ADVANCED ACCELERATED TESTING METHODOLOGY FOR LONG-TERM LIFE PREDICTION OF CFRP

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Abstract
The advanced accelerated testing methodology (ATM-2) for the long-term life prediction of CFRP laminates exposed to an actual loading having general stress and temperature history is proposed in this paper. Three conditions as the basis of ATM-2 are introduced with the scientific bases. The long-term fatigue strength of CFRP laminate under an actual loading is formulated based on the three conditions. The creep compliance and time-temperature shift factors of matrix resin, which perform an important role for time and temperature dependence of long-term life of CFRP laminates, are also formulated based on the time-temperature superposition principle. The applicability of ATM-2 is confirmed by predicting the long-term fatigue strength of three kinds of CFRP laminates for marine use.

1 Introduction

Carbon fiber reinforced plastics (CFRP) are now being used for the primary structures of airplanes, spacecrafts and others as well as ships, in which the high reliability should be kept during the long-term operation. Therefore, it would be expected that the accelerated testing methodology for the long-term life prediction of CFRP structures exposed under the actual environments of temperature, water, and others must be established.

A strategy of accelerated testing is shown as the following steps, 1) data collections by accelerated testing, 2) durability design, 3) development of highly reliable structures. First, the accelerated testing methodology should be established for polymer composites. Our developed methodology will be generic and can be applied to centrifuge, generator, flywheel, aircraft, wind turbine, marine and automobile.

In this paper, we propose an advanced accelerated testing methodology (ATM-2) which can be applied to the life prediction of CFRP laminates exposed to an actual load and environment history. First, three conditions as the basis of ATM-2 are introduced with the scientific bases. One of these conditions is the fact that the time and temperature dependence on the strength of CFRP is controlled by the viscoelastic compliance of matrix resin [1]. Second, the formulations of creep compliance and time-temperature shift factors of matrix resin are carried out based on the time-temperature superposition principle. And the formulations of long-term life of CFRP under an actual loading are carried out based on the three conditions. Third, the applicability of ATM-2 for the long-term life prediction of three kinds of CFRP laminates is confirmed.

2 ATM-2

The ATM-2 is established with three following conditions, (A) the failure probability is independent of temperature and load histories, (B) the time and temperature dependence of strength of CFRP is controlled by the viscoelasticity of matrix resin. Therefore, the time-temperature superposition principle for the viscoelasticity of matrix resin holds for the strength of CFRP, (C) the strength degradation of CFRP holds the linear cumulative damage law as the cumulative damage under cyclic loading.

With the condition (A), the reference strength and the failure probability can be obtained by measuring the static strength of CFRP at an arbitrary strain rate under room temperature [2]. With the condition (B), it is possible to calculate the strength variation of CFRP by the viscoelastic compliance of matrix resin determined by the creep compliance of matrix resin

and the history of load and temperature changed with time. With the condition (C), it is possible to calculate the strength degradation by load cycles undergoing to the linear cumulative damage law. The formulation for long-term fatigue strength of CFRP exposed to an actual load and environment history are conducted under the three conditions of ATM-2. The procedure for determining the materials parameters in the formulation of ATM-2 is illustrated in Fig.1.

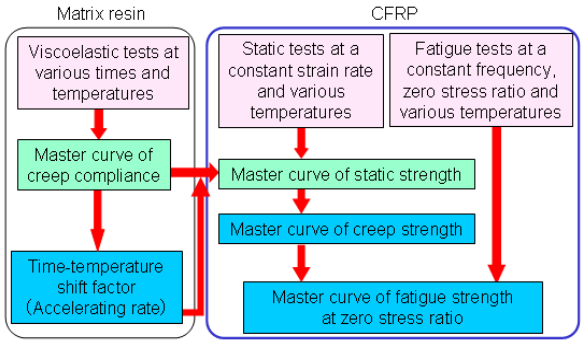

Fig.1 Procedure of ATM-2

The long-term fatigue strength exposed to the actual loading where the temperature and load change with time can be shown by the following equation based on the conditions of A, B and C.

