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TIME-TEMPERATURE DEPENDENCE OF TENSILE FATIGUE STRENGTH FOR GFRP/METAL AND CFRP/METAL BOLTED JOINTS

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SUMMARY: The tensile constant elongation-rate (CER) and fatigue tests for GFRP/metal bolted joint and CFRP/metal bolted joint were carried out under various loading rates and temperatures. The fatigue failure loads as well as CER failure loads for these two types of FRP bolted joint depend clearly on loading rate and temperature. The time-temperature superposition principle holds for fatigue failure loads as well as CER failure loads for these FRP bolted joints, therefore the master curves for fatigue failure load can be obtained from these results. The dependence of these fatigue failure loads upon number of cycles to failure as well as time to failure and temperature can be characterized from the master curves for these FRP bolted joints.

KEY WORDS: Fiber Reinforced Plastics, Bolted Joint, Time-Temperature Dependence, Fatigue

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 polymer composites also significantly depends on time and temperature even below T_g which is within the normal operating temperature range.

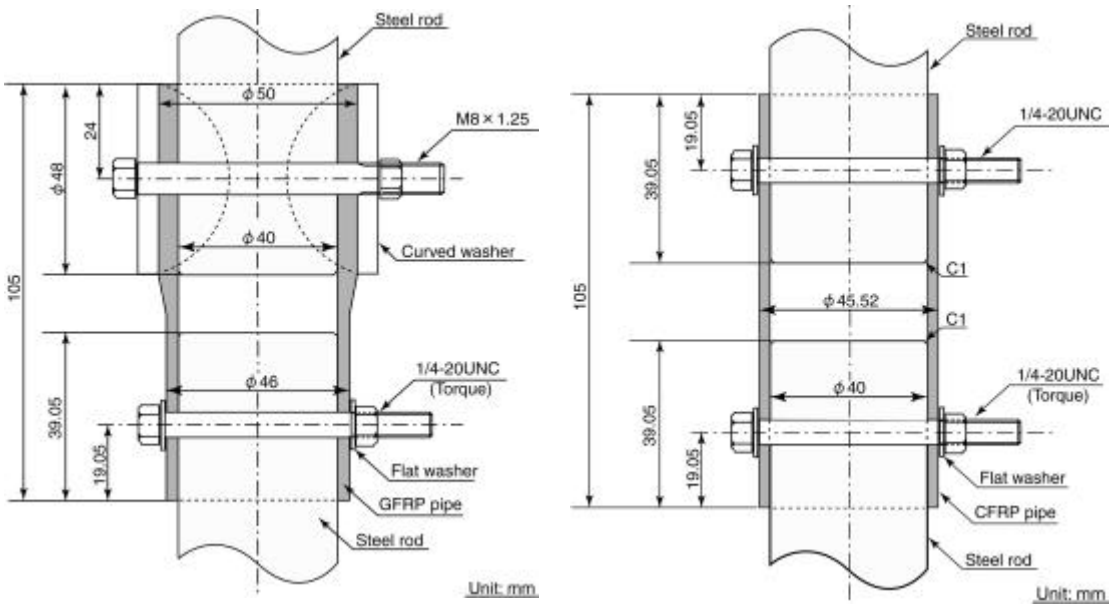
The time-temperature dependence of the tensile and flexural strengths under constant strain-rate (CSR) and fatigue loadings for various kinds of FRP has been studied in our previous papers [1-8]. It was observed that the fracture modes are almost identical under two types of loading over a wide range of time and temperature, and the same time-temperature superposition principle holds for CSR and fatigue strengths. Therefore, the master curves of fatigue strength for these FRP can be obtained.

In this paper, the tensile fatigue tests as well as tensile constant elongation-rate (CER) tests for GFRP/metal bolted joint and CFRP/metal bolted joint are carried out under various loading rates and temperatures. The time-temperature dependence of tensile fatigue behavior for these two FRP bolted joints is discussed.

EXPERIMENTAL PROCEDURE

Preparation of FRP bolted joints

The GFRP/metal bolted joint and CFRP/metal bolted joint are constructed from a GFRP pipe or CFRP pipe, steel rod (C45), and bolt as shown in Fig. 1. In the case of GFRP/metal bolted joint, the GFRP pipe is joined to steel rod by two bolts. One is the ¼-20UNC bolt with small washer, where the thickness of GFRP pipe is 3mm, and the other is M8×1.25 bolt with large washer, where the thickness of GFRP pipe is 5mm. In the case of CFRP/metal bolted joint, the CFRP pipe is joined to steel rod by two ¼-20UNC bolt with small washer. The thickness of CFRP pipe is 2.6mm. The fracture of these bolted joints occur at the corner of GFRP pipe and CFRP pipe at ¼-20UNC bolt. Details of GFRP pipe and CFRP pipe are shown in Table 1.



