APPLICABILITY OF TIME-TEMPERATURE SUPERPOSITION PRINCIPLE TO THE MODE I INTERLAMINAR FRACTURE BEHAVIOR OF CFRP LAMINATES

T. Moromizato[1*], M. Nakada[2], Y. Miyano[2]

[1]*Graduate School, Kanazawa Institute of Technology, 7-1, Ohgigaoka, Nonoichi, Ishikawa 921-8501, Japan*
[2] *Materials System Research Laboratory, Kanazawa Institute of Technology, 3-1, Yatsukaho, Hakusan, Ishikawa, 924-0838, Japan*
** moro-11@venus.kanazawa-it.ac.jp*

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Abstract
The applicability of time-temperature superposition principle to the mode I interlaminar fatigue crack propagation of CFRP laminate was discussed. The double cantilever beam (DCB) tests of CFRP laminate under static and fatigue loadings were performed at various loading rates and temperatures. The smooth master curves of mode I interlaminar crack propagation under static and fatigue loadings were obtained based on the time-temperature superposition principle for viscoelastic behavior of matrix resin. Therefore, the applicability of time-temperature superposition principle to the mode I interlaminar crack propagation under static and fatigue loadings for CFRP laminates was confirmed experimentally.

1 Introduction
The mechanical behavior of polymer resins 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 FRP using polymer resins as matrices also depends on time and temperature even below T_g which is within the normal operating temperature range. Therefore, it is strongly expected that the accelerated testing methodology (ATM) for the long-term life prediction of composite structures exposed under the actual environments of temperature and others is established.

In our previous papers, we have studied the time and temperature dependence of fatigue strength as well as static strength of various kinds of FRP under tensile, compressive and bending loadings. It was cleared that the time-temperature superposition principle (TTSP) for the viscoelastic behavior of matrix resin holds for fatigue strength as well as static strength of FRP using the corresponding matrix resin [1-3].

In this paper, the double cantilever beam (DCB) tests of CFRP laminate under static and fatigue loadings were performed at various loading rates and temperatures. The applicability of time-temperature superposition principle to the mode I interlaminar crack propagation of CFRP laminate was discussed.

2 Experimental Procedures

Materials used in this study were CFRP laminates which consist of unidirectional carbon fiber T300 and epoxy resin 2500. Stacking sequence was $[0]_{12}$ and the thickness of laminate were approximately 3mm. Molding method of CFRP laminate was the autoclave process. CFRP laminates were cured at 130^{o}C for 2hour, then after cured at 160^{o}C for 2hour and at 110^{o}C for 50hour.

The dynamic viscoelastic analysis (DMA) for the transverse direction of unidirectional CFRP mentioned above was conducted in order to obtain the time-temperature shift factor of the storage modulus of matrix resin. Geometry of specimen was 50mm in length, 6.4mm in width and 1.6mm in thickness. DMA was conducted by RSA 3 (TA Instruments), and test mode was dual cantilever bending. Span was 36.7mm.

DCB tests were conducted according with ISO 15024 “Determination of mode I interlaminar fracture toughness, GIC, for unidirectionally reinforced materials”. Naflon film of 30μm in thickness was placed in the neutral plane of this laminate in order to insert a precrack. The specimen of DCB test was shown in Fig.1.

All DCB tests were conducted with electro-hydraulic servo testing machine (EHF-FB05-4LE 5kN, Shimadzu Corporation). The temperature dependency on the mode I interlaminar crack propagation under static loading was evaluated in the constant testing speed V=0.05mm/min, 0.5mm/min, 5.0mm/min, and 50mm/min. Temperature conditions were varied as follows: T=25^{o}C, 80^{o}C, 100^{o}C, 110^{o}C and 120^{o}C. The temperature dependency on the mode I interlaminar crack propagation under fatigue loading was evaluated in the frequency of f=0.02Hz and 2Hz. Temperature conditions were varied as follows: T=25^{o}C, 80^{o}C, 104^{o}C, 110^{o}C, 112^{o}C, 115^{o}C and 120^{o}C. Test conditions were shown in Table 1.

The crack lenth a for DCB static and fatigue tests is expressed by

$$a = 2H(\alpha_1 (B\lambda)^{\frac{1}{3}} + \alpha_0) \qquad (1)$$

$$\alpha_1 = 10 D_1 (E_L)^{\frac{1}{3}} \qquad (2)$$

where $2H$ is nominal thickness of specimen, B is width of specimen, λ is crack opening displacement (COD) compliance, α_1, α_0 and D_1 (=0.25) are coefficients, E_L is modulus of elasticity in static bending.

