal direction of unidirectional CFRP laminates under Dry, Wet, and Wet + Dry conditions were evaluated by our developed ATM.

The parameters in our ATM formulae, the scale and shape parameters of static strength and the viscoelastic parameter could be determined. The flexural static strength of CFRP laminates under Dry, Wet, and Wet + Dry conditions can be expressed by using these parameters and relaxation modulus of matrix resin.

The creep strength of CFRP laminates can be predicted by shifting the static strength along with log-scale of failure time by our ATM.

Thank you for your kind attention !

Acknowledgments

The authors thank Prof. R. Christensen of Stanford University as a consultant on these projects. The authors also thank Mr. Y. Yoshikoshi who was a graduate student in Kanazawa Institute of Technology as cooperative researcher.