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Hot spot stress analysis on rib–deck welded joint in orthotropic steel decks☆

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ABSTRACT

Orthotropic steel decks are used in beams and cable-supported bridges. Fatigue cracks of the vertical rib–deck welded joint have been found in some of the bridges. In this paper, the structural hot spot stress (SHSS) approach is applied to evaluate the rib–deck fatigue. Refined solid models are built using a multi-sub-model technique. Stress around the weld tip is analyzed and effects of the weld profile, the weld toe radius and mesh size are discussed. The SHSS is analyzed using the surface stress extrapolation method, the stress linearization method and the 1 mm stress method. Fatigue strength of the joint based on the SHSS is proposed. Results of this study show that the refined multi-sub-model considering the weld detail can reflect the mechanical behavior of the rib–deck joint. Variation of the SHSS by the three methods decreases to less than 10% and a convergent SHSS is achieved using the refined models. The derived fatigue strength for the rib–deck joint using the SHSS of the refined models is close to FAT100. A more precise fatigue strength prediction can be achieved using the refined model while the coarse models result in a conservative design.

1. Introduction

Steel girders with orthotropic steel decks supported on twin I beams are used in highway bridges and city viaducts. The web plates of the I-shaped beams are usually stiffened with vertical ribs to resist the web buckling. The top wedges of the vertical ribs are welded to the deck plate bearing truck wheels. Due to repeat traffic induced bending, the fatigue cracks of the rib–deck welded joint are reported [1], as shown in Fig. 1. The cracks can be divided into 2 types: the cracks that appear on the bottom surface of the deck plates are named as toe-deck fatigue and the cracks on the vertical ribs are called toe-rib fatigue. The toe-deck cracks may propagate through the deck plate and cause the wearing surface damage and the deck corrosion which are reported in the trough rib–deck welded joint [2–4]. The cracks should be avoided in design application. Otherwise, the deck plate may require regular inspection and retrofit to extend the service life as the trough ribs [3,4]. This study focuses on the toe-deck crack of the rib–deck welded joint.

Some experimental and analytical studies on the rib–deck fatigue have been carried out. Small scale specimens subjected to bending were conducted by [1] to represent the fatigue of the rib–deck welded joint. The fatigue strength of the joint based on the nominal stress was proved to be close to G (50 MPa) level which was specified by Japanese Society of Steel Construction (JSSC) [1,5]. The gusset plate subjected to tension is specified as E (70 MPa) category in American Association of State Highway Transportation Officials (AASHTO) [6] and the bending fatigue strength is not provided. The fatigue strength of the joint might be not strong enough to endure the heavy city traffic and the fatigue cracks were found. The fatigue retrofit and repair techniques such as hole drilling, weld tip ground, shot blasting and Impact Crack Closure Retrofit (ICR) treatment were studied and applied to enhance the fatigue strength of the rib–deck welded joint [7–9]. These efforts help the researchers and engineers to get a better understanding of the rib–deck fatigue.

Full scale tests of the vertical plate rib–deck fatigue might be needed since the tests by Sim and Uang [10] proved that fabrication procedures with close boundary constrains as the real bridge did have influence on the trough rib–deck welded joint. A few full scale fatigue data are available compared with the data of tough rib–deck joint [3,11]. In-site measurement of the rib–deck joint might also be needed compared with the trough rib–deck joint [12].

The fatigue results based on the nominal stress might be an effective way to evaluate the fatigue of the out-plane gusset plates. The methodology for fatigue design of design specifications are based on the assessment of nominal stresses calculated by simplified methods such as P/A or Mc/I and not localized peak stresses at details [6,13]. However, it is difficult to be applied to predict the rib–deck fatigue in the orthotropic steel decks due to the unspecified section modulus and the corresponding moment and membrane forces [14]. Finite element method is usually used to analyze the fatigue of the orthotropic steel decks [4,12,15].

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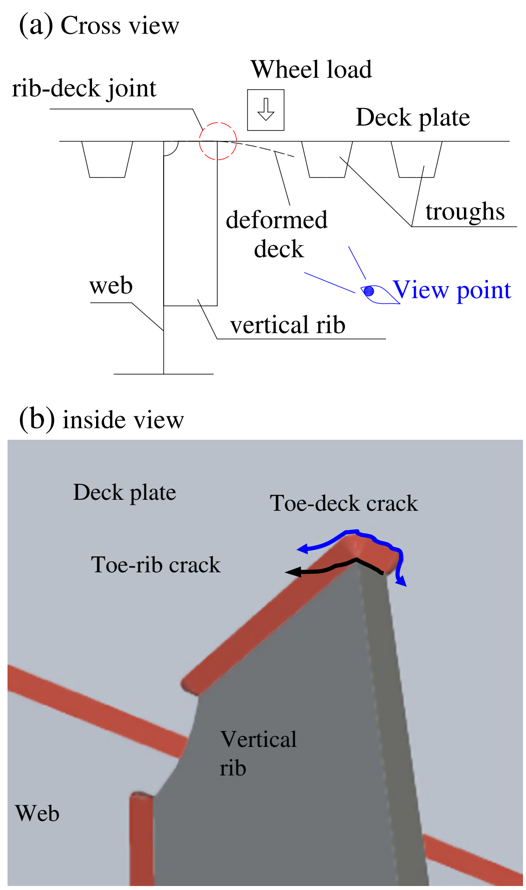

Fig. 1. Fatigue cracks of the vertical rib–deck welded joint (a) cross view (b)inside view.

