REPAIR OF FATIGUE CRACKS INITIATED AT OUT-OF-PLANE WELDED GUSSET JOINTS USING PRE-TENSIONED CFRP STRIPS

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ABSTRACT

This paper deals with the repair of typical fatigue cracks initiated at out-of-plane welded gusset joints in steel bridges using externally-bonded pre-tensioned CFRP strips. The pre-tensioning technique for CFRP strips has been developed in the previous study. Test specimens (L1,350×W400×t9 mm) with real size out-of-plane welded gusset plates (L500 W300×t9×mm) were fabricated and initial fatigue cracks (2a=50mm) occurred at welded toes by fatigue tests. In order to evaluate the effect of repair, fatigue tests of three kinds of methods have been conducted as follows: the specimen without repair, with repair by not pre-tensioned CFRP strips and with repair by pre-tensioned CFRP strips. The compressive force due to the release of the pre-tension is approx. 65 kN by four pre-tensioned CFRP strips. As a result, under the nominal stress range of 100 MPa, fatigue lives were improved drastically, and the effect of 7.7 times in pre-tensioned CFRP strips and 1.6 times in not pre-tensioned CFRP strips was obtained as compared without repair. The prediction of fatigue lives based on LEFM was evaluated conservatively. The repair method using compressive pre-stress results in a reduction of the nominal stress range in consideration of the crack closure condition.

1 INTRODUCTION

In urban highway steel bridges, fatigue damage has occurred with an increase in traffic and the passage of overloaded vehicles. As a simple and easy method for repairing fatigue cracks, the repair method using externally-bonded CFRP strips attracts attention [1], and we have developed a repair method using externally-bonded multi-layered CFRP strips [2], [3]. The more effective repair method by using externally-bonded pre-tensioned CFRP strips has been developed and investigated [4], [5], [6], [7], [8].

In this paper, the repair effect for typical fatigue cracks initiated at welded joints in steel bridges has been investigated experimentally by using externally-bonded pre-tensioned CFRP strips. The pre-tensioning technique for CFRP strips have been developed in the previous study [8].

Test specimens with real size out-of-plane welded gusset plates were fabricated and initial fatigue cracks occurred at welded toes by fatigue tests. In order to evaluate the repair effect, fatigue tests of three kinds of methods have been conducted. The prediction of fatigue lives based on linear elastic fracture mechanics (LEFM) has been investigated.
2 EXPERIMENTAL AND ANALYTICAL PROCEDURE

2.1 Test specimen with real size out-of-plane welded gusset joints

Figure 1 shows the test specimen with real size out-of-plane welded gusset joints. Both sides of the steel plate (L1350×W400×t9 mm) were attached to out-of-plane gusset plates (L500×W300×t9 mm) by fillet welding. The gusset plate was fabricated as a real size in typical plate girder bridges. To initiate fatigue cracks from only one side, the condition of welded joint in the other side was to install a half of hole (R50) and to be full penetration weld as shown in Figure 1. Table 1 shows material properties.

<table>
<thead>
<tr>
<th></th>
<th>Steel plate JIS SM400</th>
<th>CFRP strip</th>
<th>Epoxy resin adhesive (Konishi E250)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>202</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>292</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>420</td>
<td>2808</td>
<td>30</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>37</td>
<td>1.9</td>
<td>–</td>
</tr>
</tbody>
</table>

2.2 Repair method and condition of fatigue test

All fatigue tests have been conducted using a servo-hydraulic test machine (dynamic load capacity: 750 kN) under load control mode. By fatigue test, the initial crack, whose length is approx. 25 mm, has been propagated from the center of gusset plate to both ends, and fatigue cracks were repaired using externally-bonded CFRP strips.

Three kinds of methods have been examined as follows: (a) not repaired for a reference specimen (PWGN), (b) repaired by externally-bonded four CFRP strips (L450×W50×t1.2 mm) without pre-tension (PWGC) and (c) repaired by externally-bonded four CFRP strips (L450×W50×t1.2 mm) with pre-tension (PWGP).

The pre-tension was installed to CFRP strips using the pre-tensioning device [8]. Figure 2 shows the developed pre-tensioning device. Pre-tensioned CFRP strips were bonded. After hardening, the pre-tension was released and the compressive stress was installed into the specimen. In the specimen of PWGP, the tensile strain of 2,500×10^-6, namely, the tension of 22.5 kN was installed into the CFRP strip. Table 2 shows the condition of fatigue test.
Table 2 Condition of fatigue test

