Experimental Study for the Effect of Additional Weld on Fatigue Strength in Out-of-Plane Gusset Welded Joints

by KOTANI Yuki **, TSUYAMA Tadahisa**, TSUTSUMI Seiichiro*** and BUERLIHAN Ayang****

Grinding of weld toes is generally used to improve the fatigue strength of fillet weld joints. In this study, a technique employing additional welds was applied to out-of-plane gusset welded joints and the relationship between the shape of the additional weld and fatigue strength was investigated. The shape of the additional weld was controlled by changing the aiming position. When there was more distance between the first weld toe and the aiming position of the additional weld, the flank angle and toe radius tended to be smaller and larger, respectively. In the nominal stress range of 150 MPa, fatigue life was extended to 2.7 times that of weld joints without additional welds. Although the toe radius of the additional weld was smaller than that created by grinding, the resultant fatigue strength of the additional weld joint was almost equivalent to that of the grinding case. This can be explained in terms of stress concentration, since the flank angle and toe radius in the additional weld toe can be improved without reducing the throat thickness.

Key Words: Out-of-Plane Gusset Welded Joints, Additional Weld, Fatigue Strength, Toe Radius, Flank Angle

1. Introduction

In recent years, steel bridges built during the period of high economic growth have been becoming decrepit, and many fatigue cracks caused by increased traffic have been reported. In 2018, about 25% of road bridges had been in service over 50 years. Moreover, this is expected to rapidly increase to about 50% in 10 more years [1]. Therefore, existing bridges are being reinforced and repaired. For new bridges, there are more stringent quality requirements to prevent fatigue cracking [2-4]. In particular, the fillet weld toes of out-of-plane gusset welded joints used for stiffener of steel bridges tend to be points of high stress concentration, where the stress causes fatigue cracks. In the fatigue design recommendations for steel structures of the Japanese Society of Steel Construction (JSSC), the fatigue class for out-of-plane gusset welded joints goes up one class when they are finished at the weld toe, although that is very low. Thus, in order to improve the fatigue strength of fillet weld joints, various techniques [5-11] have been proposed such as peening, TIG dressing, ultrasonic impact treatment (UIT), additional welding with low transformation temperature (LTT) welding consumables and a finishing technique that employs grinding. It has been reported that fatigue strength can be increased by improving the weld toe shape or decreasing the residual stress [5-11]. Grinding with a bur grinder to improve the weld toe shape is generally applied because it can be relatively easily done. However, all these techniques are post-weld processes and must be adopted after welding with dedicated tools, which reduces productivity.

In this study, an additional welding technique using a conventional welding consumable was applied to fillet welds of out-of-plane gusset joints, and the relationship between the bead shape of the additional weld and fatigue strength was investigated experimentally.

2. Experimental procedure

2.1 Welding conditions

The specimens used in this experiment were out-of-plane gusset welded joints consisting of a 12 mm thick main plate and two gusset plates as shown in Fig. 1. The steel plate was JIS G 3106 SM490YA, and the welding consumable was a flux-cored wire with a diameter of 1.2 mm, JIS Z 3313 T49J0T1-C0A-UH5. Welded joints between the main plate and the gusset plate were

![Fig. 1 Specimen configuration](image-url)
horizontal fillet welded by CO₂ gas shielded arc welding with a leg length of 6 mm, and each gusset plate has two boxing welds, with the additional welding being performed after the fillet welding. Table 1 shows the fillet weld and additional welding parameters. These parameters were adjusted by trial and error so that the additional weld bead shape could be flatter. Table 2 shows the conditions of the test specimens. AW is as-welded without grinding and the additional weld. AWG is as-welded finished by grinding without the additional weld. The shape of the additional weld was controlled by changing the aiming position. The aiming position for the additional welding was set to three conditions of 0, 2, and 4 mm from the fillet weld (AW) toe. They were designated B0, B2, and B4. Finishing of the weld toe by a bur grinding tool was controlled so that the toe radius of the specimen (AWG) became more than 3 mm, and the toe radius was confirmed with a dedicated gauge [3].

2.2 Measurement of Weld Toe Shape

The weld bead profiles were taken by a 3D scanner for each type of a test specimen having four boxing welding. Figures 2 and 3 show the examples of a boxing weld bead shape and the cross-sections of the weld beads for specimens AW and B4, respectively.

The weld bead shape was evaluated for 9 cross-sections per a boxing welding, resulting in a total of 36 cross-sections per specimen. The toe radius and flank angles' maximum, minimum, and mean values were determined using 36 cross-section data of all tested specimens.

