

# LONG-TERM LIFE PREDICTION OF CFRP STRUCTURES BASED ON MMF/ATM METHOD

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## Abstract

The advanced accelerated testing methodology (ATM-2) for the fatigue life prediction of CFRP laminates proposed and verified theoretically and experimentally in the previous studies is expanded to the fatigue life prediction of the structures made of CFRP laminates. The procedure of MMF/ATM method combined with our ATM-2 and the micromechanics of failure (MMF) developed by Professor Sung-Kyu Ha and others is proposed for the fatigue life prediction of the structures made of CFRP laminates. The master curves of MMF/ATM critical parameters of CFRP are determined by measuring the static and fatigue strengths at elevated temperatures in the longitudinal and transverse, tension and compression directions of unidirectional CFRP. The fatigue lives of quasi-isotropic CFRP laminates with a central hole under compression load as an example of CFRP structures are measured at elevated temperatures, and these experimental data are compared with the predicted results based on MMF/ATM method.

## 1 Introduction

The accelerated testing methodology (ATM) [1] was proposed for the prediction of long-term fatigue strength of CFRP laminates based on the time-temperature superposition principle (TTSP). Based on ATM, the long-term fatigue strength for CFRP laminates can be predicted by measuring the short-term fatigue strengths at elevated temperatures. The applicability of ATM was confirmed for CFRP laminates combined with PAN based carbon fibers and thermosetting resins [2-4]. Furthermore, the advanced accelerated testing methodology (ATM-2) was proposed in which the formulation for the master curves of time-temperature dependent fatigue strength was performed based on Christensen's

theory [5] which describes statistically the crack kinetics in viscoelastic body.

The failure criteria of separated fiber and matrix in polymer composites have been developed and the failure of composite structures has been predicted based on the analyses on micromechanics, laminates and structure levels. Recently, the stress-based micromechanics of failure (MMF) have been proposed by Sung-Kyu Ha and others [6] for polymer composite with viscoelastic matrix.

In this paper, the procedure of MMF/ATM method combined with our ATM-2 and MMF is proposed for the fatigue life prediction of the structures made of CFRP laminates. The validity of MMF/ATM method is confirmed through the following two steps. As the first step, the master curves of MMF/ATM critical parameters of CFRP are determined by measuring the static and fatigue strengths at elevated temperatures in the longitudinal and transverse, tension and compression directions of unidirectional CFRP. As the second step, the fatigue strengths of quasi-isotropic CFRP laminates with a central hole under compression load as an example of CFRP structures are measured at elevated temperatures, and these experimental data are compared with the predicted results by using the master curves of MMF/ATM critical parameters of CFRP based on MMF/ATM method.

## 2 Procedure of MMF/ATM method

The procedure of proposed MMF/ATM method is shown schematically in Figures 1 and 2.

Figure 1 shows the first step for the prediction procedure by MMF/ATM method that is the process of determination of MMF/ATM critical parameters.

