CHARACTERIZATION OF TIME-TEMPERATURE DEPENDENT STATIC AND FATIGUE BEHAVIOR OF UNIDIRECTIONAL CFRP

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Abstract

This paper deals with the constituent-based characterization of long term strength of CFRP structure components with the combined method of micromechanics failure (MMF) and the accelerated testing methodology (ATM) developed by Tsai, Christensen, Miyano and others. The time-temperature dependent master curves of MMF/ATM critical parameters were constructed by tensile and compressive static and fatigue tests for the longitudinal and transverse directions of unidirectional CFRP under various temperatures based on the time-temperature superposition principle which holds for the viscoelastic creep compliance of matrix resin. These basic master curves can be used for predicting the fatigue strength of composite structures with multi-directional laminations at any time, temperature and number of cycles to failure. The applicability of MMF/ATM combined method to predict the long term strength of CFRP structures was experimentally confirmed by prediction of the open hole compression fatigue strength of the quasi-isotropic CFRP laminates.

1 Introduction

As you know, recently carbon fiber reinforced plastics (CFRP) has been widely used for the innovative application in aerospace and automotive fields and others, where the reliability should be high priority during the long-term operation. Therefore, it is strongly expected that the accelerated testing methodology for the long-term life prediction of composite structures exposed under the actual environments of temperature and others should be established.

The ply-based accelerated testing methodology (ATM) was proposed for the prediction of long-term fatigue strength of CFRP laminates based on the time-temperature superposition principle (TTSP) and the applicability of this methodology was confirmed for all of CFRP laminates and structures combined with PAN based carbon fibers and thermosetting resins [1-5]. The long-term fatigue strength for CFRP laminates and structures under an arbitrary loading condition can be predicted by measuring the short-term fatigue strength under time compressive loading condition at elevated temperature.

On the other hand, the failure criteria of separated fiber and matrix in polymer composites has been developed and the failure of composite structures has been predicted based on the analyses on micro-mechanics, laminates and structure levels. Gosse and Christensen [6] proposed a new failure criterion for CFRP that can predict initial and final failures of composite laminates and structure based on the strain invariant failure theory (SIFT) in which the failure is governed by three critical parameters, that is the equivalent strains of carbon fiber and the equivalent and volumetric strains of matrix resin. Recently, stress-based micromechanics of failure (MMF) have been proposed by Christensen [7] for polymer composite with viscoelastic matrix.

In this paper, the constituent-based characterization of long term strength of CFRP structure MMF/ATM is studied. The time-temperature dependent master curves of MMF/ATM critical parameters are constructed according to CSR and cyclic load tests of four directions on unidirectional CFRP under various temperatures and measuring the time-temperature shift factor of creep compliance of matrix resin. The long term open hole compression (OHC) fatigue strength of QIL is predicted using the master curves of MMF critical parameters based on MMF/ATM combined method and structural stress analysis by finite element method.

2 Micromechanics of failure

The strain invariant failure theory (SIFT) was proposed by Gosse and others [6] to predict the strength of CFRP laminates based on fiber and polymer matrix failure mechanism. This failure criterion is mechanistic in that it relates effective strength properties in macro-level to micromechanical failure of matrix and fiber. SIFT will provide keys to predict the strength of complex structures from basic properties, and will reduce the numbers of durability tests. These basic properties can be obtained from simple tension or compression tests for unidirectional laminates. The SIFT failure criterion has been involved in the Super-Mic-Mac (SMM) software developed by Tsai and others .

Christensen proposed recently a stress-based MMF based on the fact that strain-based failure criterion has not scientific basis for the polymer composite showing viscoelastic behavior. Because ultimate failure is controlled by the stresses, the stress-based invariants are used to characterize the constituent strength.

For matrix, because the matrix is isotropic, its yield under complex stress must directly result from the intensity of stress or strain, and be independent of the direction of the coordinate system. According to the non-interactive failure criterion, failure will be governed by either volumetric expansion or flow of the polymer. The volumetric expansion is related with the stress invariant I_1 , and flow of the polymer is related with the Von Mises equivalent stress which is a function of I_1 and I_2 as follows,

$$
\begin{aligned}
I_1 &= \sigma_1 + \sigma_2 + \sigma_3 \\
I_2 &= \sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3 \\
\sigma_{eqv} &= \{0.5[(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2]\}^{0.5} \\
&= (I_1^2-3I^2)^{1/2} \qquad (1)
\end{aligned}
$$

where, σ_1, σ_2, and σ_3 are the three principal stresses, I_i are the invariants of the stress tensor.

