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Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
Fatigue
FATIGUE PERFORMANCE OF RIB-TO-DECK JOINTS STRENGTHENED WITH INTERNAL WELDING

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Abstract: Rib-to-deck joints of orthotropic steel decks (OSDs) in steel bridges are susceptible to longitudinal fatigue cracking, which often results in considerable costs as well as traffic interruption. This paper numerically simulated the Crack II of rib-to-deck joint and analyzed the crack failure mode of the joint. To mitigate such cracking, a strengthening method using internal welding was investigated. The effects of initial crack size, internal weld size and crack depth on the stress intensity factor (SIF) of crack tip on rib-to-deck fatigue details were studied by finite element method. The finite element analysis demonstrated that the proposed method can significantly improve the detailed stress range of the weld root, lead to the transfer of crack development mode, and prolong the fatigue life of rib-to-deck joints. Numerical analysis validated the beneficial effect of strengthening measures on the stress intensity factors at crack tips. Calculation of stress intensity factors at crack tips resulted that the crack development law, and the application range of reinforcement method was analyzed. This study provided a reference to the design and application of internal welding in the strengthening of weld details in OSDs.

Keywords: Rib-to-deck joints; Crack II; Internal welding; Crack size; Finite element model

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1 INTRODUCTION

Orthotropic steel deck (OSD) features light weight and high strength, and is an important landmark innovation achievement of modern bridge engineering and the preferred bridge deck structure for long-span bridges [1-4]. Existing studies show that [5-7]: (1) the fatigue cracking cases of longitudinal rib-to-deck joints and longitudinal rib-to-diaphragm joints account for 30.2% and 61.0% of the total fatigue cracking cases of steel bridge deck respectively, and the total proportion of the two is as high as 91.2%. The two types of welded joints are the key structural details that determine the fatigue performance of steel bridge deck. Figure 1 shows the fatigue cracking mode of welded joints between deck plate and longitudinal rib as well as cross details of longitudinal rib and diaphragm.

The key factors affecting the fatigue life of steel deck structure mainly include internal and external factors. The former mainly includes random characteristics such as structural system, structural detail design, weld geometric parameters and manufacturing defects, and the latter mainly refers to service environment and random traffic load conditions [6-9]. In recent years, fatigue cracking cases of steel bridge deck have occurred frequently, showing the characteristics of ‘universality, early occurrence, multiple occurrence and reproducibility’. Scholars have made fruitful research on the fatigue crack reinforcement methods of steel
bridge deck, and put forward a variety of fatigue crack reinforcement methods, including crack arrest hole method, welding repair method, local reinforcement method, combined system method and fabricated reinforcement method [10-16], as shown in Figure 2. The research content mainly focuses on the effect of reinforcement methods on the stress amplitude, stress amplitude and the reduction of stress intensity factor at fatigue crack tip and the inhibition effect of fatigue crack propagation are carried out.

![Figure 1: Typical fatigue cracking mode of OSD](image1)

Previous research showed that the dominant cracking modes of the rib-to-deck joints and the longitudinal rib-to-diaphragm cross joints are closely related to the structural system design parameters and structural detail design of the steel bridge deck, and the fatigue life of the dominant cracking mode determines the fatigue life of the structural details. When the penetration depth is less than the critical penetration depth, the dominant cracking mode of longitudinal rib-to-deck joint (single side weld) is crack-III; When the penetration depth is greater than the critical penetration depth, the dominant cracking mode of longitudinal rib-to-deck joint (single side weld) is crack-II.

![Figure 2: Strengthening method for fatigue cracking of OSD: (a) crack-arrest hole and welding repair; and (b) assembly reinforcement method.](image2)

Taking the dominant cracking mode of longitudinal rib and deck welding details, crack-II adopts internal weld reinforcement as an example. Through finite element analysis, this paper presents the application of internal weld for strengthening cracked OSDs. Numerical analysis validated the beneficial effect of strengthening measures on the stress intensity factors at crack tips. Calculation of stress intensity factors at crack tips resulted that the crack development law, and the application range of reinforcement method was analyzed. This study provided a reference to the design and application of internal weld in the strengthening of weld details in OSDs.
2 FAILURE MODE OF OSD

