Repair effect of installation of pre-tensioned CFRP strips on fatigue cracks initiated at out-of-plane welded gusset joints

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This paper deals with the repair of the typical fatigue cracks initiated at the out-of-plane welded gusset joints in the steel bridge using externally bonded pre-tensioned CFRP strips. The specimens (L1,350×W400×t9 mm) with the real size out-of-plane welded gusset plates (L500×W300×t9 mm) were fabricated and the initial cracks (2a = 50 mm) occurred at the welded toes by the fatigue tests. In order to evaluate the effect of repair, the fatigue tests of three method types have been conducted as follows: the specimen without repair, with repair by non pre-tensioned CFRP strips and with repair by pre-tensioned CFRP strips. The value of the compressive force due to the release of the pre-tension is approximately 65 kN by four pre-tensioned CFRP strips. As the experimental results, under the nominal stress range of 60–120 MPa, the fatigue lives were improved drastically, and the effects of 6.5–8.9 times in the pre-tensioned CFRP strips and 3.5–5.5 times in the non pre-tensioned CFRP strips were obtained against the non repair. The predicted fatigue lives based on LEFM were evaluated.

Keywords: CFRP strip, pre-tensioning technique, repair of fatigue crack, welded gusset joints

1. INTRODUCTION

In urban highway steel bridges, fatigue damage has occurred with rapid increase in traffic and the passage of overloaded vehicles. This has raised the need for the appropriate and effective maintenance method in order to rehabilitate and maintain the metallic bridge structures in service in healthy condition1). Although some existed repairing and strengthening methods such as stop-hole method or high-strength bolt frictions joining method is widely used to reduce stress concentration at crack tip1), those methods demand heavy specialized equipment and special technique in order to operate it. Regarding to this, a simple and easy method for repairing fatigue cracks, the repair method using externally-bonded CFRP strips has immensely attracted attention2). The efficiency and effectiveness of repair method using externally-bonded multi-layered CFRP strips have been studied and developed3,4). Moreover, effective repair method by using externally-bonded pre-tensioned CFRP strips which utilizes the advantage of pre-tension releasing has been progressively developed and investigated5–9).

In this paper, the repair effect for the typical fatigue cracks initiated at the welded joints in the steel bridge was investigated experimentally by using externally bonded pre-tensioned CFRP strips. The pre-tensioning technique for CFRP strips have been developed in the previous study9).

The crack propagation analysis was conducted based on the linear elastic fracture mechanics (LEFM) and the evaluation of fatigue life was investigated.
2. EXPERIMENTAL PROCEDURES

2.1 Test Specimen Geometry and Material

Fig. 1 shows the geometry and dimensions of the experimental specimen with the real size out-of-plane welded gusset joints. The both sides of the steel plate (L1350×W400×t9 mm) was attached to the out-of-plane gusset plates (L500×W300×t9 mm) by fillet welded joints with the leg length of 6 mm. The gusset plate was fabricated as a real size in the typical plate girder bridges. In order to control and initiate the fatigue crack from only one side, a semi-circular hold with the radius of 50 mm was installed and full penetration weld was applied at the other side of the joint condition as shown in Fig. 1 (a). For the repaired specimens, CFRP strips (L450×W50×t1.2 mm) were externally adhesively bonded at the focused part as shown in Fig. 1 (b). Table 1 shows the material properties of steel plate, CFRP strip and epoxy resin. Two-pack type ambient-curable (cold hardening type) epoxy resin of Konishi E250 was used as adhesive.

Table 1 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</td>
<td>202</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>Yield strength</td>
<td>305</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>434</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 Experimental Condition

All fatigue tests were conducted using a servo-hydraulic test machine with the dynamic load capacity of 750 kN under load control mode as presented in Fig. 2. The gripping portions were frictionally jointed utilizing the high-strength bolts (F10T, M22) fastened by nut runner with the design bolt tension.

The waveform of the load was a sine wave, and the load, displacement and each strain values were measured at 1/100 seconds (1/5000 seconds for loading frequency 5 Hz of specimen PWGP_10) interval using the dynamic strain-meter (Keyence NR-600). Moreover, Beach Mark Method was also adopted in order to measure crack propagation speed.

