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Prediction of tensile fatigue life under temperature environment for unidirectional CFRP

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Abstract—A method for prediction of fatigue strength under temperature environment was proposed for polymer composites and its validity was confirmed for the flexural fatigue strength of satin-woven CFRP laminates and others. This method is based upon the four hypotheses: (A) same failure process under constant strain-rate (CSR), creep, and fatigue loadings, (B) same time-temperature superposition principle for all failure strengths, (C) linear cumulative damage law for a nondecreasing stress process, and (D) linear dependence of fatigue strength upon stress ratio. Data are provided for tensile CSR, creep, and fatigue tests at various loading rates, frequencies, and temperatures in the longitudinal direction of unidirectional CFRP. In this paper, experimental verification of the prediction method is discussed for the tensile fatigue strength of unidirectional CFRP.

Keywords: Polymer composites; carbon fiber reinforced plastics; fatigue; life prediction; time-temperature dependent properties.

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. These examples are shown by Aboudi *et al.* [1], Sullivan [12], Gates [3], Miyano *et al.* [6], and Nakada *et al.* [11].

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The time-temperature dependence of the flexural CSR (constant strain-rate), creep, and fatigue strengths of various CFRP laminates has been studied by Miyano *et al.* [7] and by McMurray *et al.* [5]. It was observed by Enyama *et al.* [2] that the fracture modes are almost identical under the three types of loading over a wide range of time and temperature. Similar results were also reported by Karayaka *et al.* [4] at room temperature. The literature survey indicates the validity of the two hypotheses for CFRP: the same failure process and the same time-temperature superposition principle for CSR, creep, and fatigue failure.

In our previous papers [8–10], a prediction method for fatigue strength of CFRP under an arbitrary frequency, stress ratio, and temperature was proposed based on the above two hypotheses and two additional hypotheses: the linear cumulative damage law for a nondecreasing stress process and the linear dependence of fatigue strength upon stress ratio. The validity of the method and the hypotheses was confirmed by three-point bending tests of satin-woven CFRP laminates and others.

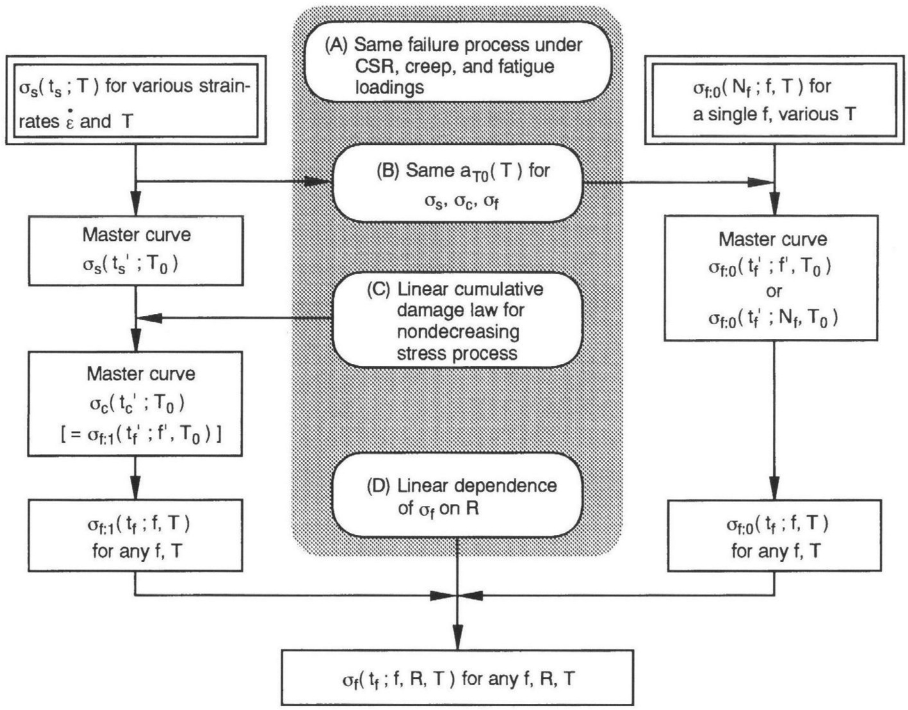
In this paper, this prediction method is applied to the tensile fatigue strength of unidirectional CFRP and its validity is confirmed experimentally by the tensile fatigue tests using resin impregnated strand. Our proposed approach leads to a simpler estimate of life of polymer composites than the traditional S-N approach and may be extended to life-prediction of polymer-composite structures under combined loading and temperature histories.

