Influence of Water Absorption on Temperature Dependent Static Strength of Unidirectional CFRP

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Abstract

The static strengths for typical four directions of unidirectional CFRP were measured under various temperatures at a single loading rate for Dry and Wet specimens. The four directions were the longitudinal tension and bending, transverse bending and compression, respectively. The effects of water absorption as well as temperature on these static strengths of unidirectional CFRP were discussed. As results, the static strengths in these four directions of unidirectional CFRP decrease with increasing water absorption as well as temperature. The effects of water absorption as well as temperature on these static strengths can be characterized by the viscoelastic behavior of matrix resin and the failure mode.

1. Introduction

Carbon fiber reinforced plastics (CFRP) are now being used for the primary structures of airplanes, ships and others, 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.

We have proposed a general and rigorous advanced accelerated testing methodology (ATM) which can be applied to the life prediction of CFRP exposed to an actual load and environment history based on the three conditions. 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]. The formulations of creep compliance and time-temperature shift factors of matrix resin are carried out based on the time-temperature superposition principle (TTSP). The formulations of long-term life of CFRP under an actual loading are carried out based on the three conditions.

In this paper, the tensile and compressive static strengths in the longitudinal and transverse directions of two kinds of unidirectional CFRP under wet condition are evaluated using ATM. The applicability of ATM and the effect of water absorption on time and temperature dependence of these static strengths are discussed.

2. ATM

ATM is established with following three conditions: (A) the failure probability is independent of time, temperature and load history [2]; (B) the time and temperature dependence of strength of CFRP is controlled by the viscoelasticity of matrix resin. Therefore, the TTSP 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.

The master curve of static strength can be shown by the following equation based on ATM.

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

The first term of right part shows the reference strength (scale parameter for the static strength) at reduced reference time t_0' under the reference temperature T_0. The second term shows the scatter of static strength 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 D^* in (1) can be shown by the following equation,

$$D^*\left(t',T_0\right)=\frac{\varepsilon\left(t',T_0\right)}{\sigma\left(t',T_0\right)}=\frac{\int_0^{t'}D_{\mathrm{c}}\left(t'-\tau',T_0\right)\frac{d\sigma\left(\tau'\right)}{d\tau'}d\tau'}{\sigma\left(t',T_0\right)},\qquad t'=\int_0^t\frac{d\tau}{a_{T_0}\left(T\left(\tau\right)\right)} \tag{2}$$

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, a_{T0} shows the time-temperature shift factor of matrix resin and $T(\tau)$ shows the temperature history. The viscoelastic compliance D^* under constant deformation rate loading (static loading) can be shown by

$$D^*\left(t',T_0\right)\cong D_{\mathrm{c}}\left(t'/2,T_0\right) \tag{3}$$

Condition (C) is not considered here because the static loading employed in the tests is monotonic.

3 Experimental procedures

Two kinds of unidirectional CFRP laminates were employed in this study. One is T300/EP which consists of carbon fiber T300 and epoxy resin 2500 (Toray). The laminates were cured by autoclave technique at 135°C for 2hours and then post-cured at 160°C for 2hours. The aging treatment for post-cured specimen was conducted at 110°C for 50hours. The Wet specimens by soaking the aged specimen (Dry specimen) in hot water of 95°C for 121hours for 1mm thick specimen in longitudinal direction, 95°C for 144hours for 2mm thick specimen in longitudinal direction and 95°C for 121hours for 2mm thick specimen in transverse direction were respectively prepared. The water content of all of wet specimen was 1.9wt%. The other is the T700/VE which consists of carbon fiber T700 unidirectional non-crimp fabric (Toray) and vinylester resin Neopol 8250L (Japan U-PICA). The laminates were molded by vacuum assisted resin transfer molding technique and then cured at room temperature for 24hours. The post-cure is conducted at 150°C for 2hours. The Wet specimens by soaking the aged specimen (Dry specimen) in hot water of 95°C for 25hours for 1mm thick specimen in longitudinal direction, 95°C for 50hours for 2mm thick specimens in longitudinal and transverse directions were respectively prepared. The water content of wet specimen was 0.5wt%.

