Effect of Pre-overload on Fatigue Life Extension of U-rib Steel Floor Slab Root

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Fatigue damage has been recognized as one of the critical issues in the design of welded structures. Among different welded joints, one-sided welding of fillet joints is a common practice that has the advantages of an excellent workability and to reduce the manufacturing costs. However, it is characterized by the presence of weld roots. The same type of welding is often used for U-rib steel components, where, in many cases, fatigue cracks are initiated from the weld root. Subsequently, the cracks often propagate and penetrate the upper deck or the weld bead. These cracks, originated from weld root, are not easy to be detected even by using novel non-destructive inspection techniques. A novel method to improve the fatigue performance of the weld root of U-rib has been developed by the co-authors of this work. The new strategy consists in introducing a compressive residual stress field by applying a tensile pre-overload from inside of the U-rib structure. The effect of the pre-overload on fatigue performance was experimentally clarified in a previous work. However, the benefits of this expedient remain to be elucidated theoretically in order to optimize the pre-overloading process. The purpose of this study is to clarify the mechanism of the fatigue life extension due to the application of a pre-overload by means of FE analyses based on a novel cyclic elastoplastic model.

Key Words: Fatigue, U-rib, Overload, Crack Initiation, Crack Propagation

1. Introduction

In recent years, fatigue problems of welded structures, such as steel bridges, have become relevant, and they are responsible for many types of structural failure. The fatigue phenomenon is crucial in welded joints, where the stress tends to concentrate. Many cases have been reported in which fatigue cracks occur from the welds and cause structural failure. Furthermore, it is estimated that the fatigue failure phenomenon would become a more severe problem in the future since a large number of existing structures would reach the end of the service life. Among different types of welding, the one-sided welding of fillet joints is a common type since it has excellent workability and is relatively low-cost. However, this type of welding is characterized by the presence of welding roots, which are often the starting point of fatigue cracks. The same joint type is usually used in U-ribs, investigated in this study. It has been reported that cracks initiate from the root and often propagate either through the deck plate or the weld bead, leading to severe problems. These cracks are not easy to be detected even by using novel non-destructive inspection techniques. The reason for the formation of these cracks is most likely due to the cyclic loads induced by the transit of vehicles and also possibly by the superimposition of welding residual stresses.

The residual stress field at weld root of U-rib structure was measured by the contour methods.

On the other hand, previous studies showed that fatigue life can be extended by the application of a pre-overload to high stress concentrated parts such as roots and crack tips. The co-authors of the present paper developed a technique that can introduce a compressive residual stress field by applying a tensile pre-overload from the inside of the U-rib, improving the fatigue performance of the weld root. The effect of the pre-overload to the fatigue performance was experimentally clarified. However, the results were obtained under specific experimental conditions, and a theoretical explanation of the mechanism remains unclear.

The purpose of this study is to clarify the mechanisms of fatigue life extension of U-rib components after over-loading by means of non-linear FE analyses, adopting a novel cyclic elastoplastic model.

2. Outline of numerical analysis

Fig. 1 shows the FE models and boundary conditions created to simulate the pre-overload and the fatigue loading process of the test specimen.

The numerical analyses consist of 3 steps. The pre-overload and subsequent crack initiation life assessment were performed considering the local cyclic plasticity deformation. In the final step, the crack propagation life was assessed by linear fracture mechanics analyses using the J-integral method and the X-FE technique. The elastoplastic behavior of the material was described.
by means of a novel elastoplasticity model, named Fatigue SS model\textsuperscript{8,10}. The feature of the model is to generate plastic deformations for every change in the stress state that satisfies the loading criterion. The results exhibit more realistic descriptions of the material ratcheting and plastic accumulation\textsuperscript{8-12}. The constitutive equations of the Fatigue SS model were implemented via user subroutine for the commercial software ABAQUS (ver. 6.14-5) and used to carry out the numerical simulations.

Roots, with a length of 1.5mm, are placed on the two weld joints in the 2D FE models (see Fig. 1). A mesh refinement was performed around the roots with a minimum element size of about 0.05mm.

The effects of several parameters related to the geometry of the root, angular distortions, and the effect of welding residual stresses were not considered at the present stage. Future works will investigate these aspects.

2.1 Effect of pre-overload

Firstly, numerical analyses were performed to investigate the effect of the pre-overload on fatigue life by reproducing the experimental conditions. A loading and subsequent unloading are applied by means of a rigid body from the inside of the U-rib at a 30mm height from the deck plate. This procedure reproduces the conditions adopted in the previous experimental study\textsuperscript{7}.