2. PREDICTION PROCEDURE OF FATIGUE STRENGTH

The prediction method rests on the four hypotheses, (A) same failure process under CSR, creep, and fatigue loadings, (B) same time-temperature superposition principle for all failure strengths, (C) linear cumulative damage law for a nondecreasing stress process, and (D) linear dependence of fatigue strength upon stress ratio.

When these hypotheses are met, the fatigue strength under an arbitrary combination of frequency, stress ratio, and temperature can be determined based on the following test results: (a) master curve of CSR strength and (b) master curve of fatigue strength for zero stress ratio. The master curve of CSR strength can be constructed from the test results at various constant strain-rates and temperatures. On the other hand, the master curve of fatigue strength at zero stress ratio can be constructed from the test results at a single frequency under various temperatures. We regard the master curve of fatigue strength at stress ratio $R = 0.1$, the least stress ratio possible in our testing machine, as the master curve at $R = 0$. Further, we consider the CSR strength is the fatigue strength at $R = 0$ and the number of cycles to failure $N_f = 1/2$ based on the similarity of the two histories.

The outline of this method is shown schematically in Fig. 1 together with definitions of some notations. The detail of the method will be presented with experimental results.



T, T_0	:	temperature, reference temperature
f, f'	:	frequency, reduced frequency
t_s, t_c, t_f	:	time to failure under constant strain-rate (CSR), creep, and fatigue loadings
t_s', t_c', t_f'	:	reduced time to failure
$a_{T0}(T)$	:	time-temperature shift factor ($a_{T0}(T) = t_s/t_s' = t_c/t_c' = t_f/t_f' = f'/f$)
R	:	stress ratio ($R = \sigma_{min}/\sigma_{max}$)
N_f	:	number of cycles to failure ($N_f = f\, t_f$)
σ_s, σ_c, σ_f	:	CSR, creep, and fatigue strengths
$\sigma_{f:0}$, $\sigma_{f:1}$	:	σ_f for R=0 and R=1

Figure 1. Prediction procedure of fatigue strength of polymer composites.

3. EXPERIMENTAL PROCEDURE

3.1. Preparation of specimen

The unidirectional CFRP (epoxy resin impregnated carbon fiber strand; CF/Ep strand) produced by the filament winding method consists of high strength carbon fibers TORAYCA T400-3K (Toray) and a general purpose epoxy resin EPIKOTE 828 (Yuka Shell Epoxy). The CF/Ep strand was cured at 70°C for 12 h and postcured at 150°C for 4 h, and then at 190°C for 2 h. The glass-transition temperature T_g of the epoxy resin is 112°C. The diameter of CF/Ep strand is approximately 1 mm.

3.2. Test procedures

The conditions under which the tests were carried out are shown in Table 1. The tests are of two kinds: one is to obtain the data necessary for the proposed prediction method of fatigue strength and the other is for confirming the validity of this methodology which are indicated by an asterisk in Table 1.

