Fatigue Behavior of Blast-treated Out-of-plane Gusset Fillet Welded Joints

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Abstract

Blast cleaning prior to coating has been applied in newly built steel structures for cleaning forged surface and increasing adhesive property of applied coating systems. However, the effect of surface preparations by blast cleaning treatment on fatigue behavior of welded joints is not considered in Fatigue Design Codes. In this paper, fatigue tests were carried out on four types of out-of-plane gusset fillet welded joints, as-welded gusset specimens and three types of blast-treated gusset specimens, and then the effect of the blast cleaning treatment on the fatigue behavior of the welded joints was studied. The radius of curvature at weld toe of the blast-treated specimens was larger than that of as-welded specimens. The fatigue test results showed that the fatigue life of the blast-treated specimens is longer than that of as-welded specimens in low stress ranges, even though there is no significant difference in fatigue life between the two types in high stress ranges. Over 167% increase in fatigue limit could be realized by using blast cleaning treatment.

Keywords: steel structure, fatigue, welded joint, fatigue life, blast cleaning, out-of-plane gusset joint

1. Introduction

Fatigue strength of weld joints affects durability of steel structures. The fatigue strength of welded joints is very low compared with that of base metals. The considerable difference between the unwelded components and as-welded components is the fatigue crack initiation dominated the fatigue life of unwelded components, while the fatigue crack propagation life occupies most of the fatigue life of as-welded components. The low fatigue strength of welded joints is caused by stress concentration (Sander et al., 1965) and tensile residual stress (Fisher, 1971; Ohta et al., 1981). The stress concentration and residual stress are unavoidable in welded joints and they can not be eliminated completely.

Fatigue strength improvement is one of the first considerations in design, built and maintenance of steel structures and many methods have been found out and applied in welded structures in order to increase their fatigue strength. The improvement methods for fatigue strength of welded joints mainly focus on extending the fatigue crack initiation life. These methods improve the weld geometry (improve weld profile and remove weld defects), the welding residual stress (remove tensile residual stresses and introduce compressive residual stress) or the environmental conditions of welded joints (Lihavainen et al., 1990; Haagensen, 2001; Roy et al., 2005). Some methods are also used in retarding the crack propagation in order to increase fatigue crack propagation life.

Blasting is the operation of cleaning or preparing a surface by forcibly propelling a stream of abrasive metals against it (Zimmerli, 2008). In fabrications of steel bridges, blast cleaning is performed at the prior stage of coating to remove surface contaminants and to roughen a surface for increasing adhesive property of applied coating systems. Due to the impact of the abrasive metals on a surface of welded joints, blasting is expected to improve weld geometry and introduce compressive residual stress on surface of welded joints, and eventually it may increase fatigue life of welded joints. However, the beneficial effect of blast cleaning prior to coating on fatigue life is not considered in the Fatigue Design Codes, such as AASHTO (2007), IIW (1995), and JSSC (1993).

In order to clarify the effect of blast cleaning on fatigue behavior of welded joint, fatigue tests were carried out on as-welded and blast-treated out-of-plane gusset joints in this study. The fatigue test results showed that fatigue life and fatigue limit of welded joints can be improved by the blast cleaning treatment.
2. Experimental Program

2.1. Fabrication of test specimens

The steel of main plates and gussets used are of grade SM490B with nominal yield stress of 322 MPa. The chemical composition and mechanical properties of the steels are shown in Table 1. The FCAW (flux core arc welding) process was used in joining two gussets to the main plate. All the welding starts and stops were located in the middle of the longitudinal gussets in order to avoid discontinuities at the end of gussets, where fatigue cracking usually initiates on the weld toe. The designed throat thickness of fillet weld was 6 mm. The welding and blasting conditions are shown in Table 2 and 3, respectively. Roughness after blast cleaning requires from 25 to 75 µm for steel bridge painting. The geometry and dimension of the specimens are shown in Fig. 1.

In the test, four types of out-of-plane gusset welded joints, which are as-welded specimens and three types of blast-treated specimens, were prepared. As-welded specimens (AW specimens) are out-of-plane gusset fillet welded joints without blast cleaning treatment, and blast-treated specimens (BT specimens) are blast-treated joints after the out-of-plane gusset fillet welding. According to the number of times in application of blasting, the blast-treated specimens (BT specimens) are divided into three types, specimens that are treated with blasting once (BT1 specimens), specimens treated with blasting twice (BT2 specimens), and specimens treated with blasting three-times (BT3 specimens). The method of treating with blasting once corresponds to the blast cleaning commonly used in real steel bridges. The fabrication process of the specimens is shown in Table 4.