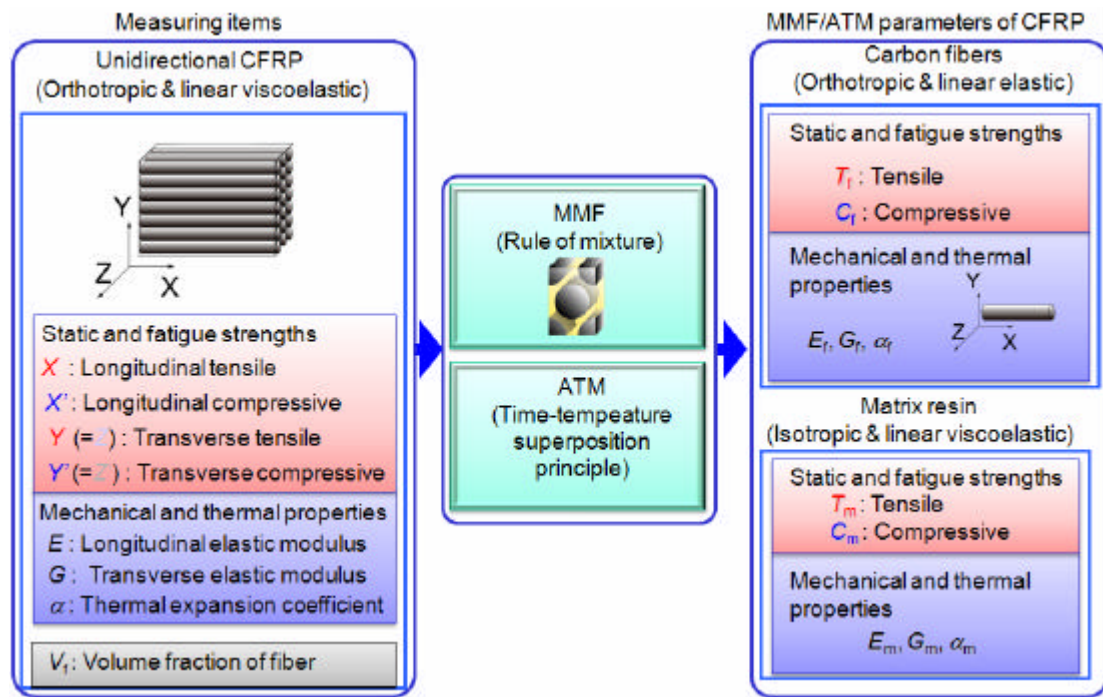


Figure 1 First step for prediction procedure by MMF/ATM method:  
Determination of MMF/ATM critical parameters

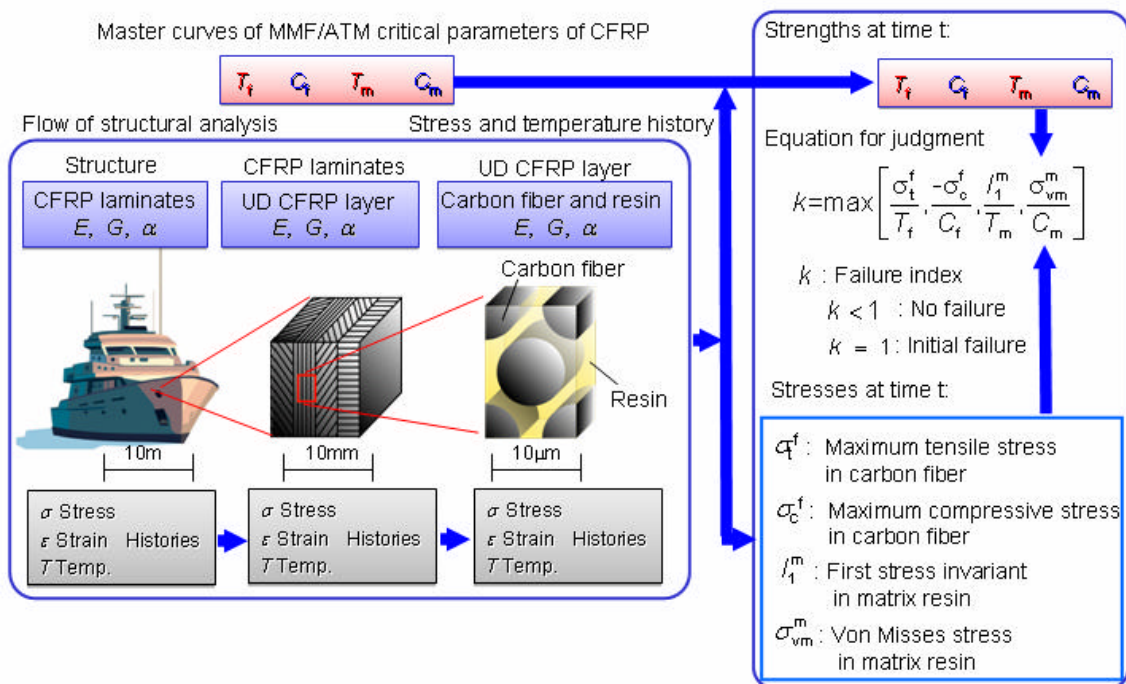


Figure 2 Second step for prediction procedure by MMF/ATM method:  
Life determination of CFRP structures