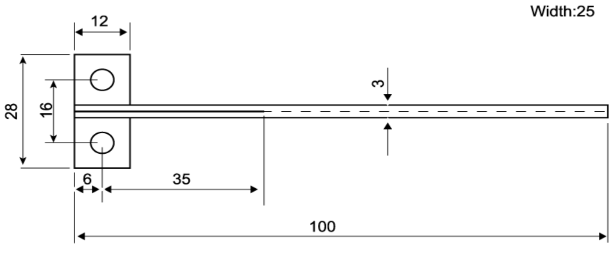

Figure 1. DCB test specimen

Table 1. Test condition of DCB tests under static and fatigue loadings

	Test speed	Test temperature
Static	0.05, 0.5, 5.0, 50mm/min	25, 80, 100, 110, 120℃
Fatigue	2Hz	25, 80, 110, 120℃
	0.02Hz	25, 104, 112, 115℃

3 Result and discussion

3.1 Viscoelastic Behavior of Matrix Resin

The left side of Fig.2 shows the loss tangent tanδ versus testing time t (=1/*f*) at various temperatures *T*. The right side shows the master curve of tanδ which is constructed by shifting tanδ 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°C. Since tanδ at various constant temperatures can be superimposed so that a smooth curve is constructed, the TTSP is applicable for tanδ.

The left side of Fig.3 shows the storage modulus *E*' versus testing time *t* at various temperatures *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 tanδ and logarithmic scale of *E*' until they overlapped each other, for the reduced time *t*' at the reference temperature T_0=25°C. Since *E*' at various constant temperatures can be superimposed so that a smooth curve is constructed, the TTSP is applicable for *E*'. The horizontal time-temperature shift factor $a_{To}(T)$ and the vertical temperature shift factor $b_{To}(T)$ at a reference temperature T_0=25°C are plotted in Fig.4.