(a) GFRP/metal bolted joint (b) CFRP/metal bolted joint

Fig. 1 Configuration of FRP/metal bolted joint

Table 1 Details of FRP pipe

	GFRP pipe	CFRP pipe
Fiber	Glass plain woven cloth	Unidirectional carbon fiber
Laminate constitution	$[0]_n$	$[0/45/90/-45]_3$
Resin	Epoxy resin	Epoxy resin
Cure condition	120..4h+150..4h+180..4h	120..2h+150..2h

Test procedure

Details of CER and fatigue test are shown in Table 2. The tensile CER tests were carried out under various loading rates and temperatures using an Instron type testing machine. The loading rates were 0.01, 1 and 100mm/min. The tensile fatigue tests were carried out under various temperatures at two frequencies f=5 and 0.05Hz using an electro-hydraulic servo testing machine. Load ratio R (minimum load/maximum load) was 0.05.

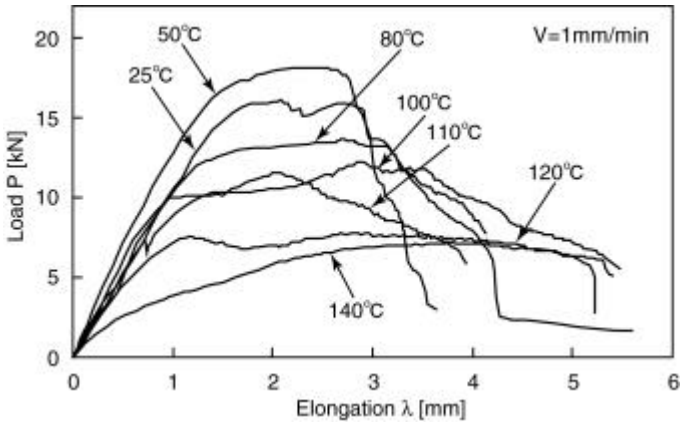
Table 2 Details of test condition for FRP bolted joints

	CER test		Fatigue test	
	Test temp. T [.]	Loading rate V [mm/min]	Test temp. T [.]	Frequency f [Hz]
GFRP/metal bolted joint	25, 50, 80, 100, 110, 120, 140	0.01 1 100	25, 80 110, 120	5 0.05
CFRP/metal bolted joint	25, 50, 80 100, 120		25, 80 100, 120	

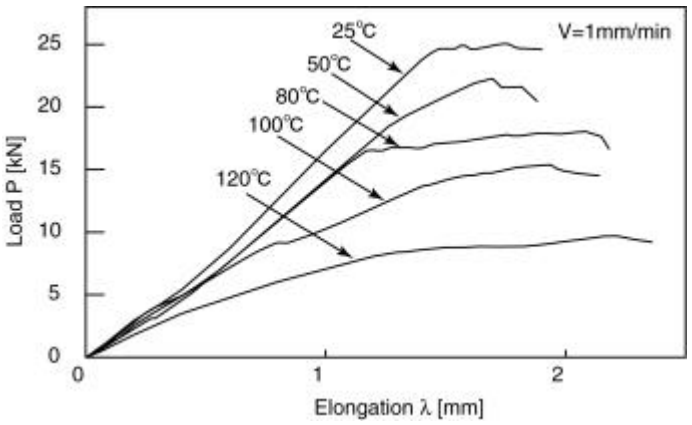
RESULTS AND DISCUSSION

Load-elongation curves

Typical load-elongation curves for two types of FRP bolted joint under CER loading with elongation rate V=1mm/min are shown in Fig. 2. The load-elongation curves show nonlinear behavior until maximum load. The CER failure load P_s is defined by maximum load.



