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Fatigue evaluation of rib-to-deck welded joint using averaged strain energy density method

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ABSTRACT

This paper investigates the feasibility of an averaged strain energy density (SED) method for fatigue evaluation of rib-to-deck weld joint in orthotropic steel deck. The effect of weld geometry on fatigue resistance of rib-to-deck joint is evaluated. The analysis results of the presented average SED method are validated against fatigue testing data and compared with the results of the conventional hot-spot stress and effective notch stress methods. A W-N curve is derived using the averaged SED method and used for evaluating the fatigue strength of rib-to-deck welded joints. The averaged SED method is also used to investigate the effect of weld geometrical variables on the fatigue failure mode transition, and the fatigue strength of full-scale orthotropic steel deck specimens. The results indicate that the averaged SED method provides superior ability in evaluating fatigue resistance and failure mode of rib-to-deck welded joint.

1. Introduction

Due to the advantages such as light weight, high load-bearing capacity, and rapid construction, orthotropic steel deck (OSD) has become an essential component in many long-span bridges and urban viaducts [1–7]. A typical OSD is composed of a deck plate, transverse diaphragms, and longitudinal U-ribs, as illustrated in Fig. 1(a). These components are welded together to form an integrated part. Among different welded joints, rib-to-deck joints have a long total length and are subjected to high stresses in OSD. Thus, fatigue of rib-to-deck welded joint is one of the most serious issues [7–18]. Fig. 1(b) illustrates the typical types of fatigue cracks in a rib-to-deck welded joint, including the toe-to-deck crack (Crack I), toe-to-rib crack (Crack II), root-to-deck crack (Crack III), and weld throat crack (Crack IV) [17,18]. Crack I to Crack IV respectively initiate from the deck toe, rib toe, deck root, and deck root. Cracks I and III propagate through the deck thickness; Crack II propagates through the rib; Crack IV propagates through the weld throat. Different fatigue failure modes have different fatigue properties and influence on the long-term durability of OSD structures. It is important to understand the effect of different fatigue failure modes on the fatigue performance of OSD.

Different methods have been developed for the fatigue evaluation of welded joints, such as the nominal stress method [19], hot-spot stress method [20], effective notch stress method [19,21], *J*-integral method [22], peak stress method [23], the critical distance method [24], and averaged strain energy density (SED) method [25]. Among these methods, the nominal stress method [19], hot-spot stress method [20], and effective notch stress method [19,21] are three prevailing fatigue evaluation methods for rib-to-deck welded joint in OSD. Geometric discontinuity and stress concentration are the main causes of fatigue damage in rib-to-deck welded joints [16–18]. Nominal stress method implicitly considers the weld geometric configuration and stress concentration effects using a series of S-N curves [19]. However, due to the definition of the nominal stress, the nominal stress method only provides a rough estimation in fatigue assessment for complex welded joints [21]. Hot-spot stress method uses extrapolated stresses for stress concentration problems [19,20]. Although the hot-spot stress method was proven effective in evaluating the welded joints with cracks that initiate from the weld toe, the applicability of the hot-spot stress method for root cracks remains unclear [20]. Effective notch stress method is a local approach based on the fictitious notch rounding concept [21]. Effective notch stress method introduces a fictitious notch at weld toe or weld root and uses an average stress at the fictitious notch as the equivalent local stress of notch tip in fatigue evaluation [21]. An effective notch stress S-N curve of FAT 225 (225 MPa at 2×10^6 cycles) was derived for steel welded joints and recommended in the IIW specification [19]. However, the S-N curve may overestimate the fatigue resistance of weld toe and underestimate the fatigue

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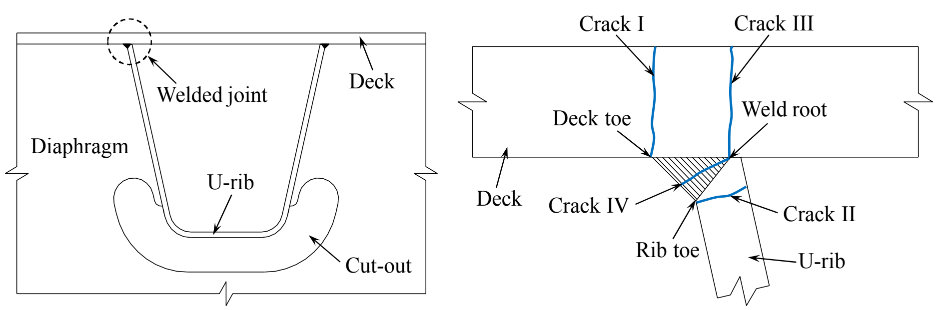
Nomenclature