The stress invariants are amplified through the use of representative micromechanical block, shown in Fig.1, whereby individual fiber and matrix are modeled by three-dimensional elements. These representative micromechanical blocks are given prescribed load with average unit stresses in three cases of normal stresses and three cases of shear stresses as well as unit temperature in the block. The local stresses are extracted from various positions in the model, 17 points in fiber and 19 points in matrix. The extracted stresses are normalized as thermal-mechanical amplification factors. The thermal residual stresses occurred from the temperature difference from the curing temperature to room temperature are considered. In the followed analysis, the output of macro-stresses from classical laminated plate theory or from the macro-finite element analysis is amplified through these amplification factors before stress invariant calculation. One output stress state of macro-solution corresponds to 36 states, 17 states for fiber and 19 states for matrix. The critical point is identified by comparing the values of stress invariants in these points with the MMF/ATM critical parameters of the constituents.

To extract the constituent-based properties for CFRP, specific tests with expected failure mechanism are carried out, and the maximum value of the parameters in fiber or in matrix, depending on failure mechanism, is taken as the MMF/ATM critical parameters of the constituents.

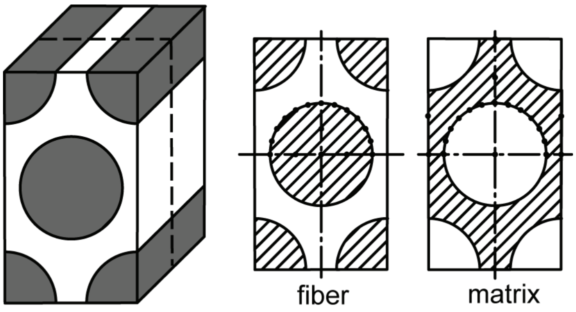
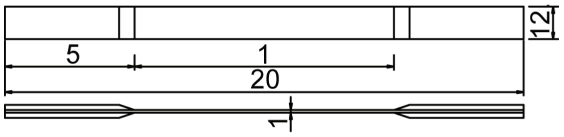


Fig. 1 Micromechanical representative block

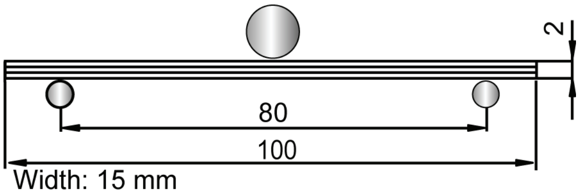
3 Experimental procedure

The CFRP test specimens are fabricated from unidirectional (UD) laminate and quasi-isotropic laminate (QIL) [45/0/-45/90]3s of TR30S/epoxy. The UD laminates are used to extract the constituent properties. The QIL is used for strength prediction verification. All the laminates are made by hot pressing technique. The curing procedure includes 130°C for 1 hour and 150°C for 2 hours, and subsequent 75°C for 7500min physical aging to increase Young's modulus. The volume fraction of fiber is approximately 0.6. The laminates are cut by diamond-grit wheel to the specific size for the tests. The specimen size and configuration are shown in Figs.2.

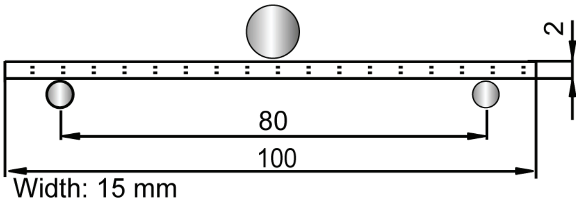
The creep test as one of viscoelastic tests is performed at various temperatures for the transverse unidirectional CFRP laminate. The shift factors for constructing creep compliance master curve hold for strength master curve of CFRP, and constituent critical parameters' master curves.