Fig. 2 shows the relationship between the stress along the x-axis and the y-axis evaluated at the root tip node and the loading point displacement. These numerical results confirmed the previous experimental observations that the compressive residual stresses tend to stabilize with the increase of impressed displacements. Subsequently, the fatigue life evaluation was performed by assuming the stress distribution obtained by applying a rigid-body displacement of \(d=2.5\) mm, where the residual stress value is considered to be saturated.

Fig. 3 shows the contour fields of the x-axial stress, y-axial stress, and cumulative equivalent plastic strain distribution around the root after the application of the pre-overload. It is shown that the area around the root is highly plasticized, and large compressive residual stress fields are induced. Moreover, the size of the root gap
was enlarged as a result of local plasticity, reducing the stress concentration. The measurement of the root blunting behavior needs to be experimentally confirmed in future studies.

2.2 Fatigue life assessment

In order to assess the fatigue crack initiation life, cyclic elastoplasticity FE analyses were performed on the models considering, or not, the pre-overload. A wheel-load was assumed in the simulations, similarly to the setup reported in the experimental study.

Fig. 3 Contour field distributions near the root after pre-overload

![Stress distribution along the x-axis](image1)

(a) Stress distribution along the x-axis

![Stress distribution along the y-axis](image2)

(b) Stress distribution along the y-axis

![Cumulative equivalent plastic strain](image3)

(c) Cumulative equivalent plastic strain

Fig. 3

![Projected stress-strain response at the root](image4)

Fig. 4

![Predicted $a\Delta K_{eq}$ curves](image5)

Fig. 5

![Comparison of predicted fatigue life with experimental results](image6)

Fig. 6

![Predicted $\Delta P_{f}-N$ curves for $N_c$ and $N_f$](image7)

Fig. 7
maximum load during the 20th cycles. From this figure, it can be confirmed that mean stresses during fatigue loading are decreased by pre-overload, suggesting the extension of the crack initiation life. The fatigue crack initiation life is calculated by means of Eq. (1), using the total strain range \( \Delta \varepsilon \) and the mean stress \( \sigma_m \) obtained in the analyses.

\[
\Delta \varepsilon \cdot M = 0.83N^0.606 + AN^B
\]

where

\[
A = \frac{2.8571 \times 10^{-5}}{10000}, \quad B = \log_{10}(C + 3.23306 \times 10^{-3})
\]

\[
C = \left( -1.95212 \times 10^{-4} \sigma_y + 2.93632 \times 10^{-1} \right)^4 + \left( 1.67957 \times 10^{-1} \right)^4^{-\frac{1}{4}}
\]

\[
M = 3/\left( 4 - (\sigma_y/\sigma_s + 1)^2 \right)
\]

Eq. (1) is proposed based on the experimental database for steel materials, which consider the effects of the yield stress and the mean stress.\(^1\)

The fatigue crack propagation life is estimated based on linear fracture mechanics. In this study, the initial equivalent stress intensity factor is calculated with the J-integral value, and the consequent \(a-\Delta K_{eq}\) relationships are predicted by using X-FE analyses. The definition of the initial equivalent stress intensity factor and the theoretical formula are obtained assuming plane strain conditions and an elastic stress regime.\(^3\)

Fig. 5 shows an example of the \(a-\Delta K_{eq}\) relationships obtained from the initial value of \(K_{eq}\) computed in the analyses (see Table 1). Note that the model with the fatigue load of \(\Delta P_f=12\text{kN}\) is defined as reaching the fatigue limit because the J-integral became negative. The prediction of fatigue propagation life is based on the Paris' law, where the material constants were assumed considering the JSSC average design material curve.\(^4\) The fatigue crack propagation life is defined as the number of cycles necessary for the crack to propagate through the deck plate thickness (i.e. 16mm).

Fig. 6 shows the predicted results of fatigue life given as the sum of crack initiation and propagation life. This figure also reports the fatigue crack initiation life results described above.

Moreover, in Fig. 7 and Fig. 8, comparison of predicted fatigue life with experiments and normalized fatigue life by w/o pre-overload are shown, respectively. The predicted numerical results seem to be conservative against the experimental results. However, the overall trends of the fatigue test results considering the effect of pre-overload are in good agreement with the experimental values obtained in a lower fatigue load regime.

3. Conclusions

The present work aimed to investigate the effect of a pre-overload on the fatigue life extension of a U-rib steel floor slab root by means of FE analyses. The results of the numerical analysis revealed that fatigue life extension due to the pre-overload is more relevant for low values of the applied fatigue load. On the contrary, the beneficial effect of the over-load tends to be reduced for higher values of the applied cyclic load. Although the numerical analysis results seem to be conservative, the trends of the experimental results could be reproduced.

Future works will consider the effects of HAZ material properties, welding residual stress fields and 3D geometry of the real joints.

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