Numerical and Experimental Study on Fatigue Life Extension of U-rib Steel Structure by Hammer Peening

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Fatigue tests and numerical analyses were carried out in order to investigate the effect of hammer peening on fatigue life of U-rib structure. The fatigue test results showed that the fatigue life of peened specimens are longer than the non-peened ones. In addition, the numerical results showed that compressive residual stresses were induced at weld toe and root by hammer peening, moreover that the accumulated plastic strains during cyclic loading can explain the experimental results in terms of fatigue life extension.

Key Words: Fatigue, Crack Initiation, Peening, FE Analysis, Residual Stress

1. Introduction

U-rib steel structures are commonly used in large bridges and viaducts. However, it has been reported that three types of fatigue cracks are usually initiated in the welded parts of U-rib 1,2; a type of crack is initiated at root and propagated through the deposited metal, the second one tends to be initiated at root and propagated into the thickness of deck plate, whereas the third type is initiated at toe on the rib and propagated through the rib. The problem to find innovating techniques in order to extend fatigue life of weld joints is currently an open issue, since the repair and maintenance costs are increasing. Among all the strategies the hammer peening showed some promising results, inducing a compressive residual stress field together with material hardening, which contribute to improve the surface geometry and fatigue performances in the weak part of the weld components of structures. In addition, this technique can also introduce compressive residual stress into even distant area from the peened area. In a previous study carried out by the authors3, it was reported that the fatigue life at the root of the U-rib became longer by means of hammer peening on the outside of the rib.

In the present paper we investigated the effect of the hammer peening on fatigue life of U-rib with both an experimental and a numerical approach based on a cyclic plasticity FEM analysis6-11.

2. Experiment

2.1 Experimental set up for fatigue test

Fig.1 shows a sketch of the test specimen. The deck plate was made of JIS-SM490Y steel and the rib plate was made of JIS-SS400 steel. The yield stress of JIS-SM490Y is more than 365MPa and that of JIS-SS400 is more than 245MPa. The rib plate is welded with an angle of 77° from the horizontal axes by a CO2 semi-automatic arc welding and the degree of welding penetration is 75%. In this study we considered three different cases: the specimen is peened inside of the rib, on both sides and non-peened. The location of the peening inside of the rib is about 1 mm from the rib plate, and the one outside of the rib is about 1 mm from the toe. After grinding, the toe radius of U3-G, U4-GP01 and U5-GP11 became about 4 mm.

Fatigue tests were carried out with a plate bending fatigue testing machine where the stress ratio was set to zero (i.e. unidirectional testing, R=0) and the frequency of the vibrator was set to 18.4 Hz. Three strain gages were put on the inside of the rib, and one strain gage was put on the outside. The strain range was calculated by means of the strain gages, and the fatigue life was defined as the number of cycles required to obtain 5% strain change. It’s about 80% of the number of cycles counted until the specimen failures (see Fig.2).
2.2 Experimental results

Figure 2 shows the example of the strain range variation during the fatigue test. The decrease or increase of the strain ranges appeared due to the crack initiation and propagation as a consequence of the stress redistribution. Fig. 3 shows the fatigue crack obtained in the experiments for the U3-G and U1-AW configurations.

Fig. 4 reports the results of the fatigue tests where the vertical axis indicates the stress range at the crack formation location, whereas the horizontal one shows the number of cycles. The results indicate that the fatigue lives of the peened specimens are longer than the non-peened ones. Grinder made the fatigue life of the toe longer. From the result of U3-G and U4-GP01, it is shown that the peening inside of the rib can make fatigue life of the root longer. From the result of U1-AW and U2-P01, it is also shown that the peening inside of the rib can make fatigue life of the toe longer. Three regression lines, with a -1/3 slope, were calculated and the fatigue life for discussion was set for the stress range of 170 MPa on those lines. As a result, it is shown that the fatigue life of the specimen peened on the inside is 2.1 times longer than that of the non-peened sample (ref. Table 1). In addition, the fatigue life of the specimen peened on the both sides is expected to be over 3.1 times longer than that of the

| Specimen Location of crack | Stress range, Δσ (MPa) | Number of cycles, N |
|----------------------------|-------------------------|---------------------|
| w/o peening                | 100                     | 1×10^6              |
| Inside                     | 200                     | 1×10^6              |
| Both sides                 | 400                     | 1×10^7              |

Table 1 Regression results

Fatigue life [×10^6 cycles] (Δσ=170MPa) Ratio of fatigue life to that of w/o peening
w/o peening 89 1.0
Inside 186 2.1
Both sides 279 3.1