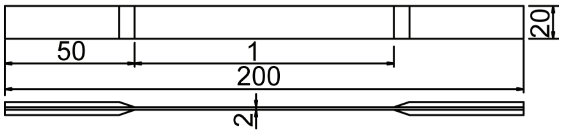
(a) longitudinal tension of UD specimen



(b) longitudinal bending of UD specimen



(c) transverse bending of UD specimen



(d) off-axis 20 degree tension of UD specimen

Fig. 2 Configuration of unidirectional specimens for CSR and fatigue tests

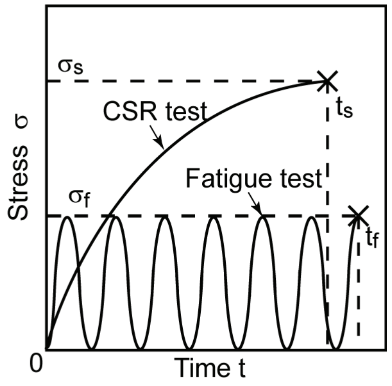


Fig. 3 Determination of strength and time to failure on CSR and fatigue tests

Constant strain rate (CSR) and cyclic load tests of four directions on unidirectional CFRP are carried out for extracting constituent critical parameters' master curves by micromechanical amplification. Longitudinal CSR and cyclic load tension tests at various temperatures are carried out for getting the longitudinal tensile CSR and fatigue strengths, Fig. 3. And these longitudinal tensile (LT) strength master curves are amplified to get the fiber critical parameters. Longitudinal and transverse CSR and cyclic load three points bending tests at various temperatures are carried out for getting the longitudinal compressive (LC) strength and the transverse tensile (TT) strength. UD off-axis 20-degree tension, instead of transverse compression (TC), CSR and cyclic loading tension tests at various temperatures are carried out for getting the shear strength along fibers. The transverse UD strength master curves are amplified to get the matrix critical parameters. The CSR and fatigue testing conditions are listed in Table. 1.

Table 1 Test conditions

Type	Deflection rate V (mm/min)	Frequency (Hz)	Stress ratio R ($\sigma_{min}/\sigma_{max}$)	Tempera-ture T (^{o}C)
LT	1	2	0.05	25,50,80, 120,140
LC	2	2	0.05	25,50,80, 120,140
TT	2	2	0.05	25,50,80, 120,140
TC	1	2	0.05	25,50,80, 120,140
QIL		2	0.05	25,80,120

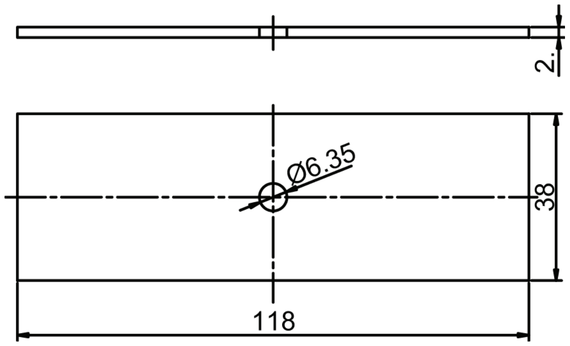


Fig. 4 Configuration of open hole QIL specimens for compressive fatigue tests

The OHC tests for QIL under various strain rates and temperatures are conducted to validate the time-temperature dependence of compressive strengths obtained from SIFT critical parameters master curves. A fixture for OHC test proposed by National Aerospace Laboratory (NAL III) is used. Figure 4 shows the configurations and sizes of QIL specimens. The test temperatures are RT, 80, 120°C, the loading frequency is 2Hz and stress ratio is 0.05.

4 Result and discussion

4.1 Master curve of creep compliance for transverse direction of unidirectional CFRP

The left side of Fig.5 shows the creep compliance D_c versus time t for the CFRP, where time t is loading time. The right side shows the master curve of D_c which is constructed by shifting D_c 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 D_c at various constant temperatures can be superimposed so that a smooth curve is constructed, the TTSP is applicable for the creep compliance for UD transverse CFRP.

Figure 6 shows the time-temperature shift factors $a_{T0}(T)$ obtained experimentally for the master curve of creep compliance for the CFRP. The shift factors are quantitatively in good agreement with Arrhenius' equation with two activation energies ΔH_1 and ΔH_2;

$$\log a_{T_o}(T) = \frac{\Delta H}{2.303G}\left(\frac{1}{T} - \frac{1}{T_0}\right) \tag{2}$$

where G is the gas constant, 8.314×10^{-3} [kJ/(K•mol)].The time-temperature shift factor obtained from the creep test is adopted to calculate the reduced time to failure t'_s which are necessary to construct the master curves of MMF/ATM critical parameters for the CFRP laminate.

$$t'_s = \frac{t_s}{a_{T0}(T)} \tag{3}$$

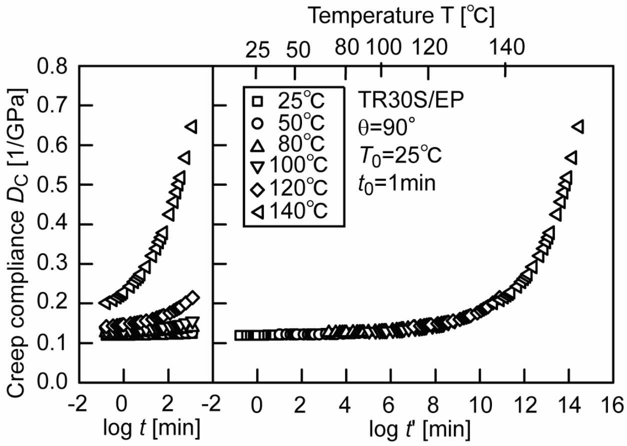


Fig. 5 Master curve of creep compliance for unidirectional CFRP in transverse direction

