Boundary Element Analysis of Fatigue Crack Growth for CFRP-Strengthened Steel Plates with Longitudinal Weld Attachments

Qian-Qian Yu1; Tao Chen2; Xiang-Lin Gu3; Xiao-Ling Zhao, F.ASCE4; and Zhi-Gang Xiao5

Abstract: In this paper, steel plates with longitudinal weld attachments strengthened by carbon fiber reinforced polymer (CFRP) laminates on one side were analyzed based on the boundary element method and compared with test data from the literature. Good agreement with the data indicated that the numerical analysis was reliable for estimation of the fatigue crack propagation of CFRP-bonded steel plates with longitudinal weld attachments. The effects of double-sided strengthening, double-sided weld attachment and CFRP stiffness on the fatigue behavior of retrofitted welded joints were also investigated. The results showed that double-sided strengthening was much more efficient than single-sided application. It was observed that the crack propagation of steel plates with weld attachments on both sides was accelerated compared with those with attachments on only one side. In comparison with steel plates without a weld attachment, the retrofitting efficiency, in terms of the fatigue life extension ratio, was significantly lowered in welded plates with single-sided repair, whereas only a slight difference was observed in those with double-sided strengthening. The effect of an increased modulus of the composite materials could result in better fatigue performance, especially with double-sided application. DOI: 10.1061/(ASCE)CC.1943-5614.0000505. © 2014 American Society of Civil Engineers.

Author keywords: Boundary element method; Carbon fiber; Reinforced polymer (CFRP) laminate; Crack propagation; Fatigue; Welded joint.

Introduction

Steel structures are susceptible to fatigue damage. Fatigue cracks may emanate and propagate in areas of stress concentration under cyclic loading of traffic volume. Structural investigation reports have revealed that fatigue fracture is one of the most common causes of significant failure behavior for steel structures (Fisher et al. 2001; Xiao et al. 2006).

Structural retrofitting provides an economical and environmentally friendly way to improve the load carrying capacity or extend the service life of structurally deficient members. Recently, the bond repair technique using carbon fiber reinforced polymer (CFRP) materials has been considered as an innovative way to handle fatigue crack repair of steel structures, avoiding the drawbacks of standard strengthening techniques, such as drilling a hole at a crack front or attaching steel plates to damaged elements.

Extensive research on the fatigue behavior of CFRP-strengthened steel plates has been conducted to investigate the strengthening efficiency of CFRP, and results have shown that composite materials have great potential in retarding crack propagation and extending fatigue lives of cracked steel plates (Colombi et al. 2003; Jones and Civjan 2003; Zhao et al. 2007; Täljsten et al. 2009; Liu et al. 2009a; Ye et al. 2010; Wu et al. 2012; Yu et al. 2013). However, studies on welded joints strengthened by composite materials have been reported less frequently (Fam et al. 2006; Nadauld and Pantevides 2007; Nakamura et al. 2009; Xiao and Zhao 2012; Xiao et al. 2012; Chen et al. 2012a, b; Wu et al. 2013).

Fam et al. (2006) proposed a series of fatigue experiments on aluminum truss joints wrapped with fiber-reinforced polymer (FRP) materials. A 90% loss of weld was simulated by grinding the weld perimeter at the intersection between the diagonals and the main chord. The test results showed that it was possible to restore the full strength of the welded joints with CFRP sheets, although the effectiveness was comparatively weak when using glass fiber reinforced polymer (GFRP) layers. Nadauld and Pantevides (2007) conducted similar research on aluminum overhead sign structures strengthened with GFRP materials.

Thin-walled cross-beam connections repaired by CFRP sheets were tested under in-plane fatigue loading by Xiao and Zhao (2012) and Xiao et al. (2012). Circumferential or transverse restraining CFRP patches were successfully applied in the corner region to prevent early debonding and led to marked increases in fatigue lives.

Chen et al. (2012a) presented an experimental and numerical study on the fatigue behavior of strengthened non-load carrying cruciform welded joints. Increased fatigue life was observed based on limited experimental results and finite element simulations. The parametric analysis revealed that the weld toe radius and the number of CFRP layers had pronounced effects on the strengthening efficiency.

