Measurement of Residual Stress Distribution at the Weld Root for a U-rib Specimen Using the Contour Method*

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This paper presents the measurement of residual stress (RS) distribution at the weld root of a U-rib specimen using the contour method. A fully automated data processing code was developed to process the measured data over the cut surfaces. In addition, the effect of the applied boundary conditions (BCs) on the resulting energy and reproduced RS was examined using different BCs cases. Full 2D maps of RS distribution were obtained where a compressive RS was induced at the weld root. Moreover, it is found that the studied BCs cases have a small influence on the resulting energy and negligible effect on the general distribution of reproduced RS.

Key Words: Residual Stress Distribution, Weld Root, U-rib, Contour Method, Boundary Conditions, FEA

1. Introduction

Orthotropic steel bridge decks are widely used in long-span bridges due to their advantages which include high strength, lightweight, durability and rapid construction. U-ribs represent about 60% of rib stiffeners employed in orthotropic steel bridge decks1). However, fatigue cracks are unavoidable at orthotropic steel deck constructions because of their complex geometries and high-stress concentration as well as RS induced due to welding. Rib-to-deck fatigue cracks are frequently initiated from the weld roots where they propagate either into the deck plate thickness or through the weld1). Due to the complexity of the rib-to-deck connection, crack initiation cannot be observed by visual inspection which might influence the bridge safety. So, many research works2-4) have investigated the fatigue problem of rib-to-deck connections using different methods.

Due to the superposition of fluctuating stress and tensile RS induced due to welding a high effective stress range is produced which leads to fatigue crack initiation from the weld root for rib-to-deck connections. It is, therefore, necessary to know RS distribution at the weld root. However, measurement of RS at the weld root is a challengeable task for such complicated joints. Different methods are available to measure RS through-thickness, for example, the neutron diffraction method and the hole drilling method. However, the neutron diffraction method is limited to a small diameter range (e.g. ~1mm). Further, the hole-drilling method is limited to specimen geometry and the presence of RS gradients. Moreover, Kainuma et al.5) have measured RS using the cutting method and the magnetostriction method. Those methods, however, do not give a full map of RS distribution. On the other hand, numerical simulations can predict RS distribution at the weld root. However, the accuracy of simulated RS is not well verified6). To predict the possible location of fatigue crack initiation, a full map of RS distribution at the weld root should be obtained. The contour method (CM), therefore, has emerged an efficient technique that provides a full 2D map of RS distribution normal to a plane of interest7-10). Using the CM, RS distribution can be examined carefully at the weld root for rib-to-deck connections.

In the present paper, full 2D maps of RS distribution at the weld root of a U-rib specimen are obtained using the CM. Furthermore, the effect of the applied boundary conditions (BCs) used in the CM is investigated where their influence on the resulting energy and RS distribution is also discussed.

2. Experimental work

2.1 Set up for welding U-rib specimen

Figure 1 shows the geometry of a one-half symmetric U-rib specimen. The rib plate and deck plate are made of JIS G3106 SM490A steel. The rib plate is assembled to the deck plate by the CO2 arc welding process using a flux-cored wire (FCM-1F). The tensile stress of the rib plate and deck plate is 554 MPa and that of weld wire is 580 MPa. A one weld pass was performed using a welding current of 350 A, arc voltage of 38 V and welding speed of 45 cm/min. A macrostructure test was performed after welding to examine the amount of penetration that achieved due to welding where about 87% weld penetration was obtained. The penetration ratios shown in Figs. 1 and 2 are higher than the minimum penetration ratio recommended by transportation standards11,12).

2.2 The CM procedure

The CM was adopted to measure RS distribution at the weld root for the target U-rib specimen. The CM involves four steps, namely,
1) specimen cutting, 2) surface topology measurement, 3) data processing and 4) linear elastic finite element analysis (FEA) to map the originally induced RS across the cut surface.