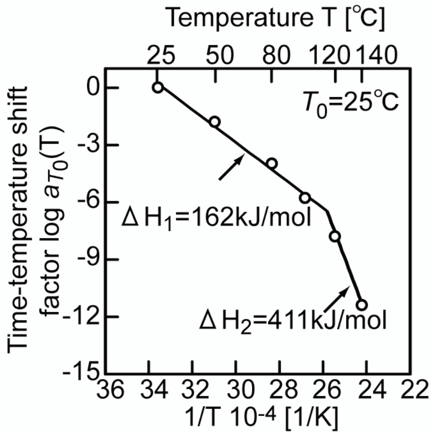


Fig. 6 Time-temperature shift factors of creep compliance for unidirectional CFRP in transverse direction

4.2 Master curves of four kinds of fatigue strength of CFTP laminates

Based on above LT, LC, TT, TC tests of UD CFRP laminates, the construction of master curves of fatigue strength become possible. The basis is that the time-temperature dependence of fatigue of CFTP laminates is same with that of creep compliance of transverse UD laminate. We regard all fours kinds of fatigue strength as function of number of load cycles to failure N_f under the condition of frequency f, stress ratio R and temperature T. The functions can be described as $\sigma_f(N_f;f,R,T)$. The CSR failure strength $\sigma_f(t_f,T)$ is considered as fatigue strength at N_f=1/2 or t_f=1/(2f), and R=0.

Figure 7-10 show all four kinds of fatigue strength σ_f versus the number of load cycles to failure N_f at frequency f=2Hz and stress ratio R=0.05. The fatigue strength decreases with time, temperature and number of load cycles clearly.

The time-temperature shift factor obtained from CFRP creep test is adopted to calculate the reduced time t_f' as well as reduced frequency f', which are necessary to construct the fatigue strength master curves for CFRP laminate. The expression is as follows:

$$f' = f \cdot a_{To}(T), \qquad t'_f = \frac{t_f}{a_{T0}(T)} = \frac{N_f}{f'} \qquad (4)$$

In order to be used easily by the followed micromechanical amplification subroutine to extract constituent critical parameter, the formulation of the master curves for the fatigue strength of CFRP laminates, which based on Christensen's theory [8] describing statistically the crack kinetics in viscoelastic body, is used. The formulation is expressed as

$$\begin{aligned} \log\sigma_f = {} & \log\sigma_{s,0}(t_0,T_0) - \log\left[1+\left(\frac{t'_s}{t'_1}\right)^{n_r}\left(\frac{t'_f}{t'_s}\right)^{n_c}\right] \\ & -\log\left(\frac{N_f}{N_0}\right)^{n_f} + \frac{1}{\alpha_f}\log\left[-\ln(1-P_f)\right] \end{aligned} \qquad (5)$$

Where n_c and n_f mean the dependences of time and number of cycles on the reduction of fatigue strength, respectively. α_f is the shape parameter in fatigue strength, which is defined by the Weibull plots.

From these four kinds of master curves in ply level, it can see clearly that the fatigue strength decreases with time, temperature and number of load cycles clearly. For the LT fatigue strength, though the master curve decreases slowly with increasing of loading time, the time-temperature dependence of this fatigue strength does exit. For the LC, TT, TC fatigue strength, strong time-temperature dependence is observed.

4.3 Master curves of constituent-based fatigue strength

Based on above CSR and fatigue test results of UD laminates, the construction of master curves of MMF critical parameters become possible. The MMF master curves are shown in Fig.11-14 LT tests give out the critical parameter of equivalent stress σ_{eq} for fiber tensile failure. For specific time, cycle number to failure, and loading frequency, the fatigue strength can be decided by the formulated formula, then map this strength to get the stress states of points in fiber in the representative block, and calculate the equivalent stress σ_{eq} for these points, the maximum value is taken as the critical parameter for fiber. By connecting the points of the equivalent stress at different loading time with same cycle number to failure, one equivalent stress σ_{eq} master curve for fiber is constructed, and a