The refined 3-D FEA for engineering design has not been fully incorporated into the design specifications to date [6].

The finite-element analyses using the effective notch stress method were performed by Sim and Uang [16] to study the trough rib–deck welded joint. The notch method may be suitable to evaluate the fatigue of the vertical plate rib–deck welded joint. The notch stress analysis model usually requires fictitious notch rounding with tiny radius and refined mesh size [17] which may increase the analysis difficulties in design application.

The structural hot spot stress (SHSS) approach has been applied to fatigue evaluation in welded steel joints of ships and offshore structures. And it has been proposed in Eurocode-3 [13], fatigue design recommendations by International Institute of Weld (IIW) [19] and JSSC [5] as a supplement to the nominal stress approach. Connor and Fisher [18] insist that the stress gradients near the weld toe are rather steep and the maximum stress used to determine the stress concentration factor will be influenced by the mesh size of the FE model used in analysis and the strain gauge location and length used in the experiments. The SHSS approach might be suitable to evaluate the fatigue of the rib–deck welded joint. However, the stress determination method and fatigue strength of the rib–deck joint based on the SHSS need to be checked.

Fatigue strength FAT90, FAT100 and FAT112 are proposed by IIW [19] and Eurocode-3 [13] while an 80 MPa S–N curve is used in JSSC [5] for the rib–deck fatigue. It shows that the fatigue strength of the joint has not yet come to an agreement. Both shell and solid finite element models are suggested by IIW [19] and the SHSS calculation method has been provided. JSSC [5] follows the models and SHSS determinations suggested by IIW [19] to evaluate the rib–deck fatigue. However, the research by Xiao and Yamada [20] showed that fatigue life of the out-plane gusset plate might be underestimated using the linear surface stress extrapolation by IIW [19] and the 1 mm stress method is suggested. Bhargava [21] studied the fatigue of the cover plate to flange welded joint. The research showed that the 1 mm stress may give mesh sensitive results compared with the stress linearization method [22] to determine the SHSS. The research by Aygül [23] showed that the shell models suggested by IIW might need modification to assess the fatigue of the longitudinal plate rib–cross beam welded joints. It indicates that the finite element models should be checked for the object welded detail to reflect the fatigue behavior. And the SHSS by a different method should be carefully investigated to get a reliable result.

The SHSS analysis method and the corresponding fatigue strength which vary in different design specifications and literatures are compared and verified in this paper. The solid multi-sub-models are built considering the influence of weld profile and toe radius to study the structural behavior of the joint. The hot spot stress of the rib–deck joint is analyzed using the surface stress extrapolation, stress linearization method and the 1 mm stress method. The stress convergence and mesh sensitivity of the 3 methods with deck layers from 2 to 120 are studied. The hot spot stress deviation among the three methods is analyzed. The fatigue strength of the joint based on the SHSS is predicted.

2. Finite element model

2.1. Specimen of rib–deck welded joint

The purpose of this paper is to investigate the SHSS analyzing model, stress determination method and the corresponding fatigue strength for the rib–deck welded joint. The joint is mainly subjected to bending in the orthotropic steel decks and the out-plane gusset plates have been used to represent the fatigue behavior of the rib–deck joint [1,8,9]. Thus, the study by Yamada [1] is followed and the out-plane gusset plate specimen is analyzed except that of an orthotropic segment.

The profile of the out-plane gusset plate specimen is shown in Fig. 2. The geometric parameter of the deck plate is length × width × depth = 700 mm × 300 mm × 12 mm. The rib is length × width × depth = 340 mm × 300 mm × 12 mm. The rib is welded to the deck plate by a fillet weld with 6 mm weld leg. The CO_2 protected arc welding is used to fabricate the specimen. The specimen is bolted to a base frame on the anchorage end. The cantilever part of the specimen is actuated with vertical load cycles to simulate the bending behavior of the joint. The 40 mm × 45 mm load area is used for each of the four point loads to represent the contact area between the actuation machine and the specimen.

2.2. Solid element modeling

The finite element model is built using the software ANSYS 13.0 [24] with academic license. The 8-node solid element Solid45 with full integration is attributed with linear elastic material properties. By taking advantage of symmetry, only one half of the specimen is modeled. The nodal displacements of the bottom surface at the anchorage end of the specimen are all constrained. The symmetric constraints are applied to the nodes of the symmetric surface. The unit static loads are applied to the cantilever end of the specimen to represent the vertical actuation forces.

Solid models with less than 10 million equations are often preferable in design application to get efficient solutions for the large scale structures with a large amount of construction stages and complex load cases and load combinations. However, the stress results may be sensitive to the weld details and a fine mesh size may be required. Thus, the idea of multi-sub-models is applied to make a balance between the accuracy and the computational cost. The multi-sub-models consist of a global model with 12 mm–3 mm element length, a medium model with 1 mm–2 mm element length and a refined model with 0.1 mm–0.5 mm element length. The weld detail is included in the solid model and the corner of the turnaround weld at gusset tip is modeled with a quarter of a cone. The global coarse model is solved firstly. The nodal displacement results from the global model at the interface between the global and the medium models are extrapolated