Journal of Constructional Steel Research 119 (2016) 113–122

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experiment on fatigue behavior of rib-to-deck weld root in orthotropic steel decks

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form 24 November 2015
Accepted 26 November 2015
Available online 17 December 2015

Keywords:
Orthotropic bridge deck
Root crack
Fatigue test
Residual stress
Weld penetration

ABSTRACT

This study experimentally investigated the fatigue behavior of the weld root in orthotropic steel decks stiffened with U-ribs in relation to the loading conditions and welding details. To examine the structural response and local stress near the welded joint, field loading tests, measurement of residual stress, and fatigue tests were carried out. A total of 12 specimens were manufactured, and the fatigue tests were performed by simulating the double tire loading of an actual vehicle. The welding residual stress distribution at the root was examined to understand the mechanism of root crack initiation and propagation behavior. Thus, fatigue behavior of the root crack was investigated and evaluated by considering different stress ratios and weld penetration rates. Based on the fatigue test results and crack patterns, it was revealed that both tensile stress and stress range could affect the root crack initiation. However, the tensile stress rather than the magnitude of stress range would be the effective stress after a crack initiated, and it was seen to be an important factor for root crack propagation. In addition, a penetration rate in the range of 0% to 75% was beneficial for fatigue durability of this structural detail.

1. Introduction

Orthotropic steel bridge decks were widely applied to long-span bridges because of their characteristics such as light weight, high strength and durability, and rapid construction [1,2]. In Japan, many orthotropic steel bridges were extensively constructed in the 1960s–80s. Recently, various types of damage damages to the steel decks were reported owing to long-term operation and the changed operating environment including the emergence of heavy-duty vehicles and increasing traffic volume.

Fatigue cracks in orthotropic steel bridges significantly occurred at partial-penetration fillet-welded connections owing to the cyclic load stress caused by a high number of vehicles. The following typical fatigue cracks have been reported in recent years [3], as shown in Fig. 1. A rib-to-deck crack is usually initiated at the weld root, and it propagates into the deck plate or through the weld bead. It has been reported that root cracks in U-rib to deck connections account for about 18.9% of the total damage types in orthotropic steel decks [4]. The weld toe crack of the deck plate, which is located at the rib-to-cross beam connection with a partially welded joint, and the crack occurring at the fillet weld toe near field-welded splice plates fixed to the webs were also common damage types in orthotropic steel bridges. In addition, there were many other types of cracks. However, crack initiation at the weld root of the longitudinal fillet welding between deck plates and closed-rib cannot be observed by visual inspection, which might have serious implications to bridge safety. Moreover, at present, U-ribs account for about 60% of rib stiffeners in the orthotropic steel deck construction. The rib-to-deck structure includes a large number of single-fillet weld joints because of the wide use of U-ribs [5]. Therefore, fatigue cracks of the weld root between the deck plate and U-rib are one of the most common and serious cracks, because of the inadequate welding details in conjunction with the residual stress induced by the welding process and unfavorable weld shape.

The root cracks have been investigated by several experimental and analytical studies. Analytical studies usually focused on the local stress around the rib-to-deck weld joint, and the fatigue durability of the structure was evaluated by finite-element simulation [6]. Past experimental studies were conducted through full-scale fatigue tests under fixed-point loading [7–9] and rib-to-deck small specimen tests [10,11]. Full-scale fatigue tests of orthotropic steel decks are usually conducted to evaluate the fatigue performance. Bending fatigue tests of small specimens can be conducted to evaluate the fatigue life of crack initiation and propagation within a certain length of the specimens, and it is possible to assess the fatigue crack growth and the fatigue strength. However, the boundary condition is different between the actual orthotropic steel decks and small specimens. It is difficult to compare the fatigue behavior of small specimens with that of actual orthotropic steel decks. This is because the tests are performed under constant

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http://dx.doi.org/10.1016/j.jcsr.2015.11.014
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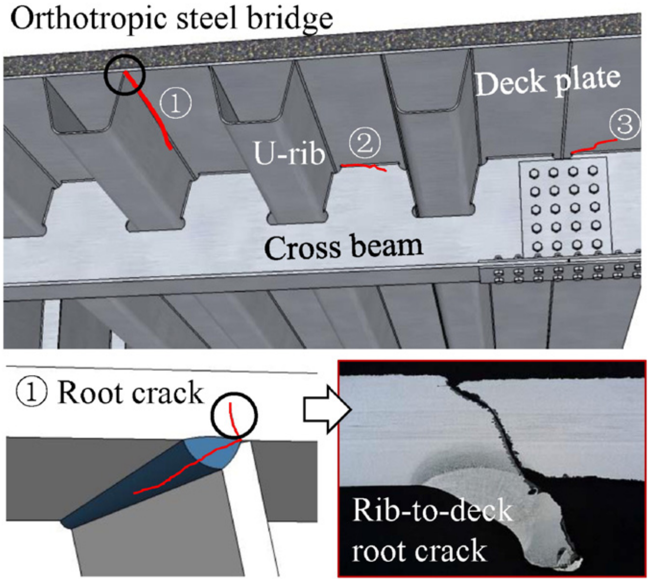

Fig. 1. Typical fatigue cracks in orthotropic steel bridges.

strain range and without restraint on the rib. Moreover, the secondary stress caused by deformation and the effect of release of the welding residual stress after crack initiation could not be properly simulated in these tests.