<table>
<thead>
<tr>
<th>Repair method</th>
<th>Specimen No.</th>
<th>Stress range $\Delta \sigma$ (MPa)</th>
<th>Maximum stress $\sigma_{\text{max}}$ (MPa)</th>
<th>Minimum stress $\sigma_{\text{min}}$ (MPa)</th>
<th>Stress ratio $R$</th>
<th>Loading speed $f$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not repaired</td>
<td>PWGN_01</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGN_02</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGN_03</td>
<td>60</td>
<td>66.7</td>
<td>6.7</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Repaired by CFRP strips with pre-stress</td>
<td>PWGP_04</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGP_05</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Repaired by CFRP strips without pre-stress</td>
<td>PWGP_07</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGC_06</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGC_08</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>PWGC_09</td>
<td>60</td>
<td>66.7</td>
<td>6.7</td>
<td>0.1</td>
<td>3</td>
</tr>
</tbody>
</table>

2.3 Analysis method analytical model

The 3D finite element analysis (FEA) has been conducted using MSC Marc 2013. The minimum element size of crack tips was 0.04 mm square. According to the symmetry of the test specimen, a quarter of the specimen was modelled using solid element. As the equivalent initial stress, the compressive pre-stress of 375 MPa was set into the CFRP strip longitudinally. The load and analysis condition was longitudinal and uniform distributed stress of 100 MPa and the linear elastic analysis.

The crack was modelled using double nodes definition. The energy release rate was calculated using virtual crack closure technique (VCCT) and the stress intensity factor was evaluated. The crack propagation analysis has been conducted based on LEFM and the evaluation of fatigue life has been investigated. The relationships between the stress intensity factor range $\Delta K_I$ and the fatigue crack growth rate based on Paris' law is expressed by Eq. (1)

$$\frac{da}{dN} = C \cdot \Delta K_I^m$$

Where $C$ and $m$ are material coefficients. In this study, recommendation values [9] in fatigue design for welded joints is adopted and $m=2.75$, $C=1.5 \times 10^{-11}$, respectively.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Evaluation of installed compressive stress into test specimens

Figure 4 shows the stress distribution due to release of pre-tension in the cracked cross section of the specimen (Figure 1). This specimen is PWGP_05. The average value of four strain gages placed longitudinally on CFRP strips was $2.450 \times 10^6$ after hardening of adhesive and then it became...
2,250×10⁻⁶ after release of pre-tension. Accordingly, the strain difference before and after release of pre-tension is the compressive pre-stress installed into the steel plate.

The experimental result shows the uniform compressive pre-stress of –18.1 MPa or the compressive pre-stress on CFRP strips of –32.1 MPa is installed into the cracked cross section. On the other hand, the analytical result indicates the former is –23.2 MPa or the latter is –37.2 MPa. Although there is the stress deference between side A and B in the specimen, the compressive pre-stress is installed properly into the specimen. The compressive force due to the release of the pre-tension is approx. 65 kN by four pre-tensioned CFRP strips. Moreover, there is the large deference of the installed compressive pre-stress near the out-of-plane gusset plate (X = 0 mm). This is attributed to release of the residual stress installed into a weld toe.

**Figure 4 Stress distribution due to release of pre-tension in the cracked cross section of the specimen**

### 3.2 Relationships between stress intensity factor and crack length

As a result of FEA, Figure 5 shows the relationships between the stress intensity factor range and crack length under the applied stress of 100 MPa. The result of PWGN without repair indicates that the values of stress intensity factor increase with increasing crack lengths. The result of PWGC and PWGP with repair by CFRP strips indicate that increasing the stress intensity factor controls with increasing crack lengths and the effect is especially remarkable in the range bonded by CFRP strips.

**Figure 5 Stress intensity factor range vs. crack length**
3.3 Relationships between crack length and number of cycles

Figure 6 shows the relationships between crack lengths and the number of cycles under the stress range of 100 MPa. The relationships between crack lengths and the number of cycles were obtained by the beach mark method experimentally. The experimental result indicates the prolongation of fatigue life is in case of PWGP, 7.7 times and in case of PWGC, 4.8 times as compared without repair, respectively. The results of fatigue life prediction indicate that in case without repair, the experimental data can be simulated with accuracy, however in case with repair, the predicted fatigue lives are less than experimental fatigue lives and are evaluated conservatively.

![Figure 6: Relationships between crack length and number of cycles](image1.png)

3.4 Results of fatigue test and prediction of fatigue life

Figure 7 shows the relationships between the stress range and the number of cycles when the crack length is from 25 mm to 150 mm. The result of regression lines of fatigue tests (dotted lines) and the fatigue life prediction (solid lines) are also showed in this figure. Although there is little test data, the scatter of experimental fatigue lives is small and in case with repair, predicted fatigue lives are less than experimental ones as mentioned above. In the case of PWGP with pre-stress, fatigue lives can be estimated roughly by crack propagation analysis.

![Figure 7: Relationships between stress range and number of cycles](image2.png)
4 CONCLUSIONS

Therefore, these results indicate that the compressive pre-stress can be installed into the cracked steel plate with out-of-plane welded gusset plates experimentally and analytically and the stress intensity factor and the fatigue crack growth rate can be reduced by release of pre-tension. Moreover, fatigue lives can be estimated roughly by crack propagation analysis and predicted fatigue lives are evaluated conservatively.

REFERENCES