Fig. 2 Strain range variation of U1-AW
Fig. 3 Fatigue crack
Fig. 4 Fatigue test results in the S-N diagram
Fig. 5 FE model
Fig. 6 Peening patterns analyzed
Fig. 7 Stress-strain curves of applied material model
3. Numerical analysis

3.1 Analysis procedure

The two-dimensional FE model is shown in Fig.5. Firstly, the welding residual stress field was computed by means of a coupled thermal elasto-plastic analysis. In this simulation, Young’s modulus, Poisson’s ratio, and yield stress which depend on temperature were applied referring to the previous study. Then the thermal expansion strain was used with the intent of simulating the stress derived by hammer peening. Its width was set to be 5 mm, according to a geometrical measurement, the depth to 3mm and the value of the thermal expansion strain introduced was set to be 0.006, referring to the paper. In this set of numerical analyses we considered three cases (Fig.6): the sample peened only on the inside, only on the outside, or on the both sides of the rib. After the peening, a cyclic loading was applied to simulate the fatigue test for a total number of 300 cycles. Fig.7 indicates the examples of the stress-strain curves calculated by the material model used in the analysis.

3.2 Numerical results

Figs.8 and 9 show the residual stress in the x-axis direction. After the peening simulation, the compressive residual stresses at toe and root of all models increased. In detail, the compressive residual stress for the inside peened sample greatly increased at the root, whereas in the outside peened sample the increase was induced at the toe.

Figs.10 and 11 show the stress-strain curves of the elements at root and toe, and Fig.12 reports the accumulated plastic strain variation for the element which generates the largest irreversible contribution, respectively located at the toe and at the root. The accumulated plastic strain rates of peened models sensibly decrease compared to the non-peened ones. In this study the crack initiation life was represented by the number of cycles when the value of the accumulated equivalent plastic strain H, for either element at the toe or the one at the root, reached a unitary by linear extrapolation of its rate at the 300 cycles (see Table 2). The modeling for the prediction of crack initiation life is still under the study, and then requires further discussion in the future. Here...
4. Conclusions

The present work aimed to investigate the effect of the hammer peening on fatigue life of U-rib by means of experimental and numerical analyses. The results of the fatigue tests revealed that the hammer peening on the inside of the rib and that on the both sides of the rib can considerably improve the fatigue life. The results of the numerical analyses revealed that the compressive residual stress and the material hardening are introduced for both at weld toe and root, and that the accumulated plastic strain during the fatigue loading became smaller, and then the predicted fatigue crack initiation life became longer.

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Reference

1) JSCE Subcommittee on Fatigue of Orthotropic Steel Bridge Deck: Fatigue of orthotropic steel bridge deck, (2010), 63-75
2) C. Miki: Fatigue and fracture of bridges, (2011), 94-123
3) T. Ishikawa, R. Matsumoto, S. Tsutsumi and H. Kawano: Fatigue strength improvement of rib-to-deck joints of orthotropic steel deck by peening, (2014)
4) Y. Ueda, K. Fukuda and K. Nakacho: Study on Type of Cracking of Fillet Weld based on Residual Stresses Calculated by F.E.M., Journal of the Japan Welding Society, Vol.44 (1975), No.3, 250-257
5) R. Matsumoto, T. Ishikawa, S. Tsutsumi, H. Kawano and K. Yamada: Analytical verification of residual stress distribution in steel plate after hammer peening, Journal of Structural Engineering JSCE, Vol.62A (2016), 685-692
6) S. Tsutsumi, M. Toyosada and K. Hashiguchi: Extended subloading surface model incorporating elastic boundary concept, Journal of Applied Mechanics JSCE, 9 (2006), 455-462
7) S. Tsutsumi, K. Murakami, K. Gotoh and M. Toyosada: Cyclic Stress-Strain Relationship during High Cycle Fatigue Process: Elastoplastic Constitutive Model Introducing Cyclic Damage Effect, Journal of the Japan Society of Naval Architects and Ocean Engineers, 7, (2008), 243-250
8) S. Tsutsumi, H. Momii and R. Fincato: Tangential plasticity effect on buckling behavior of a thin wall pier under cyclic loading condition. Q. J. Jpn. Weld. Soc. 33(2), (2015), 161–165
9) S. Tsutsumi, K. Morita, R. Fincato and H. Momii: Fatigue life assessment of a non-load carrying fillet joint considering the effects of a cyclic plasticity and weld bead shape, Fracture and Structural Integrity, 38 (2016), 240-250
10) S. Tsutsumi, K. Morita and R. Fincato: Numerical study on the effect of weld bead shape on the fatigue crack initiation and propagation lives, Journal of Structural Engineering JSCE, Vol. 63A (2017), 609-618
11) R. Fincato and S. Tsutsumi: Closest-point projection method for the extended subloading surface model, Acta Mechanica, (2017), 1-21