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Structural behavior of orthotropic steel decks with artificial cracks in longitudinal ribs

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A B S T R A C T

The butt welds at U-rib connections of orthotropic steel deck are usually connected by field welding. In recent years, long fatigue cracks have been observed in the field welds of U-ribs within the decks. In this study, to investigate the effect of rib fractures on structural response, the field tests were carried out at an actual bridge with artificial cracks by gas-cut. Moreover, FE models with the combination of artificial rib crack and rib-to-deck cracks were established. Based on the field measurement and FE analysis results, the deformation and stress fluctuation of structure details were investigated via quantitative analysis. The results show that once the fatigue cracks occurred at butt weld of ribs, the longitudinal stress withstood by the stiffener would be transferred to the localized deck plate and adjacent ribs. Besides, the butt weld crack of ribs would result two consequences: one is the effect of rib rotation on out-of-bending at crossbeams, another is the interaction between adjacent ribs. The fatigue strength recommended by the specifications might not applicable for the evaluation of butt welds when adjacent rib cracks occurred. In addition, for the combination of multiple cracks propagating to different directions, the strength reduction of structure could seriously compromise the bridge safety. Finally, the asphalt pavement variation caused by seasonal temperature has similar influence on the stress responses for cracked or no-cracked structures.

1. Introduction

Orthotropic deck bridges have been widely used in a lot of countries from decades ago. They have become an economically favorable alternative when the following criteria are important: weight lightening, ductility, thin or shallow sections, rapid bridge installation, or cold-weather construction [1]. Light weight superstructure is the primary reason for using orthotropic decks in long-span bridges. The mass can be reduced by 18%–25% for long span bridges by abandoning the conventional reinforced concrete deck approach and alternatively using an orthotropic deck system. This is extremely important since dead load causes 60%–70% of the stresses in the cables and towers [2,3]. However, an orthotropic bridge involves numerous plates and welded joints that upon shrinkage of the welded metal, potentially lead to additional locked-in stresses [4]. Recently, many fatigue cracks have been reported in orthotropic bridges in Japan and other countries [5–8]. These fatigue cracks were mostly found in the butt welds of longitudinal ribs, welding connections between the ribs, crossbeams, and deck plates, as shown in Fig. 1.

The occurrence of fatigue cracks in field-welded U-ribs has been shown to account for approximately 5.7% of the total damage to orthotropic steel decks [5]. Even though they did not comprise the largest proportion of fatigue cracks, it is one kind of fatigue cracks that most likely to extend into large size. The bottoms of the ribs are subjected to tensile stress under service life, and thus, rib-to-rib cracks might propagate to rapidly form a large crack. Additionally, longitudinal ribs are usually connected via field welding, so most rib cracks have been found within the welded material, along the lines of the butt welds [9]. Since the butt welded joints of these ribs are often fabricated on-site with incomplete penetration, they usually have lower quality than shop welds, and cracks would be easy to initiate from the stress concentrated points. The rib cracks at actual bridge in Japan as shown in Fig. 2(a). The root crack was prone to occur from the root tip of butt joint and cannot be detected easily, as shown in Fig. 2(b). Furthermore, the fatigue problem in other structural details (cut-outs of crossbeam; butt joint of adjacent ribs) might also occur due to the stress redistribution caused by cracked ribs. For instance, the large crack at butt welded joint might lead to other adjacent rib cracks in transverse. The occurrence of fatigue cracks at multiple U-ribs might lead to adverse effects on the stability of the structure, such as the deformation of deck plate, rotation of ribs, and out-of-bending at crossbeams.

In recent years, various fatigue tests, and stress analyses have been conducted on orthotropic steel decks [10–12]. But the orthotropic steel structures with long cracks are usually difficult to be tested, from the consideration of security and costs. Most of these studies

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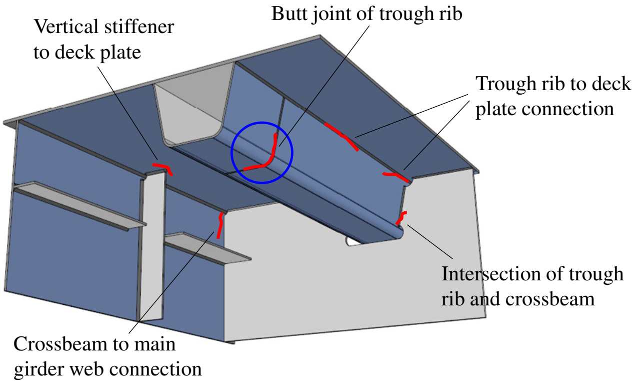
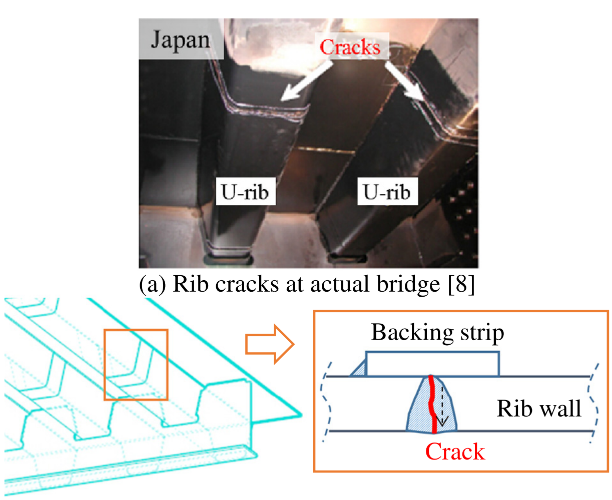