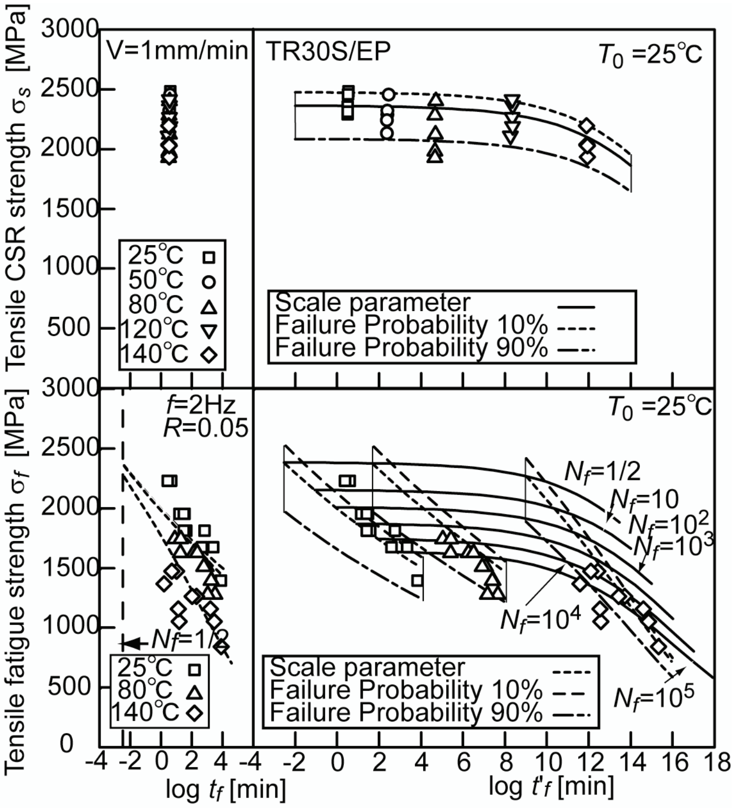


Fig.7 Master curves of tensile CSR and fatigue strength for the longitudinal direction of unidirectional CFRP(LT)

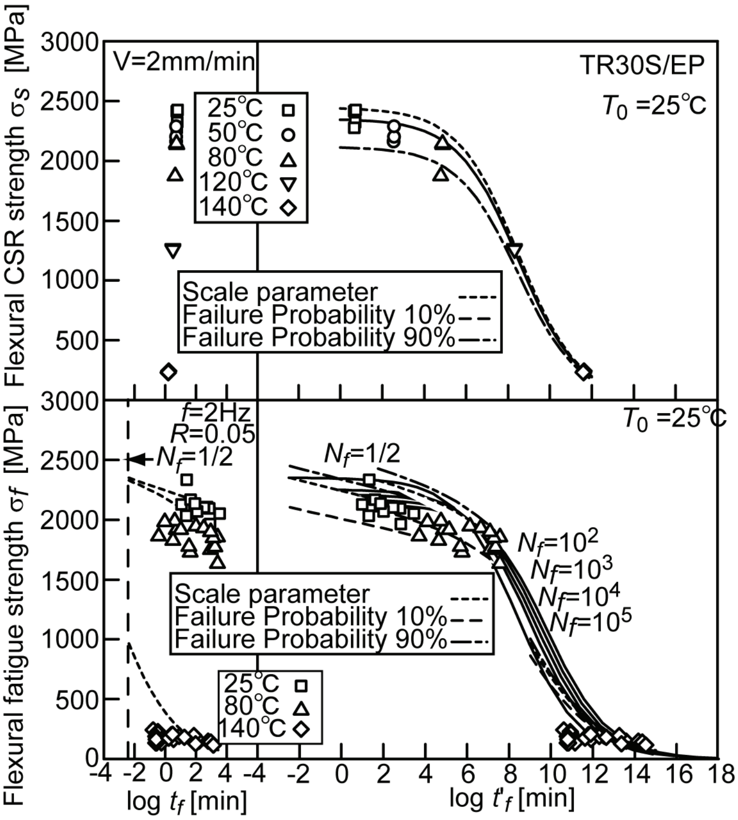


Fig. 8 Master curves of flexural CSR and fatigue strength for the longitudinal direction of unidirectional CFRP(LC)