The dynamic viscoelastic tests for the transverse direction of unidirectional CFRP were carried out at various frequencies and temperatures to construct the master curve of creep compliance for matrix resin. The static tests for typical four directions of unidirectional CFRP were carried out at various temperatures to construct the master curves of static strength for unidirectional CFRP. Longitudinal tension tests were carried out according with SACMA 4R-94. Longitudinal bending tests under static and fatigue loadings were carried out according with ISO 14125 to get the longitudinal compressive static strengths. Transverse bending tests were carried out according with ISO 14125 to get the transverse tensile static strengths. Transverse compression tests under static and fatigue loadings were carried out according with SACMA 1R-94.

4 Results and discussion

4.1 Viscoeolastic behaviour of matrix resin

The left side of Fig.1 shows the loss tangent tan δ for the transverse direction of two kinds of unidirectional CFRP (Dry specimen) versus time t, where t is the inverse of frequency. The right side shows the master curve of tan δ which is constructed by shifting tan δ at various constant temperatures along the logarithmic scale of t until they overlapped each other, for the reduced time t' at the reference temperature T_0=25$^{\mathrm{o}}$C. Since tan δ at various constant temperatures can be superimposed so that a smooth curve is constructed, the TTSP is applicable for tan δ for the transverse direction of two kinds of unidirectional CFRP. The master curve of tan δ for Wet specimens can be also constructed as shown in Fig.1. The TTSP is also applicable for tan δ under wet condition. The master curve of tan δ is shifted to the left side by water absorption as shown in Fig.1.

The left side of Fig.2 shows the storage modulus E' for the transverse direction of two kinds of unidirectional CFRP (Dry specimen) versus time t. The right side shows the master curve of E' which is constructed by shifting E' at various constant temperatures along the logarithmic scale of t using the same shift amount for tan δ and logarithmic scale of E' until they overlapped each other, for the reduced time t' at the reference temperature T_0=25$^{\mathrm{o}}$C. Since E' at various constant temperatures can be superimposed so that a smooth curve is constructed, the TTSP is applicable for E' for the transverse direction of two kinds of unidirectional CFRP. The master curve of E' for Wet specimens can be also constructed as shown in Fig.2. The TTSP is also applicable for E' under wet condition.

The time-temperature shift factor $a_{T0}(T)$ which is the horizontal shift amount shown in the upper portion of Fig.3 can be formulated by the following equation:

$$\log a_{T_0}(T) = \frac{\Delta H_1}{2.303G}\left(\frac{1}{T}-\frac{1}{T_0}\right)\mathrm{H}(T_g - T) + \left[\frac{\Delta H_1}{2.303G}\left(\frac{1}{T_\mathrm{g}}-\frac{1}{T_0}\right)+\frac{\Delta H_2}{2.303G}\left(\frac{1}{T}-\frac{1}{T_\mathrm{g}}\right)\right]\left(1-\mathrm{H}(T_\mathrm{g} - T)\right) \quad (4)$$

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

The temperature shift factor $b_{T0}(T)$ which is the amount of vertical shift shown in the lower portion of Fig.3 can be fit with the following equation:

$$\log b_{T_0}(T)=\left[\sum_{i=1}^{5} b_{i-1}\left(T-T_0\right)^{i-1}\right]\mathrm{H}\left(T_g-T\right)+\left[\sum_{i=1}^{5} b_{i-1}\left(T_{\mathrm{g}}-T_0\right)^{i-1}+\log\frac{T_{\mathrm{g}}}{T}\right]\left(1-\mathrm{H}\left(T_{\mathrm{g}}-T\right)\right) \tag{5}$$

where b_{i} are the fitting parameters.