The tensile test specimens of CF/Ep strand were prepared as shown in Fig. 2. The tensile CSR tests were conducted at 6 temperatures between 50 and 150°C, by using an Instron type testing machine with small temperature controlled chamber as shown in the left side of Fig. 3. Loading rates (cross-head speeds) were 0.01, 1, and 100 mm/min. The creep tests were conducted at three temperatures by using creep testing machines. The fatigue tests were conducted under several constant temperatures at two loading frequencies, $f = 2$ and 0.02 Hz, by using an electro-hydraulic servo testing machine with small temperature controlled chamber as shown in the right side of Fig. 3. Stress ratio R (minimum stress/maximum stress) was 0.1. Additional fatigue tests were conducted under several constant temperatures at $f = 2$ Hz and $R = 0.5$.

The tensile CSR, creep, and fatigue strengths σ of the CF/Ep strand are defined by

$$\sigma = P_{\max}\frac{\rho}{t_e}, \tag{1}$$

where, $P_{\max}$ is the maximum load [N] of the CF/Ep strand, ρ is the density of fiber [g/cm^3], t_e is the tex of fiber strand [(g/1000m)$\times 10^{-3}$]. Therefore, these strengths are calculated by using the cross-sectional area of the carbon fiber strand.

Table 1.
Test conditions for CSR, creep, and fatique tests

Loading type	Cross-head speed (mm/mm)	Frequency (Hz)	Stress ratio $\sigma_{min}/\sigma_{max}$	Temperature (°C)
CSR	0.01 1 100	—	—	50, 70, 90, 110, 130, 150
Creep*	—	—	1	50, 110, 150
Fatigue I	—	2	0.1	50, 110, 150
Fatigue II*	—	0.02	0.1	80, 130
Fatigue III*	—	2	0.5	50, 110, 150

* Test for confirming the validity of this methodology.

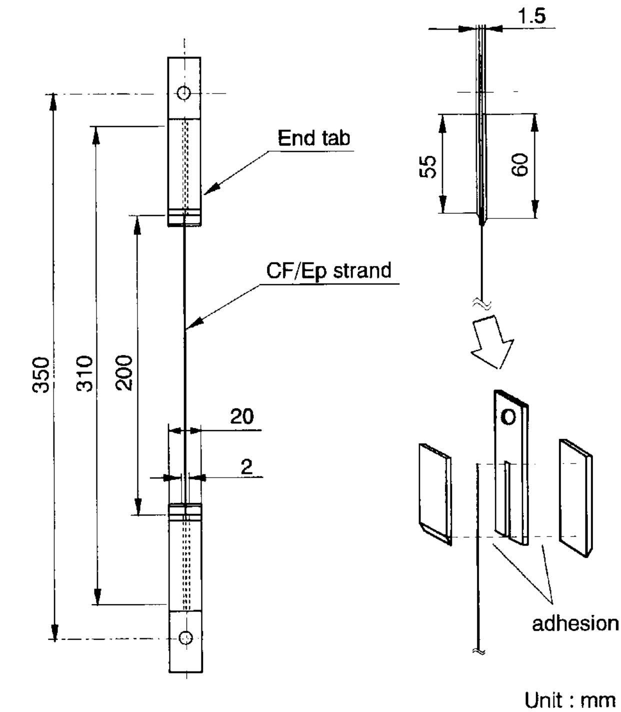


Figure 2. Configuration of specimen for tensile CSR, creep, and fatigue tests.