$$\log\sigma_{\mathrm{f}}(t',T_0,N_{\mathrm{f}},R,P_{\mathrm{f}}) = \log\sigma_{\mathrm{f0}}(t_0',T_0) + \frac{1}{\alpha}\log[-\ln(1-P_{\mathrm{f}})] - n_{\mathrm{r}}\log\left[\frac{D^*(t',T_0)}{D_{\mathrm{c}}(t_0',T_0)}\right] - \frac{(1-R)}{2}n_{\mathrm{f}}\log(2N_{\mathrm{f}}) + n_{\mathrm{f}}^*\log(1-k_{\mathrm{D}}) \quad (1)$$

The first term of right part shows the scale parameter for the strength at the reference temperature T_0, the reduced reference time t_0', the number of cycles to failure $N_{\mathrm{f}} = 1/2$ and the stress ratio $R = 0$.

The second term shows Weibull distribution as the function of failure probability P_{f} based on condition (A). α is the shape parameter for the strength.

The third term shows the variation by the viscoelastic compliance of matrix resin which depend on temperature and load histories. n_{r} is the material parameter.

The viscoelastic compliance can be shown by the following equation.

$$D^*(t',T_0) = \frac{\varepsilon(t',T_0)}{\sigma(t',T_0)} = \frac{\int_0^{t'} D_{\mathrm{c}}(t'-\tau',T_0)\frac{d\sigma(\tau')}{d\tau'}d\tau'}{\sigma(t',T_0)} \quad (2)$$

where, D_{c} shows the creep compliance of matrix resin and $\sigma(\tau')$ shows the stress history. t' is the reduced time at T_0 and can be shown by the following equation.

$$t' = \int_0^t \frac{d\tau}{a_{T_0}(T(\tau))}, \quad (3)$$

where, a_{T0} shows the time-temperature shift factor of matrix resin and $T(\tau)$ shows the temperature history.

The fourth and fifth terms show the degradation by the cumulative damage under cyclic load. The N_{f} and R in this term show the number of cycles to failure and the stress ratio at the final step, respectively. n_{f} and n_{f}^* are the material parameters. The k_{D} shows the accumulation index of damage defined as the following equation based on the condition (C).

$$k_{\mathrm{D}} = \sum_{i=1}^{n}\frac{n_i}{N_{\mathrm{f}i}} < 1, \quad (4)$$

where n_i and N_{fi} are the number of cycles and the number of cycles to failure at the loading of step i, respectively.

3 Long-term Life Prediction of CFRP Laminates

The long-term fatigue strength for three kinds of CFRP laminates under Dry and Wet conditions are formulated by substituting the measured data in Eq.(1). Three kinds of CFRP laminates are plain woven T300 carbon fibers fabric/vinylester (T300/VE), plain woven T700 carbon fibers flat fabric/vinylester (T700/VE-F) and multi-axial knitted T700 carbon fibers fabric/vinylester (T700/VE-K) for marine use. These CFRP laminates were prepared under two conditions of Dry and Wet after molding. Dry specimens by holding the cured specimens at 150°C for 2 hours in air, Wet specimens by soaking Dry specimens in hot

water of 95°C for 120 hours were respectively prepared.

3.1 Creep compliance and time-temperature shift factors

The creep compliances D_c at various temperatures under Dry and Wet conditions shown in the left side of Fig.2 were shifted horizontally and vertically to construct the smooth master curve of D_c shown in the right side of this figure. The master curve of D_c can be represented by two tangential lines, whose slopes are m_g and m_r, respectively. With these parameters, the master curve of D_c can be fit with the following equation,

$$\log D_c = \log D_{c,0}(t'_0, T_0) + \log\left[\left(\frac{t'}{t'_0}\right)^{m_g} + \left(\frac{t'}{t'_g}\right)^{m_r}\right] \quad (5)$$

where t'_g is the reduced glassy time at T_0. The parameters of $D_c(t'_0, T_0)$, t'_g, m_g and m_r are determined by fitting the D_c master curves shown in Fig.2.