The creep compliance D_{c} of matrix resin was back-calculated from the storage modulus E' for the transverse direction of two kinds of unidirectional CFRP using [3]

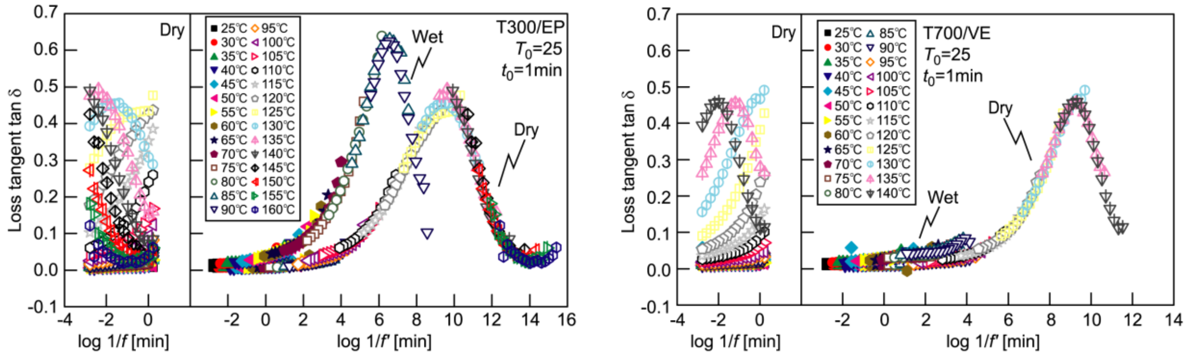
$$D_{\mathrm{c}}(t)\sim 1/E(t), \qquad E(t)\cong E'(\omega)\,|_{\omega\to 2/\pi t} \tag{6}$$

and approximate averaging method by Uemura [4].

The master curves of back-calculated D_{c} of two kinds of matrix resin are shown in Fig.4. The master curve of D_{c} can be formulated by the following equation:

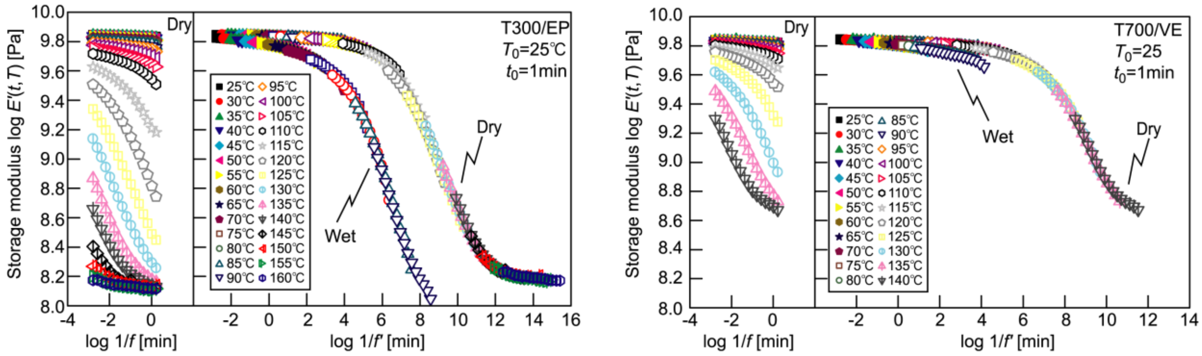
$$\log D_{\mathrm{c}}=\log D_{\mathrm{c},0}(t'_0,T_0)+\log\left[\left(\frac{t'}{t'_0}\right)^{m_{\mathrm{g}}}+\left(\frac{t'}{t'_{\mathrm{g}}}\right)^{m_{\mathrm{r}}}\right] \tag{7}$$

where $D_{\mathrm{c},0}$ is the creep compliance at reduced reference time t'_0 and reference temperature T_0, and t'_g is the glassy reduced time on T_0, and m_{g} and m_{r} are the gradients in glassy and rubbery regions of D_{c} master curve. Parameters obtained from the formulations for $a_{T_0}(T)$, $b_{T_0}(T)$, and D_{c} are listed in Table 1.