2.1 Full scale model

After 15 years of service, large amount fatigue cracks (crack-II) were found after the bridge deck pavement was removed. When considering the hidden fatigue cracks (crack-II), the fatigue cracks of each cracking mode of steel box girder account for about 54% of the fatigue cracks in the welding details of longitudinal rib and deck plate, as shown in Figure 3 (a). Among them, for the details of longitudinal rib and roof welding, the fatigue crack of crack-ii accounts for about 87%, as shown in Figure 3 (b), which is basically consistent with the predicted crack mode; At the same time, the dominant cracking mode crack-II of the structural details belongs to hidden cracks, which cannot be visually observed in the steel box girder, and the occurrence of the dominant cracking mode leads to local stress redistribution, which reduces the stress amplitude of the cracking mode crack-I and then reduces its fatigue cumulative damage. Therefore, the number of fatigue cracks of the cracking mode crack-I is small.

Zhang et al. [8,9] carried out the fatigue performance research on the welding details of longitudinal rib and deck through seven full-scale segment models. The test model includes three traditional equal thickness longitudinal ribs and four new upsetting longitudinal ribs. The full-scale segment model is composed of top plate, two longitudinal ribs and two diaphragm plates. The detailed parameters are shown in Figure 4. When the penetration rate of rib-to-deck joints were $\rho = 75\%$, the cracking mode of the model was crack II.

Hirayama et al. [17] studied the cracking mode and fatigue performance of longitudinal rib-to-deck welded joints with different penetration rates through two full-scale segment models and wheel moving loading mode. When the penetration rate of rib-to-deck joints were greater than 75%, the cracking mode of the model was crack II. Previous studies have shown that when the penetration rate at the details of rib to deck meets the requirements, the dominant cracking mode is crack II.
2.2 Sub-sized specimen model

The sub-sized specimen model is mainly used to carry out the fatigue performance research on the welded details between the longitudinal rib and the deck. There are constraints and load types of this kind of test model: (1) the transverse ends of the roof are constrained by hinge or consolidation, the longitudinal rib is in a completely free state, and the fatigue load is applied on the top surface of the roof, see Figure 5 (a); (2) the transverse ends of the top plate are restrained by hinge or consolidation, and the fatigue load is applied to the bottom plate of the longitudinal rib or to the web of the longitudinal rib through tooling, as shown in Figure 5 (b).

Figure 5. Load schematic diagram of sub-sized specimen model: (a) SM-1 [18]; and (b) SM-2 [19].

Under the loading mode SM-1, the cracking modes of crack-I and crack-III mainly occur in the welding details between the longitudinal rib and the top plate. With the improvement of penetration rate, the dominant cracking mode of the structural details moves from crack-III to crack-I [4, 20-29]. Yuan [18] carried out 185 fatigue tests by loading SM-2. The cracking mode crack-I accounted for a relatively high proportion, and the cracking modes of crack-III and crack-IV also occurred and accounted for a relatively low proportion. However, the
cracking mode of crack - II did not occur in this group of fatigue tests. Researchers Janss [30], Bruls [4] and Bigonnet [4] used similar test models to study the fatigue performance of the structural details. From the test data, the dominant cracking model is transferred from crack-III to crack-I with the increase of penetration rate of rib to deck joint.

2.3 Experimental model design

In order to study the cracking mode crack-II of rib-to-deck details, the specimen model needs to be redesigned. By adjusting the action position of fatigue load, the full-scale segment model can be used for the welding details of longitudinal rib and roof, but the model scale is large and the test cost is high; The scale of the sub-sized specimen model is moderate and the stress mode is simple, but the fatigue test results are basically the crack-I cracking mode when the penetration rate is greater than the critical penetration rate. The main reason is that the stress state of the structural details can only simulate the stress state of the actual structural cracking mode crack-I.

When the test device is used for loading, the test model of longitudinal rib and deck welding details is composed of deck and full width longitudinal rib. The deck and support column can use hinged supports to simulate hinged constraints. The bottom plate of rib is connected to angle steel through high-strength bolts to realize the constraint on the longitudinal rib, which makes the stress of the longitudinal rib between complete freedom and consolidation constraint. The purpose of basically consistent stress state of the specimen model crack-II with that of the actual structure is achieved by adjusting the angle steel thickness, support column stiffness and constraint stiffness. Figure 6 shows the schematic diagram of the test device.