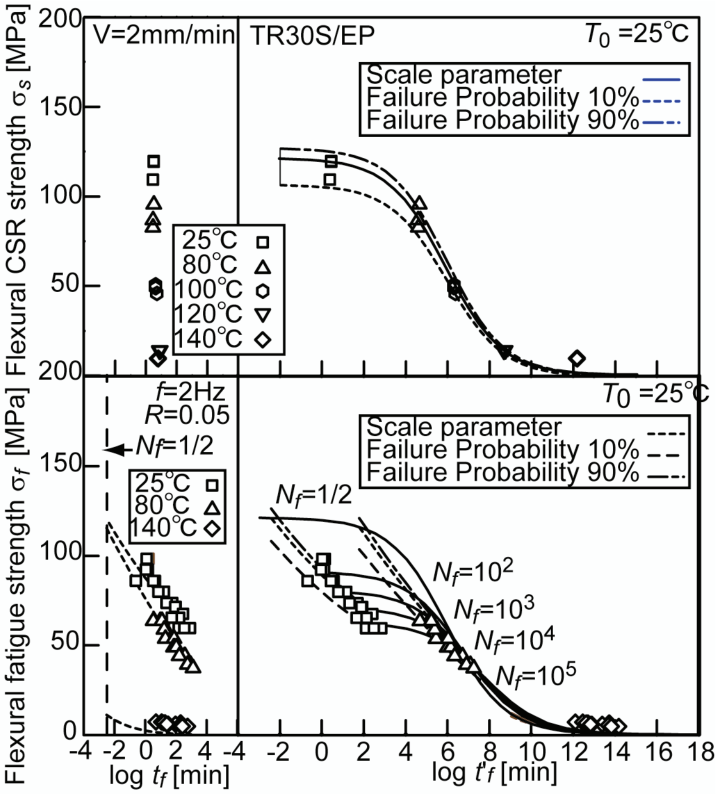


Fig. 9 Master curves of flexural CSR and fatigue strength for the transverse direction of unidirectional CFRP(TT)

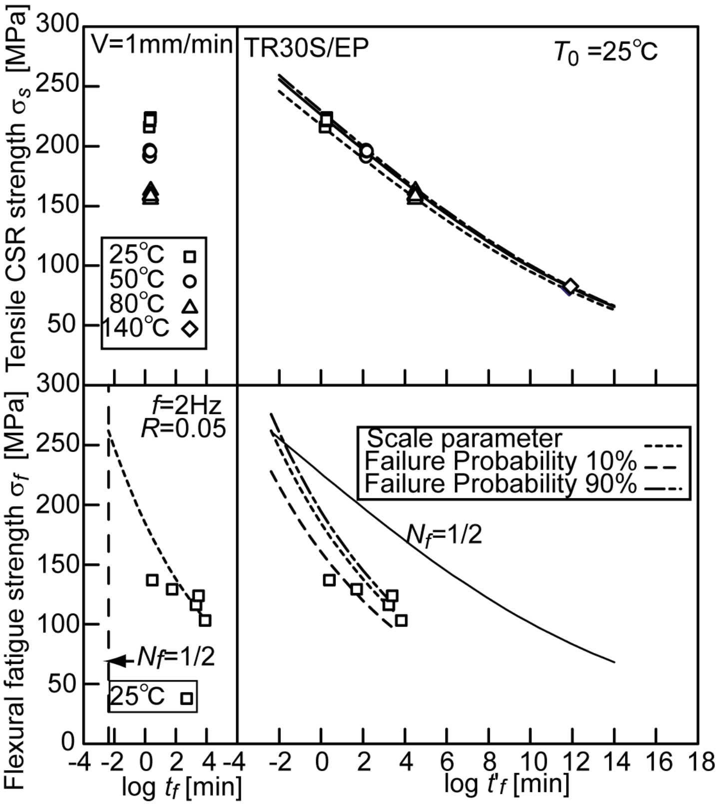


Fig.10 Master curves of tensile CSR and fatigue strength for 20° off-axis direction of unidirectional CFRP(TC)

series of equivalent stress σ_{eq} master curves with different cycle number to failure can be constructed. This process is repeated to construct other critical parameter fatigue master curves, LC tests yielding the critical parameter of equivalent stress σ_{eq} for fiber compressive failure, TT tests outputting the critical parameter of stress invariant I_1 for matrix dilatation failure, and TC tests extracting the critical parameter of equivalent stress σ_{eq} for matrix shearing failure.

For the four kinds of MMF critical parameters master curves, the time-temperature dependence principle from CFRP creep test is adopted. These basic strength properties reveal the characteristics of the single reinforcement fiber or pure matrix resin, however, the fiber property is for the fiber in the CFRP with specific combination of fiber and resin, and also the resin property is for the resin in the CFRP.

The constituent-based MMF critical parameters also are function of number of load cycles to failure N_f under the condition of frequency f, stress ratio R and temperature T. From these master curves, the monotonic trend is observed for each curve under same cycle number to failure, which is consistent with the time-temperature dependence principle from CFRP creep test.