(a) GFRP/metal bolted joint



(b) CFRP/metal bolted joint

Fig. 2 Load-elongation curves

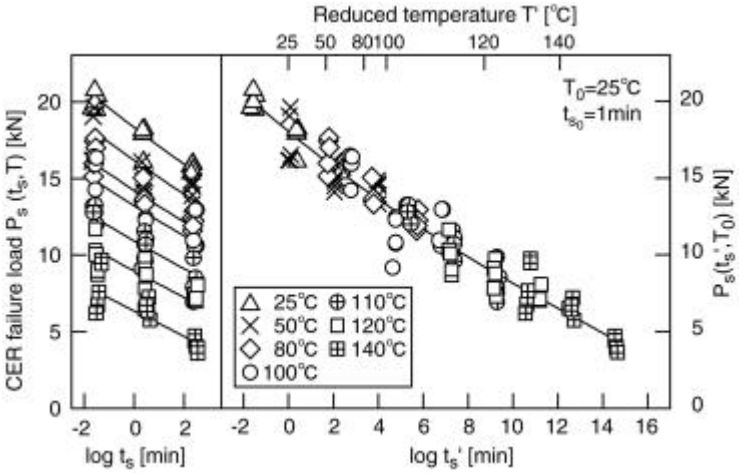
Master curve of CER failure load

The left sides of Fig. 3 show the CER failure load P_s versus time to failure t_s, where t_s is the time period from initial loading to maximum load during testing. The master curve for each P_s was constructed by shifting P_s at various constant temperatures along the log scale of t_s so that they overlap on P_s at the reference temperature T_0 or on each other to form a single smooth curve as shown in the right side of each graph. Since the smooth master curve for each P_s can be obtained, the time-temperature superposition principle is applicable for each P_s.

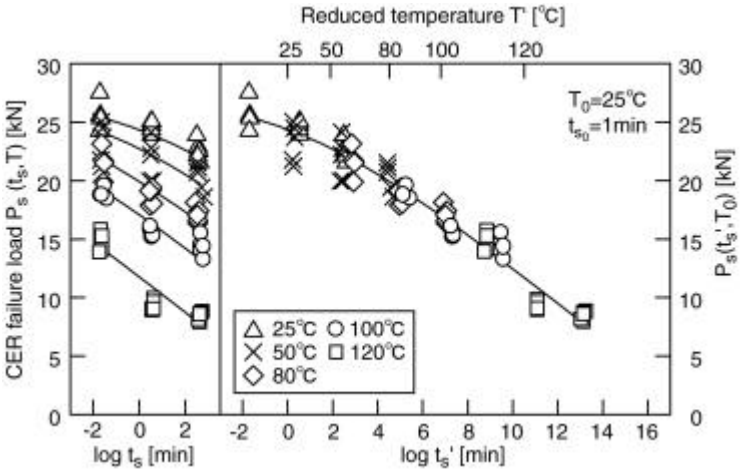
Time-temperature shift factor $a_{T_0}(T)$ is defined by

$$a_{T_0}(T) = \frac{t_s}{t_s'} \tag{1}$$

where the t_s' is the reduced time to failure.



(a) GFRP/metal bolted joint



(b) CFRP/metal bolted joint

Fig. 3 Master curves for CER failure load

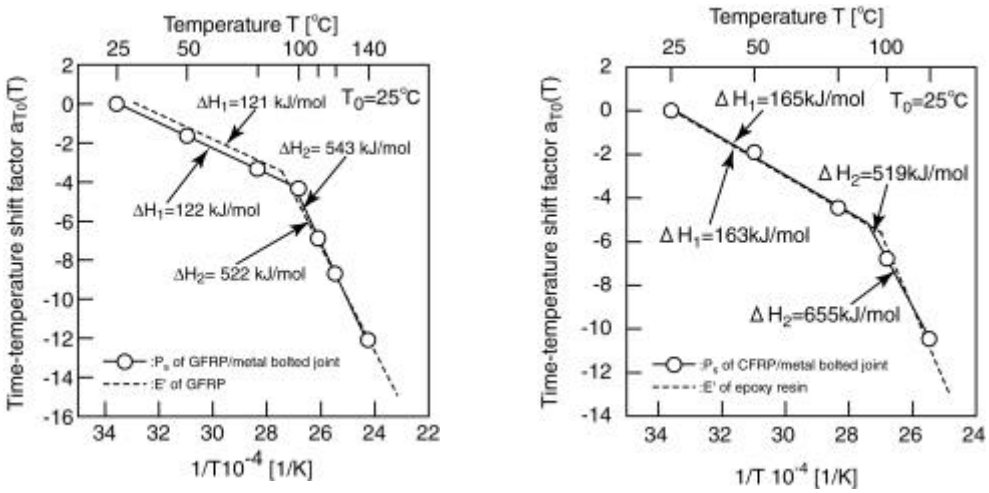
The time-temperature shift factor $a_{T_0}(T)$ for each P_s obtained experimentally in Fig. 3 is plotted respectively in Fig. 4. The $a_{T_0}(T)$ for each P_s agrees well with that for the storage modulus of