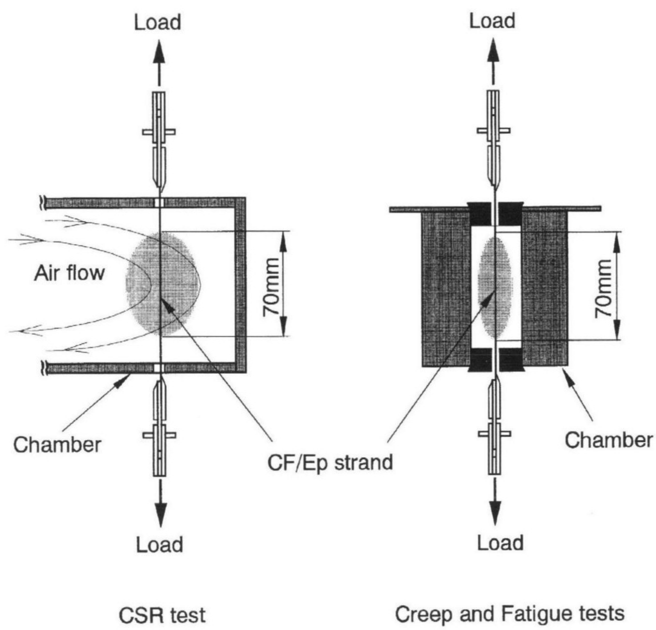


Figure 3. Configuration of small temperature controlled chamber for tensile CSR, creep, and fatigue tests.

4. RESULTS AND DISCUSSION

4.1. Master curve of CSR strength

The left side of Fig. 4 shows the tensile CSR strength σ_s *vs* time to failure t_s at various temperatures T, where t_s is the time period from initial loading to maximum load in constant strain-rate tests. The master curve was constructed by shifting σ_s at constant temperatures other than reference temperature T_0 along the log scale of t_s so that they overlap on σ_s at the reference temperature or on each other to form a single smooth curve as shown on the right side of Fig. 4. Since σ_s at various temperatures can be superimposed smoothly, the time-temperature superposition principle is applicable for σ_s.

The time-temperature shift factor $a_{T_0}(T)$ is defined by

$$a_{T_0}(T) = \frac{t_s}{t'_s}, \tag{2}$$

where, t'_s is reduced time to failure. The shift factors for the tensile CSR strength of CF/Ep strand obtained experimentally in Fig. 4 are plotted in solid circles and connected by solid line in Fig. 5. Also, plotted by open circles in Fig. 5 is the shift factor for the creep compliance of matrix resin; these plots agree well with those for tensile CSR strength. It can be presumed from this agreement and the role of load transmission to fibers on matrix resin that the time and temperature dependence of the tensile CSR strength of CF/Ep strand is controlled by the viscoelastic behavior of matrix resin. Both of these shift factors are quantitatively in good agreement with two Arrhenius' equations with different activation energies ΔH:

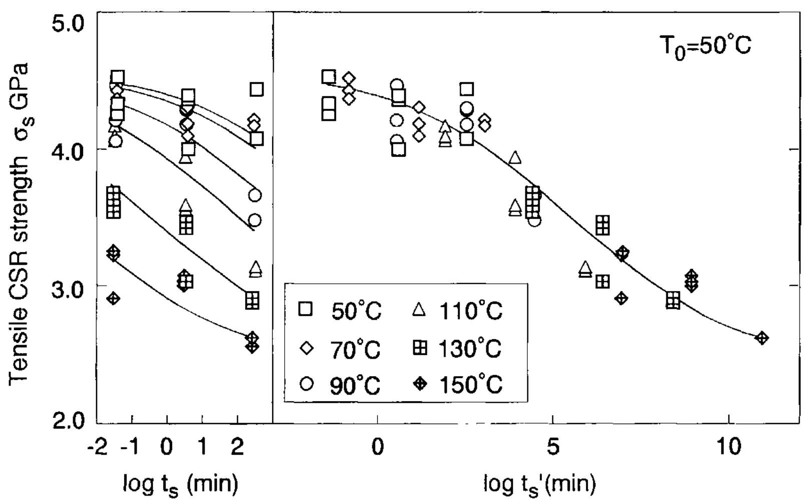


Figure 4. Master curve of tensile CSR strength of CF/Ep strand.

