FATIGUE BEHAVIOR OF STEEL PLATES STRENGTHENED WITH CFRP SHEETS AT DIFFERENT TEMPERATURES

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) is a popular material in the area of strengthening steel structures, because it has many advantages such as light weight, high tensile strength, high elastic modulus and ease of installation. Recently, studies have shown that steel plates strengthened with CFRP sheets have improved fatigue performance. However, almost no researches are aimed to study temperature effect on fatigue properties of CFRP reinforcement for steel structures. This paper describes an investigation on the behavior of steel plates strengthened with CFRP at different temperatures. Firstly, through cylinder coupon tests, mechanical properties of the resin were found to vary at different temperatures, especially when the temperature exceeds over the glass transition temperature $T_g$. Secondly, three cracked bare steel plates and five cracked steel plates strengthened with CFRP sheets were tested under cyclic loading at different temperatures. The results prove the effectiveness of CFRP reinforcement technology, which increased fatigue life by 2 to 3.4 times. It is concluded that the variation of temperature has a great influence on properties of the resin, leading to influence on fatigue life. Finally, the existing analytical method at ambient temperature was modified to predict fatigue lives by considering the temperature effect. Experimental and theoretical results are compared and reasonable agreement is achieved.

KEYWORDS

Fiber reinforced polymer, structural strengthening, resin, fatigue life, temperature.

INTRODUCTION

Existing literature shows that enhancing steel structures using CFRP is an effective and economic technique in terms of increase in fatigue life (e.g. Miller et al. 2001; Nakamura et al. 2009; Zhang et al. 2010; Feng et al. 2013). Previous studies have focused on the effect of patch systems, patch thickness (Liu et al. 2009), CFRP system, bond length, bond area (Jones and Civjan 2003) and so on. It was found that performance of resin was critical to fatigue lives. Bascom and Cottington (1976) found that adhesive fracture behaviour of an Elastomer-Epoxy Resin was sensitive to temperature, especially when temperature was near its $T_g$. Besides, it has been proven that temperature is a predominant factor determining fatigue life of carbon steels (Sakai et al. 1991) and CFRP composites (Im et al. 2001). However, limited studies were focused on effect of temperature on steel plates strengthened with CFRP sheets, especially in properties of the resin and related failure modes, which impede the reinforcement technology of CFRP.

This paper reports on experiments to investigate temperature effect on fatigue strengthening. Firstly, compressive experiments of cylinder coupons made of resin are carried out at different temperatures to investigate the effect on two aspects of resin. One is thermal deterioration, which leads to changes in physical and chemical properties of the material and further influences properties of the members. The other is thermal stress, which is from the force caused by heating or cooling. Then, five CFRP sheet strengthened steel plates and three un-strengthened ones are examined at different temperatures. The relationship of crack growth behaviour and fatigue life extension are achieved and discussed. The existing analytical method for predicting fatigue lives at ambient temperature (Liu et al. 2009; Yang et al. 2013) is modified to include variable temperatures by considering temperature factors.

MECHANICAL PROPERTIES OF RESIN

Resin E2500S was used in this study and its mechanical properties at different temperatures were examined. The glass transition temperature $T_g$ was found to be 44.95 °C using DSC method, which was proposed in GB/T19466
Moreover, standard axial compression tests of casting cylinders under different temperatures were conducted in accordance with GB/T 2567-2008 (General Administration of Quality Supervision 2008). Figure 1 shows elastic modulus and compression capacity of resin decrease with increasing temperature, and the change is great near $T_g$. Thus, below $T_g$, cracking and crushing occurred; over $T_g$, large deformation with low elastic modulus happened.

**EXPERIMENTAL STUDY**

**Specimens and Test Set Up**

Five strengthened specimens and three un-strengthened specimens were tested under varying temperatures ranging from -40°C to 60°C. U and S denote un-strengthened specimens and strengthened specimens; subscripts denote the temperature. Un-strengthened specimens were pure steel plate made of Mild carbon steel (Q235); while strengthened specimens were strengthened with CFRP (UM46) sheets. The configuration is presented in Figure 2. All the specimens were subjected to uniform cyclic loading with a constant frequency of 18HZ until the failure occurred. Loads of large range is from 150kN to 15 kN, while load of small range is from 150 kN to 82.5 kN, which enable the technique of “beach marking” to measure crack development.

**Failure Modes**

Different degrees of debonding, delaminating and rupture failures happened at different temperatures. At -40°C and-10°C, debonding was the dominating failure mode although delaminating was also observed. At 20°C, the dominating failure mode is CFRP rupture while CFRP delaminating and debonding also occurred. At 40°C, it was clear that debonding became more severe. Finally, at 60°C, the failure mode is almost totally CFRP debonding with partial CFRP rupture.