GFRP for GFRP/metal bolted joint or of the matrix resin of CFRP for CFRP/metal bolted joint indicated by dotted lines, which are described by two Arrhenius' equations with different activation energies ΔH,

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

where G is gas constant $8.314.10^{-3}$[kJ/Kmol].

From these results, the time-temperature dependence of CER failure load for the GFRP/metal bolted joint or CFRP/metal bolted joint is controlled by the viscoelastic behavior of the matrix resin of GFRP pipe or CFRP pipe, respectively.



(a) GFRP/metal bolted joint (b) CFRP/metal bolted joint

Fig. 4 Time-temperature shift factor for CER failure load

Master curve of fatigue failure load

We now turn to the fatigue failure load P_f, which is expected to have similar time dependency as CER failure load P_s. Therefore, we treat the fatigue failure load as a function of cycles to failure N_f and time to failure t_f. Since cycles and time to failure are related by frequency f, we denote fatigue failure load by $P_f(N_f, f, T)$ or $P_f(t_f, f, T)$. Further, we consider the CER failure load $P_s(t_f, T)$ as the fatigue failure load at N_f=1/2, R=0, and t_f=1/(2f).

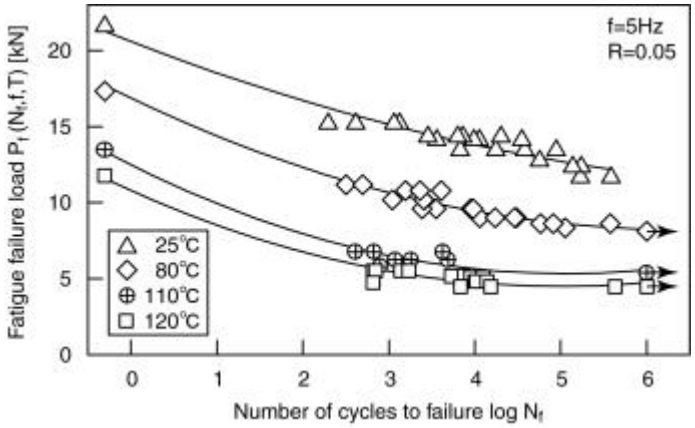
To describe the master curve of P_f, we need the reduced frequency f' in addition to the reduced time to failure t_f', each defined by

$$f' = f \cdot a_{T_0}(T), \quad t_f' = \frac{t_f}{a_{T_0}(T)} = \frac{N_f}{f'} \tag{3}$$

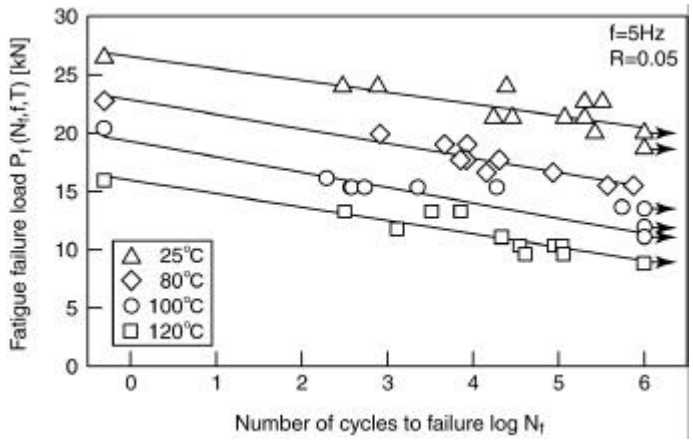
We introduce two alternative expressions for the master curve: $P_f(t_f', f', T_0)$ and $P_f(t_f', N_f, T_0)$. In the latter expression, the explicit reference to frequency is suppressed in favor of N_f. Note that the master curve of fatigue failure load at N_f =1/2 is regarded as the master curve of CER

failure load. Equation (3) enables one to construct the master curve for an arbitrary frequency from the tests at a single frequency under various temperatures.