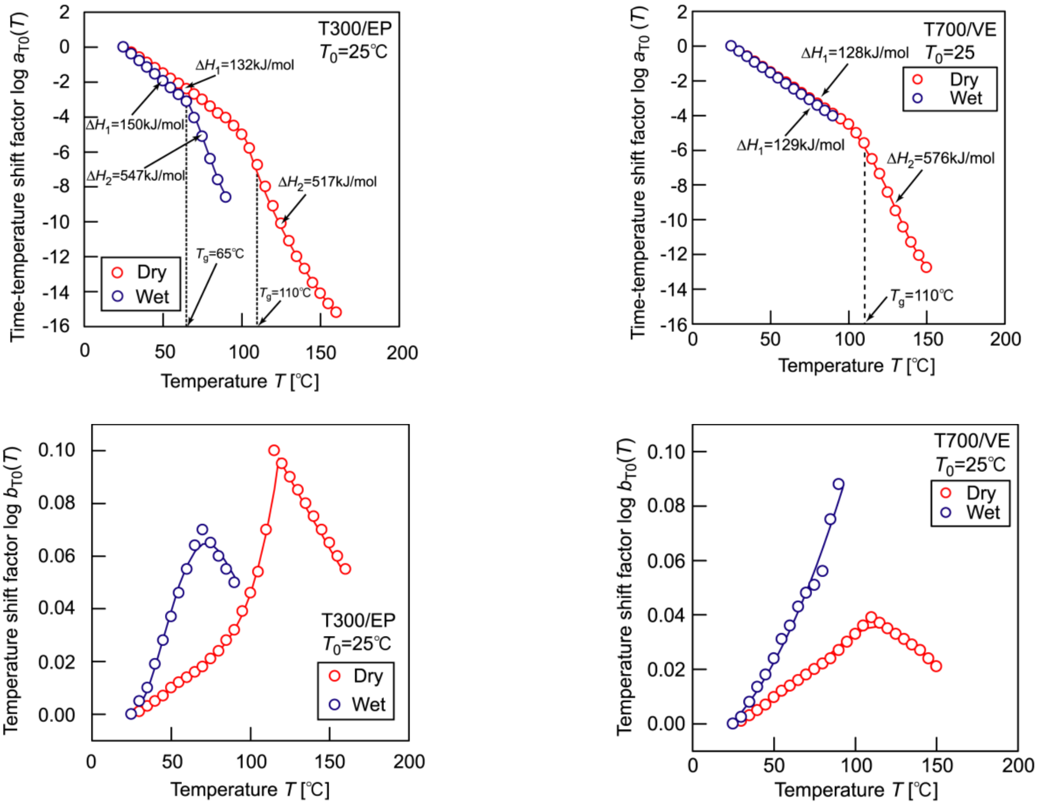
(a) T300/EP (b) T700/VE

Figure 1. Master curves of loss tangent for transverse direction of unidirectional CFRP



(a) T300/EP (b) T700/VE

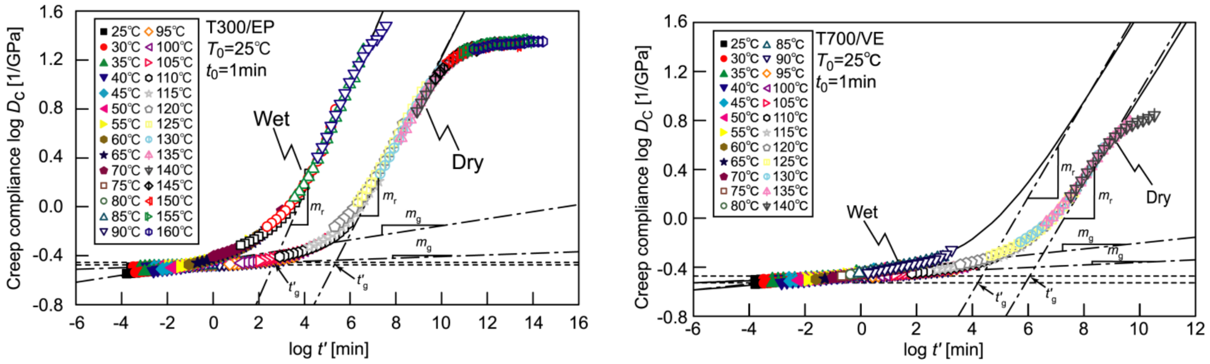
Figure 2. Master curves of storage modulus for transverse direction of unidirectional CFRP