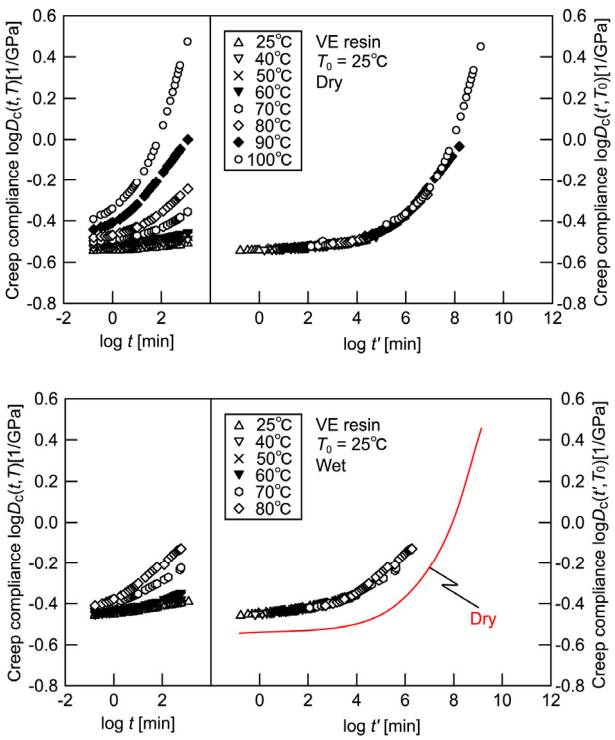

Fig.2 Master curves of creep compliance of matrix resin

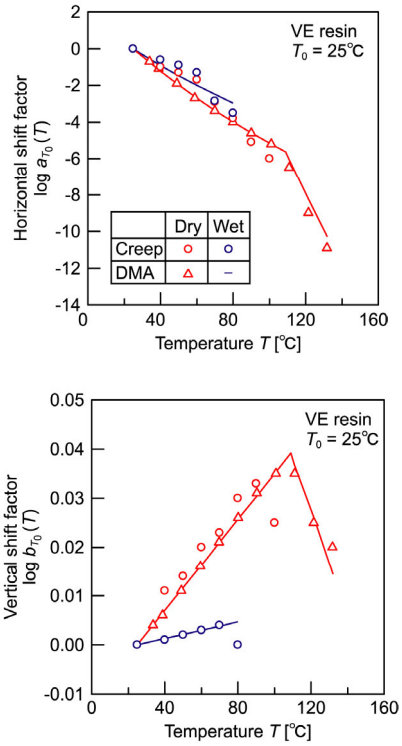

Fig.3 Horizontal and vertical shift factors

The horizontal time-temperature shift factor $a_{T0}(T)$ and the vertical temperature shift factor $b_{T0}(T)$ are shown in Fig.3. Additionally, the storage moduli under Dry condition measured at various temperatures in the relative high temperature range were also shifted horizontally and vertically to construct the smooth master curve of storage modulus. These shift factors were formulated by Eqs.(6) and (7),

$$\log a_{T_0}(T) = \frac{\Delta H_1}{2.303G}\left(\frac{1}{T} - \frac{1}{T_0}\right)\mathrm{H}(T_g - T) + \left[\frac{\Delta H_1}{2.303G}\left(\frac{1}{T_g} - \frac{1}{T_0}\right) + \frac{\Delta H_1}{2.303G}\left(\frac{1}{T} - \frac{1}{T_g}\right)\right](1 - \mathrm{H}(T_g - T)) \quad (6)$$

$$\log b_{T_0}(T) = b_1(T - T_0)\mathrm{H}(T_g - T) + [b_1(T_g - T_0) + b_2(T - T_g)](1 - \mathrm{H}(T_g - T)) \quad (7)$$

where G is the gas constant, 8.314×10^{-3} [kJ/(Kmol)], ΔH_1 and ΔH_2 are activation energies below and above the glass transition temperature T_g. H is the

Heaviside step function. b_1 and b_2 are the slopes of two line segments below and above T_g.