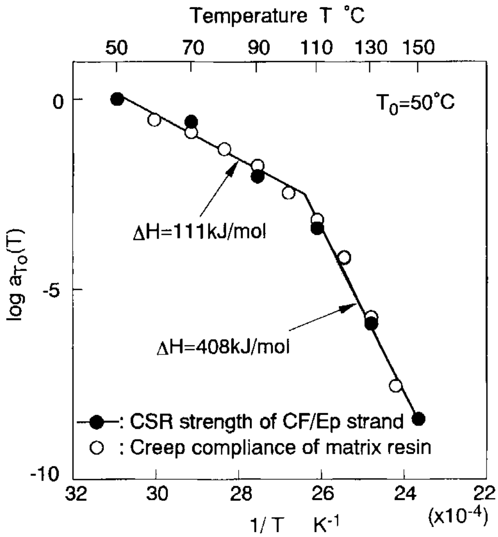


Figure 5. Time-temperature shift factor for tensile CSR strength of CF/Ep strand.

$$\log a_{T_0}(T) = \frac{\Delta H}{2.303G}\left(\frac{1}{T} - \frac{1}{T_0}\right), \tag{3}$$

where G is the gas constant, 8.314×10^{-3} [kJ/(K mol)].

4.2. *Master curve of creep strength*

A prediction method of creep strength σ_c from the master curve of CSR strength using the linear cumulative damage law was presented in our previous paper [8]. Let $t_s(\sigma)$ and $t_c(\sigma)$ be the CSR and creep failure time for the stress σ. Suppose that the material experiences a nondecreasing stress history $\sigma(t)$ for $0 \leqslant t \leqslant t^*$ where t^* is the failure time under this stress history. The linear cumulative damage law states

$$\int_0^{t^*} \frac{dt}{t_c[\sigma(t)]} = 1. \tag{4}$$

When $\sigma(t)$ is equal to constant stress σ_0, the above formula reduces to $t^* = t_c(\sigma_0)$.

The left side of Fig. 6 shows the creep strength σ_c at three different temperatures which are shifted using the shift factor for CSR strength to the data at the reference temperature $T_0 = 50°C$ on the right side. On the right side, the solid curve represents the master curve of creep strength calculated based on equation (4) using the master curve of CSR strength plotted in the dashed curve. The agreement between the predicted curve and the creep test results is satisfactory; this indicates the validity of the linear cumulative damage law and a common shift factor.

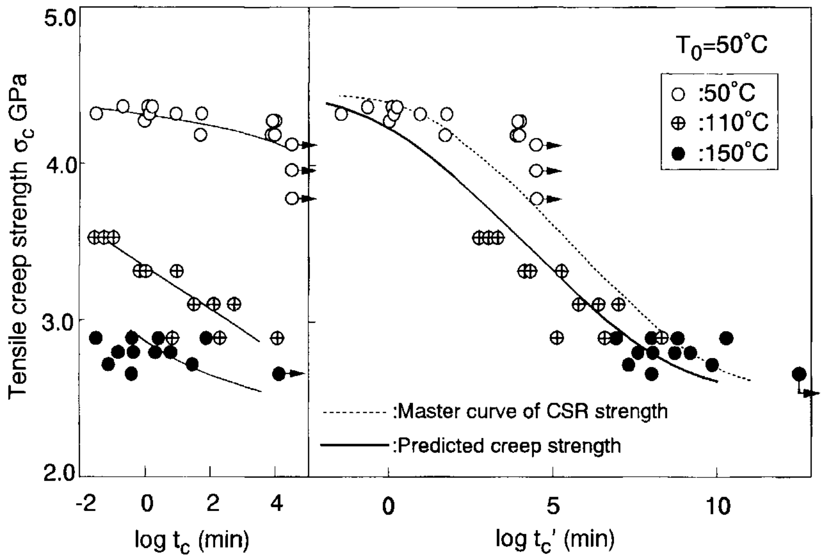


Figure 6. Prediction of tensile creep strength by using linear cumulative damage law.