![Figure 6: Schematic diagram of fatigue test device for specimen model.](image)

![Figure 7: Design of test model (unit: mm)](image)

The top plate thickness of the test model is 18mm and the longitudinal rib size is 300mm ×
300mm × 8mm, and the geometric outline dimension of the test model is 300mm × 800mm × 318mm. The penetration rate of single-sided welding is 75%, the weld leg size is \( l = h = 7 \) mm, and Q345qD steel is used for the test model, as shown in Figure 7.

3 ESTABLISHMENT OF FE MODEL

3.1 An equivalent structural stress

According to the loading mode of the test model, the equivalent structural stress method was used to study the influence of the change of transverse loading position on each cracking mode. The loading area is set to 200mm × 200mm. The transverse loading position moves from the longitudinal rib center to the support position 25 mm each time. Nine load cases were set. Variation of equivalent structural stress with load transverse position in typical cracking mode of rib-to-deck joints, as shown in Figure 8. The maximum equivalent structural stress of each cracking mode is different in the transverse loading position, but the equivalent structural stress of the cracking mode Crack-II is greater than that of the cracking mode Crack-I, that is, the cracking mode of the test model is independent of the transverse loading position.

![Figure 8: Equivalent structural stress of typical cracking modes varying with transverse loading position.](image)

3.2 Weld root crack mode

Test loading process is defined as two stages: (1) Stage I: test model before strengthened with internal weld; (2) Stage II: test model after strengthened with internal weld. According to structural stress, weld root cracking occurred in stage I of test model, that is, crack-II appeared in the test model. According to the test model size, loading conditions and boundary constraints, the finite element model (FEM) of fatigue crack with crack mode crack-II was established. The initial micro-crack is \( a_0 = c_0 = 0.1 \) mm, as shown in Figure 9. The load amplitude is 50 kN, and the load action area is 200 × 200. The action position is the position when the structural stress is the largest in Figure 8.

Figure 10 shows the crack concerns of the weld root cracking mode include point A in the crack surface direction and point C in the crack depth direction. The variation of crack length \( c \) with crack propagation depth \( a \) is shown in Figure 11. The results show that with the increase of crack propagation depth, the ratio of crack length to depth increases slowly at first and then increases rapidly at a large rate. With the continuous propagation of cracks, especially in the late stage of propagation, the crack grows faster in the length direction and slower in the depth direction.
The variation of the stress intensity factor (SIF) amplitudes of Type I ($\Delta K_I$), Type II ($\Delta K_{II}$), and Type III ($\Delta K_{III}$) at the fatigue crack focus points with the crack propagation depth under the weld root cracking mode is shown in Figure 12 (a). It can be seen from the figure that the amplitude of Type I SIF is much larger than that of type II and type III SIF under the root cracking mode, and it is a composite crack dominated by Type I cracking. The amplitude variation of Type I stress intensity factor at two points A and B is slightly different with the
crack propagation. The amplitude variation of equivalent stress intensity factor at Point A directly affects the crack growth rate along the surface length direction. The larger the amplitude of stress intensity factor, the faster the crack growth. The amplitude of equivalent stress intensity factor increases rapidly in the early stage of crack propagation, and then reaches the peak gradually in the stable growth stage. When the crack propagation depth reaches about 1/2 of the plate thickness, the stress intensity factor decreases gradually, and the propagation rate along the surface length direction decreases gradually. The amplitude variation of equivalent stress intensity factor at Point C directly affects the crack propagation rate along the roof thickness direction. At the early stage of crack propagation, the amplitude of equivalent stress intensity factor increases rapidly and then enters the stable propagation stage. When the crack propagation depth reaches about 1/2 of the plate thickness, the stress intensity factor begins to decrease rapidly, indicating that the crack propagates slowly along the depth direction.