2.2. Fatigue test procedure

Fatigue tests were carried out on seven AW specimens, eight BT1 specimens, two BT2 specimens and two BT3 specimens. Constant amplitude sinusoidal stress cycles with a frequency of 3 to 7 Hz were applied to the specimens using an electric hydraulic servo-system testing machine with a dynamic capacity of ±250 kN. Minimum stress was kept constant at 10 MPa. The data of fatigue test is listed in Table 5.

The set up of fatigue tests is shown in Fig. 2. In each fatigue test, four strain gauges were mounted on front-back surfaces and right-left sides of the main plates to check balance of the specimens.

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**Table 1. Chemical composition and mechanical properties of material**

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Chemical composition (%)</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>SM490B</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Table 2. Welding parameters**

<table>
<thead>
<tr>
<th>Welding wire shielding gas</th>
<th>Welding Current (A)</th>
<th>Arc voltage (V)</th>
<th>Welding speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCAW Dual Shield 7100 (E71T-1)</td>
<td>265</td>
<td>28</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Table 3. Blast conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Grit or ball size (mm)</th>
<th>Pressure (MPa)</th>
<th>Roughness of surface after blasting (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grit blast</td>
<td>diameter 0.7</td>
<td>0.7</td>
<td>60</td>
</tr>
</tbody>
</table>

**Figure 1. Dimensions of fatigue test specimens (mm).**
2.3. Measurement of weld toe profile

When fatigue cracks initiate and propagate from the fillet weld toes, fatigue crack initiation life is greatly affected by the weld toe profile (Mashiri et al., 2001). Flank angle and radius of weld toes are two main parameters of weld shape. The flank angle and radius of weld toe were measured on two as-welded specimens. These specimens are blast-treated by one-, two- and three-time blasting, and after each blasting treatment the flank angle and radius of weld toe were also measured. In measurement, the imprint technique was used, as shown in Fig. 3. In the first, the weld toe was molded by a silicon-compound generally used by dentists to mold teeth. The mold was then sliced into 6 pieces, each approximately 2 mm thick. The root radii were measured by about 20-fold magnification of the side view of the slices. The mean values and standard deviations of measured flank angles and radii of weld toes are shown in Table 6.

The radii of weld toe of blast-treated (BT) specimens increase in compared to that of as-welded (AW) specimens, even though the flank angle of weld toe is almost the same. According to the number of times in application of blasting, the radii of blast-treated specimens are increased in order of BT1, BT2 and BT3. These indicate that the weld profile of BT specimens is smoother than that of AW specimens. If there is a smooth transition between the main plate and the weld metal, the stress concentration will be low (Maddox, 1991). The stress concentration is depicted by the stress concentration factor and the increase in radius of weld toe will decrease the stress concentration factor ($K_t$).

\[
K_t = 0.2848 \log \frac{r}{t} + 0.6801
\]

where $r$, $L$, $h$, and $e$ are radius of weld toe, length, depth, and thickness of gusset, respectively, and $t$ is thickness of main plate.

The larger the radius of weld toe is, the lower the stress concentration results, and thus it is insusceptible to fatigue crack initiation. As shown in Table 6, stress concentration factor of BT specimens is smaller than that of AW specimens. Comparing with AW specimens, therefore, BT specimens may be show the longer fatigue crack initiation life and eventually both fatigue life, $N_f$, and fatigue endurance limit of BT specimens may be increased.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Mean radius (mm)</th>
<th>Mean flank angle (°)</th>
<th>Increment (%)</th>
<th>Stress concentration factor ($K_t$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW</td>
<td>0.54</td>
<td>133.78</td>
<td>3.58</td>
<td>2.82</td>
</tr>
<tr>
<td>BT1</td>
<td>0.62</td>
<td>133.32</td>
<td>3.15</td>
<td>2.75</td>
</tr>
<tr>
<td>BT2</td>
<td>0.65</td>
<td>133.44</td>
<td>4.10</td>
<td>2.73</td>
</tr>
<tr>
<td>BT3</td>
<td>0.70</td>
<td>132.95</td>
<td>3.39</td>
<td>2.69</td>
</tr>
</tbody>
</table>

