Fatigue Test on Out-of-Plane Gusset Welded Joints Strengthened with Carbon Fiber Reinforced Polymer Materials

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ABSTRACT

This paper reports an experimental study on out-of-plane gusset welded joints strengthened with carbon fiber reinforced polymer (CFRP) sheets or plates. Weld toe radius and flank angle were measured with silicon based impression materials before fatigue tension test. Constant amplitude fatigue loadings were applied to 8 specimens with CFRP sheets, 8 specimens with CFRP plates and 5 specimens without reinforcement as the control group. Their fatigue lives and failure modes were observed. All cracks initiated from weld toes on the base plate that are adjacent to longitudinal plate ends. Fatigue lives of all the specimens, which were plotted in S-N graphs, were above the fatigue design F-class curve recommended for steel structures (Japanese Society of Steel Construction). Fatigue life was extended to some extent although scatters were observed in the test results of strengthened specimens. Possible explanations are discussed in the paper and future work is pointed out.

KEYWORD

fatigue test, carbon fibre reinforced polymer, strengthening, out-of-plane gusset welded joint
1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) materials have been successfully employed in patching metallic structures in aerospace and automotive industries [1]. However, limited work has been conducted on steel structures in civil engineering. Fatigue cracks are often attributed to the cracks emanating from welded joints, which are assumed as weak parts for steel structures [2]. Repair of welded metallic structure is essential to prolong their fatigue life. The conventional method of repairing or strengthening metallic structures is to cut and replace damaged portions, or to attach external steel plates. These plates are usually bulky, heavy, difficult to fix and prone to corrosion or fatigue. Use of CFRP materials in civil engineering is relatively new for steel structures.

Previous research indicated that CFRP retrofitting to steel structures can decrease stress concentration factor at crack initiation site or stress intensity factor at fatigue crack tip, thereby reducing crack growth rate and extending fatigue lives of damaged steel members [3] [4] [5]. Recent state-of-the-art studies [6] have comprehensively summarized the research on using fiber reinforced polymer (FRP) for strengthening steel structures. However, most of the previous investigations are focused on steel members and discussions on welded joints are limited. Artificial defects, such as central cracks or edge cracks, were adopted to investigate crack initiation and propagations in steel plates [7][8][9]. These specimens, however, are different from welded joint in real application. Nakamura et al. [10] presented experimental study on repair methods of fatigue cracks initiated at welded web gusset joints using CFRP strips. Several repair systems were investigated experimentally focusing on weld details. It was found that fatigue life after repair was significantly improved. Xiao et al. [11] demonstrated that CFRP can significantly increase the fatigue life of damaged cross-beam joints. Suzuki [12] conducted fatigue test on out-of-plane gusset welded joint specimen strengthened by glass fiber reinforced polymer materials. In addition, finite element method and fracture mechanics were employed to the stress and crack propagation analyses. The studies revealed that bonded patch can decrease the stress level and enhance the fatigue life, even by an order of magnitude. Fatigue test of welded joints strengthening with CFRP is still necessary to get a further understanding of the strengthening.

This paper presents three groups of fatigue test of out-of-plane gusset welded joints strengthened with CFRP materials under different stress ranges. Failure modes and corresponding fatigue lives were recorded. Scatter results were observed for strengthened or un-strengthened specimens. It was found that more fatigue tests are needed to demonstrate the improved the fatigue performance of such welded joints.

2. SPECIMEN DESIGN

2.1 Configuration of the Test Specimens

The out-of-plane gusset welded joints specimen consists of a main plate (700mm×80mm) and two gusset plates (100mm×80mm), as shown in Fig. 1a. Strengthened specimen was illustrated in Fig. 1b.

![Specimen without CFRP](image)

![Specimen strengthened with CFRP](image)

Fig. 1 Geometry configurations of out-of-plane gusset welded joint

2.2 Materials

Mild carbon steel (Q345) conforming to Chinese Standard GB 50017-2003 in the form of rolled plates of 8mm thickness was used as the base material throughout the investigation. The mechanical properties and chemical composition of the steel are presented in Tables 1 and 2,
respectively. Retrofitting material were CFRP sheet, CFRP plate and the corresponding adhesives. Their property details are listed in Table 3 and Table 4.