![Graphs showing fatigue crack propagation characteristics of crack-II: (a) variation law of SIF amplitude with crack depth; (b) variation law of point-A SIF amplitude with crack depth; and (c) variation law of point-C SIF amplitude with crack depth.](image)

Figure 12: Fatigue crack propagation characteristics of crack-II: (a) the variation law of SIF amplitude with crack depth; (b) variation law of point-A SIF amplitude with crack depth; and (c) variation law of point-C SIF amplitude with crack depth.

Table 1 lists the equivalent stress intensity factor amplitude of the key points of the rear crack of the longitudinal rib medial fillet weld with 6mm, 8mm and 10mm welding feet under the most unfavorable loading conditions. Figure 13 shows the rib-to-deck joint with internal weld. The amplitude of equivalent stress intensity factor of crack key points decreases after internal welding, which proves the effectiveness of steel bridge deck reinforcement. Other factors remain unchanged, and the amplitude of equivalent stress intensity factor decreases
with the increase of welding foot size. When the internal weld foot size is 10 mm, the equivalent stress intensity factor amplitude of the crack focus is 88.3 MPa·mm$^{1/2}$ and 97.6 MPa·mm$^{1/2}$, respectively. Compared with the equivalent stress intensity factor amplitude of the crack focus point before reinforcement, the decrease of Point A is 80.1 %, and the decrease of B point is 67.4 %. The calculation results show that the introduction of internal welding can effectively delay the further propagation of cracks and obtain an ideal crack arrest effect. Figure 14 shows the variation of SIF with weld size. It can be seen from the figure that the weld size of 6 mm can meet the requirements of internal weld reinforcement, and the effect of increasing the welding size is similar.

![Figure 13: Rib-to-deck joint with internal weld. (unit: mm)](image)

Table 1 The SIF of crack before and after internal welding reinforcement

<table>
<thead>
<tr>
<th>Weld size (mm)</th>
<th>Point A $\Delta K$ (MPa·mm$^{1/2}$)</th>
<th>Decreasing range (%)</th>
<th>Point B $\Delta K_{eff}$ (MPa·mm$^{1/2}$)</th>
<th>Decreasing range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage I</td>
<td>Stage II</td>
<td></td>
<td>Stage I</td>
<td>Stage II</td>
</tr>
<tr>
<td>6</td>
<td>443.5</td>
<td>108.7</td>
<td>75.5</td>
<td>299.3</td>
</tr>
<tr>
<td>8</td>
<td>443.5</td>
<td>94.0</td>
<td>78.8</td>
<td>299.3</td>
</tr>
<tr>
<td>10</td>
<td>443.5</td>
<td>88.3</td>
<td>80.1</td>
<td>299.3</td>
</tr>
</tbody>
</table>

![Figure 14: The SIF of crack.](image)

In order to further simulate the influence of crack length and depth on the reinforcement effect of internal welding, four crack sizes were selected for the model. According to the crack size, the numerical model of internal weld reinforcement is established, and the crack stress intensity factor is calculated. In order to compare the reinforcement effect of different crack sizes by internal weld, the crack size corresponding to different crack depths is selected. The calculation results are shown in Table 2.

The results show that: (1) The SIF amplitude at the crack tip of Crack-II can be effectively
reduced by using internal-weld reinforcement method. The main reason is that the existing cracks become internal defects by applying fillet welds inside the longitudinal ribs, and the local stress characteristics are changed to reduce the SIF amplitude. (2) When different crack sizes are reinforced, the amplitude reduction of SIF at crack tip is basically the same, indicating that when the reinforcement method of structural details is determined, the reinforcement effect of crack size within a certain range is basically determined, but whether the existing cracks continue to expand is closely related to the size of external load.

<table>
<thead>
<tr>
<th>Crack size (mm)</th>
<th>Load stage</th>
<th>SIF ΔK (MPa·mm^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>c</td>
<td>Stage I</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>325.4</td>
</tr>
<tr>
<td>4</td>
<td>8.5</td>
<td>383.4</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>406.9</td>
</tr>
<tr>
<td>8</td>
<td>23.5</td>
<td>416.3</td>
</tr>
</tbody>
</table>