For penetration rate, most researchers considered that a higher penetration rate could lead to a higher strength in the weld joint. However, the welding process of full penetration weld is more complex. Its reheat cycle would reduce the performance of the welded joint and easily cause weld defects. Recently, full-scale fatigue tests of orthotropic steel decks conducted by some researchers have proved that a shallower weld penetration at the partial joint penetration (PJP) joint appeared to have a positive effect on enhancing the fatigue resistance. Rib-to-deck fatigue tests of small specimens also showed that the specimens with weld melt-through seemed to have slightly lower fatigue strengths than those with 80% PJP [11,12]. Although most researchers agree that a penetration rate below 75 ~ 80% is beneficial to fatigue durability, it is still inconclusive whether full penetration could enhance the fatigue strength of a rib-to-deck weld joint.

In this study, the fatigue behavior at different penetration rates at the PJP weld joint was experimentally evaluated. The structural responses of the reference points near the weld joints were examined using field measurements and fatigue tests. The residual stress at the weld root of the deck plate to U-rib connection was measured using a cutting method. The test results also explained the cause identification of the crack initiation of this structural detail. In addition, based on the measurement of the welding residual stress and fatigue test results, the fatigue behavior and cracking mechanism of the weld root between the deck plate and U-rib were investigated by considering the effective stress.

2. Loading test of orthotropic deck bridge

A1 Bridge is located in the heavy traffic route of the Tokyo Metro bay area in Japan. A1 Bridge consists of two simple box girder bridges and a three-span continuous box girder bridge with orthotropic steel decks. Large vehicles account for 45.2% of the daily traffic volume. The dimensions of the orthotropic steel deck are given in Table 1. Asphalt pavement damage in A1 Bridge was visually inspected in 2004, and severe root cracks were observed during the re-paving construction process in 2005. The root cracks occurred around the intersections of the U-rib at the weld joints between diaphragms, and the maximum length of cracks was over 400 mm [13].

Table 1
Dimensions of the orthotropic steel decks of A1 Bridge (unit: mm).

Thickness of asphalt pavement	75
Thickness of deck plate	12
Dimension of U-rib	340 × 284 × 8
Spacing of the transverse rib	3000
Spacing of U-rib	680
Spacing of web of girder	2800
Distance between diaphragms	5600

Based on A1 Bridge, this study focused on the rib-to-deck weld joint where the root cracks had been observed. A field loading test was conducted in August (2005) when the influence of the asphalt pavement was most negligible at high temperatures. The mid-span of the U-rib was set as the target section, and the measured transverse stresses near the target used as “reference stress”, which were 5 mm away from the weld toe at the bottom of the deck plate. The measured reference stress range was about −40 MPa to 6 MPa under the rear tires, as shown in Fig. 2. Although the tensile stress was much lower than the compressive stress, it has the potential to open the weld root gap, and lead to the initiation and propagation of the root cracks [9]. In this study, a stress ratio σt,max/σc,max equal to 0.13 was obtained from field measurement data. The stress range of A1 Bridge was determined by a stress histogram measurement, which was carried out for 3 days by using the rain-flow method, and the maximum stress range was 170 MPa [14,15]. These results were used in the following fatigue tests.

3. Fatigue test

3.1. Test specimen

A total of 12 fatigue tests were conducted on full-scale orthotropic steel deck specimens. Each specimen was 1400 mm wide and consisted of two U-ribs of 2000 mm span between two cross beams. Steel grade of JIS G3106 SM400A [16] was used for the tested specimens, whose chemical composition and mechanical properties are listed in Table 2(a). Each specimen consisted of a 12-mm-thick deck plate and 6-mm-thick U-rib, and was welded by a semi-automatic CO_2 welding method. Three types of specimens were fabricated with 0%, 75%, and 100% penetration rates at the U-rib to deck plate connection. The dimensions and welding conditions of these specimens are listed in Table 3, where D and U are the thickness of the deck plate and U-rib, respectively, and SP is the penetration rate. Thus, D12U6SP0, for example, represents a 12-mm-thick deck plate and 6-mm-thick U-rib with a weld joint of 0% penetration rate. Photographs of the weld joints of the specimens in the etching test are shown in Fig. 3; in the figure, the heat affected zone caused by the welding process can be observed. The welding area varies between the specimens with different penetration rates.

The dimensions of the specimens and the loading positions are shown in Fig. 4. The dynamic loading area at the mid-span was based on the actual double tires. As the weld root tip stress could not be measured during the test, the transverse stress of points that were 5 mm away from the weld toe in this weld line was considered as the reference stress. The stress at the weld root tips and the reference points tend to have a positive correlation. The tested primary reference stress at the mid-span was considered as the stress condition for each specimen.

3.2. Test set-up

The experimental set-up consisted of two hydraulic jacks that controlled static loading P_s and dynamic loading P_d. The loading positions are shown in Fig. 5. P_s could be changed to vary the stress ratio so that both the tensile stress and compressive stress could be simulated. P_d