4.3. Master curve of fatigue strength

We regard the fatigue strength σ_f either as a function of the number of cycles to failure N_f or of the time to failure $t_f = N_f/f$ for a combination of frequency f, stress ratio R, temperature T and denote them by $\sigma_f(N_f;\ f, R, T)$ or $\sigma_f(t_f;\ f, R, T)$. Further, we consider the CSR strength $\sigma_s(t_f;\ T)$ the fatigue strength at $N_f = 1/2$, $R = 0$, and $t_f = 1/(2f)$; this is motivated by closeness of the line connecting the origin and $(\pi, 1)$ and the curve $[1 + \sin(t - \pi/2)]/2$ for $0 < t < \pi$. At this point, we introduce special symbols for fatigue strength at zero and unit stress ratios by $\sigma_{f:0}$ and $\sigma_{f:1}$ where the latter corresponds to creep strength.

To describe the master curve of $\sigma_{f:0}$, we need the reduced frequency f' in addition to the reduced time t'_f, each defined by

$$f' = f \cdot a_{T_0}(T), \quad t'_f = \frac{t_f}{a_{T_0}(T)} = \frac{N_f}{f'}. \tag{5}$$

We introduce two alternative expressions for the master curve at zero stress ratio: $\sigma_{f:0}(t'_f;\ f', T_0)$ and $\sigma_{f:0}(t'_f;\ N_f, T_0)$. In the latter expression, the explicit reference to frequency is suppressed in favor of N_f. Note that the master curve of fatigue strength at $N_f = 1/2$ is regarded as the master curve of CSR strength. Equation (5) enables one to construct the master curve from the tests at a single frequency for various temperatures.

Figure 7 displays, for three temperatures, the fatigue strength $\sigma_{f:0}$ *vs* the number of cycles to failure N_f ($\sigma_{f:0}$–N_f curve) at a frequency $f = 2$ Hz, stress ratio $R = 0.1$ together with the CSR strength which is regarded as the fatigue strength at $N_f = 1/2$, $R = 0$. In the analysis to follow, we regard $\sigma_{f:0}$ to be the master curves

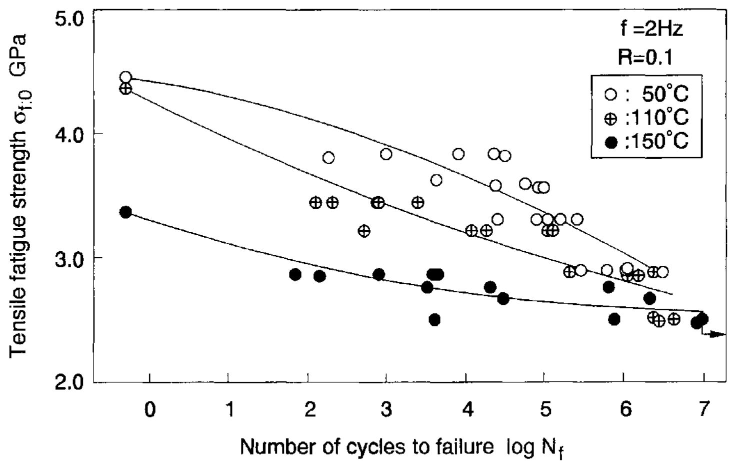


Figure 7. Tensile fatigue strength *vs* number of cycles to failure ($f = 2$ Hz).