By fatigue test, the initial crack, whose length was 25 mm, was propagated from the center of gusset plate at welded toes to the both ends, and the fatigue cracks were repaired using externally-bonded CFRP strips. The initial crack length was controlled by attached the enameled copper wires (φ0.4 mm) on the specimen, so that the testing machine can be automatically stopped when the copper wire was cut.

Table 2 Experimental condition

<table>
<thead>
<tr>
<th>Repair method</th>
<th>Specimen No.</th>
<th>Stress range $\Delta \sigma_{sn}$ (MPa)</th>
<th>Maximum stress $\sigma_{sn max}$ (MPa)</th>
<th>Minimum stress $\sigma_{sn min}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not repaired</td>
<td>PWGN 11</td>
<td>120</td>
<td>133.3</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>PWGN 01</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>PWGN 02</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>PWGN 03</td>
<td>60</td>
<td>66.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Repaired by CFRP strips without pre-stress</td>
<td>PWGC_12</td>
<td>120</td>
<td>133.3</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>PWGC_06</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>PWGC_08</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>PWGC_09</td>
<td>60</td>
<td>66.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Repaired by CFRP strips with pre-stress</td>
<td>PWGP_13</td>
<td>120</td>
<td>133.3</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>PWGP_05</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
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<tr>
<td></td>
<td>PWGP_07</td>
<td>80</td>
<td>88.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>PWGP_10</td>
<td>60</td>
<td>66.7</td>
<td>6.7</td>
</tr>
</tbody>
</table>
as follows: (a) not repaired type for a reference specimen (PWGN), (b) repaired type by externally-bonded four CFRP strips ($L_{450} \times W_{50} \times t_{1.2}$ mm) without pre-tension (PWGC) and (c) repaired type by externally-bonded four CFRP strips ($L_{450} \times W_{50} \times t_{1.2}$ mm) with pre-tension (PWGP).

The loading force condition was considered based on the nominal stress range from 60–120 MPa with the stress ratio $R$ of 0.1 and the loading frequency $f$ was 3 Hz, except for the specimen PWGP_10 which the loading frequency of 5 Hz was conducted (during the initial crack of 15–25 mm was 3 Hz).

(1) Repair method by non pre-tensioned CFRP strips

For the repair method by non pre-tensioned CFRP strips, first, the non repaired specimen was subjected to fatigue test until the

Fig. 3 Fixture setup during CFRP strips adhesion on PWGC

Fig. 4 Configuration of the developed pre-tensioning device

Fig. 5 Fixture setup during CFRP strips adhesion on PWGP
crack propagated to 25 mm as an initial crack. Then the test specimen was repaired by externally-bonded four CFRP strips (L450×W50×t1.2 mm). In Fig. 3, the steel angle bars (75×75 mm) were used as fixture during the CFRP strips adhesion and adhesive curing of specimen PWGC. M16 screw bolts (hexagon socket head cap type) were used to fix the angle bars to the specimen, and to fix and adjust the CFRP strips during the adhesion as shown in the figure.

Photo 1 shows the image of repair method by non pre-tensioned CFRP strips. Konishi E250 was used as an adhesive and the thickness was controlled to be approximately 0.4 mm utilizing the glass beads. After bonding, the specimen was cured at 40 °C for 24 hours and the fatigue test was restated again after the test specimen was back to the room temperature.

(2) Repair method by pre-tensioned CFRP strips

The repair method by pre-tensioned CFRP strips is similar to the repair method by non pre-tensioned CFRP strips. Four pre-tension CFRP strips (L450×W50×t1.2 mm) were externally-bonded into the non repaired specimen after 25 mm of an initial crack was conducted.

The pre-tension was installed in advance into the CFRP strips before externally-bonded into the non repaired specimen using the pre-tensioning device9), as shown in Fig. 4. CFRP strips were kept at the temperature of 30 °C during the pre-tension installation and the adhesion and adhesive curing of 24 hours were conducted at approximate temperature of 35 °C. After curing, the specimen was rapid cooled down by the electric fan to the room temperature, pre-tension was released and pre-stress was installed.