Table 5. Fatigue test program and results

<table>
<thead>
<tr>
<th>Type No.</th>
<th>$\Delta \sigma$ (MPa)</th>
<th>Fatigue life ($10^3$ cycles)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW 1</td>
<td>70.0</td>
<td>10,000.0</td>
<td>No failure</td>
</tr>
<tr>
<td></td>
<td>237.5</td>
<td>141.8</td>
<td>Retest</td>
</tr>
<tr>
<td>AW 2</td>
<td>75.0</td>
<td>10,000.0</td>
<td>No failure</td>
</tr>
<tr>
<td>AW 3</td>
<td>81.3</td>
<td>7,641.0</td>
<td></td>
</tr>
<tr>
<td>BT1 4</td>
<td>100.0</td>
<td>1,788.5</td>
<td></td>
</tr>
<tr>
<td>BT1 5</td>
<td>124.0</td>
<td>1,121.0</td>
<td></td>
</tr>
<tr>
<td>BT1 6</td>
<td>150.0</td>
<td>543.0</td>
<td></td>
</tr>
<tr>
<td>BT1 7</td>
<td>195.0</td>
<td>188.5</td>
<td></td>
</tr>
<tr>
<td>BT2 1</td>
<td>100.0</td>
<td>10,000.0</td>
<td>No failure</td>
</tr>
<tr>
<td>BT2 2</td>
<td>125.0</td>
<td>10,000.0</td>
<td>No failure</td>
</tr>
<tr>
<td>BT2 3</td>
<td>135.0</td>
<td>1,377.0</td>
<td></td>
</tr>
<tr>
<td>BT2 4</td>
<td>135.0</td>
<td>773.0</td>
<td></td>
</tr>
<tr>
<td>BT2 5</td>
<td>150.0</td>
<td>620.0</td>
<td></td>
</tr>
<tr>
<td>BT2 6</td>
<td>150.0</td>
<td>576.0</td>
<td></td>
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<tr>
<td>BT2 7</td>
<td>165.0</td>
<td>375.0</td>
<td></td>
</tr>
<tr>
<td>BT2 8</td>
<td>237.5</td>
<td>112.5</td>
<td></td>
</tr>
<tr>
<td>BT3 1</td>
<td>135.0</td>
<td>857.0</td>
<td></td>
</tr>
<tr>
<td>BT3 2</td>
<td>150.0</td>
<td>449.0</td>
<td></td>
</tr>
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</table>

Figure 2. Set up of fatigue testing.
2.4. Measurement of residual stress

Measurement of residual stress was carried out on one specimen for each type of AW, BT1, BT2, and BT3 specimens by cutting method. Nine uni-axial strain gauges with length of 1 mm were attached on the surface of main plate at position of 2 mm away from the weld toe, as shown in Fig. 4. The specimens were cut in transverse and longitudinal direction between the strain gauges, and finally cut in layer of 2 mm beneath of surface attached strain gauges. In this way, strain was relieved by cutting four of five sections enclosing each strain gauge.

The measured residual stresses in the longitudinal direction are plotted in Fig. 5. AW specimens showed tensile residual stress of 170 MPa near weld toe and compressive residual stresses at both edges of main plate, as well known. On the other hand, the impact of steel grits and shots may cause plastic deformation of the surface layers, and leads to introduction of compressive residual stresses on the surface of BT specimens. As shown in Fig. 5, compressive residual stresses of -30 to -50 MPa were introduced near weld toes of the BT specimens.

As well known, when high compressive residual stresses can be induced at the weld toes, improvement in fatigue life will result. Therefore, the longer fatigue life is expected in BT specimens in comparison with AW specimens.

3. Fatigue Test Results

3.1. Fatigue crack initiation and propagation

Typical fracture surfaces of fatigue test specimens were shown in Fig. 6. All fatigue cracks were initiated from weld toes at the end of longitudinal weld of gussets, perpendicular to the applied stress. The cracks then propagated through the thickness of the plate. All specimens failed in this manner and blasting had little effects on the fatigue crack initiation and propagation behavior of the test specimens.

3.2. Fatigue life

The fatigue test results of all specimens were listed in Table 5. The fatigue test results of AW specimens and BT specimens were plotted with stress range in Fig. 7 and Fig. 8, respectively. In this study, no failed data until $10^7$ stress cycles are shown by symbol with an arrow and maximum stress range among them was taken as fatigue limit for AW (as-welded) specimens and BT (blast-treated) specimens accordingly. The mean regression lines and standard deviations, $s$, for AW and BT specimens were computed by the least square fit method from the failed data. The confidence limits plotted at a distance of two deviations, 2$s$, from the means was also plotted in Fig. 7 and Fig. 8. In Fig. 8, the test data of BT2 and BT3 specimens are distributed within the confidence lines (mean±2$s$ lines) of BT1 specimens. This indicates that the fatigue lives of blast-treated specimens with different blasting times are almost the same and the
number of times in application of blasting have little effect on fatigue life of BT specimens.