Nakamura et al. (2009) investigated the fatigue behavior of CFRP retrofitted steel plates with longitudinal weld attachments.
They studied CFRP application in combination with drill-holes and included the effect of repair on the bonded strength and fatigue performance. It was found that fatigue life after repair was significantly improved.

Chen et al. (2012b) tested 21 out-of-plane gusset welded joints under tensile fatigue loading, and the results showed that the fatigue life was prolonged to some extent after retrofitted with CFRP materials. Wu et al. (2013) carried out a series of fatigue tension tests on steel plates with longitudinal weld attachments with a primary emphasis on the application of ultra-high modulus CFRP laminates (460 GPa). Test results showed that the fatigue life of the welded joints bonded by ultra-high modulus CFRP laminates on a single side could be increased up to 141% of that of unstrengthened ones.

To the best knowledge of the authors, there have been limited attempts to perform a crack propagation analysis using numerical simulation on steel plates with longitudinal weld attachments strengthened with composite materials. The boundary element method was employed in this paper to study the fatigue crack propagation of steel plates with longitudinal weld attachments strengthened with CFRP laminates. The fatigue life was calculated with the NASGRO law and compared with test data reported by Wu et al. (2013). It was demonstrated that the boundary element method could accurately estimate the fatigue behavior of CFRP-bonded steel plates with longitudinal weld attachments.

The effects of the strengthening configuration, weld attachment, and composite modulus on the fatigue life were then further examined. This study extends the understanding of CFRP-repaired steel plates with longitudinal weld attachments and provides some useful suggestions for the strengthening method.

Experimental Study from the Literature

Specimen Geometry and Materials

Wu et al. (2013) conducted fatigue tests on steel plates with longitudinal weld attachments strengthened with ultra-high modulus CFRP laminates. The specimens were made of a base plate with a longitudinal attachment fillet welded on one side. To exclude the scatter effect of the weld attributable to various initial defects, such as bubbles and slags, a crack starter was positioned at the end of the weld attachment, which was also located at the center of the steel plate. The initial notch consisted of a 5 mm hole and two initial cracks that were 1 mm long and 0.3 mm wide at the center. The detailed geometry of the specimen and dimensions are given in Fig. 1.

Ultra-high modulus CFRP laminates were positioned by structural adhesive on either side of the steel plate. The material properties of the steel plates, adhesive, and CFRP laminates are listed in Table 1 (Wu et al. 2013).

Specimen Configuration

Five retrofitting configurations, as illustrated in Fig. 2, were adopted to investigate the effects of the bond length, bond width, and bond location on the strengthening efficiency. Configurations a, b, and c indicate the specimens strengthened with CFRP laminates with the areas enclosed by ‘a1 − a2 − a3 − a4’, ‘b1 − b2 − b3 − b4’ and ‘c1 − c2 − c3 − c4’, respectively. The geometries were designed to study the effects of the bond’s width and length. Configurations d and e had the same bond width and length as configuration b, but different application positions were used to investigate the effect of the CFRP bond location on the fatigue performance of the welded joints. The CFRP laminate was split into halves and placed at the edge of the plate and near the weld.

A total of eight different specimen types, as listed in Table 2, were designed in the test program. Referring to the specimen nomenclature, F indicates that the composite material was attached on the flat side of the specimen without the weld attachment, whereas W refers to the specimens with CFRP laminates bonded on the weld side. The bond’s length and width are defined as the length and width of the attached CFRP laminate. Five cases (configurations a-e) were repaired on the flat side, whereas only two cases (configurations d and e) were repaired on the weld side resulting from the geometric limitations.

Fatigue Loading

All the specimens were loaded under tensile cyclic loading, which ranged from 13.5 to 135 kN with a frequency of 10 Hz and a stress ratio R (minimum load/maximum load) of 0.1. The crack propagation with fatigue cycles was monitored using the beach marking technique (Wu et al. 2013).

Fatigue Crack Propagation Prediction with BEM

BEASY, a commercial software package, was employed in this study to analyze crack propagation and predict fatigue life using the dual boundary element method technique. Three-dimensional boundary element models were built based on the configurations of the test specimens. Only half of the welded joint was adopted because of the symmetric model geometry and boundary conditions. The welding was excluded during the modeling process for the following reasons: (1) the weld size was not recorded during the test program; (2) the measured weld size of the remaining specimens appeared scattered; and (3) the literature review indicated that cracks usually initiate from the weld toe at the end of the weld.