The same fixture was used during the adhesion of pre-tensioned CFRP strips on specimen of PWGP. The fixture setup is presented in Fig. 5. Photo 2 shows the repair method by pre-tensioned CFRP strips. At the end, after hardening, the removal of the steel anchor plates was conducted using steel wedges (Fig. 4).

2.3 Installation of Pre-Tensioned CFRP Strips
(1) Change of strain during curing

<table>
<thead>
<tr>
<th>Gauge name</th>
<th>During pre-tension installation ε₀</th>
<th>Before release ε₁</th>
<th>After release ε₂</th>
<th>Introduced strain Δε = ε₁–ε₂</th>
<th>Pre-stress σ₀ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1L</td>
<td>2542</td>
<td>2560</td>
<td>2395</td>
<td>165</td>
<td>33.5</td>
</tr>
<tr>
<td>C1R</td>
<td>2563</td>
<td>2527</td>
<td>2321</td>
<td>206</td>
<td>41.4</td>
</tr>
<tr>
<td>C2L</td>
<td>2570</td>
<td>2442</td>
<td>2233</td>
<td>209</td>
<td>42.0</td>
</tr>
<tr>
<td>C2R</td>
<td>2543</td>
<td>2472</td>
<td>2290</td>
<td>182</td>
<td>36.8</td>
</tr>
<tr>
<td>C3L</td>
<td>2519</td>
<td>2283</td>
<td>2155</td>
<td>128</td>
<td>24.9</td>
</tr>
<tr>
<td>C3R</td>
<td>2503</td>
<td>2270</td>
<td>2171</td>
<td>99</td>
<td>19.2</td>
</tr>
<tr>
<td>C4L</td>
<td>2331</td>
<td>2435</td>
<td>2300</td>
<td>135</td>
<td>26.9</td>
</tr>
<tr>
<td>C4R</td>
<td>2301</td>
<td>2396</td>
<td>2233</td>
<td>163</td>
<td>32.5</td>
</tr>
<tr>
<td>Average</td>
<td>2484</td>
<td>2423</td>
<td>2262</td>
<td>161</td>
<td>32.5</td>
</tr>
</tbody>
</table>

Pre-tension installation condition was controlled by the strain values which were attached on CFRP strips and steel plates. Fig. 6 presents the change of strain value during adhesive curing in the case of PWGP_05. The horizontal axis is elapsed time and the vertical axis is strain value and temperature. The red dot line, blue dot line and black line are the changes of average strain value of CFRP strips, average strain value of steel plates and average temperature of CFRP strips.

Fig. 6 shows the change of strain during curing in the case of PWGP_05. From figure, the average value of four strain gauges placed longitudinally on CFRP strips was 2,423×10⁻⁶ after hardening of adhesive and then it became 2,262×10⁻⁶ 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 change of strain value is
161×10⁻⁶, which is equivalent to the compressive pre-stress of 32.5 MPa installed into the steel plates.

Fig. 7 shows the stress distribution due to release of pre-tension in the cracked cross section of the specimen in the case of PWGP_05. The horizontal axis is distance from center of specimen and the vertical axis is longitudinal stress. The distance ranges of \( X = -25 \) mm to \( X = -75 \) mm and \( X = 25 \) to \( X = 75 \) mm from the center show the ranges of externally-bonded CFRP strips. The experimental result shows the average compressive pre-stress on the whole steel plates of –18.1 MPa or the average compressive pre-stress on steel plates in bonded CFRP strips range is –32.5 MPa. On the other hand, the analytical result indicates the average compressive pre-stress on the whole steel plates is –23.2 MPa or the average compressive pre-stress on steel plates in bonded CFRP strips range is –37.2 MPa. Although there is the stress difference between side A and B in the specimen, the compressive pre-stress was installed properly into the specimen. The compressive force due to the release of the pre-tension was approximately 65 kN by four pre-tensioned CFRP strips. Moreover, there was the large difference 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. The release of residual stress is considered to be controlled by CFRP strips which leads to the large difference between the experimental and analytical compressive pre-tension near the out-of-plane gusset plate. It should be noted that the residual stress was not considered in analytical evaluation. However, the convergence of pre-stress to the end of steel plate at both sides (\( X = -200, 200 \) mm) indicate the same trend in either experimentally or analytically.