2.3 Fatigue Testing

Fatigue testing was performed under uniaxial tensile under the following conditions: stress ratio = 0.05, test frequency = 7 Hz, with nominal stress ranges of 125, 150, 175, and 200 MPa. Strain gauges were affixed to 5 mm away from each boxing weld toe on the main plate. The strain range was recorded every 5000 cycles. Fatigue life (Nf) and crack initiation life (Nc) were defined as the numbers of cycles at which the specimen fractured and at which the measured strain decreased by 5% from the initial value, respectively.

3. Result and discussion

Figures 4(a) and (b) show the mean and minimum value of the toe radius, and the mean and maximum value of the flank angle, respectively. For the joints with additional welds, the larger the distance between the first weld toe and the aiming position of
additional weld, the smaller the toe radius and larger the flank angle tended to be. The toe radius for AWG was the largest, while the toe radius by manual finishing is likely to be scattered to some extent.

Figures 5(a) and (b) show the results of the fatigue tests. The horizontal axis of the graph shows the number of cycles, the vertical axis shows the nominal stress range, and the average design curve of the JSSC for each fatigue class is shown by a dotted line in the graph.

For the additional weld joints, fatigue life tended to be longer when the additional weld was set farther from the fillet weld. Figure 4 also shows that the toe radius is larger and the flank angle is smaller with farther aiming positions, indicating that toe shape is greatly related to fatigue life. The fatigue life of the additional weld joint (B4) was almost equivalent to that of the ground one (AWG), although the toe radii of the additional weld specimens were smaller than that of the ground specimen. These results suggest that it is necessary to consider the effects of both the toe radius and flank angle to understand the relationship between fatigue life and weld toe shape. For the AWG specimen, in the nominal stress range of 175 MPa, there were cases where fracture occurred, while in others it did not. This is thought to be due to variations in the toe shape that can occur with manual finishing.

In the joints with additional weld, B4 had the longest fatigue life. In the nominal stress range of 150 MPa for B4, the fatigue life (Nf) and the crack initiation life (Nc) were extended 2.7 times and 9.4 times, respectively, as compared with those of the as-welded joint without the additional weld (AW). Fatigue life is thought to extend because the weld toe shape can be improved by

![Graph showing toe radius and flank angle](image)

![Graph showing fatigue life](image)

![Graph showing S-N diagrams](image)
the additional weld without reducing the throat thickness of fillet weld as happens during finishing by grinding.

All of the fatigue test specimens were fractured at the weld toe, so the strain distributions around the weld toes were measured using Digital Image Correlation (DIC) for repeated loads in the stress range of 125 MPa. Figures 6(a) and (b) show the maximum principal strain distribution ($\varepsilon_1$) around the boxing weld toe when the initial maximum load is applied in static load testing for specimens AW and B4, respectively. Figures 7(a) and (b) show the distribution of maximum principal strain range ($\Delta\varepsilon_1$) defined in the third cycle. The lines of weld toe are shown by a dotted line in Figs. 6 and 7.

For Figs. 6(a) and (b), the large and localized strain distributions in the form of a slip line were observed. These are estimated that the so-called Lüder's lines, represented by the material yielding and the resultant plastic slips, were induced as reported in the past research results [12]. In the AW specimen, it was confirmed that the maximum strain value was generated at the weld toe, where the stress tends concentrates for both AW and B4. On the other hand, in the B4 specimen, the maximum strain was generated at a point slightly farther from the weld toe. It is considered that the plastic deformation at the weld toe of B4 was

![Fig. 6 Initial strain distribution around the weld toe, $\varepsilon_1$](image1)

![Fig. 7 Strain distribution around the weld toe, $\Delta\varepsilon_1$](image2)
suppressed in the multiplier effect of distributions of both the hardness of HAZ and the stress concentration.

On the other hand, as shown in Figs. 7(a) and (b), the magnitude of strain was drastically reduced in the third loading cycle. It was thought that the material hardening of the area was induced leading to the smaller deformation, then the entire area deformed almost elastically. Also, the magnitude of strain was smaller in the B4. Therefore, it would be concluded that crack initiation life (Nc) was extended by the additional weld through the reduction of the strain at the weld toe, where is the most preferential site for the fatigue crack.

4. Conclusions

In this study, the effect of additional welds on the fatigue life extension of out-of-plane gusset welded joints was examined experimentally, prompting the following conclusions.

(1) The weld toe shape of the additional welds was changed by selecting the proper aiming position to be flattened with larger toe radius and smaller frank angle.

(2) The fatigue life of the joints was improved by the additional welding using a conventional welding consumable.

(3) DIC measurement revealed that the local strain distribution around the weld toe was reduced by the additional weld, and it could be the reason for the fatigue life extension.

To further improve fatigue life, further experimental examination, in which welding conditions are adjusted and explored together with numerical simulation. Especially to find an optimum condition of the additional welding process, the evaluation of fatigue crack initiation life considering material elastoplasticity behavior [13-15] would be required, since total life of high-quality joints is dominated by crack initiation life.

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