Fig. 1. Geometric configurations of welded joints (unit: mm, not to scale)
attachment in this type of welded joints with attachments welded all around to the base plates (Nakamura et al. 2009; Chen et al. 2012b). In this test, the fillet weld was not applied along the thickness direction of the weld attachment: only two longitudinal fillet welds were applied, as shown in Fig. 1. An artificial defect was introduced to initiate the fatigue crack and guide the propagation through the weld.

In test specimens F-e and W-e, the CFRP laminates were attached beside the welding in the test program and were, therefore, assumed to be positioned 6 mm away from the attachment in the boundary element model. The surfaces of the steel plates and the CFRP laminates were modeled using quadrilateral-shaped, reduced quadratic order elements. An experimental study at Monash University (Liu et al. 2010) showed that the fatigue loading has very limited influence on the bond strength between steel and CFRP. Based on the findings in Liu et al. (2010), the influence of the debonding could be ignored for the level of loading and the number of fatigue cycles applied in the current program. Fernando et al. (2009) revealed that the uniaxial tensile stress-strain behavior of Araldite 420 adhesive has a nonlinear part after the linear elastic stage. However, the materials in this work (steel, CFRP, and adhesives) were all considered under the linear elastic stage for the fatigue loading applied in the current program. The nonlinear part of the material behavior was not relevant. The Araldite 420 adhesive was, therefore, modeled as a linear spring element, as shown in Fig. 3. The spring stiffness values, defined in terms of normal and

<p>| Table 1. Material Properties of Steel, CFRP, and Adhesive |
|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Material property</th>
<th>Steel (MPa)</th>
<th>Araldite 420 (MPa)</th>
<th>CFRP laminate (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>345.7</td>
<td>28.6</td>
<td>1,602.4</td>
</tr>
<tr>
<td>Yield strength</td>
<td>223.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>191.8</td>
<td>1.9</td>
<td>477.5</td>
</tr>
<tr>
<td>Laminate thickness (mm)</td>
<td>10</td>
<td>—</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Table 2. Reference Test Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bond region</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Repair side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare plate</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>F-a</td>
<td>$a_1 - a_2 - a_3 - a_4$</td>
<td>250</td>
<td>90</td>
<td>Flat side</td>
</tr>
<tr>
<td>F-b</td>
<td>$b_1 - b_2 - b_3 - b_4$</td>
<td>250</td>
<td>50</td>
<td>Flat side</td>
</tr>
<tr>
<td>F-c</td>
<td>$c_1 - c_2 - c_3 - c_4$</td>
<td>100</td>
<td>50</td>
<td>Flat side</td>
</tr>
<tr>
<td>F-d</td>
<td>$d_1, d_4$</td>
<td>250</td>
<td>$25 \times 2$</td>
<td>Flat side</td>
</tr>
<tr>
<td>F-e</td>
<td>$e_1, e_4$</td>
<td>250</td>
<td>$25 \times 2$</td>
<td>Weld side</td>
</tr>
<tr>
<td>W-d</td>
<td>$d_1, d_2$</td>
<td>250</td>
<td>$25 \times 2$</td>
<td>Weld side</td>
</tr>
<tr>
<td>W-e</td>
<td>$e_1, e_2$</td>
<td>250</td>
<td>$25 \times 2$</td>
<td>Weld side</td>
</tr>
</tbody>
</table>

The shear spring stiffness $K_t$ and $K_u$ and axial spring stiffness $K_n$ could be evaluated with Eqs. (1) and (2), respectively

\[
K_t = K_u = \frac{G_a}{t_a} \quad (1)
\]

\[
K_n = \frac{E_a}{t_a} \quad (2)
\]

\[
G_a = \frac{E_a}{2(1 + \nu)} \quad (3)
\]

where $G_a$ and $E_a$ represent the shear modulus and Young’s modulus of the adhesive, respectively; $t_a$ is the measured adhesive thickness of the test specimen; and $\nu$ is Poisson’s ratio of the adhesive.