(a) T300/EP

(b) T700/VE

Figure 3. Shift factors of storage modulus for transverse direction of unidirectional CFRP



(a) T300/EP

(b) T700/VE

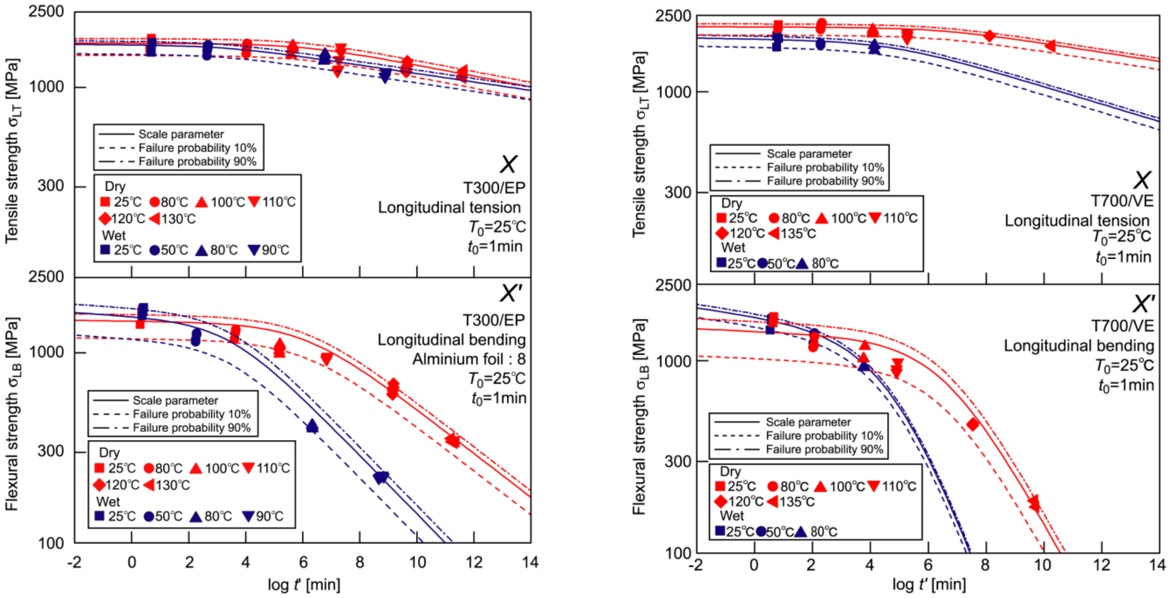
Figure 4. Master curves of creep compliance for matrix resin calculated from the storage modulus for the transverse direction of unidirectional CFRP

Table 1. Parameters for master curve and shift factors of creep compliance for matrix resin

	T300/EP		T700/VE	
	Dry	Wet	Dry	Wet
T_0 [°C]	25	25	25	25
T_g [°C]	110	65	110	(90)
D_{c0} [1/GPa]	0.337	0.351	0.337	0.339
t'_0 [min]	1	1	1	1
t'_g [min]	1.54E06	2.34E03	1.36E06	(1.80E04)
m_g	0.0101	0.0348	0.00893	0.0195
m_r	0.405	0.466	0.373	(0.373)
ΔH_1 [kJ/mol]	132	150	128	129
ΔH_2 [kJ/mol]	517	547	576	-
b_0	1.65E-02	0.150	3.24E-04	-8.77E-03
b_1	-1.86E-03	-1.39E-02	-1.99E-04	1.45E-04
b_2	6.64E-05	4.26E-04	8.64E-06	9.63E-06
b_3	-8.29E-07	-4.71E-06	-1.75E-08	-
b_4	3.81E-09	1.73E-08	-1.71E-10	-