3.2 Flexural static and fatigue strengths of CFRP laminates under Dry and Wet conditions

The left side of each graph in Fig.4 shows the flexural static strength σ_s versus time to failure t_s at various temperatures T for three kinds of CFRP laminates under Dry and Wet conditions. The master curves of σ_s versus the reduced time to failure t_s' were constructed by shifting σ_s at various constant temperatures along the log scale of t_s using the same shift factors a_{T_0} (T) shown in Fig.3. The flexural static strength were formulated by using Eq.(1). It is cleared from Fig.4 that the σ_s for all of three CFRP laminates strongly decreases with increasing time, temperature and water absorption and that these behaviors for the flexural static strength is just the same for three kinds of CFRP laminates. Therefore, the time, temperature and water absorption dependent behavior for the flexural static strength of CFRP laminates is perfectly controlled by the viscoelastic behavior of matrix resin.

The master curves of fatigue strength versus the reduced time t' for distinct N_f can be constructed as depicted in solid curves in Fig.5. It is cleared from this figure that the σ_f of all three CFRP laminates strongly decreases with time to failure, temperature although the σ_f decreases scarcely with N_f. The effect of number of load cycles on the flexural strength of these CFRP laminates is negligible small.

The parameters obtained by formulation are shown in Table 1. It can be found from these results that the material parameter n_f which is related to the effect of number of load cycles on the flexural strength is negligible small compared with n_r which is related to the variation by the viscoelasticity of matrix resin.