A relatively fine mesh was adopted in the area around the center hole in consideration of high stress concentration. The element size was less than one fourth of that in areas far away from the center. The models were split into zones numbered from nine to 16, because of the aspect ratio limitation and computational efficiency. A uniform tensile loading of 135 MPa was applied on each end surface, and weak springs were used over the middle elements to provide a rigid body restraint for this BEASY problem. A typical boundary element model (W-d) is presented in Fig. 4.

An edge through crack was embedded to simulate the initial slot along the center hole in BEASY’s Crack Growth Wizard. In this study, the stress intensity factor was determined with the J-integral approach, and the crack propagation life was integrated using the NASGRO 3 law expressed by Eq. (4)

\[
\frac{da}{dN} = C : (1 - f)^n : \Delta K^n : (1 - \frac{\Delta K_{th}}{\Delta K})^p \quad (4)
\]

where $N =$ number of applied fatigue cycles; $a =$ crack length; $R =$ stress ratio; $\Delta K =$ stress intensity factor range; $C$, $n$, $p$ and $q =$ empirically derived constants that are contained in the NASGRO fatigue database; $f =$ crack opening function; $\Delta K_{th} =$ threshold stress intensity factor range; and $K_c =$ critical stress intensity factor.

In this work, the material constants $C$ and $n$ were taken as $6.77 \times 10^{-13}$ and $2.88$ (da/dN in mm/cycle and $\Delta K$ in MPa$\cdot$mm$^{1/2}$), as recommended by the British Standards Institution (BSI 2005; Mashiri et al. 2000; Chen et al. 2013). Exponents $p$ and $q$ both had values equal to 0.5; and, values of 148.6 MPa$\cdot$mm$^{1/2}$ and 6,950 MPa$\cdot$mm$^{1/2}$ were adopted for $\Delta K_{th}$ and $K_c$, respectively, as given in the BEASY database file.

**Results and Comparison**

**Comparison of Fatigue Life**

Table 3 presents a summary of the fatigue test date and the predicted results. The thickness of the adhesive layer was used to calculate the spring stiffness in the fatigue analysis. The data of specimens W-d-1, W-d-2, W-e-1, and W-e-2 were not recorded in the test program and were, therefore, assumed to be 0.5 mm. A dual specimen was designed in the test program for each strengthening configuration considering the scattering nature of

![Fig. 3. Illustration of internal spring boundary condition](image)

![Fig. 4. Typical boundary element model for specimen W-d](image)
fatigue experiments, whereas the numerical simulation analyzed only one model for each strengthening configuration based on the average thickness of the bond layer, which were then compared with the average fatigue life of the test specimens.

Table 3 shows that the ratio of the predicted fatigue cycles to the tested fatigue life ranged between 1.01 and 1.14; and, the mean value and the coefficient of variation were calculated as 1.08 and 0.045, respectively. The numerical fatigue lives were within 14% of their experimental results, indicating that the boundary element method could be used to estimate the fatigue life of CFRP-repaired steel plates with longitudinal weld attachments with reasonable accuracy. The boundary element analysis slightly overestimated the fatigue behavior of the specimens, which can be attributed to the negative effect introduced by the weld.

### Comparison of Fatigue Crack Propagation

The analytical results showed that the fatigue crack propagation was symmetric with the plate width but uneven throughout the plate thickness. For unstrengthened specimens and those with composite materials attached on the flat side, the cracks propagated faster on the weld side than on the flat side. For those specimens retrofitted on the weld side, the crack growth on the flat side appeared to spread relatively quickly.

Fig. 5 presents the crack length variation from one side to the other of specimens F-d and W-d. The coordinates chosen were the half crack length ‘a’ measured from the center of the specimen and the fatigue cycle numbers. This phenomenon is primarily associated with the stress concentration attributable to the weld attachment, the shift of the neutral axis caused by the overlay patch, and the constraint effect of the composite materials on the crack opening displacement. As the crack grew, the difference in the crack front between the weld and flat sides occurred gradually; and, the numerical analysis terminated when the maximum growth distance was more than 50 times the minimum growth distance, owing to limitations of the used software. It is believed that at that time, the crack propagation was quite fast, and the corresponding number of fatigue cycles was negligible.

The rough trend of the crack shapes of different specimens was observed to be consistent with the test results (Wu et al. 2013). Because only the crack size on the flat side was recorded during the test program, the crack propagation with fatigue cycles of the numerical results on the flat side is displayed and compared with the test data in Fig. 6.