Table 4 shows the experimental and analytical results of the uniformly average compressive pre-stress on the whole steel plates and average compressive pre-stress on steel plates in bonded CFRP strips range for each repaired specimens by pre-tensioned CFRP strips. It should be noted that the average compressive pre-stress on the whole steel plates is calculated from the strain values of strain gauges attached on steel plates and on CFRP strips, while the average compressive pre-stress on steel plates in bonded CFRP strips range is obtained from strain gauges attached on CFRP strips. Analytical result shows that the uniformly average compressive pre-stress on the whole steel plate was –23.2 MPa and the average compressive pre-stress on steel plates in bonded CFRP strips range was –37.2 MPa. For the experimental result, the average compressive pre-stress on the whole steel plate and on steel plate in bonded CFRP strips range were approximately –20.0 MPa and –30 MPa to –40 MPa, which give good agreement to the analytical result.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Average compressive pre-stress on the whole section of steel plates ( \sigma_s ) (MPa)</th>
<th>Average compressive pre-stress on steel plates in bonded CFRP strips range ( \sigma_c ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWGP_05</td>
<td>Experi. –18.1</td>
<td>Analy. –23.2</td>
</tr>
<tr>
<td>PWGP_07</td>
<td>Experi. –20.9</td>
<td>Analy. –23.2</td>
</tr>
<tr>
<td>PWGP_10</td>
<td>Experi. –20.8</td>
<td>Analy. –23.2</td>
</tr>
<tr>
<td>PWGP_13</td>
<td>Experi. –21.8</td>
<td>Analy. –23.2</td>
</tr>
</tbody>
</table>

Table 5 Material coefficients

<table>
<thead>
<tr>
<th>Material coefficients</th>
<th>Unit</th>
<th>CASE 1 Experimental value</th>
<th>CASE 2 Recommendation value⁽¹⁾</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C )</td>
<td>m⁻¹(σ/MPa)²</td>
<td>1.93×10⁻¹⁰</td>
<td>1.50×10⁻¹⁰</td>
</tr>
<tr>
<td>( m )</td>
<td>–</td>
<td>3.35</td>
<td>2.75</td>
</tr>
</tbody>
</table>
3. PROCEDURES OF ANALYTICAL EVALUATION

3.1 Analytical Method and Model

The 3D finite element analysis (FEA) was conducted using Msc. Marc2013. Fig. 8 shows the analytical model. According to the symmetry of the test specimen, a quarter of the specimen was modelled using solid element.

The minimum element size of crack tips was 0.04 mm square. The thickness of steel plate, CFRP strips and epoxy resin is the same as the experimental specimen, 9 mm, 1.2 mm and 0.4 mm, respectively. The boxing toe is a fillet welded joints with the leg length of 6 mm and from the welded toe to the side surface fillet, it was modelled with the arch length of 6 mm.

As the equivalent initial stress, the compressive pre-stress of 375 MPa was set into the CFRP strips longitudinally. The load and analysis condition was longitudinal and uniform distributed stress of 100 MPa. It was conducted in linear elastic analysis. Note that the amount of compressive pre-stress set into the CFRP strips (375 MPa) was calculated by Eq. (1) below.

\[ \sigma_{C} = E_{c} \varepsilon_{p} \]  

(1)

Here, \( E_{c} \) is longitudinal elastic modulus of CFRP strips, and \( \varepsilon_{p} \) is pre-tensioned strain value installed into CFRP strips (2500×10\(^{-6}\)).

The cracks were modelled using double nodes definition. The energy release rate was calculated using the virtual crack closure technique (VCCT) and the stress intensity factor was evaluated. The crack propagation analysis was conducted based on linear elastic fracture mechanics (LEFM) and the evaluation of fatigue life was investigated. The relationships between the stress intensity factor range \( \Delta K \) and the fatigue crack growth rate based on Paris' law is expressed by Eq. (2).

\[ \frac{da}{dN} = C \cdot \Delta K^{m} \]  

(2)

Here, \( a \) [m] is crack length, \( N \) [cycle] is number of cycles, \( \Delta K \) [MPa\( \cdot \)m\(^{1/2}\)] is stress intensity factor range (the difference between the stress intensity factor at the maximum and minimum loading), and \( C \) [m\(^{1/2}\)/(MPa\( \cdot \)cycle)] and \( m \) [no unit] are the material coefficients.