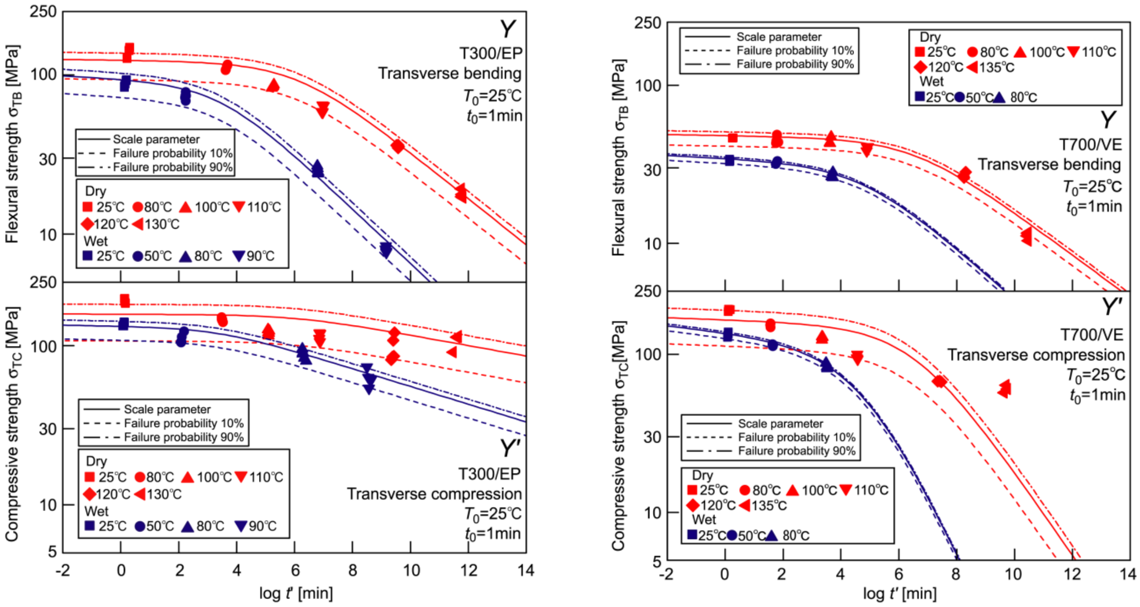
4.2 Master curves of static strengths for unidirectional CFRP

Figures 5 and 6 show the master curves of static strengths for longitudinal tension *X*, longitudinal compression *X'*, transverse tension *Y* and transverse compression *Y'* for Dry and Wet specimens of two kinds of unidirectional CFRP obtained from the strength data at various temperatures by using the time-temperature shift factors a_{To} shown in Fig.3. The solid and dotted curves in these figures show the fitting curves by Eq.(1) using the master curves of creep compliance of matrix resin in Fig.4. The parameters obtained by formulation are shown in Table 2. From these figures, the static strengths of two kinds of unidirectional CFRP decrease with increasing time, temperature and water absorption. The time, temperature and water absorption dependencies of static strength of unidirectional CFRP are different with the loading direction.