**Fatigue Life**

As shown in Table 1, when temperature ranges from -40°C to 60 °C, fatigue lives of strengthened ones increased from 2 to 3.4 times (increased ratio is fatigue life of strengthened specimen divided by that of un-strengthened one at the same temperature). It indicates that CFRP reinforcement technology can perform well in the temperature ranging from -40 to 60°C. Besides, from Figure 3, temperature has a relatively less effect on
strengthened specimens when it is below \( T_g \). However, when temperature increases beyond \( T_g \), the strengthening effect is severely deteriorated, because the resin starts to transform from glass state to high elastic state whose elastic modulus decreased a lot, which resulted in much less reinforcement.

### Table 1. Test results of fatigue life

<table>
<thead>
<tr>
<th></th>
<th>U-40</th>
<th>S-40</th>
<th>S-10</th>
<th>U20</th>
<th>S20</th>
<th>S40</th>
<th>U60</th>
<th>S60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle number</td>
<td>544,425</td>
<td>1,429,785</td>
<td>1,083,635</td>
<td>352,214</td>
<td>1,244,142</td>
<td>1,310,350</td>
<td>306,490</td>
<td>624,000</td>
</tr>
<tr>
<td>Increased ratio</td>
<td>2.6</td>
<td>—</td>
<td>3.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

(a) Crack length v.s. number of fatigue cycles (b) Effect of temperature on specimens

Figure 3. Fatigue life

**THEORETICAL ANALYSIS**

From the experimental observation, temperature effect on resin, steel plates and composites can not be ignored. Some temperature factors are proposed in this paper to theoretical analysis for both bare specimens and strengthened specimens.

**Fatigue Life Prediction for Un-strengthened Specimens**

Based on previous study, fracture toughness and stress intensity range of steel rise with increasing temperature (Wu 2004), hence, temperature factor \( f_t \) is added to modify stress intensity factor \( K \). Based on Paris Law, Linear elastic fracture method (LEFM) is proposed as Eq. 1

\[
\frac{da}{dN} = C(\Delta K^n - \Delta K_0^n) \tag{1}
\]

where \( a \) is half crack length; \( N \) is fatigue life; range of stress intensity \( \Delta K \) is calculated according to Eqs 2-5.

\[
\Delta K = K_{\max} - K_{\min} \tag{2}
\]

\[
K_{\max,\min} = f(\sigma_0)_{\max,\min} \sqrt{\pi a} \tag{3}
\]

\[
f = f_s f_w f_g f_e f_t \tag{4}
\]

\[
(\sigma_0)_{\max,\min} = F_{\max,\min} / (b t_s) \tag{5}
\]

External force \( F_{\max} \) is 150KN and \( F_{\min} \) is 15KN; \( \sigma_0 \) is the nominal stress in the steel plate; \( b \) is the total width of the steel plate and \( t_s \) denotes thickness of steel plate. \( f \) modifies the idealized case of a central crack in an infinite plate. \( f_s, f_w, f_g, f_e \) and \( f_t \) account for the effects of free surface, finite thickness or width, non-uniform opening stress, elliptic crack fronts and temperature, respectively(Albrecht and Yamada 1977). \( f_w, f_g \) and \( f_e \) are all 1.0. Here, the factors \( f_s \) and \( f_t \) are determined as the proposed equations.

\[
f_s = \frac{\text{sec}(\pi a / b)}{b} \tag{6}
\]

\[
f_t = 0.002 T + 0.63 \tag{7}
\]

where \( T \) is value of temperature(°C). Thus, the predicted fatigue life \( N_p \) is calculated by integration as

\[
N_p = \int_{a_i}^{a_f} \frac{1}{C(\Delta K^n - \Delta K_0^n)} da \tag{8}
\]

where \( a_f \) and \( a_i \) are initial and final length of half crack. \( C, m \) and \( \Delta K_0 \) are material constants, which cover factors such as temperature, humidity and loading frequency. Here, \( C = 6.77 \times 10^{-13} \), \( m = 2.88 \) and \( \Delta K_0 \)
Fatigue Life Prediction for Strengthened Specimens

Previous study (Liu et al. 2009) achieved equivalent modulus and thickness of the composites

\[ E_t = \frac{E_c t_c + G_r t_r}{n(t_f + t_r) \sum k_i} \]

where \( E, G \) and \( t \) denote elastic modulus, shear modulus and one layer thickness; subscripts \( c, f, r \) and \( s \) denote composite, CFRP sheet, resin and steel plate, respectively. \( n \) (=2) is the number of CFRP layers of one side;

\[ E_r = 204 \text{GPa}; \quad G_r = \frac{(1 + \nu_r)}{2} \]

\( k_i \) is the factor between the strain in the \( i^{th} \) layer of fiber sheet and steel plate. Because shear modulus of resin decreases with increasing temperature, the strain of the steel plate has a similar reducing tendency. Thus values of \( k_2 \) are modified from \( k_2, \text{normal} = 0.73 \), which is the value at normal temperature (Fawzia et al. 2007, 2010).

\[ \sigma_s = \frac{E_t}{2(1 + \nu_r)} \]

Relevant parameters are given in Table 2.