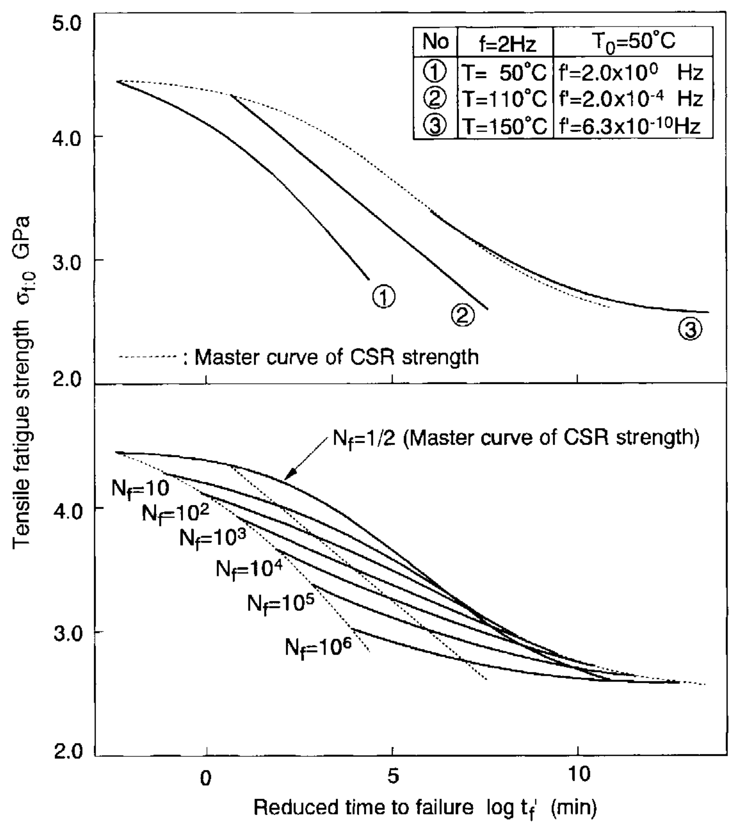


Figure 8. Master curves of tensile fatigue strength.

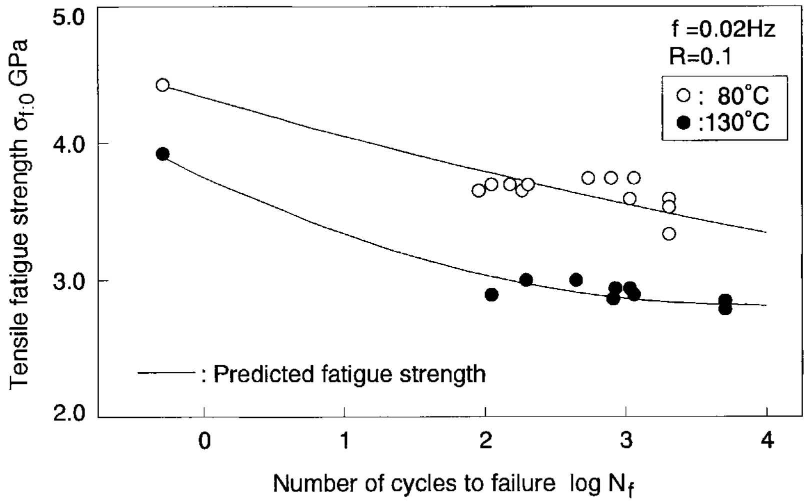


Figure 9. Prediction of tensile fatigue strength by using the master curves of fatigue strength.

at $R = 0.1$. In the upper side of Fig. 8, master curves of $\sigma_{f:0}$ *vs* the reduced time to failure for three frequencies at the reference temperature $T_0 = 50°C$ are depicted in solid curves using the shift factor for CSR strength; the master curve for CSR strength is included in the figure in dashed curve. The master curves of $\sigma_{f:0}$–t'_f for fixed N_f are constructed by connecting the points of the same N_f on the curves of each frequency as shown in the lower half of Fig. 8.

The predicted $\sigma_{f:0}$–N_f curves at $f = 0.02$ Hz for two temperature levels are displayed in Fig. 9 together with test data. These curves are constructed from the master curves in the lower half of Fig. 8 by use of equation (5). Since the predicted $\sigma_{f:0}$–N_f curves capture test data satisfactorily, the time–temperature superposition principle for the CSR strength also holds for the fatigue strength indicating the validity of the hypothesis (B) for fatigue strength.