Fig. 6(a) demonstrates that the numerical model could predict the crack propagation of unstrengthened welded joint accurately. The final crack length was overestimated because of the stopping criteria in the numerical simulation. The analysis ended when the stress intensity factor exceeded the fracture toughness (K_c) value given in the fatigue properties. In the test program, the residual cross section of the steel plate at the late stage of crack propagation could not carry the maximum load applied in each cycle; therefore, the specimen ruptured suddenly. The curve at the late stage appeared to be vertical, which also indicates that the crack propagated very quickly at the final stage of crack propagation, and that the corresponding fatigue cycles were negligible.

For the specimens strengthened with composite materials, the simulated crack propagation of the strengthened plates agreed well with the experimental results, particularly in the early stage of fatigue life. The differences primarily occurred at the late stage of crack propagation, when a distinct turning point appeared in the test curve.

It should be noted the beach marking technique was utilized in this study to capture the fatigue crack growth. The disadvantage of this method is the difficulty in capturing many points towards the end of the fatigue life when the fatigue crack growth rate quickly increases. This is most likely the reason for the discrepancy between the measured and predicted values. More research is needed to explore other means to capture sufficient points on the fatigue crack growth curve, such as the use of fatigue crack propagation gauges (Yu et al. 2014a).

**Table 3. Comparison between Predicted Results and Test Data**

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Bond thickness (mm)</th>
<th>Tested fatigue cycles</th>
<th>Averaged fatigue cycles (N_e)</th>
<th>Predicted fatigue cycles (N_p)</th>
<th>N_p/N_e</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>—</td>
<td>270.970</td>
<td>275.701</td>
<td>287.532</td>
<td>1.04</td>
<td>0.045</td>
</tr>
<tr>
<td>B2</td>
<td>—</td>
<td>266.820</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>—</td>
<td>289.312</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-a-1</td>
<td>0.49</td>
<td>320.252</td>
<td>337.219</td>
<td>346.116</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>F-a-2</td>
<td>0.37</td>
<td>354.186</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-b-1</td>
<td>1.16</td>
<td>313.333</td>
<td>299.040</td>
<td>340.434</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>F-b-2</td>
<td>0.31</td>
<td>284.746</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-c-1</td>
<td>0.31</td>
<td>303.365</td>
<td>282.933</td>
<td>320.838</td>
<td>1.13</td>
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<tr>
<td>F-c-2</td>
<td>0.43</td>
<td>262.500</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>F-d-1</td>
<td>0.37</td>
<td>336.101</td>
<td>306.048</td>
<td>338.543</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>F-d-2</td>
<td>0.44</td>
<td>275.995</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-e-1</td>
<td>0.46</td>
<td>363.221</td>
<td>337.811</td>
<td>342.599</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>F-e-2</td>
<td>0.34</td>
<td>312.401</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-d-1</td>
<td>0.50^a</td>
<td>386.025</td>
<td>372.291</td>
<td>399.349</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>W-d-2</td>
<td>0.50^a</td>
<td>358.557</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-e-1</td>
<td>0.50^a</td>
<td>388.938</td>
<td>372.854</td>
<td>409.854</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>W-e-2</td>
<td>0.50^a</td>
<td>356.770</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
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<td>1.08</td>
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<tr>
<td>Coefficient of variation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.045</td>
</tr>
</tbody>
</table>

^a Assumed adhesive thickness.

![Fig. 5. Comparison of crack propagation between weld side and flat side: (a) specimen F-d; (b) specimen W-d](image-url)
Fig. 6. Comparison of $N - a$ curves between BEASY results and test data: (a) bare plate; (b) specimen F-a; (c) specimen F-b; (d) specimen F-c; (e) specimen F-d; (f) specimen F-e; (g) specimen W-d; (h) specimen W-e
This study also revealed that the simulated final crack lengths of specimens F-a, F-b and F-c were comparatively small, because the CFRP laminate was applied on the flat side and close to the crack initiation in these three specimens. The existence of secondary bending had a considerable effect on the crack propagation and made the variation of the crack propagation from one side to the other more severe, thereby resulting in an early termination of the fatigue crack propagation analysis.

