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Fatigue behaviour of orthotropic steel bridge decks with inner bulkheads

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ABSTRACT

Tests on a full-scale orthotropic steel deck (OSD) specimen were conducted to investigate the effects of inner bulkheads set inside the U-ribs on the static and fatigue behaviours of the OSD. The total length and width of the OSD specimen are 5 m and 2.24 m, respectively. It contains three longitudinal floorbeams and four transversal U-ribs. U-ribs with and without inner bulkheads are symmetrically arranged in the cross section of the specimen. Finite element (FE) analyses on the OSD specimen model and sub-models were conducted to further study the effects of the inner bulkhead design and different bulkhead shapes. Results of the test and corresponding FE analysis of the specimen showed that inner bulkheads can be used to improve the fatigue life of the OSD. Meanwhile, fatigue cracking in the rib-to-bulkhead details was introduced by installing the inner bulkhead. Results of the FE analysis of the sub-models showed that the distance from the bottom edge of the inner bulkhead to the tip of the floorbeam cutout affects the stress state of the rib-to-floorbeam connection weld significantly. Additionally, the bulkhead shape affects the hot spot stress of the weld toe of the rib-to-floorbeam connection weld significantly. Thus, proper bulkhead shape should be determined by considering the specific stress distribution of the rib-to-floorbeam connection area.

1. Introduction

The orthotropic steel deck (OSD) has been widely used for long- and medium-span bridges due to its advantages in light weight, high ultimate bearing capacity, expedient construction, structural redundancy, etc. [1,2]. An OSD typically consists of a thin-walled steel deck plate, stiffened by a series of closely spaced open or closed longitudinal ribs and transverse diaphragms or floorbeams [3,4]. Decks with closed ribs, particularly U-ribs, are widely used because they are very light weight, have fewer welds, and have higher torsional and flexural stiffness than those with open ribs [5]. Longitudinal U-ribs and transverse diaphragms or floorbeams are typically welded to the underside of the deck plate. Thus, the system may experience many types of fatigue problems at its welding joints, resulting from high cyclic stresses in connections with inadequate welding support [6–10]. In order to reduce the high secondary stress at the bottom of the U-rib, resulting from out-of-plane stresses, a cutout is typically set in the diaphragm or floorbeam [11]. However, more complex stress states and higher stress concentrations at the welded connection of the U-rib web and the cutout area of the diaphragm, called the rib-to-diaphragm (RD) or rib-to-floorbeam (RF) connection, occur after setting the cutout [12–15]. The complex stress state of the cutout is significantly affected by the rib height and inclination, as well as the shape of the cutout [16–18]. The welding procedure is complicated, and the weld quality can barely meet design requirements. Recent reports of cracking in RD or RF connection welds, or in the area near the cutout of OSD decks, which necessitated extensive and costly repairs, created the impression among many bridge engineers and authorities that such damage was widespread and typical [19]. This led to the reliability of orthotropic decks being called into question [20–22].

In order to improve the fatigue behaviour of the RF connection weld and the surrounding area, an inner bulkhead installed inside the U-rib, as shown in Fig. 1(a), was introduced by designers [23]. The bulkhead was installed to reduce the excessive stress concentrations in U-rib webs, resulting from the cutout in the diaphragm. U-ribs with inner bulkheads were first applied to the Williamsburg Bridge in America. In recent years, researchers have performed investigations on the fatigue behaviours and fatigue design of rib-to-deck, RD and RF connections in OSDs containing U-ribs with inner bulkheads. Tsakopoulosp and Fisher [24] conducted laboratory fatigue tests of a full-scale prototype and an as-built orthotropic deck panel to compare the fatigue resistances of two different welded rib-to-diaphragm (RD) connections. Connor and Fisher [25] proposed evaluation procedures for the fatigue designs of RD and rib-to-bulkhead connections. Gu and Zhou [26]

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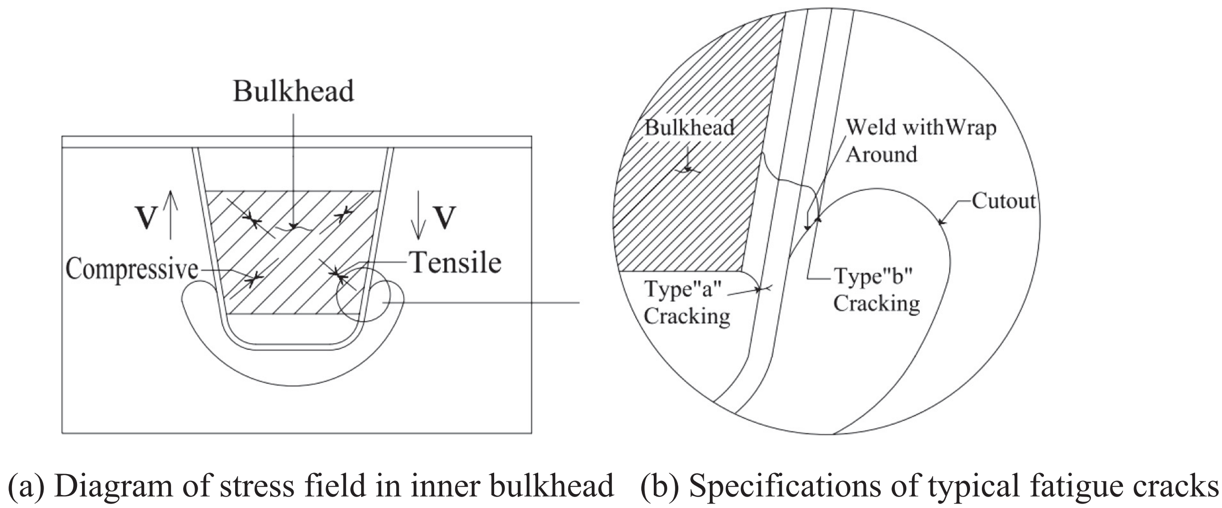