Figure 5 displays the fatigue failure load P_f versus the number of cycles to failure N_f (P_f-N_f) curves at a frequency f=5Hz for two cases: (a) GFRP/metal bolted joint and (b) CFRP/metal bolted joint. The CER failure loads regarded as the fatigue failure load at N_f =1/2 are included in these figures.



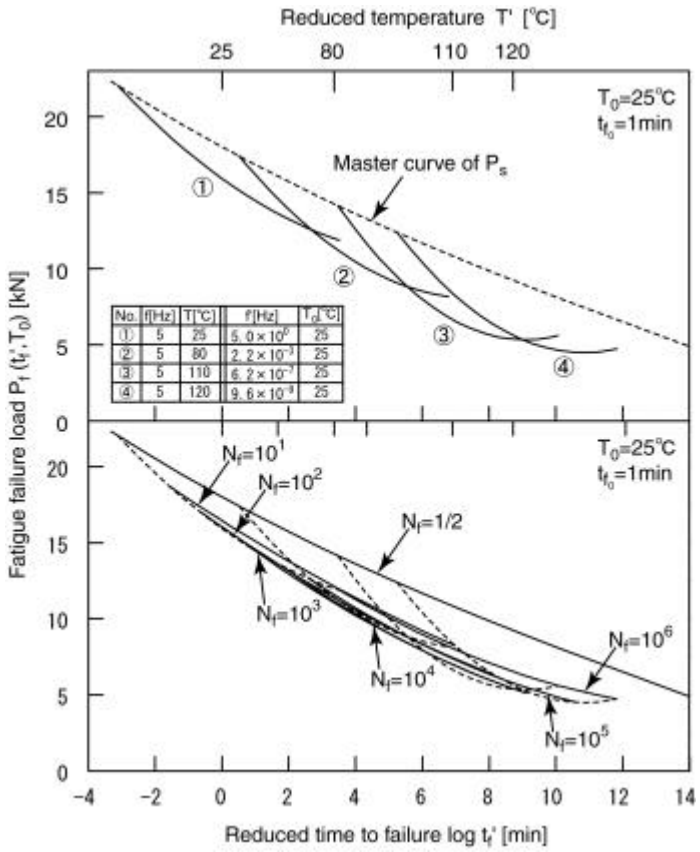
(a) GFRP/metal bolted joint



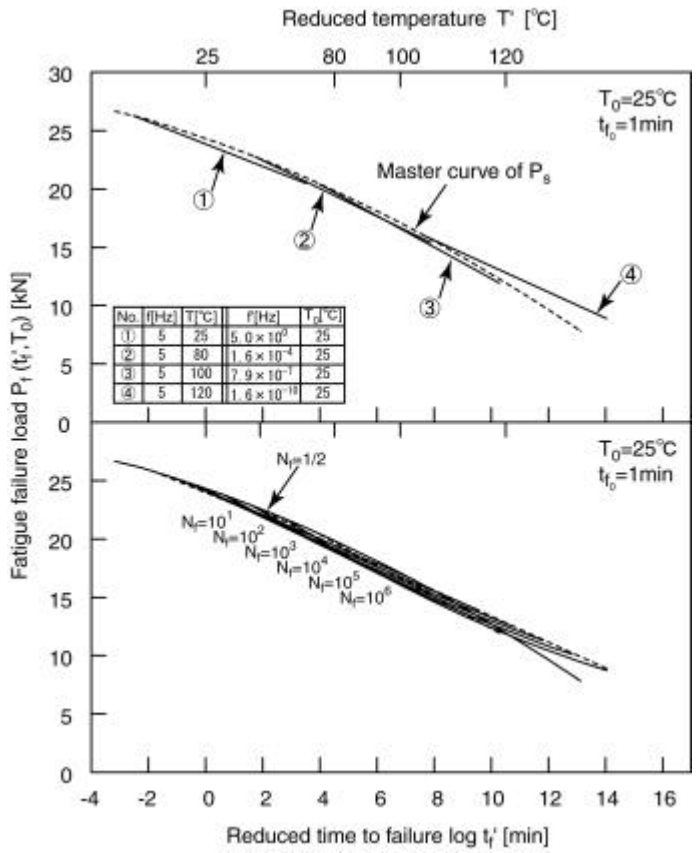
(b) CFRP/metal bolted joint

Fig. 5 Fatigue failure load versus number of cycles to failure at frequency f=5Hz

In the upper figure of Fig. 6, P_f versus the reduced time to failure t_f' curves for several reduced frequencies f' at the reference temperature T_0 are depicted by solid lines, which are obtained by converting N_f of Fig. 5 into t_f' using equation (3) and the shift factor for CER failure load. The master curves of P_f for fixed N_f indicated by solid lines in the lower figure are constructed by connecting the points of the same N_f on the curves of each f' indicated by dotted lines in these figures.