**Effect of Retrofitting Configuration**

In the test program of Wu et al. (2013), all specimens were repaired with CFRP laminates on a single side. Because the fatigue crack propagation of the strengthened steel plates with longitudinal weld attachments could be estimated with reasonable accuracy by the boundary element model, a double-sided strengthening configuration was adopted in our work to investigate the influence of the retrofitting scheme on fatigue behavior. Only configurations d and e were suitable for double-sided strengthening attributable to geometric limitations, as presented in Table 4, where D indicates that the composite materials were attached on both sides of a specimen. The bond region is shown in Fig. 2, and the thickness of the adhesive layer was set as a constant at 0.5 mm.

**Fatigue Life Analysis**

The fracture analysis was performed based on BEASY’s Fracture Analysis Wizard. Fig. 7 illustrates the relationship between the repair scheme and the improvement in fatigue life. In this figure, $N_{p, CFRP}$ is the fatigue crack propagation life of a specimen strengthened with CFRP, whereas $N_{p, plate}$ is the fatigue crack propagation life of a bare steel specimen. The specimens strengthened with configuration e always performed better than those strengthened with configuration d, which was consistent with the test results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bond region</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Repair side</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-d</td>
<td>$d_1, d_2, d_3, d_4$</td>
<td>250</td>
<td>25 x 2</td>
<td>Double sides</td>
</tr>
<tr>
<td>D-e</td>
<td>$e_1, e_2, e_3, e_4$</td>
<td>250</td>
<td>25 x 2</td>
<td>Double sides</td>
</tr>
</tbody>
</table>

Fig. 7. Fatigue propagation life improvement versus repair scheme

Moreover, the effect of bond location appeared to be more evident in the double-sided repair cases compared with that in single-sided retrofitted specimens. Therefore, it is concluded that it is better to position the composite materials as close to the crack initiation as possible, particularly for double-sided strengthened specimens.

It should be noted that single-sided strengthening, especially when applied on the flat side, only led to very limited improvement; however, a considerable extension of the fatigue life was achieved with double-sided strengthening. The fatigue life of the configuration d bonded specimen was extended by 3.2 times through double-sided repair, whereas the single-sided repair on the flat side only prolonged the fatigue life by 1.2 times.

Specimen F-a results lead to the conclusion that, when narrow CFRP strips are applied on both sides far away from the initial slot, the strengthening effect is much more pronounced compared with that of a specimen where the whole surface of the flat side is covered.

Wu et al. (2013) also conducted a series of fatigue tests on nonwelded steel plates strengthened by ultra-high modulus CFRP laminates on a single side to compare the fatigue life extension ratios of both welded and nonwelded specimens. The geometry and dimensions of the steel plates (without a weld attachment), fatigue loading, and test setup were all the same as those of the welded connections.

The fatigue crack propagation processes of nonwelded steel plates were correspondingly analyzed using the boundary element method, which is similar to the fatigue life prediction reported in Yu et al. (2014b), where more details can be obtained. The calculated fatigue life extension ratios of specimens with configurations d and e are compared in Fig. 8, which indicates that the fatigue life extension ratio of a single-sided strengthened welded specimen was significantly lower than that of a nonwelded specimen with the same strengthening configuration. However, the difference was considerably less between welded and nonwelded specimens using the double-sided strengthening system.

Taking repaired configuration e specimens as an example, the fatigue extension ratio of the single-sided strengthened welded plate (F-e) was lowered by 121% of that of the nonwelded specimen with the same strengthening configuration. However, for the double-sided strengthened cases, the difference between the welded and nonwelded specimens was only 38%. It is also worth noting...
that the extension ratios of the welded joints were always less than those of the nonwelded plates. This may be attributed to the negative effect of the attached gusset plate. Further studies are required to determine the effect of the gusset plate.

**Fatigue Crack Propagation Analysis**

Fig. 9 shows the beach marks on the fracture surfaces extracted from the numerical data of configuration d strengthened specimens. Only half of the cross section is displayed, because of the symmetry with the width direction. The horizontal axis represents the plate width from the center to the edge, and the vertical axis represents the plate thickness. The first vertical line indicates the artificial slot.