In this study, two cases of material coefficients \( C \) and \( m \) value were considered and applied in the analysis process as given in Table 5. CASE 1 in the second column is the value obtained from fatigue experiment of the material cut from the gusset plate which will be explained in section 3.2. CASE 2 in the third column shows the recommendation values adopted in fatigue design for welded joints by JSSC.

3.2 Material Coefficient Measurement from Web Plate

(1) Experimental specimen

The subjected specimens to determine the material coefficients were the cut materials from the web portions of the out-of-plane welded gusset joints of primary specimens. Fig. 9 shows the shape and dimensions of the specimen. As an original crack, the hole with the radius of 2 mm in the center and 2 mm length of 0.3 mm width of saw-cut crack from both sides of the hole were introduced.

![Fig. 9 Specimen geometry](image)

**Table 6 Experimental condition**

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Stress range ( \Delta \sigma ) (MPa)</th>
<th>Maximum stress ( \sigma_{max} ) (MPa)</th>
<th>Minimum stress ( \sigma_{min} ) (MPa)</th>
<th>Loading frequency ( f ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPL 1</td>
<td>70</td>
<td>77.7</td>
<td>7.7</td>
<td>15</td>
</tr>
<tr>
<td>WPL 2</td>
<td>100</td>
<td>111.1</td>
<td>11.1</td>
<td>10</td>
</tr>
<tr>
<td>WPL 3</td>
<td>150</td>
<td>116.7</td>
<td>16.7</td>
<td>10</td>
</tr>
</tbody>
</table>

![Fig. 10 da/dN and stress intensity factor range](image)

The testing machine used in this experiment was electro-hydraulic servo type material strength testing machine (Shimadzu Servo Pulser EHF-EV200-040). By fatigue test, first, the original crack of 6 mm was propagated to 12 mm, marked as the initial crack, and then propagated until the failure of specimen. Moreover, Beach Mark Method was also adopted in order to measure crack propagation speed.

(2) Experimental condition

Table 6 shows the condition of each fatigue test. The loading force condition is considered utilizing the nominal stress range of 70, 100 and 150 MPa with the stress ratio \( R \) of 0.1 and the loading frequency \( f \) is 15, 10 and 10 Hz, respectively.

The fatigue testing machine used in this experiment was electro-hydraulic servo type material strength testing machine (Shimadzu Servo Pulser EHF-EV200-040). By fatigue test, first, the original crack of 6 mm was propagated to 12 mm, marked as the initial crack, and then propagated until the failure of specimen. Moreover, Beach Mark Method was also adopted in order to measure crack propagation speed.
Experimental result

Fig. 10 presents the result of the experiment. The horizontal axis is stress intensity factor and vertical axis is crack propagation amount per number of cycle (da/dN). The relationship shows a good agreement in almost straight line with high correlation coefficient. The material coefficients C and m were calculated from the regression line equation as presented Eq. (3) and its result is shown in Table 5.

\[ \frac{da}{dN} = 1.9296 \times 10^{-12} dK^{3.499} \]  \hspace{1cm} \text{(3)}

Note that the stress intensity factor \( dK \) for a through crack length of 2a under uniform stress range \( \Delta \sigma \) at the center is calculated utilizing the equation Eq. (4a) below.

\[ dK = F \Delta \sigma \sqrt{\pi a} \]  \hspace{1cm} \text{(4a)}

Here, \( F \) is the correction factor in considering the effect of finite width which is calculated by equation Eq. (4b) and Eq. (4c) below. Note that \( W \) is the width of steel plate.

\[ F = \left( 1 - 0.025 \xi^2 + 0.06 \xi^4 \right) \sqrt{\sec \frac{\pi \xi}{2}} \]  \hspace{1cm} \text{(4b)}

\[ \xi = \frac{2a}{W} \]  \hspace{1cm} \text{(4c)}

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Crack propagation and failure of CFRP strips

Fig. 11 is an example of crack propagation in case of PWGP_13 captured by microscope after the test was completed. As seen in the figure, Beach Mark was properly introduced into fracture surface of the specimen, and crack propagation length is obtained experimentally from the interval of Beach Mark.

