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.

![Diagram of FRP/metal bolted joint](image)

Fig. 1  Configuration of FRP/metal bolted joint

![Diagram of CFRP/metal bolted joint](image)

Table 1  Details of FRP pipe

<table>
<thead>
<tr>
<th></th>
<th>GFRP pipe</th>
<th>CFRP pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Glass plain woven cloth</td>
<td>Unidirectional carbon fiber</td>
</tr>
<tr>
<td>Laminate constitution</td>
<td>[0]ₐ</td>
<td>[0/45/90/-45]ₐ</td>
</tr>
<tr>
<td>Resin</td>
<td>Epoxy resin</td>
<td>Epoxy resin</td>
</tr>
<tr>
<td>Cure condition</td>
<td>120,.4h+150,.4h+180,.4h</td>
<td>120,.2h+150,.2h</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>CER test</th>
<th>Fatigue test</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Test temp. **</td>
<td><strong>Loading rate</strong></td>
<td><strong>Test temp.</strong></td>
</tr>
<tr>
<td>T [°C]</td>
<td>V [mm/min]</td>
<td>T [°C]</td>
</tr>
<tr>
<td>GFRP/metal bolted joint</td>
<td>25, 50, 80, 100, 110, 120, 140</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>110, 120</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100, 120</td>
</tr>
<tr>
<td>CFRP/metal bolted joint</td>
<td>25, 50, 80, 100</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>100, 120</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Load-elongation curves

Typical load-elongation curves for two types of FRP bolted joint under CER loading with elongation rate $V=1\text{mm/min}$ 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.

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

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

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 $\Delta H$,

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

where $G$ is gas constant $8.314 \times 10^{-3}$[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.

![Fig. 4 Time-temperature shift factor for CER failure load](image)

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

**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

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

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.
Fig. 6  Master curves of fatigue failure load
In order to verify the master curves, we predicted the $P_f-N_f$ curves at $f=0.05$Hz 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.

![Fatigue failure load versus number of cycles to failure at frequency $f=0.05$Hz](image)

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

**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.

REFERENCES