The general trend of the crack propagation was found to be consistent with the beach marks recorded during the test program. In the plain welded plate without strengthening, the crack on the weld side propagated slightly faster than on the flat side because of the stress concentration resulted from the weld attachment. After retrofitting the flat side, the difference in crack propagation between the weld and flat sides appeared much more considerable, as shown in Fig. 9(b). The application of the CFRP laminate moved the neutral axis of the specimen, thus accelerating the crack growth on the weld side.

Moreover, the composite materials supplied a bridge effect on the crack surface, which restrained the crack propagation of the flat side. Although the attached composite materials helped to share the far field loading, the positive effect was partly counteracted by the existence of secondary bending. This also explains why only very limited improvement was achieved by attaching the CFRP laminate on the flat side. However, specimen W-d with overlay on the weld side appeared to have the crack on the flat side propagate faster than the crack on the weld side. It should be noted that the crack fronts on both sides in specimen D-d were more likely to grow synchronously, and very little difference was observed at the early stage. The arrest phenomenon was attributed to the constraint effect of the CFRP laminates.

Fig. 10 compares crack lengths on both the flat and weld sides of specimens with different repair schemes versus the fatigue cycles. This figure indicates that crack propagation on both the flat and weld sides was significantly slowed for the double-sided strengthened specimen in comparison with that of the single-sided repair. Therefore, this study recommends the adoption of double-sided strengthening whenever possible.

This study’s conclusion on the superiority of double-sided strengthening does not agree with the results of Chen et al. (2014). Their examination of nonload carrying welded joints showed
single-sided repairs on cracked surfaces to be more effective than double-sided retrofitting. This may be attributed to different crack types and crack propagation directions.

**Effect of Longitudinal Weld Attachment**

In comparison with nonwelded steel plates, the weld attachment in a single-sided welded joint resulted in stress concentration on the weld side, thus leading to unsymmetrical crack shapes. To further examine the effect of weld attachments, steel plates with longitudinal welded attachments on both sides were analyzed, and the details are listed in Table 5. Similar to the cases with double-sided repairs, only configurations d and e were considered because of geometric limitations. Considering the symmetry of the specimen with attachments on both sides, S was used to indicate that the composite material was attached on a single side of the specimen. The bond region is shown in Fig. 11.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bond region</th>
<th>Bond length (mm)</th>
<th>Bond width (mm)</th>
<th>Repair side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare plate (double-side welded)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>S-d (double-side welded)</td>
<td>d₁, d₂</td>
<td>250</td>
<td>25 × 2</td>
<td>Single side</td>
</tr>
<tr>
<td>S-e (double-side welded)</td>
<td>e₁, e₂</td>
<td>250</td>
<td>25 × 2</td>
<td>Single side</td>
</tr>
<tr>
<td>D-d (double-side welded)</td>
<td>d₁, d₂, d₃, d₄</td>
<td>250</td>
<td>25 × 2</td>
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<td>e₁, e₂, e₃, e₄</td>
<td>250</td>
<td>25 × 2</td>
<td>Double sides</td>
</tr>
</tbody>
</table>

**Table 5. Double-Sided Welded Specimens**

A comparison of the fatigue life extension ratios was also conducted for double-sided welded plates. Fig. 13 shows the ratio of $N_{p-CFRP}$ to $N_{p-plate}$ against the repair scheme. The general trend of

**Fatigue Life Analysis**

The fatigue cycle numbers of single-sided welded specimens compared with double-sided welded specimens with different repair schemes are shown in Fig. 12. This figure shows that the double-sided welded joints resulted in shorter fatigue lives than those of single-sided welded joints.

A comparison of the fatigue life extension ratios was also conducted for double-sided welded plates. Fig. 13 shows the ratio of $N_{p-CFRP}$ to $N_{p-plate}$ against the repair scheme. The general trend of

![Fig. 12. Fatigue cycles of single- and double-sided welded specimens](image)

![Fig. 11. Configuration of double-sided welded specimens (unit: mm, not to scale): (a) configuration d; (b) configuration e](image)
the double-sided welded plates appeared consistent with the single-sided welded plates. In comparison with the nonwelded steel plate, the difference in the fatigue life extension ratios between the applications of single- and double-sided repairs was especially significant. Single-sided strengthening for double-sided welded joints had only reached a very limited strengthening effect; however, it was possible to extend their fatigue lives by 3.3 and 4.4 times with double-sided strengthening of configurations d and e, respectively. The extension ratio was approximately that of the nonwelded plate.