4.4. Prediction of fatigue strength for arbitrary stress ratio

We have the master curve for creep strength $\sigma_c(t'_c;\, T_0)$ from which follows the creep strength at any temperature T. The creep strength, in turn, may be regarded as the fatigue strength $\sigma_{f:1}(t_f;\, f, T)$ at unit stress ratio $R = 1$ and arbitrary frequency f with $t_c = t_f$. Further, from the master curve for fatigue strength at zero stress ratio $\sigma_{f:0}(t'_f, f', T_0)$ obtainable from tests with a single frequency and various temperatures as shown in Fig. 8, we can deduce by use of equation (5) the fatigue strength $\sigma_{f:0}(t_f;\, f, T)$ at zero stress ratio for any frequency f and temperature T.

Implementing hypothesis (D), we propose a formula to estimate the fatigue strength $\sigma_f(t_f;\, f, R, T)$ at an arbitrary combination of f, R, T by

$$\sigma_f(t_f;\, f, R, T) = \sigma_{f:1}(t_f;\, f, T)R + \sigma_{f:0}(t_f;\, f, T)(1 - R). \tag{6}$$

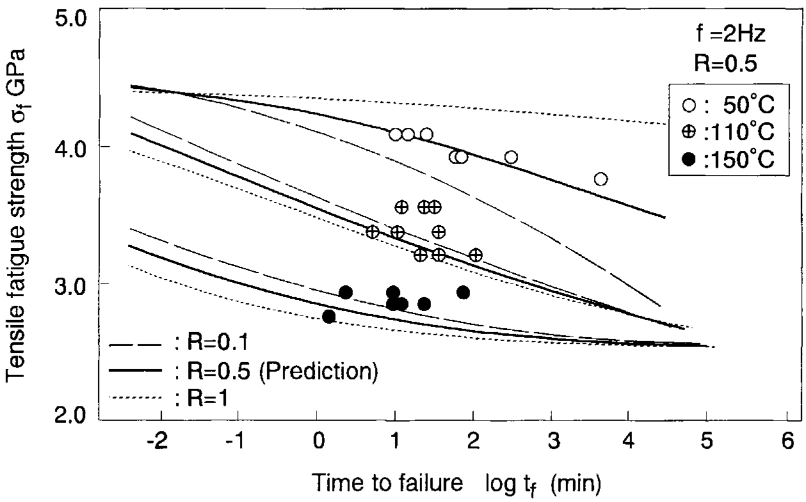


Figure 10. Prediction of tensile fatigue strength at stress ratio $R = 0.5$.

Figure 10 displays the experimental data of $\sigma_f - t_f$ at $f = 2$ Hz, $R = 0.5$, and $T = 50$, 110, 150°C. The curves of $R = 0$ and $R = 1$ represent the least squares fit for experimental data of fatigue test at $R = 0.1$ and creep test. The curve of $R = 0.5$ is calculated from equation (6) on the basis of the curves for $\sigma_{f:0}$ and $\sigma_{f:1}$. As can be seen, the predictions correspond with the test data adequately.

Since the tensile failure under CSR, creep, and fatigue loadings occur instantly and all these specimens are failed in fine pieces, we could not confirm the validity of hypothesis (A): the same failure process under CSR, creep, and fatigue loadings. However, the validity of three hypotheses: (B) same time–temperature superposition principle for all failure strengths, (C) linear cumulative damage law for nondecreasing stress process, and (D) linear dependence of fatigue strength upon stress ratio, can be confirmed experimentally. Therefore, we consider that the hypothesis A is not always necessary for this prediction method.

5. CONCLUSION

Tensile CSR, creep, and fatigue tests for unidirectional CFRP were carried out under various temperatures and loading rates. We observed remarkable dependence of these strengths upon temperature and loading rate as well as the number of cycles to failure. The fatigue prediction method proposed previously for flexural fatigue strength of satin-woven CFRP laminate [8] is applied successfully to the tensile fatigue strength of unidirectional CFRP.

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