Regarding to the failure of CFRP strips adhesion, there is no sign of debonding occurs between CFRP strips and steel plates of specimens is seen during the test.

4.2 Relationship between Stress Intensity and Crack Length

As a result of FEA, Fig. 12 shows the relationships between the stress intensity factor range and crack length under the applied nominal stress range of 100 MPa. From the figure, in overall, the stress intensity factor range of PWGP (repair with pre-tensioned CFRP strips) is relatively smaller than that of PWGC (repair with non pre-tensioned CFRP strips), and the stress intensity factor range of PWGC is relatively smaller than that of PWGN (non repair).

Moreover, the result of PWGN without repair indicates that the values of stress intensity factor range are linearly increase with the increasing of crack lengths. On the other hand, the results of PWGC and PWGP with repair by CFRP strips indicate that the stress intensity factors are almost constant in the bonded range of CFRP strips. This is due to the effect of repair by externally-bonded CFRP strips. It should be noted that although the stress intensity factor ranges are increasing beyond the CFRP strips bonded range, the slopes are comparatively smaller than that of PWGN.
The difference between PWGN, PWGC and PWGP can be further explained in Fig. 13. The figure shows the relationship between nominal tensile stress and the stress intensity factor in case of nominal stress range of 100 MPa at crack length of \(a = 50\) mm. In the figure, when the slope of the line is smaller, the stress intensity factor is larger and the crack tends to propagate faster. The stress intensity factor of PWGC is smaller than that of PWGN due to the effect of externally-bonded CFRP strips, and PWGP’s is smaller than PWGC’s due to the effect of pre-stress installed into the specimen.

4.3 Relationship between Crack Length and Number Cycles

Fig. 14 shows the relationships between crack lengths and the number of cycles under the applied nominal stress range of 100 MPa. The pointed solid lines were obtained experimentally by the Beach Mark Method. The solid lines and dash lines are obtained analytically based on LEFM for CASE 1 (experimental value) and CASE 2 (JSSC recommendation value), respectively. Red, blue and green lines are for PWGN, PWGC and PWGP specimen series, respectively.

From the figure, the prolongation of fatigue life can be experimentally and analytically confirmed in case of PWGC and PWGP. For PWGC, it accounts approximately 7.7, 7.2 and 5.2 times, while for PWGP, it accounts approximately 4.5, 2.7 and 2.3 times compared to PWGN for experiment, analysis CASE 1 and CASE 2, respectively.

Furthermore, the results of fatigue life prediction (CASE 1 and CASE 2) indicates that in case of non repair PWGN, the experimental data can be simulated with accuracy, however, in case of repair PWGC and PWGP, the predicted fatigue lives are less than experimental fatigue lives. This is due to the release of residual stress at bead portions of the specimens. In case of non repair PWGN, it is considered that the whole residual stress is released when the crack occur. On the other hand, in case of repair PWGC and PWGP, the release of residual stress when the crack occurs is controlled by the bonded CFRP strips. The remaining residual stress assists and takes part in slowing the crack propagation. However, in analytical evaluation, the consideration of residual stress was not taken into account in call cases. Introduction of residual stress in analytical model is one of future issues in this study.