The slight reduction of the corresponding data for the single-sided welded plate was considered to be associated with the unsymmetrical specimen geometry.

**Fatigue Crack Propagation Analysis**

Crack propagation with fatigue cycles of specimens with single- or double-sided weld attachments is presented in Fig. 14. For simplicity, the vertical axial in Fig. 14 represents half of the crack length on the centerline of the plates. The results of the bare plate without strengthening, single-sided repair on the flat side, single-sided repair on the weld side and double-sided strengthening are illustrated. It is noted that there was only one case of a single-sided repair for specimens with double weld attachments. It is clearly shown from the figure that the crack propagation in the double-sided welded specimen was faster than that of the single-sided welded specimen, resulting in a shorter fatigue life and indicating that the existence of the additional gusset plate accelerated the crack propagation.

**Effect of CFRP Modulus**

In Wu et al. (2013), ultra-high modulus CFRP laminates with an elastic modulus of 460 GPa were utilized in the test program. Although high modulus composite materials are considered to be more effective in most applications, these materials are still not widely employed in practice. Therefore, normal modulus CFRP laminates with a modulus of 210 GPa were considered in this study to evaluate the effect of the CFRP stiffness.

Fig. 15 shows the ratio of the specimen’s fatigue life with ultra-high modulus CFRP laminate to that of the specimen with normal
modulus CFRP laminate. In this case, \( N_{p-CFRP,H} \) was the fatigue crack propagation life of a specimen strengthened with ultra-high modulus CFRP laminates, whereas \( N_{p-plate,X} \) was the fatigue crack propagation life of a specimen strengthened with normal modulus CFRP laminates. Both the single- and double-sided welded plates were discussed.

Fig. 15 shows that only limited improvement was achieved by using ultra-high modulus CFRP laminates for single-sided repair, whereas the fatigue life was extended by 174–186% for the double-sided strengthened specimens when the CFRP modulus increased from 210 to 460 GPa. It is noteworthy that the fatigue life of specimen F-a was even longer with lower modulus CFRP laminate. This is related to the fact that higher modulus CFRP laminate leads to more severe secondary bending, especially for specimen F-a, which had the largest cross section of CFRP laminate. Therefore, it is recommended that if double-sided strengthening is available, it is better to utilize high modulus CFRP laminate to improve the strengthening effect. However, for single-sided repair, the improvement of CFRP stiffness is not considered to be of great significance.

Conclusions

In this paper, the boundary element method was employed to investigate the fatigue crack propagation of steel plates with longitudinal weld attachments strengthened with CFRP laminates under tension. Three-dimensional boundary element models were established based on the configurations of the reference test specimens. The method was validated with good agreement between the numerical results and the experimental data. The influence of double-sided strengthening, double-sided weld attachment and CFRP laminate modulus on the fatigue behavior of strengthened welded joints was then examined. The following conclusions have been drawn:

- The boundary element method is well suited for simulating the fatigue behavior of CFRP-bonded steel plates with longitudinal weld attachments. The crack propagation variation from one side to the other was also revealed.
- Double-sided repair was more efficient. The single-sided welded plate with a composite patch of limited width applied far away from the initial crack on both sides performed much better than single-sided repair with the composite materials covering the whole surface of the flat side. Moreover, double-sided application was shown to effectively provide a constraint effect to the crack propagation.
- In double-sided welded joints, the additional weld attachment accelerated the crack propagation and led to a shorter fatigue life compared with the single-sided welded joints.
- In terms of the fatigue life extension ratio, the retrofitting efficiency was significantly lower in welded joints repaired on a single side compared with steel plates without a weld attachment; whereas only a slight difference was observed for double-sided repaired welded joints. Moreover, the effect of the bond location on the fatigue behavior of strengthened specimen appeared more evident in cases of double-sided strengthening.
- The modulus of the CFRP laminate had a considerable influence on the specimens with composite materials attached on both sides. For the single-sided strengthened specimens, the improvement of the fatigue behavior by using ultra-high modulus CFRP laminates was limited.
- This study extends the understanding of CFRP-repaired steel plates with longitudinal weld attachments and provides some useful suggestions for the strengthening method. More experimental study is planned for the future to validate the extended numerical analysis and investigate the negative effect of the weld.

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