### Table 2. Parameters of the predicting method

<table>
<thead>
<tr>
<th>( T \ (^{\circ} \text{C}) )</th>
<th>( E_r ) (GPa)</th>
<th>( G_r ) (GPa)</th>
<th>( \sum k_i )</th>
<th>( E_c ) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>3.53</td>
<td>24.46</td>
<td>(1+0.74)/2</td>
<td>147.0</td>
</tr>
<tr>
<td>-10</td>
<td>2.91</td>
<td>20.16</td>
<td>(1+0.74)/2</td>
<td>144.6</td>
</tr>
<tr>
<td>20</td>
<td>2.36</td>
<td>16.35</td>
<td>(1+0.73)/2</td>
<td>141.6</td>
</tr>
<tr>
<td>40</td>
<td>2.29</td>
<td>15.87</td>
<td>(1+0.73)/2</td>
<td>141.4</td>
</tr>
<tr>
<td>60 (&gt; ( T_g ))</td>
<td>0.042</td>
<td>0.291</td>
<td>(1+0.66)/2</td>
<td>127.2</td>
</tr>
</tbody>
</table>

Comparison of Analytical and Experimental Fatigue Lives

### Table 3. Comparison of experimental and predicted fatigue lives for un-strengthened and strengthened specimens

<table>
<thead>
<tr>
<th>Specimens</th>
<th>( N_i ) (million)</th>
<th>( N_p ) (million)</th>
<th>Ratio ( N_i/N_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-40</td>
<td>0.54</td>
<td>0.55</td>
<td>1.02</td>
</tr>
<tr>
<td>U20</td>
<td>0.35</td>
<td>0.35</td>
<td>1.00</td>
</tr>
<tr>
<td>U60</td>
<td>0.31</td>
<td>0.28</td>
<td>0.90</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>COV</td>
<td></td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>S-40</td>
<td>1.43</td>
<td>1.56</td>
<td>0.92</td>
</tr>
<tr>
<td>S-10</td>
<td>1.08</td>
<td>1.18</td>
<td>0.92</td>
</tr>
<tr>
<td>S20</td>
<td>1.24</td>
<td>1.21</td>
<td>1.02</td>
</tr>
<tr>
<td>S40</td>
<td>1.31</td>
<td>1.32</td>
<td>0.99</td>
</tr>
<tr>
<td>S60</td>
<td>0.62</td>
<td>0.68</td>
<td>0.91</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>COV</td>
<td></td>
<td></td>
<td>0.05</td>
</tr>
</tbody>
</table>
Fatigue lives $N_p$ are calculated and comparison results are shown in Table 3. The difference is lower than 10%. Generally, the difference might also be attributed to inaccuracy of $C$, $m$ and $K$. Furthermore, it is difficult to record exact cycle numbers before the failure is to occur. According to the complexity of fatigue problems, the mean value and covariance is acceptable, which proves the adaptability of our modified method and verifies good agreement between experiment and analytical calculation.

CONCLUSIONS

This paper has reported on experimental investigations of fatigue lives of steel plates strengthened with CFRP sheets at different temperatures. The following conclusions were reached.

(1) The temperature effect on fatigue life of CFRP strengthened specimens depended heavily on the mechanical properties of the resin. Below $T_g$, the temperature had a relatively less effect, but the effect became great once it exceeded $T_g$.

(2) By introducing temperature factors $f_t$, $\alpha_t$ and $\beta_t$, prediction method of fatigue lives for bare steel plates and CFRP-strengthened ones are both improved. $f_t$ is an temperature factor effected on stress intensity factor of all specimens according to varying temperature; $\alpha_t$ modifies the factor between the strain in the $i$th layer of fiber sheet and steel plate according to varying shear modulus of resin; $\beta_t$ corrects equivalent modulus of the composite by considering temperature effect on CFRP reinforcement. Good agreement of experimental and theoretical results is achieved, which verifies the test results and the applicability of the new method.

ACKNOWLEDGEMENT

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REFERENCE