4.4 Repaired Effect and Prediction of Fatigue Life

Fig. 15 shows the relationships between the nominal stress range and the number of cycles for the propagation crack length \(a\) from 25 mm to 100 mm. The pointed dotted lines, solid line and dash lines are fatigue life from experiment, prediction fatigue life for CASE 1 and CASE 2, accordingly. Also, Red, blue and green lines are for PWGN, PWGC and PWGP specimen series, respectively. The regression line equations and their coefficients are presented in Eq. (5) below.

\[
\Delta \sigma_{sn} = 5187.28 N^{-0.344}, R^2 = 0.9999 \quad (5a)
\]

\[
\Delta \sigma_{sn} = 4018.77 N^{-0.266}, R^2 = 0.9965 \quad (5b)
\]

\[
\Delta \sigma_{sn} = 5684.82 N^{-0.300}, R^2 = 0.9939 \quad (5c)
\]

It should be noted that these regression line equations above are limited to the thickness of steel plate \(t = 9\) mm, the dimension of CFRP strips \(L=450 \times 50 \times t=1.2\) mm and the position of externally-bonded CFRP strips distance ranges of \(X = -25\) mm to \(X = -75\) mm and \(X = 25\) to \(X = 75\) mm from the center. Concerning the general estimation of the equations of different specimens, properly analytical evaluation are required and followed by the confirmation from the experiment.

Regarding to the prediction of fatigue life, in non repair PWGN, good estimation is obtained either in CASE 1 or CASE
2. However, in CASE 1, although underestimation is seen in small stress ranges and overestimation in large stress ranges, in overall stress ranges of 60–120 MPa, CASE 1 shows high prediction accuracy. In repair method, except in low stress ranges of PWGP, the same trend can be seen. However, in overall result of repair method, the predicted fatigue life is underestimated. This is because the influence of residual stress was not considered. The residual stress was released due to crack propagation and although the crack opening displacement becomes larger, it was controlled by bonded CFRP strips. It should be noted that in low stress range of PWGP, the predicted fatigue life is overestimation. The loss of pre-stress is considered as the reason since the fatigue tests took long time (approximately 1 month in case of nominal stress range of 60 MPa). The loss of pre-stress might tend to be faster in dynamic behavior under fatigue test. This issue is required for further investigation.

In PWGC, regression line of CASE 1 are almost parallel to the experimental regression line. Compared to CASE 1, although in CASE 2, the underestimation is small at large nominal stress ranges, underestimation becomes large when the nominal stress ranges are small. In PWGP, with the current experimental result in which pre-stress loss is considered particularly at the small nominal stress range as mentioned above, any conclusions on CASE 1 and CASE 2 will be our future work. The evaluation of pre-stress loss also needed to be investigated.

Finally, regarding to the experimental prolongation fatigue lives detailed in Table 7, the result shows that the prolongation of fatigue lives of the repair method PWGP and PWGC is 6.5–8.9 times and 3.5–5.5 times compared to the non repair PWGN, respectively, and the repair PWGP is 1.6–1.9 times greater than repair PWGC under the applied nominal stress ranges of 60–120 MPa.

5. CONCLUSIONS

In conclusion, the findings in this paper are summarized as follows:

(1) The compressive pre-stress can be properly installed into the initial cracked steel plate of out-of-plane welded gusset plates and their prolongations of fatigue lives can be evaluated.

(2) The experimental prolongation of fatigue lives of repair method by pre-tensioned and non pre-tensioned CFRP strips is 6.5–8.9 times and 3.5–5.5 times, respectively, compared to the non repair under the nominal stress range of 60–120 MPa.

(3) Underestimation result is found in the prediction of fatigue life of repair method by non pre-stress PWGC and in large nominal stress ranges of repair method by pre-stress PWGP. Overestimation is seen in fatigue life prediction of repair method by pre-stress PWGP in small nominal stress ranges. The underestimation is considered to be resulted from the control of the release of residual stress by externally-bonded CFRP strips. The overestimation is considered due to the pre-stress loss since the experiment under dynamic behavior took long period of time.

(4) In overall view, the original material coefficients (CASE 1) give a better fatigue life prediction than that of CASE 2 (JSSC design recommendation).

(5) In analytical evaluation, the consideration of residual stress set into weld toe of the specimen model is required for further study. The amount of pre-stress loss under dynamic behavior also needed to be confirmed.

Finally, concerning the improvement on practical application in construction work of discussed pre-tensioning technique, further process are required to be examined in details. Particularly, the fixing method of the devices during the adhesion of CFRP strips on repaired structures, the curing method in unstable condition outside the room, and long-term pre-stress control method are subjected to be discussed.

References

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