Fig. 1. Common fatigue cracks in orthotropic steel decks [5].

investigated the fatigue behaviors of rib-to-deck welded joints [13,14], rib-to-diaphragm welded joints [15], as well as the variation of these flexural stresses at the deck plate and U-ribs under the action of wheel loads [16]. Related study on fatigue life predictions of rib crack were conducted with LEFM method, indicating that the lack of penetration zones of 2–3 mm resulted in low fatigue strength of the butt welded joints [9]. The influence of fatigue rib cracks on deflection and stress of orthotropic steel decks has been partially elucidated by numerical shell models [17]. However, most of these researches were only applicable for local fracture areas, without considering the effect of large cracks on global structure. Until now, the relationship between rib cracks and their corresponding structural responses are still unclear.

In this study, to investigate the effect of rib fractures and the large crack combinations, the field tests were carried out at an actual bridge under the static single and double tire loading. The artificial cracks were set at the rib bottom in the mid-span by gas-cut. Moreover, FE models with the combination of artificial rib crack and rib-to-deck cracks were established. Based on the field measurement and FE analyze results, the structural responses of orthotropic steel deck were compared considering the initiation of the rib crack from mid-span and quarter span. Besides, the torsional rigidity of ribs with butt weld crack was investigated via quantitative analysis. The effects of multiple ribs fracture on structural responses were also discussed considering various crack combinations and three type of typical transverse load positions. Finally, the effect of asphalt pavement on structure stiffness was also clarified, considering the different Young's modulus of asphalt under different temperatures.



(a) Rib cracks at actual bridge [8]

(b) The possible crack types at field welded joint

Fig. 2. Fatigue cracks in orthotropic steel decks.

2. Field measurement in actual bridge

In actual bridge, the butt welded joints of ribs are usually set at the quarter span, for the construction convenience and to avoid the largest bending moment occurred at welded joint. In this study, to investigate the stress responses of structure with artificial rib cracks, the field test was carried out by considering the most adverse crack position: the artificial cracks were set at the cross section of mid-span by gas-cut. Therefore, the complicated growth path of root-to-deck crack in longitudinal direction could be simplified as symmetric. The occurring of crack at mid-span would result in most adverse loading case in longitudinal, causing the largest displacement or torsion at the deck plate and ribs.

The objective bridge used for field measurements was an orthotropic steel bridge with two spans in national the Expressway. The total length of the main girder is 99 m, with the 2.5 m longitudinal spacing between two crossbeams, and 3.5 m transverse spacing between girders. The orthotropic steel deck consisted of a 12 mm-thick deck plate, 6 mm-thick U-rib, and 12 mm-thick crossbeam. The dimension of the longitudinal U-rib is $320 \times 240 \times 6$ mm and the thickness of the asphalt pavement is 80 mm, as shown in Fig.3(a).

Field static testing in the actual bridge was conducted in November. The loading truck used was a three-axle truck with a total weight of 217.6 kN (22.2 tonf) and an axle width of 2 m. The second and third axles both weighed 78.4 kN (8.0 tonf). The wheel base of first and second axles is 5.75 m. The rear wheels were all double tires and the wheel base is 1.30 m. The double tire area, transverse loading position, and the strain locations, are shown in Fig. 3(b; c). In longitudinal direction, loadcase1 is the loading at mid-span, and loadcase2 is the loading at quarter span. The biaxial strain gauges were attached to the bottom of the deck plate, measuring the longitudinal and transverse stress, and a uniaxial strain gauge was attached to the bottom of the U-rib to monitor the transverse stress.

For the safety consideration of the test bridge, the rear tire loading test was only carried out on the no-crack structure. The front tire loading tests was conducted on the structure before and after the artificial cutting process. Fig. 4 shows the location of artificial cracks in actual bridge by gas-cut. The cut sequence was conducted depending on general initiation and propagation process of fatigue crack. The cut direction was alone the butt weld ①, ② and rib-to-deck weld ③. The bead crack at rib-to-deck welded joint was easy to occur due to the effect of fractured ribs and incomplete penetration. The rib-to-deck artificial cracks propagated in both of longitudinal directions, from mid-span to quarter span. The stresses were measured at mid-span and quarter span at several cracking stages.

3. Comparison of field measurement and FEA

3.1. FE models

The FE models of one-span orthotropic steel deck between two girders were built according to the standard dimensions of an actual bridge in Expressway. The elastic models by comprising the solid elements and rigid loading surfaces were established by Marc Mentat 2012, with the Young's modulus of 206,000 MPa and Poisson's ratio of 0.3 applied as the steel material properties. All of the welded joints and cope holes were simulated in models using a minimum mesh size of 1×1 mm. The aspect ratio of elements is closed to 1.0 at refined mesh locations. The boundary conditions, element mesh division, the load positions of single tire at mid-span and quarter span are shown in Fig. 5(a). This model was fully-constrained at the connection to the main girders, denoted as model N (no-crack model). In addition, the stress interaction between the transverse and longitudinal wheels should be small [18], thus it was ignored in this study, and only the one side tire of the first/s axle was simulated as a loading surface in the models. The loading area of one tire was simulated by a rigid body