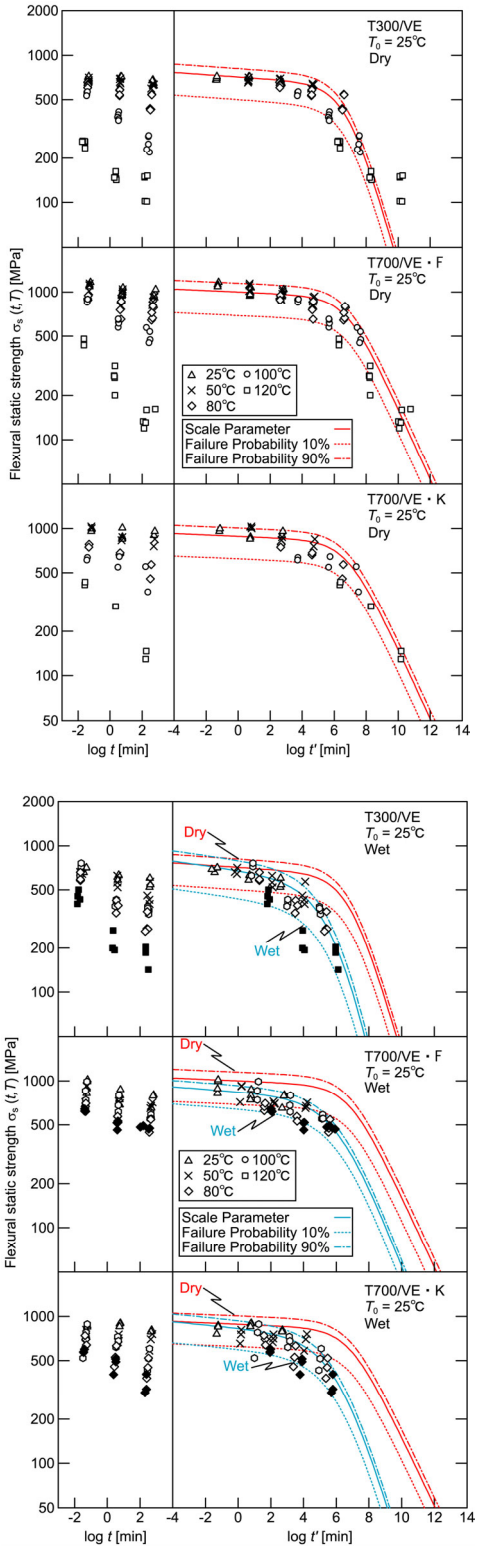

Fig.4 Master curves of flexural static strength of three kinds of CFRP laminates

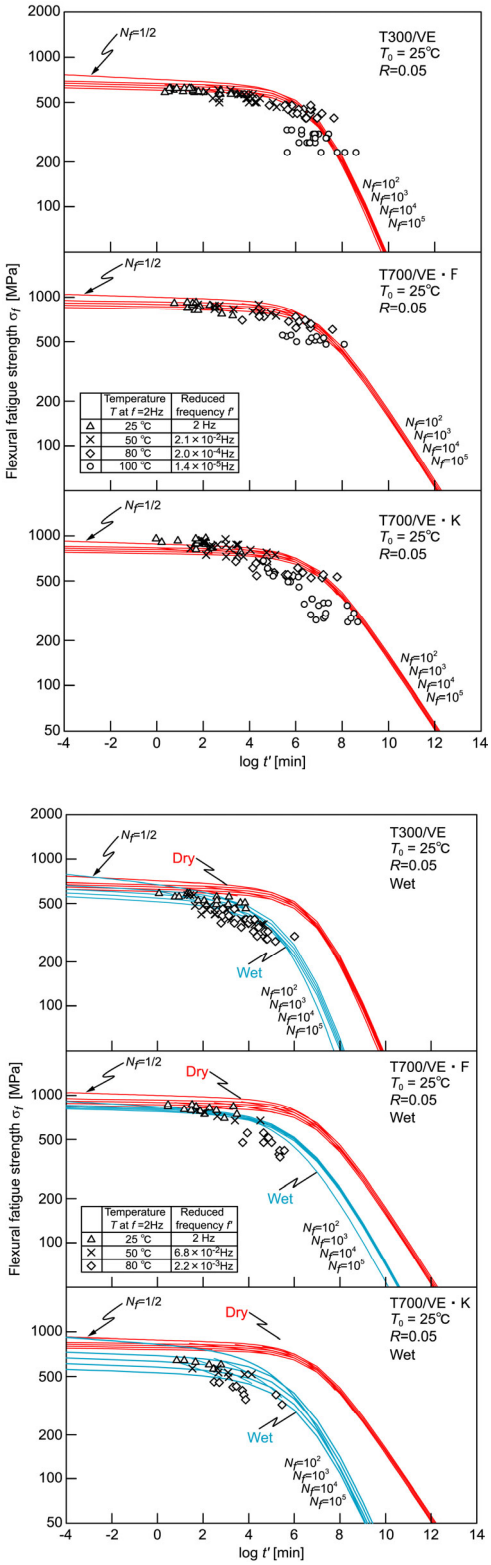

Fig.5 Master curves of flexural fatigue strength of three kinds of CFRP laminates

Table 1 Parameters obtained by formulation

		Dry	Wet
Resin	T_0 [℃]	25	25
	t'_0 [min]	1	1
	$D_{c,0}(t'_0, T_0)$ [1/GPa]	0.287	0.352
	m_g	0.010	0.010
	m_r	0.49	0.35
	t'_g at T_0 [min]	2.5 x 10⁶	5.0 x 10⁵
	ΔH_1 [KJ/mol]	146	108
	ΔH_2 [KJ/mol]	600	–
	T_g [℃]	109	–

		T300/VE		T700/VE-F		T700/VE-K	
		Dry	Wet	Dry	Wet	Dry	Wet
CFRP	$\sigma_{s,0}(t'_0, T_0)$	709	673	995	837	880	826
	α_s	6.4	5.2	6.1	8.4	6.4	6.8
	α_f	5.7	7.3	8.4	6.9	5.0	5.8
	n_r	0.77	1.57	0.48	0.84	0.47	1.07
	n_f	0.03	0.05	0.03	0.02	0.03	0.08

4 Conclusion

The advanced accelerated testing methodology (ATM-2) for the long-term life prediction of CFRP exposed to an actual loading having general stress and temperature history was proposed and the applicability of ATM-2 was confirmed by predicting the long-term fatigue strength of three kinds of CFRP laminates for marine use.

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