First, the viscoelastic modulus in the transverse direction of unidirectional CFRP is measured at various temperatures. The master curve and the time-temperature shift factor are determined by using these test data based on the TTSP. Second, the static and fatigue strengths in the typical four directions of unidirectional CFRP are measured at various temperatures at a single loading rate and single loading frequency, respectively. The strengths in four directions are the longitudinal tension  $X$ , the longitudinal compression  $X'$ , the transverse tension  $Y$  and the transverse compression  $Y'$ , respectively. Third, the master curves of these strengths are determined by using the measured data and the time-temperature shift factor for viscoelastic modulus. Fourth, the master curves of four MMF/ATM critical parameters, the fiber tensile strength  $T_f$ , the fiber compressive strength  $C_f$ , the matrix tensile strength  $T_m$ , and the matrix compressive strength  $C_m$  are determined through the method described in [7].

Figure 2 shows the second step for the prediction procedure by MMF/ATM method that is the life determination of CFRP structures. With the master curves of the MMF/ATM critical parameters, the long-term strength prediction of CFRP becomes possible. Three-step stress analyses are necessary to process the test result, including stress analysis for "homogenous" CFRP structures and CFRP laminates in macro level and stress analysis for the constituents in micro level by stress amplification. From the master curves of MMF/ATM critical parameters and failure criteria for fiber and matrix, the strength of CFRP structure under arbitrary time to failure and temperature can be determined.

### 3 Experimental procedure

The test specimens were fabricated from unidirectional CFRP and quasi-isotropic CFRP laminate (QIL)  $[45/0/-45/90]_{2s}$  of MR60H/1053 which consists MR60H carbon fiber and epoxy resin 1053. The unidirectional CFRP were used to back-calculate the constituent properties. The QIL was used for strength prediction verification. All the laminates were made by the autoclave technique. The curing procedure includes 180°C for 2 hours and then postcured at 160°C for 70 hours. The volume fraction of fiber is approximately 0.55. The laminates were cut by diamond-grit wheel to the specific size for the tests. The dynamic viscoelastic

tests were performed for various frequencies and temperatures for the transverse direction of unidirectional CFRP. The shift factors for constructing master curve hold for the strength master curves of CFRP and constituent critical parameters' master curves. The static and fatigue tests for four directions of unidirectional CFRP were carried out to extract constituent critical parameters' master curves by micromechanical amplification. Longitudinal tension tests under static and fatigue loadings were carried out at various temperatures according with ISO 527 to get the longitudinal tensile static and fatigue strengths. Longitudinal bending tests under static and fatigue loadings were carried out at various temperatures according with ISO 14125 to get the longitudinal compressive static and fatigue strengths. Transverse bending tests under static and fatigue loadings were carried out at various temperatures according with ISO 14125 to get the transverse tensile static and fatigue strengths. 20° off-axis tension tests under static and fatigue loadings were carried out at various temperatures to get the transverse compressive static and fatigue strengths. The compression tests for QIL under static and fatigue loadings were carried out at various temperatures using the open hole compression test specimens as shown in Figure 3. The experimental results have been already reported on [8-10].

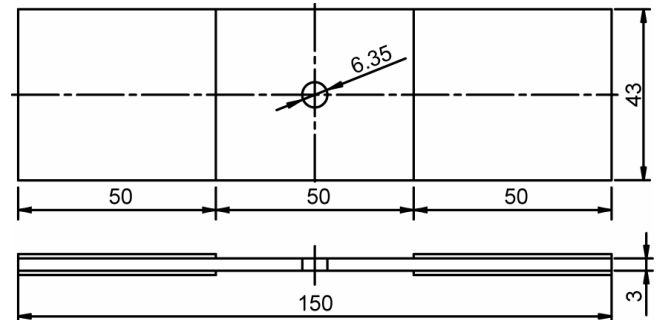


Figure 3 Open hole compression (OHC) tests for QIL

### 4 MMF/ATM critical parameters

The MMF/ATM critical parameter master curves  $T_f$ ,  $C_f$ ,  $T_m$  and  $C_m$  are shown in Figures 4 and 5. The details of determination by using the measured data to the tension and compression static and fatigue tests for longitudinal and transverse directions of unidirectional CFRP are neglected here.