(a) T300/EP (b) T700/VE

Figure 5. Master curves of tensile and compressive strengths in the longitudinal direction of unidirectional CFRP



(a) T300/EP

(b) T700/VE

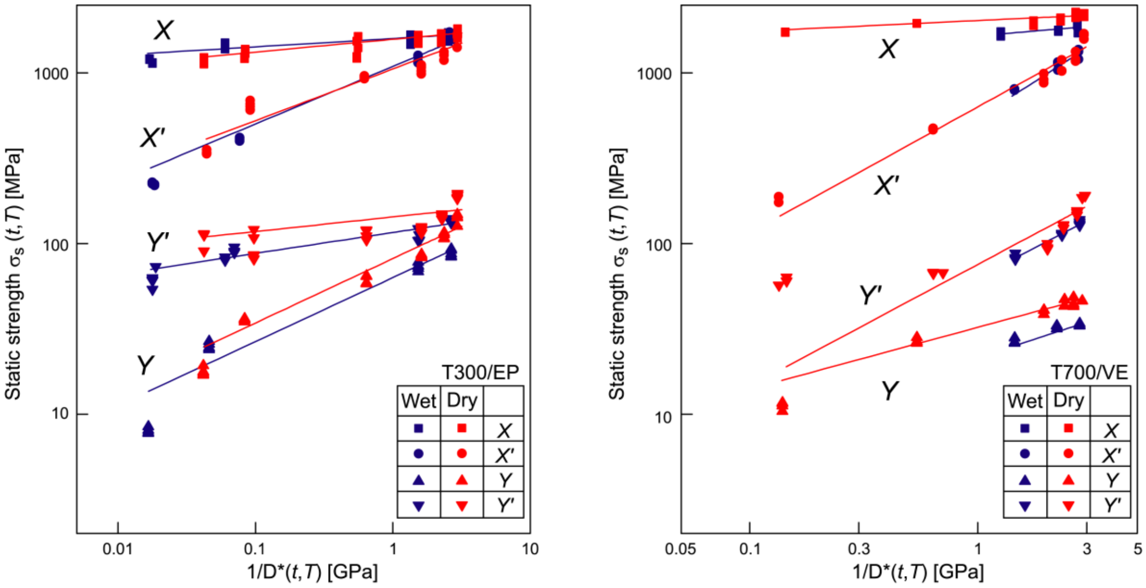
Figure 6. Master curves of tensile and compressive strengths in the transverse direction of unidirectional CFRP

Table 2. Parameters for master curve of static strength of unidirectional CFRP

		T300/EP		T700/VE	
		Dry	Wet	Dry	Wet
X	σ_{s0} [MPa]	1700	1675	2169	1911
	n_r	0.0762	0.0528	0.056	0.129
	α	14.7	20.7	22.2	20.6
X'	σ_{s0} [MPa]	1446	1535	1431	1363
	n_r	0.316	0.356	0.782	0.956
	α	10.0	7.18	7.00	19.6
Y	σ_{s0} [MPa]	121	90.6	47.0	34.0
	n_r	0.387	0.371	0.337	0.319
	α	7.04	7.97	14.0	21.8
Y'	σ_{s0} [MPa]	156	131	161	133
	n_r	0.0868	0.130	0.662	0.934
	α	5.68	11.4	5.70	20.8

4.3 Relationship between static strengths and viscoelasticity of matrix resin

Figure 7 shows the relationship between the static strength of two kinds of unidirectional CFRP and the viscoelastic compliance of corresponding matrix resin. The slop of this relation corresponds to the parameter n_r in Table 2. The slop depends on the loading direction while that changes scarcely with water absorption. It is cleared from these facts that the time, temperature and water absorption dependencies of static strength of unidirectional CFRP can be uniquely determined by the viscoelastic behavior of corresponding matrix resin.



(a) T300/EP

(b) T700/VE

Figure 7. Master curves of tensile and compressive strengths in the transverse direction of unidirectional CFRP

5 Conclusion

The tensile and compressive static strengths in the longitudinal and transverse directions of two kinds of unidirectional CFRP under wet condition are evaluated using ATM. The applicability of ATM can be confirmed for these static strengths. The time, temperature and water absorption dependencies of static strength of unidirectional CFRP can be determined by the viscoelastic behavior of matrix resin.

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