Fig. 1. Stress state of bulkhead and typical fatigue cracks.

conducted tests and numerical analyses on two OSDs having U-ribs with and without inner bulkheads in order to improve bulkhead impact on the fatigue performance of RD connection welds, based on the specific construction details of a steel railway bridge deck. The inner bulkhead was connected to both the deck plate and the U-rib side walls using welds. Thus, the stress state and fatigue life of the RD connection were effectively improved.

With the continuous accumulation of relevant research, researchers have found that the inner bulkhead presented in Fig. 1(a) can improve the fatigue behaviour of rib-to-deck and RD/F connections. However, it may also cause new fatigue problems in U-rib webs, particularly when the size of the bulkhead is not appropriately designed. When the inner bulkhead was set disconnected to the deck plate, discontinuous horizontal shear caused it to act more like a beam in double curvature. The resulting stress fields were graphically illustrated in Fig. 1(a). The tensile stresses might cause two typical types of fatigue cracks, namely type “a” cracking (at the weld end of the bulkhead-to-rib connection) and type “b” cracking (root cracking in the bulkhead and toe cracking in the diaphragm) shown in Fig. 1(b) [27]. In recent years, a few optimization studies on bulkhead shapes have attempted to leverage the full advantages of bulkheads while avoiding the disadvantages discussed above. Oh and Hong [28] proposed the curved bulkhead shown in Fig. 2(a) and conducted a full-scale OSD test, as well as a numerical study. The results revealed that the curved bulkhead was better than the trapezoidal bulkhead discussed above for reducing the stress concentrations at RD connections. A curved bulkhead plate with top radius of 300 mm and a bottom radius of 200 mm was proposed as a final solution. Fanjiang et al. [29] proposed two internal separated stiffeners in the U-rib, as shown in Fig. 2(b), and conducted an experimental study and finite element (FE) analysis on a new design for Bronx-Whitestone Bridge decks. The results revealed that the tension stress in the bulkhead could be effectively eliminated after the separated inner stiffener was applied and that the stress concentration at the RF connection was also significantly reduced.

In this study, a test of a full-scale deck and FE analyses of both an OSD model and OSD sub-models were performed to investigate the effects of bulkheads installed in U-ribs on the static and fatigue behaviours of the OSD. First, based on the OSD design details of a suspension bridge, as well as relevant design and fabrication standards, a full-scale OSD specimen was designed and fabricated. The effects of the inner bulkhead installed in the U-rib of the specimen on the behaviours of the rib-to-deck and RD welds were evaluated based on the test results. Second, a FE model of the OSD specimen was constructed and verified based largely on the static test results. Third, sub-models for the deck plate RF connection were built based on the OSD model and verified by using the results of the test and parametric analysis on element and weld sizes. Finally, the effects of inner bulkheads on the fatigue behaviours of the OSD specimen were investigated by applying the verified OSD model. The effects of the construction design and shape design of the bulkhead were also studied by using the sub-model analysis method.

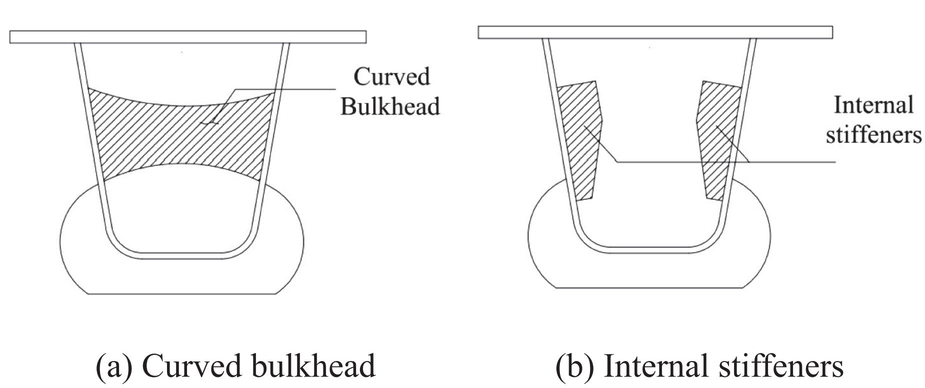

Fig. 2. Two bulkhead shapes.