All fatigue test results is re-plotted in Fig. 9. The mean regression curves of AW and BT1 specimens show that the fatigue life of BT specimens are slightly increased as the stress range decreased. Fatigue endurance limits of AW and BT specimens is 75 and 125 MPa, respectively. The fatigue limit of BT specimens is increased by 167% in comparison to that of AW specimens. These results indicate that the blast cleaning prior to coating results in slight improving fatigue life of out-of-plane gusset fillet welded joints in low stress range and significant increase in fatigue endurance limit while the blasting have no benefit in high stress range.

3.3. Effect of weld profile and residual stress on fatigue life

As can be seen from Fig. 9, the fatigue life and fatigue limit of BT specimens were increased in comparison to that of AW specimens. Due to the impact of steel grits and shots on surface of the specimens, the weld toe may be eliminated pre-existing flaws and give a smoother profile. As mentioned above, weld toe geometry is improved.
with increase in radius of weld toe and compressive residual stress is induced on surface of BT specimen. The increase in radius of weld toe results in the smoother transition between the weld metal and main plate. It is well known that a smooth transition between the weld metal and main plate can be expected to improve fatigue performance by introducing a significant fatigue crack initiation life into the fatigue life and thus increase both fatigue life and fatigue endurance limit (Kusko et al., 2004; Manteghi et al., 2006). Radius of weld toe directly influences the stress concentration factor, as described in Eq. (1), namely stress concentration factor of BT specimen is less than that of AW specimen. This is apparent that the geometry of weld toe becomes smoother by using blast treatment, stress concentration will be reduced and result in extending fatigue crack initiation life.

Fatigue crack propagation rate $da/dN$ can be determined by following formula (IIW, 1995; JSCE, 1993):

$$\frac{da}{dN} = C(\Delta K)^m$$  \hspace{1cm} (2)

where $K$ is stress intensity factor range, $C$ and $m$ are material constants.

Fatigue crack propagation life $N_p$ required for an initial crack of size $a_i$ to propagate to a final crack of size $a_f$ is determined by integrating Eq. (2)

$$N_p = \int_{a_i}^{a_f} \frac{da}{C(\Delta K)^m}$$  \hspace{1cm} (3)

The stress intensity factor range can be calculated as following formula (Yamada et al., 1986):

$$\Delta K = F_g F_a F_t F_i \Delta \sigma \sqrt{\pi a}$$  \hspace{1cm} (4)

where $F_a$, $F_t$, $F_i$, are correction factors for crack shape, surface crack, finite thickness and width of plate, respectively.

$F_g$ is correction factor for stress gradient (ESDEP, 2008)

$$F_g = \frac{K_i}{Q} - \frac{K_i}{Q} \frac{q}{d} \frac{d^2}{d} \frac{a}{a}$$  \hspace{1cm} (5)

As mentioned above, there are no significant difference in fatigue crack initiation and propagation behavior of AW and BT specimens, and the dimension of all specimens used in this test is the same. In this reasons, the correction factors can be assumed as constant values for AW and BT specimens, except $F_g$. The ratio of fatigue crack propagation life of BT specimens to AW specimens can be expressed by following formula:

$$\frac{N_{p,BT}}{N_{p,AW}} = \left( \frac{F_{g,BT}}{F_{g,AW}} \right)^m \frac{(F_{t,BT})^m}{(F_{t,AW})^m} \frac{(F_{i,BT})^m}{(F_{i,AW})^m} \frac{(\Delta \sigma_{BT})^m}{(\Delta \sigma_{AW})^m} \frac{K_{i,BT}}{K_{i,AW}}$$  \hspace{1cm} (6)

The ratio of fatigue crack propagation life of AW specimens to BT1 specimens can be determined by following calculation:

$$\frac{N_{p,BT}}{N_{p,AW}} = \left( \frac{2.82}{2.75} \right)^{1.02}$$  \hspace{1cm} (7)

where $m$ is taken as 2.75 conforming to JSSC fatigue design recommendation (JSCE, 1993).