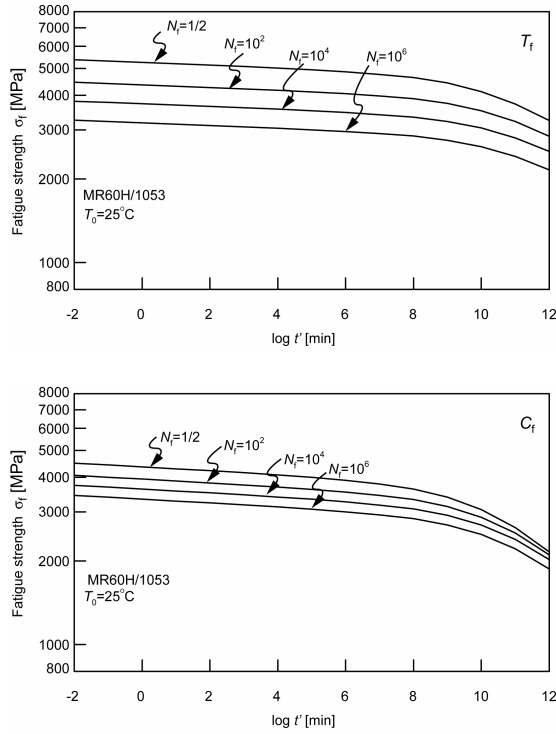


Figure 4 Master curves of MMF/ATM critical parameters  $T_f$  and  $C_f$

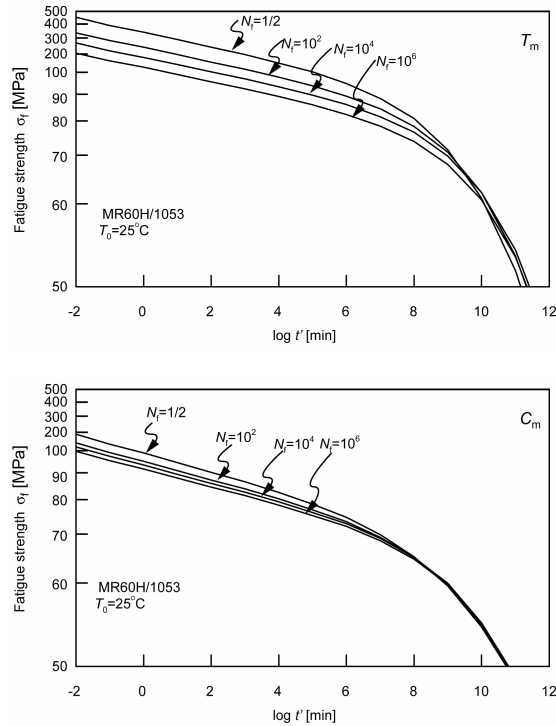


Figure 5 Master curves of MMF/ATM critical parameters  $T_m$  and  $C_m$

## 5 Life determination of CFRP structures

As an example of application of MMF/ATM critical parameters master curves, the long-term OHC strength for QIL was predicted. Figure 6 shows the initial failure mechanism for static loading by comparing the failure indexes of MMF/ATM parameters under, for example,  $T=25^\circ\text{C}$ .  $k_{Tf}$  is failure index of fiber under tension,  $k_{Cf}$  is failure index of fiber under compression, and  $k_{Tm}^*$  is failure index of matrix under tension, and  $k_{Cm}^*$  is failure index of matrix under compression [7]. When one of these failure indexes reaches to unity, the initial failure of laminate occurs. It is cleared from this figure that the OHC failure of QIL was triggered by fiber compressive failure in  $0^\circ$  layer.