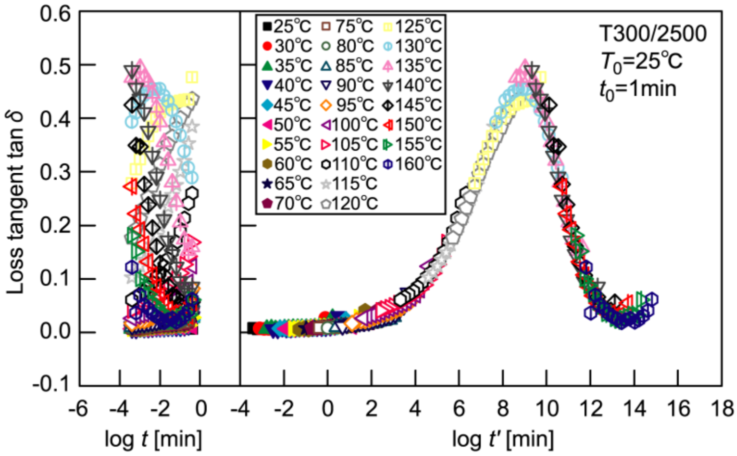

Figure 2. Master curve of loss tangent for matrix resin

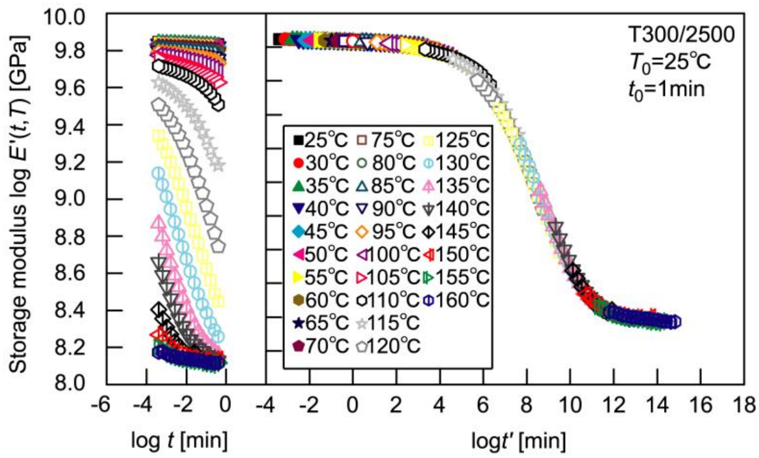

Figure 3. Master curve of storage modulus for matrix resin

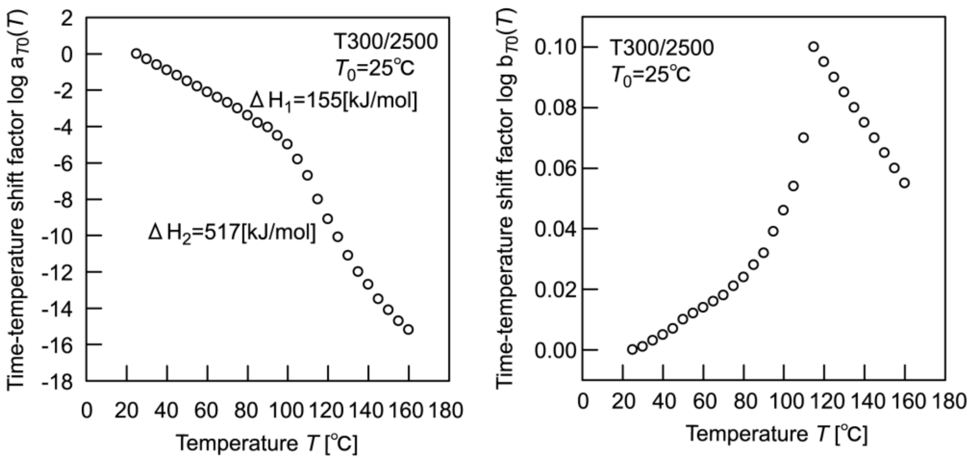

Figure 4. Time-temperature shift factor and temperature shift factor for storage modules of matrix resin

3.2 Mode I interlaminar crack progress behavior of DCB static test

Figure 5 shows the load-COD curves at various temperatures when the test speed V=5mm/min. At all temperatures, the load is increased for increase of the COD and gradually decreases when reach the maximum load point.

Figure 6 shows the relationship between crack propagation Δa and COD at various temperatures when the load speed V=5mm/min. Solid lines in the figure are the calculated value obtained by Equation (1) and the dotted lines are the measured value of Δa. As shown in Fig.6, the progress of the crack for increase of the COD becomes slow by increase of temperature. In addition, calculated and measured values of Δa agree well with each other.

Figure 7 shows the relationship between Δa and temperature, where Δa are calculated from the change of COD compliance between the COD=7mm from the point of maximum load by Equation (1). As shown in Fig.7, Δa decreases by increase of temperature and decrease of test speed.

Figure 8 shows the master curve of Δa versus the reduced time to failure t' which was constructed by shifting Δa at various temperatures and test speeds along the log scale of t (COD/V) using the same $a_{T0}(T)$ for E' of matrix resin shown in Fig.4. Since the smooth master curve of Δa can be obtained, the same TTSP for E' of matrix resin is applicable for the Δa of CFRP laminates under static loading.