### Table 1 Mechanical property of steel

<table>
<thead>
<tr>
<th>Type</th>
<th>Yield stress (N/mm²)</th>
<th>Ultimate strength (N/mm²)</th>
<th>Elongation (%)</th>
<th>Young’s Modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q345</td>
<td>273.17</td>
<td>437.18</td>
<td>36.5%</td>
<td>2.27×10⁵</td>
</tr>
</tbody>
</table>

### Table 2 Chemical compositions of steel (%)

<table>
<thead>
<tr>
<th>Type</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q345</td>
<td>0.13</td>
<td>0.17</td>
<td>0.47</td>
<td>0.020</td>
<td>0.037</td>
</tr>
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</table>

### Table 3 Mechanical properties of CFRP sheet and adhesive

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness (mm)</th>
<th>Tensile strength (N/mm²)</th>
<th>Elastic modulus (N/mm²)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC2-2</td>
<td>0.167</td>
<td>4180</td>
<td>2.50×10⁵</td>
<td>1.7</td>
</tr>
<tr>
<td>TJ</td>
<td>-</td>
<td>≥40</td>
<td>≥2500</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Table 4 Mechanical properties of CFRP plate and adhesive

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness (mm)</th>
<th>Tensile strength (N/mm²)</th>
<th>Elastic modulus (N/mm²)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC3-1.2-50</td>
<td>1.2</td>
<td>2516</td>
<td>1.66×10⁵</td>
<td>1.7</td>
</tr>
<tr>
<td>TGJ-P</td>
<td>-</td>
<td>71</td>
<td>2651</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### 2.3 As-welded Specimens

The base metal and the two gusset plates were fabricated using CO₂ gas shield fillet welding and kept in the as-welded condition. In order to improve the welding quality and reduce the residual stress, the sequence welding (from Step 1 to Step 3) was adopted as shown in Fig. 2.

### 2.4 Strengthened Specimens

Middle part of specimens were ground with sand paper and cleaned by acetone. Thereafter, three CFRP sheet layers, 300 mm × 30 mm each, were glued using wet lay-up method. The surfaces were finally finished using polymer adhesive and left to cure in room temperature. One layer of CFRP plate, 300 mm × 25 mm each, was also glued to each side of the steel plate (as shown in Fig. 3).

2.5 Weld Toe Geometry

Weld toe geometry, which consists of weld toe radius and flank angle, has been confirmed to be key parameters influencing the stress concentration factor for the joints. They were obtained by silicon imprint technique prior to the fatigue tests. Statistical results were graphed in Fig. 4. It can be observed that the weld toe radius ranges from 0.22-5.27mm with an average toe radius of 2.06mm and the flank angle ranges from 20°-69° with an average angle of 38.65°.

3. FATIGUE TESTS AND RESULTS

3.1 Test Procedure

Specimens were loaded in uniaxial tension-tension cyclic loading at room temperature and moisture in the material laboratory (Fig. 5). For specimens
strengthened with CFRP sheets, an Instron1343 servo hydraulic testing machine with hydraulic controlled grips was used for conducting all of the fatigue tests of the steel specimens. A constant amplitude sine wave of 10 Hz frequency was applied and the stress ratio \( R (=\frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}) \) for all axial tension loading levels was kept constant at 0.1. The test stopped once the displacement of the specimen reached 80 mm after crack appearance. MTS fatigue machine was employed for specimens strengthened with CFRP plates. A constant amplitude sine wave of 6 Hz frequency was applied with a load ratio \( R \) of 0.1. A total of 8 specimens with CFRP sheets, 8 specimens with CFRP plates and 5 specimens without reinforcement were tested.

3.2 Test Result

The specimens were tested with four stress ranges, which were 216, 180, 153 and 120MPa, respectively. Corresponding numbers of specimens were 6, 7, 6 and 2. From the observation of fatigue tests, all specimens fractured from weld toe. Cracks initiated from the intersection of the base plate and attachments, and then propagated along the transverse directions of base plate. This matches with the expectation due to the stress concentration near the end of the gusset plate. Finally, specimens were pulled to fracture with bond failure between the CFRP materials and the steel plates (Fig. 6).

Total fatigue lives of the 21 specimens were plotted in Fig. 7. The F-class line (for out-of-plane gusset welded joint) specified in JSSC (Japanese Society of Steel Construction) was also plotted in the figure. All the test data points are above F-class line.

Scatters were observed by comparing fatigue lives of specimens with or without strengthening. Fig. 7 demonstrated some improvement in fatigue life due to CFRP strengthening. The scatter may be caused by severe scatter in weld toe radius and flank angle as shown in Fig. 4. In order to clearly demonstrate the improvement in fatigue life some
measures are needed to reduce the scatter in weld toe radius and flank angles. For example post weld treatment could be utilized to ensure all the specimens have similar weld toe radius and flank angles.

(a) CFRP sheet strengthened specimen

(b) CFRP plate strengthened specimen

(c) Fracture section

Fig. 6 Fatigue failure mode

Fig. 7 Fatigue test results

4. CONCLUSIONS

In this study, fatigue life of CFRP materials strengthening out-of-plane gusset welded joints was investigated experimentally. Large scatter was found for weld toe radius and flank angles in as welded joints. Consistent failure mode was observed as fracture near the end of the gusset plate due to the stress concentration at that location. Limited test results showed some promising sign of improved fatigue life due to CFRP strengthening of such welded joints. However more tests are needed in the future to derive more consistent results by controlling the weld toe radius and flank angles of the specimens.

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