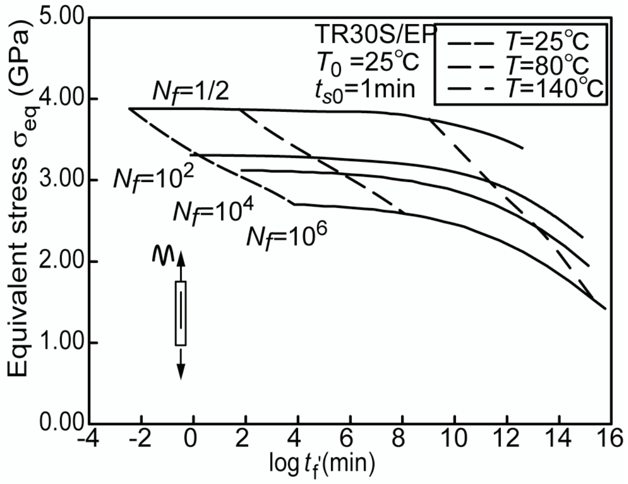


Fig.11 Tensile fatigue failure critical parameter σ_{eq} master curve for fiber of TR30S/Epoxy

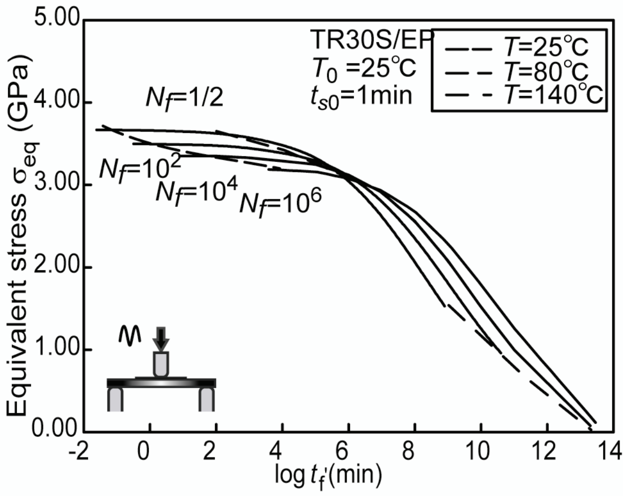


Fig.12 Compressive fatigue failure critical parameter σ_{eq} master curve for fiber of TR30S/Epoxy

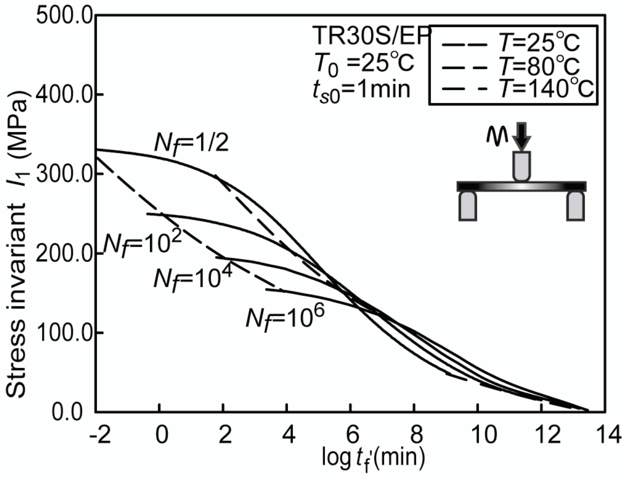


Fig.13 Tensile fatigue failure critical parameter I_1 master curve for matrix of TR30S/Epoxy

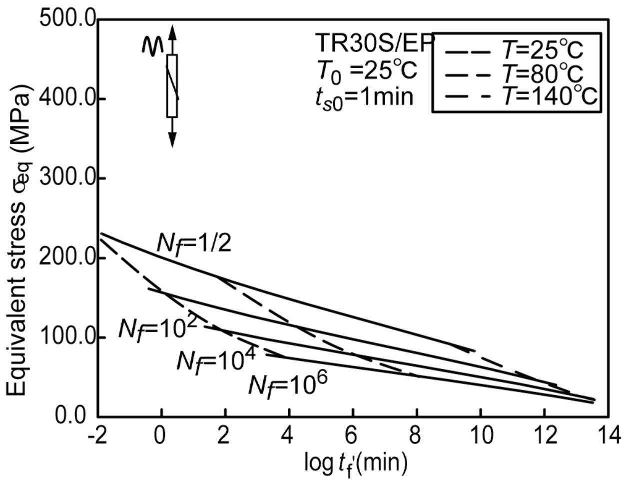


Fig.14 Fatigue failure critical parameter σ_{eq} master curve for matrix of TR30S/Epoxy

4.4 Application of MMF/ATM for life prediction of open-hole compression fatigue strength for quasi-isotropic CFRP laminates

As an example of application of MMF/ATM critical parameters master curves, long term compressive fatigue strength for quasi-isotropic CFRP laminates with open hole is predicted, as mentioned above in Fig.4. The reason why choose this specimen is that the main purpose of this paper is to characterize the basic properties of the CFRP, and the OHC specimen is a simplest CFRP structure with stress concentration near the interior edge of the hole, in addition, ultimate failure occurs almost simultaneously as crack initiation by fiber failure. It means the applied external load resulting in initial failure equals to the ultimate load. In the Fig.15, the stress along the vertical axis is the mean stress in the end of the specimen.