The U-rib specimen was cut at the weld root location using the wire electric discharge machining process as shown in Fig. 2. Cutting was performed using a brass wire of diameter 0.2 mm with a cutting speed of about 0.002 mm/s. A single cut (i.e. skim cut settings) was carried out to achieve a fine surface finishing. The cutting wire was parallel to the rib plate as shown in Fig. 2(a). As a result, oblique cut surfaces were obtained as illustrated in Fig. 2(b). The topology (i.e. displacement normal to the cut surface) of cut surfaces was then measured using the One-Shot 3D Measuring Macroscope. This macroscope scans the topology of the cut surface with repeatability (i.e. height measurement) of 0.4 μm where the pitch of the measured data is 47.141 μm. Therefore, huge data (i.e. about 1.5 million data) were measured for each cut surface.

Data processing is required after measuring the cut surfaces topology to filter any artifacts or noise in the measured data. Due to the entrance and exit of the wire during cutting as shown in Fig. 2 (a), data at the specimen edges are untrusted. For this reason, before performing data processing, data at the specimen edges were trimmed. A 0.79 mm and 0.5 mm of the measured data were trimmed at each edge along deck length and through deck thickness, respectively. The trimmed data were then linearly extrapolated based on the measured data using the ‘TREND’ function available in the Microsoft spreadsheet to fit the finite element (FE) cut surface used for reproducing RS distribution. Since huge data were measured for each cut surface, this makes the data processing a tedious work and requires a long time where this may influence the accuracy of the processed data if it is performed manually. For this reason, a fully automated data processing code was developed. The developed code processes the raw measured data and prints out the processed measured data as constraints to be used in the linear elastic FEA. The developed code considers each node on the FE cut surface as a center of a virtual circle placed on the measured cut surface. The virtual circle encloses some of the measured data that surrounds the target node (i.e. circle center). The circle radius \( r \) can be adjusted in the developed code to control the amount of the measured data. In this study, a circle with a radius \( r = 1.0 \) mm was used after examining the impact of different values of \( r \) on the processed data. Measured data located in the designated circle are firstly weighted using the Gaussian function. The weighted data are then averaged in which the averaged data is applied to the target node (i.e. circle center) on the FE cut surface. This process is repeated for each node on the FE cut surface. After that, the smoothed data on the two cut surfaces are averaged. The smoothed data distributions over the two cut surfaces are illustrated in Figs. 3 and 4. The developed code prints out the processed data as constraints normal to the cut surface with an inverse sign for the two cut surfaces. These constraints are used for reproducing RS distribution using a stress-free FE model. Figure 5 shows the FE models used in linear elastic FEA. Figure 5 (a) shows the welded
FE model that consists of 382,184 elements and 398,692 nodes, while Fig. 5 (b) displays the flat FE model that consists of 293,910 elements and 308,154 nodes. A relatively fine mesh with an element size of about 0.1 mm was generated at the weld root location and near the cut surface to improve the accuracy of the reproduced RS. The applied FE cut surface is composed of 8,526 nodes. Linear elastic FEA was performed using WARP3D code\(^\text{13}\), an open-source code based on FEM, to map RS distribution across the cut surface.

2.3 Effect of applied BCs

To map RS distribution using the CM, BCs are needed to prevent rigid body motion during linear elastic FEA. However, the BCs used in the experiment are unknown. It is, therefore, necessary to examine the effect of the applied BCs on the accuracy of reproduced RS distribution. For this reason, Fig. 6 shows six cases for different BCs that were studied to examine their influence on the resulting energy and reproduced RS distribution. Where Case 1 represents less tight BCs while Case 6 represents the tightest BCs used in this study. Note that Ux, Uy, and Uz, presented in Fig. 6, refer to displacement in x-, y- and z-direction, respectively. The applied displacements (i.e. Ux = ±value) to the cut surface represent the processed displacements obtained by the developed code. The same processed displacements were applied to the FE cut surface for the six cases of the applied BCs. For the sake of simplicity, Fig. 6 shows only the applied BCs cases for the flat side. However, the same six cases were also applied to the welded FE model.