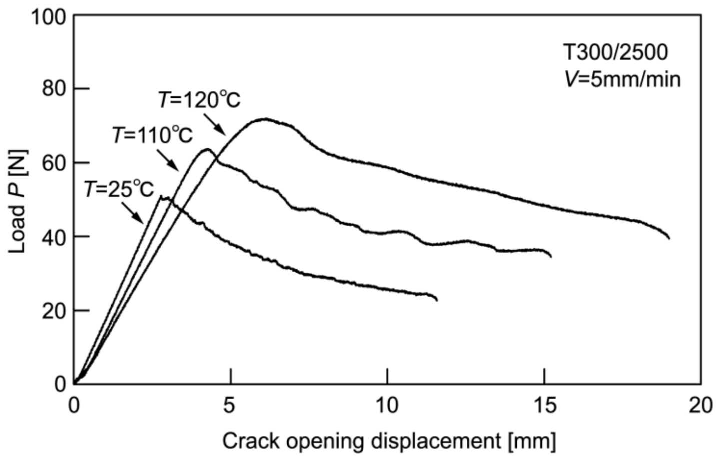

Figure 5. Typical load-COD curves for static test

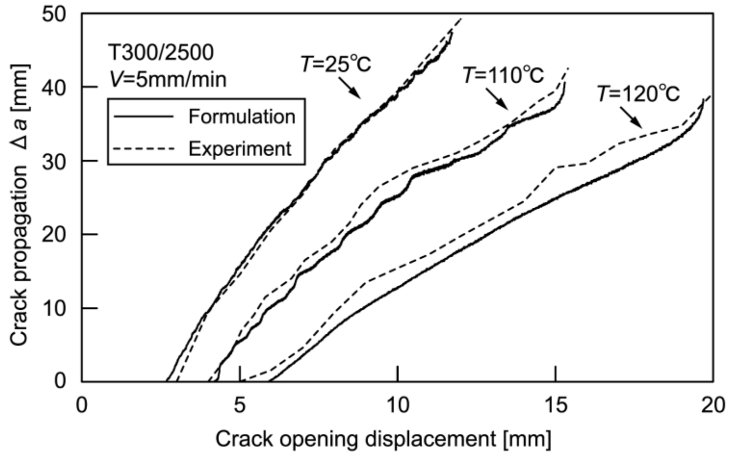

Figure 6. Typical crack propagation Δ*a* versus COD for static test

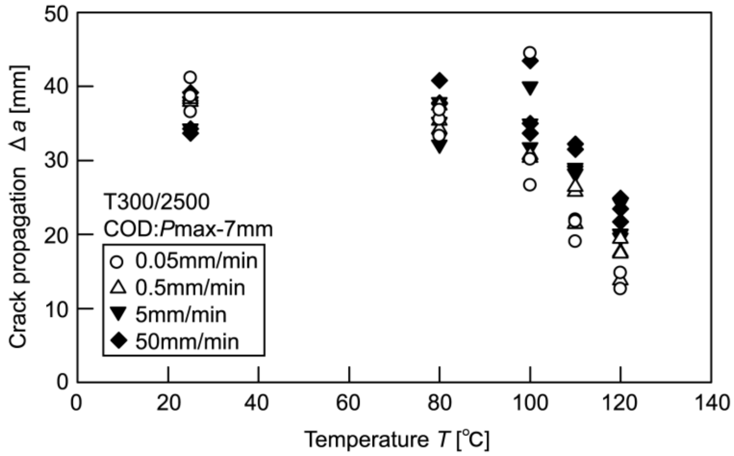

Figure 7. Crack propagation Δ*a* versus temperature for static test

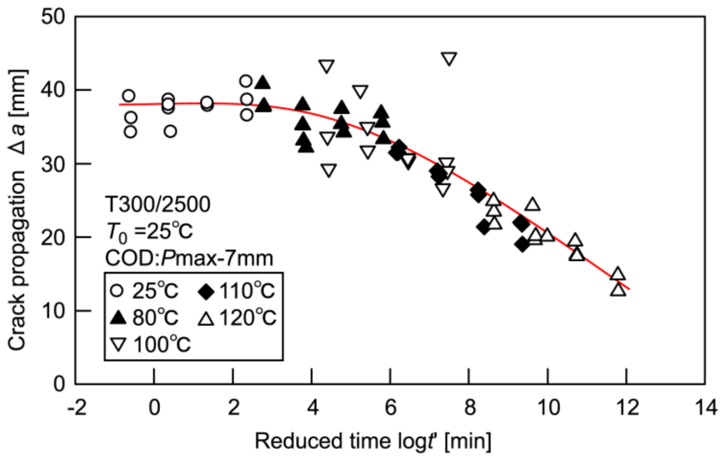

Figure 8. Master curve of crack propagation Δ*a* for static test

3.3 Mode I interlaminar crack progress behavior of DCB fatigue test

Figure 9 shows the maximum load versus number of cycle at various temperatures for the frequency *f*=2Hz. The maximum load decreases with increase of number of cycle, and the decrease of maximum load is remarkable with increase of temperature.

Figure 10 shows the relationship between Δa and load from the N=1 to 2000cycle. Solid lines in the figure are the calculated value by Equation (1) and the dotted lines are the measured value. As shown in Fig.10, Δa increases with increase of temperature. In addition, the calculated and measured values did not agree with each other under high temperatures. In this paper, we evaluated the calculated Δa by Equation (1) for all temperature tested.
Figure 11 shows the relationship between Δa and temperature from the N=1 to 2000cycle. As shown in Fig.11, Δa increases with increase of temperature and decrease of test speed.
Figure 12 shows the master curve of Δa versus the reduced time to failure t' which was constructed by shifting Δa at various temperatures and frequencies along the log scale of t (=N/f) using the same $a_{T_0}(T)$ for E' of matrix resin shown in Fig.4. Since the smooth master curve of Δa can be obtained, the same TTSP for E' of matrix resin is applicable for the Δa of CFRP laminate under fatigue loading.