For long term strength prediction, the procedure includes stress analysis for each ply in macro-level, stress amplification for each stress state into stress states for fiber and matrix in the selected key points, and failure criterion parameters' calculation and comparison with the critical parameters defined by the master curves. By this approach, the maximum external applied load at given frequency, loading time, temperature and failure probability can be determined with the master curves. Or the life of loading at given load, frequency, temperature and failure probability can be determined also with the master curves with the same approach. For the simple multidirectional laminates, the classic plate theory can be used for stress analysis in marco-level. For complicate 3-dimensional structures, finite element analysis need to be used for stress analysis in marco-level. For OHC structure, the critical point and fatigue failure mechanism is identified by comparing MMF parameter with the critical parameters in each element in each plies by ANSYS codes. The critical point of OHC structure locates in the interior edge of the hole. Totally, four failure mechanisms are possible, and only one is critical which control the initial failure, here the final failure, i.e. the ultimate load.

In the Fig. 15, the experimental plots at various temperatures distribute inside the Weibull A-base interval. Because the obtained constituent-based MMF/ATM critical parameters are the basic properties for specific combined CFRP, these properties can be extended for progressive failure analysis, final failure analysis of complicate CFRP structure as well as structure design. Even these fundamental properties can be related with delamination and interface failure between the fiber and the matrix.

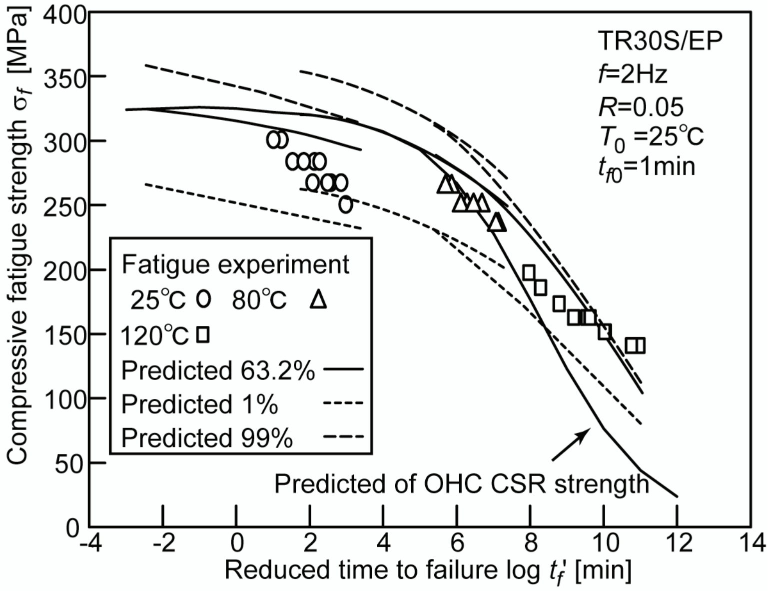


Fig.15 Predicted OHC fatigue strength of QIL [45/0/-45/90]3s of TR30S/epoxy for matrix of TR30S/Epoxy

2 Conclusion

For the new methodology (MMF/ATM) by combining MMF with ATM to predict the long-term static and fatigue life of CFRP structures, the time and temperature dependent static and fatigue behavior of unidirectional CERP laminates were characterized.

The master curve of creep compliance and the time-temperature shift factor was determined by using the creep compliances at various temperatures based on the time-temperature superposition principle. The static and fatigue strengths in the four directions of unidirectional CFRP laminates were measured at various temperatures at a single loading rate.

The master curves of these strengths were determined by using the measured data and the time-temperature shift factor for the creep compliance. These formulated master curves are used for the determination of critical parameters for MMF/ATM analysis. Four master curves of MMF/ATM critical parameters were constructed, two for fiber and two for matrix.

The compressive strength of quasi-isotropic CFRP laminates [45/0/-45/90]3s can be predicted using the master curves of MMF/ATM critical parameters based on fiber and matrix resin failure mechanism with micromechanics analysis. The validity of MMF/ATM method has been demonstrated.

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