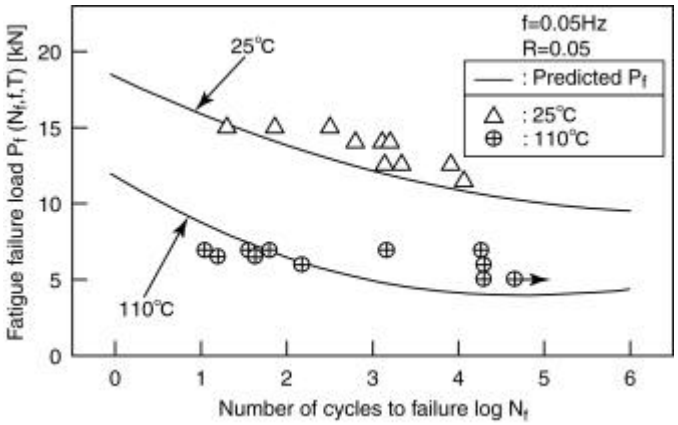
(a) GFRP/metal bolted joint



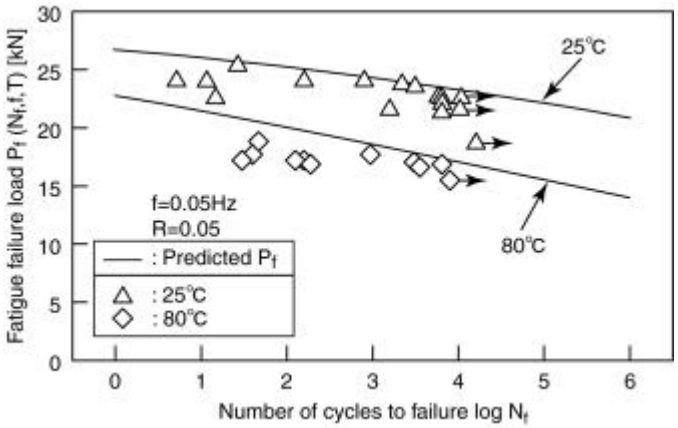
(b) CFRP/metal bolted joint

Fig. 6 Master curves of fatigue failure load

In order to verify the master curves, we predicted the P_f-N_f curves at f=0.05Hz and compared them with the test results, as shown in Fig. 7. Since the P_f-N_f curves predicted on the basis of the superposition principle agree well with the test results, we can conclude that the time-temperature superposition principle holds for fatigue failure load. It also shows the validity of using the time-temperature shift factor for CER failure load for the construction of fatigue master curves.



(a) GFRP/metal bolted joint



(b) CFRP/metal bolted joint

Fig. 7 Fatigue failure load versus number of cycles to failure at frequency f=0.05Hz

Comparison of the master curves of fatigue failure load

The time-temperature dependent fatigue behavior of two types of FRP bolted joint can be characterized by the master curves of tensile fatigue failure load shown in Fig. 6. For both GFRP/metal bolted joint and CFRP/metal bolted joints, the fatigue failure loads clearly decrease with time to failure and temperature. The fatigue failure load for GFRP/metal bolted joint also decreases with increasing N_f, but that for CFRP/metal bolted joint shows almost no dependency on cycles to failure. These results indicate that the fatigue failure prediction for CFRP/metal bolted joint should be based on time to failure and temperature rather than on cycles to failure.

CONCLUSION

The time and temperature dependence of tensile fatigue behavior for GFRP/metal bolted joint and CFRP/metal bolted joint are determined experimentally. The time-temperature superposition principle holds for the tensile fatigue failure loads as well as CER failure loads for these FRP bolted joints, therefore, the master curves of fatigue failure load for these FRP bolted joints can be obtained. It was found by comparing of these fatigue master curves that the fatigue failure loads clearly decrease with time to failure and temperature. The fatigue failure load for GFRP/metal bolted joint also decreases with increasing N_f, but that for CFRP/metal shows almost no dependency on cycles to failure. These results indicate that fatigue failure prediction for CFRP/metal bolted joint should be based on time to failure and temperature rather than on cycles to failure.

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