### 3.3 Fatigue life

Structural stress method [31] decomposes the highly nonlinear stress existing in weld toe section under external load into membrane stress $\sigma_m$, bending stress $\sigma_b$ and nonlinear peak stress $\sigma_{nl}$ generated by local notch effect. The resultant force of membrane stress $\sigma_m$ contributed by in-plane tensile effect and bending stress $\sigma_b$ contributed by out-plane bending effect is structural stress $\sigma_s$. Structural stress $\sigma_s$ can be integrated by finite element method according to the following equation:

$$
\sigma_s = \sigma_m + \sigma_b = \frac{f_x}{t} + \frac{6m_z}{t^2}
$$

(1)

Considering the thickness effect and loading mode effect, the equivalent structural stress amplitude $\Delta S_s$ is

$$
I(r)^{1/m} = 0.0011r^6 + 0.0767r^5 - 0.0988r^4 + 0.0946r^3 + 0.022r^2 + 0.014r + 1.2223
$$

(2)

$$
\Delta S_s = \frac{\Delta \sigma_s}{I^{(2-m)/2m}I(r)^{-1/m}}
$$

(3)

$$
 r = \frac{\Delta \sigma_s}{\Delta \sigma_m} = \frac{\Delta \sigma_s}{\Delta \sigma_m + \Delta \sigma_b}
$$

(4)

Where $t$ is plate thickness; $f_x$ is the linear force along $x$ axis; $m_z$ is the linear bending moment around $z$ axis; $I(r)$ is the dimensionless constant of load bending ratio $r$; crack propagation index $m$ is 3.6 [31].
The principal $S$-$N$ curve equation of fatigue life is solved by equivalent structural stress amplitude:

$$N = \left( \frac{\Delta S}{C_d} \right)^{-1/h} \quad (5)$$

In the equation, $N$ is fatigue life; $C_d$ and $h$ are test constants.

The damage $D_i$ of each crack propagation step subjected to $\Delta n_i$ cycles under the load amplitude $\Delta \sigma_i$ is calculated, where $\Delta N_i$ needs to be calculated by the main $S$-$N$ curve equation according to $\Delta \sigma_i$; The fatigue cumulative damage $D$ in the process of crack propagation is obtained by linear accumulation of damage degree $D_i$ according to Eq. (6) and (7).

$$D_i = \frac{\Delta n_i}{\Delta N_i} \quad (6)$$

$$D = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{\Delta n_i}{\Delta N_i} (i = 1, 2, \ldots, k) \quad (7)$$

The fatigue cumulative damage of crack-II before and after strengthening is calculated according to Eq. (7); The calculation results are shown in Figure 15. After strengthening of internal weld, the cumulative rate of fatigue damage in stage II is significantly lower than that in stage I. It is necessary to further research for different reinforcement timing and crack size. The fatigue crack reinforcement design of steel bridge deck will change the propagation characteristics of existing fatigue cracks and the stress state of key structural details, thus directly affecting the fatigue life of the reinforcement system. Therefore, the fatigue crack reinforcement design of steel bridge deck should be carried out around the fatigue life of the reinforcement system.

![Figure 15: Fatigue cumulative damage.](image-url)

4 CONCLUSIONS

In this paper, it is taken as the research object that the weld details between longitudinal rib and deck of OSD, and the crack propagation characteristics of crack mode Crack-II are analyzed. The stress intensity factor at the crack tip of the welding details for rib-to-deck joints after strengthen is calculated, and the weld-root crack mode and the strengthening effect are evaluated. The main conclusions are as follows:

(1) The three-dimensional numerical simulation of the crack propagation process of the weld root on rib-to-deck joints was carried out by using the finite element software. Under
fatigue failure mode, the crack propagation from initial defect to critical crack size is dominated by type I crack. The shape of crack becomes flatter with the increase of crack depth.

(2) In the strengthening method of internal weld, when the size of the welding foot is 10 mm, the stress intensity factors at the crack focus points A and B decrease the most. After internal weld, the strain of each key measuring point is basically restored to the initial stress state of stage I. This method has obvious repair effect on the local stiffness of the structural details.

REFERENCES


[22] Li M. *Fatigue Evaluation of Rib-to-Deck Joint in Orthotropic Steel Bridge Decks*. Kyoto: Kyoto University, 2014.


These proceedings contain the papers at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation - joined a few years later by the Hong Kong Institute of Steel Construction.

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