3. Results and discussion

3.1 Effect of the applied BCs on the resulting energy

After performing the linear elastic FEA using the six cases of BCs, the resulting energies due to the applied BCs were examined
for the welded side and flat side as shown in Figs. 7 and 8. It is observed that the resulting energies obtained by the welded side (Fig. 7) for the six cases are higher than those given by the flat side (Fig. 8) where this may be due to the different geometries of the two FE models. Moreover, it is noticed that the applied BCs have no considerable influence on the resulting energies for the first four cases (i.e. Case 1–4) as shown in Figs. 7 and 8. On the other hand, it is found that the energies produced by Cases 5 and 6 are higher than those obtained by Cases 1–4 where no remarkable difference is observed in the resulting energies by Cases 5 and 6. Further, Case 6 which represents the tightest BCs exhibits 22.73% larger energy compared to that induced by Case 1 that represents the less tight BCs for the welded side. While for the flat side, Case 6 exhibits 27.53% larger energy compared to that produced by Case 1. It is, therefore, clear that the applied BCs have a higher impact on the resulting energies obtained by the flat side compared to those produced by the welded side when the applied BCs become tighter.

3.2 Effect of the applied BCs on reproduced RS distribution

Figures 9 and 10 illustrate full 2D maps of RS distribution due to the applied BCs six cases for the welded side and flat side, respectively. A compressive RS was induced at the weld root as illustrated in Fig. 9. It is noticed that the compressive RS induced at the beginning and end of the weld root are different from that produced in the middle of the weld root. This may be due to the same behavior of the processed displacements at the weld root (at z = 16 mm) as shown in Fig. 3. Moreover, tensile RS is observed in the middle of the deck plate thickness. At the bottom surface of the deck plate, a combination of tensile RS and compressive RS fields were produced. Further, it is observed that RS distributions obtained by Cases 5 and 6 reveal small differences compared to those given by Cases 1–4. These differences in RS distributions
might be due to the difference in the resulting energies of Cases 5 and 6 compared to those of Cases 1–4 as shown in Figs. 7 and 8. On the other hand, it is observed that the examined BCs cases in this study have a trivial influence on the general distribution of reproduced RS. Therefore, from the results illustrated in Figs. 9 and 10, it is found that linear elastic FEA used in the CM may not be sensitive to the type of the applied BCs where the general RS distribution may not be affected considerably.

To get a general image of the mapped RS distribution across the cut surface especially at the weld root, the scattering in the processed data was removed by averaging the processed data along each line through the thickness of the FE cut surface in which plane strain condition was performed. Linear elastic FEA was then carried out using the averaged processed data. The analysis was performed using only the BCs of Case 1 as the applied BCs cases, in this study, do not have a significant influence on the general distribution of reproduced RS. Figure 11 illustrates a comparison of the 2D maps of RS distribution obtained by the plane strain condition (Fig. 11(a)) and that given by the actual processed displacements (Fig. 11(b)). Figure 11(a) shows a clear 2D map of reproduced RS distribution through the deck plate thickness. It is clear that compressive RS is obtained at the weld root using the actual smoothed displacements (Fig. 11(b)) and the averaged processed displacements (Fig. 11(a)) which demonstrate the efficiency of the CM in measuring RS distribution at the weld root for U-ribs.

Fig. 11 Comparison of the 2D maps of RS distribution normal to the cut surface ($\varepsilon_{\text{m}}$) for the welded side using the BCs of Case 1. (a) using averaged processed displacements (i.e. plane strain condition), (b) using actual processed displacements.

4. Conclusions

RS distribution was measured at the weld root for a U-rib specimen using the CM. A fully automated data processing code was developed to process the raw measured data in which the processed data were printed out as constraints normal to the FE cut surface. Using the developed data processing code, full 2D maps of reproduced RS distribution were obtained. The influence of the applied BCs on RS distribution was also examined. Based on the results shown in this study, the following conclusions can be drawn:

1. Full 2D maps of RS distribution at the weld root of a U-rib specimen were obtained in which compressive RS was observed at the weld root.
2. The contour method can be considered an efficient tool to measure RS distribution at the weld root for U-rib connections.
3. The different cases of the BCs applied in this study have a small influence on the resulting energies. While they have a negligible impact on the general distribution of reproduced RS.

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