Figure 7 shows the initial failure of OHC for QIL under static loading observed from the specimen in which the OHC test was stopped at 98% level of maximum stress under  $T=25^\circ\text{C}$ . The microbuckling of fiber in  $0^\circ$  layer as well as the transverse crack in  $45^\circ$  layer are observed. In the  $-45^\circ$  and  $90^\circ$  layers, any failures can not be observed. Furthermore, any failures can not be observed for the specimen in which the OHC test was stopped at 95% stress level of maximum stress under all temperatures tested.

For all temperature conditions tested, the same failure was observed with the above simulation. Therefore, the predicted master curves of OHC strength for QIL were constructed based on the MMF/ATM parameter of compressive strength of fiber. Figure 13 shows the predicted master curves of OHC strength for QIL with experimental data. The predicted strength agrees well with the experimental data for all region of time to failure  $t'$ .

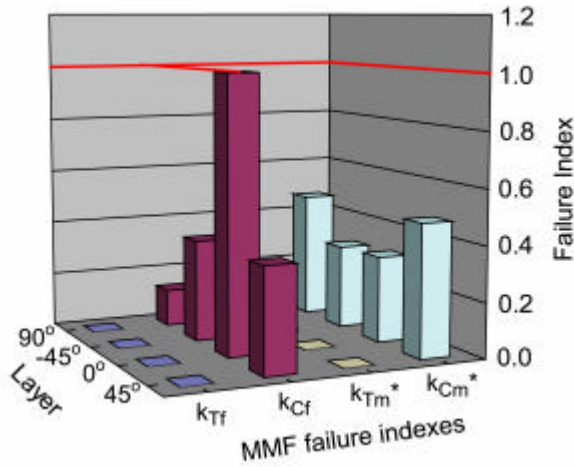


Figure 6 Judgment of initial failure of OHC for QIL under static loading ( $T=25^{\circ}\text{C}$ ,  $t'=1$  min)



Figure 7 Observation of initial failure of OHC for QIL under static loading ( $s_{max}=0.98s_s$ ,  $T=25^{\circ}\text{C}$ ,  $V=0.1\text{mm/min}$ )

## 6 Conclusion

The time-temperature dependent master curves of MMF/ATM critical parameters were constructed for CFRP laminates MR60H/1053 by tensile and compressive tests under static and fatigue loadings for the longitudinal and transverse directions of unidirectional CFRP under various temperatures based on the time-temperature superposition principle which holds for the viscoelastic behavior of matrix resin. It was confirmed experimentally that the long-term OHC strength of quasi-isotropic CFRP laminates  $[45/0/-45/90]_{2s}$  can be predicted using these master curves of MMF/ATM critical parameters. Therefore, the verification of proposed MMF/ATM method was confirmed experimentally.

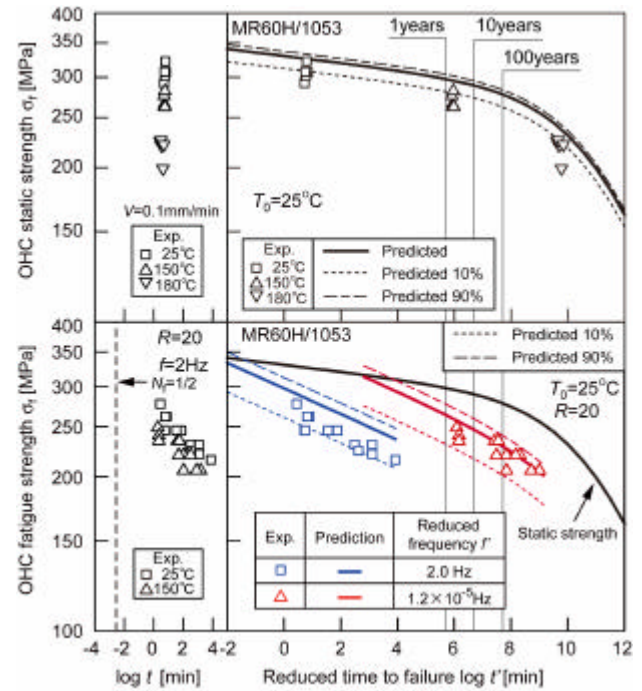


Figure 8 Predicted OHC static and fatigue strengths for QIL

## 7 Acknowledgements

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