From Table 6 and Eq. (7), stress concentration factor of BT1, BT2, and BT3 specimens ($K_{i,BT1} = 2.75$, $K_{i,BT2} = 2.73$, and $K_{i,BT3} = 2.69$) is decreased about 2%, 3%, and 5%, respectively, in comparison with that of AW specimen ($K_{i,AW} = 2.82$), the fatigue crack propagation life of BT1, BT2, and BT3 specimens slightly is increased about 7%, 9%, and 13%, respectively against that of AW specimen. This indicates that blast treatment has little effect on fatigue crack propagation life of gusset welded joint by improvement of weld geometry.

Considering effect of blast treatment on fatigue endurance limit of gusset welded joints due to stress concentration based on stress intensity range $\Delta K_{th}$. At fatigue endurance limit,

$$\Delta K_{th,AW} = F_{g,AW} F_a F_t F_i \Delta \sigma_{AW,Limit} \sqrt{\pi a}$$  \hspace{1cm} (8)

$$\Delta K_{th,BT} = F_{g,BT} F_a F_t F_i \Delta \sigma_{BT,Limit} \sqrt{\pi a}$$  \hspace{1cm} (9)

Because $F_a$, $F_t$, $F_i$, can be assumed as the same value for AW and BT1 specimen, therefore:

$$F_{g,AW} \Delta \sigma_{AW,Limit} = F_{g,BT} \Delta \sigma_{BT,Limit}$$  \hspace{1cm} (10)

$$\frac{K_{i,BT}}{Q} \Delta \sigma_{BT,Limit} = \frac{K_{i,AW}}{Q} \Delta \sigma_{AW,Limit}$$  \hspace{1cm} (11)

$$\frac{\Delta \sigma_{BT,Limit}}{\Delta \sigma_{AW,Limit}} = \frac{F_{g,BT} \Delta \sigma_{BT,Limit}}{F_{g,AW} \Delta \sigma_{AW,Limit}} = \frac{2.81}{2.75} = 1.02$$  \hspace{1cm} (12)

From Eq. (12), fatigue limit of BT1, BT2, and BT3 specimen increases respectively about 2%, 3%, and 5%, in comparison with that of AW specimen while fatigue test results shows that fatigue limit of BT specimen is 67% greater than that of AW specimen. It is assumed from aboved analysis and fatigue test results that the increase in fatigue endurance limit of BT specimen is not due to improvement of weld profile, but primarily due to compressive residual stress introduced in BT specimen.

The introduction of compressive residual stress in BT specimen has beneficially affected on fatigue crack
initiation and propagation (Maddox, 1991). Evaluating effect of residual stresses on fatigue behavior based on the concept of effective stresses range. The effective stress range resulting from the superposition of the applied nominal stress and residual stresses may be tensile or compressive depending on their relative magnitude. The minimum and maximum effective stress can be expressed as followings (Nussbaumer et al., 2001):

\[ \sigma_{\text{min,eff}} = \sigma_{\text{min}} + \sigma_r \]  

\[ \sigma_{\text{max,eff}} = \sigma_{\text{max}} + \sigma_r \]  

where \( \sigma_r \) is the level of the residual stresses.

From Fig. 5, it is assumed that the compressive residual stress induced in BT specimen and tensile residual stress induced in AW specimen. For AW specimen, effective stress range was not changed but both maximum and minimum effective stresses increase amount of tensile residual stress \( \sigma_r \). In BT specimens, conversely, both maximum and minimum effective stresses decrease amount of compressive residual stress \( \sigma_r \) and minimum effective stress may be became compression and then the effective stress range in this case also decrease in comparison with applied nominal stress range. Therefore, it is assumed that fatigue limit of BT specimens is 67% greater than that of AW specimen due to decrease in effective stress range for BT specimens.

4. Conclusion

Fatigue tests were carried out on as-welded out-of-plane gusset specimens and three types of blast-treated out-of-plane gusset fillet welded joints. The effects of blast cleaning prior to coating on fatigue behavior of the gusset welded joints were investigated. The test results can be summarized as follows.

1) The weld geometry is improved by using blast cleaning, namely the radius of weld toe of blast-treated specimens increased by 115–130%, against those of as-welded specimens. However, it is assumed that the effect of the weld geometry improvement on fatigue life and fatigue endurance limit of out-of-plane gusset fillet welded joints is not significant.

2) The fatigue endurance limit of blast-treated out-of-plane gusset specimens increased about 167% in comparison with that of as-welded specimen, due to introduction of compressive residual stress.

3) Over one-time blasting, effect of the number of times in application of blasting on fatigue life of out-of-plane gusset welded joints is little.

References