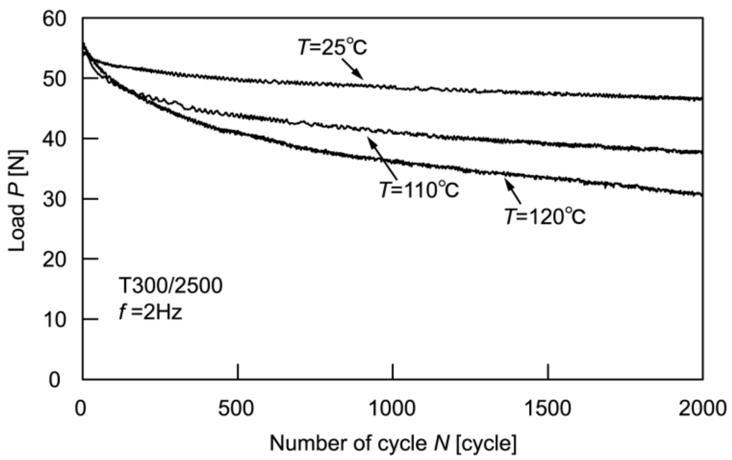

Figure 9. Typical load-number of cycle curves for fatigue test

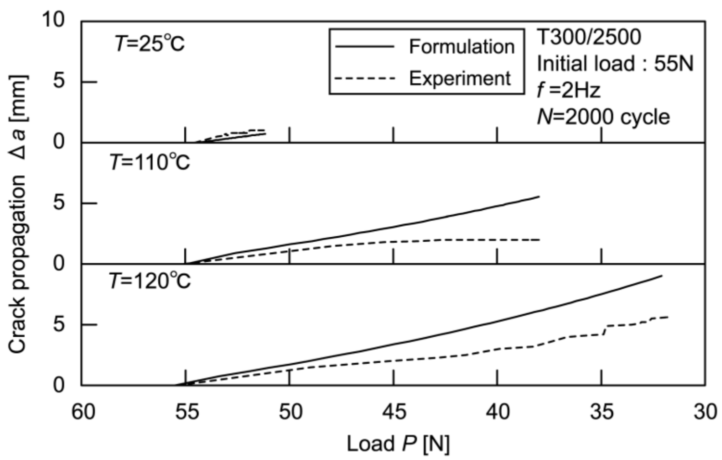

Figure 10. Typical crack propagation Δa versus load for fatigue test

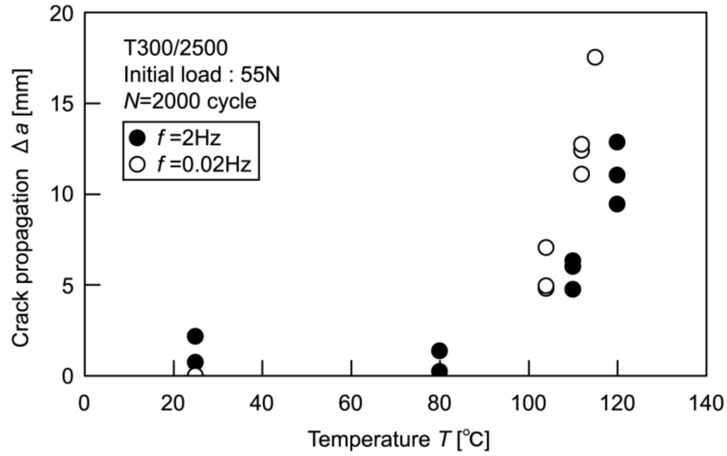

Figure 11. Crack propagation Δa versus temperature for fatigue test

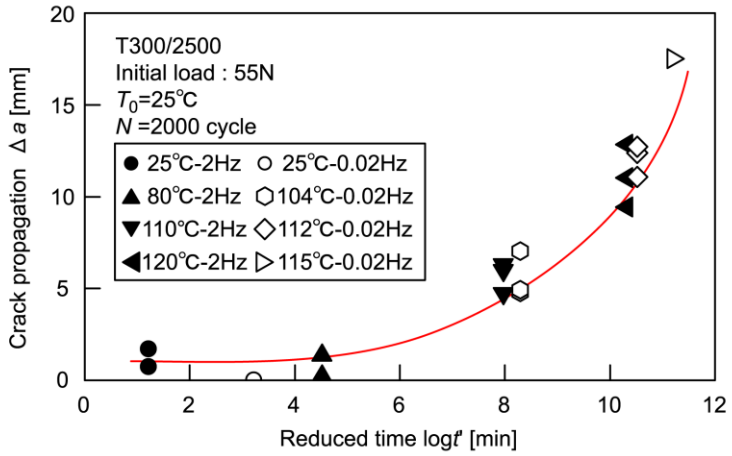

Figure 12. Master curve of crack propagation Δa for fatigue test

4 Conclusion

The double cantilever beam (DCB) tests of CFRP laminate under static and fatigue loadings were performed at various loading rates and temperatures. The crack propagation under static loading decreased by increase of temperature and decrease of test speed. However, the crack propagation under fatigue loading increased by increase of temperature and decrease of test speed. The applicability of time-temperature superposition principle to the mode I interlaminar crack propagation under static and fatigue loadings for CFRP laminates was confirmed experimentally.

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