r, θ	polar coordinates
r	radial distance from notch tip
θ	polar angle
$\sigma_{\theta\theta}$, σ_{rr}, $\tau_{r\theta}$	circumferential, radial, and shear stress components
σ_{zz}	normal stress in z-direction
2α	notch opening angle
λ_1, λ_2	eigenvalue of singularity for Mode I and Mode II in Williams equation
K_1^N, K_2^N	notch stress intensity factors for Mode I and Mode II
K_1, K_2	stress intensity factors for Mode I and Mode II
$f_1(\theta)$, $f_2(\theta)$	symmetric and antisymmetric stress functions
χ_1, χ_2	parameters for symmetric and antisymmetric stress components
e_1, e_2	parameters for SED evaluation
ν	Poisson's ratio
W	strain energy density, SED
E	Young's modulus
$\bar{W}$	averaged value of SED over the control circle or sector
R_0	radius of control circle or sector
A_0	area of control circle or sector
β	included angle between deck and rib
ρ	notch tip radius or fictitious round notch radius
σ_0	nominal bending stress in deck plate
R	stress ratio
p, h	weld penetration depth and weld height
t_d, t_r	deck thickness and rib thickness
l	intersect length between deck and rib web
log (A)	constant in S-N or W-N curves
m	inversed slope of S-N or W-N curves
$\Delta\sigma$, ΔW	stress amplitude and SED amplitude
N	fatigue loading cycles
N_f	loading cycles to failure
SD	standard deviation
ΔP_{min}	minimum fatigue load amplitude of all specimens
ΔP	fatigue load amplitude of each specimen
R_L	load amplitude ratio defined as $\Delta P/\Delta P_{min}$; and
R^2	coefficient of determination of regression analysis



(a) Rib-to-deck welded joint (b) Typical fatigue cracks

Fig. 1. Typical fatigue cracks at a rib-to-deck welded joint of an OSD.

resistance of weld root, because the cross section is strengthened at weld toe and weakened at weld root by the fictitious notch [21].

Under such circumstances, this paper proposes the averaged SED method for fatigue evaluation of rib-to-deck welded joint. An averaged SED method was proposed and developed by Lazzarin et al. [25–29] for fatigue evaluation of V-notched components and welded structures. It is a well-developed method and has been successfully applied to multiaxial fatigue and high temperature fatigue applications [30–32]. Recent applications of the averaged SED method were summarized in reference [33]. It is apparent that the averaged SED method has the capacity of dealing with fatigue issues for welded joints with complex geometry and unifying the fatigue evaluation of weld toe and weld root cracks [34], which is quite meaningful for rib-to-deck welded joints in OSD. However, to date, the averaged SED method has not been used for rib-to-deck welded joints.

This study investigates the feasibility of the averaged SED method in evaluating the fatigue properties of rib-to-deck welded joints. A W-N curve in terms of averaged SED was proposed for the fatigue strength evaluation of rib-to-deck welded joints. The averaged SED method was also used to investigate the effects of weld geometrical variables on the fatigue failure mode transition, and finally evaluate the fatigue strength of full-scale orthotropic steel deck specimens.

2. Averaged strain energy density method

2.1. Stresses at V-shaped notch

Fig. 2 shows a polar coordinate system (r, θ) at a V-shaped notch. The original point is located at the notch tip; the line along the notch bisector is defined zero angle ($\theta = 0°$); the counter-clockwise direction is the positive direction. The stress components $\sigma_{\theta\theta}$, σ_{rr}, $\tau_{r\theta}$ are the circumferential stress, radial stress, and shear stress, respectively. When the notch opening angle (2α) approaches to zero, the notch will become a "crack-like" root notch.

In the polar coordinate system, the stresses in the vicinity of the notch tip can be expressed using the Williams' series expansions [35], as shown in Eq. (1).

$$\begin{Bmatrix} \sigma_{\theta\theta} \\ \sigma_{rr} \\ \tau_{r\theta} \end{Bmatrix} = \sum_{i=1}^{2} \lambda_i r^{\lambda_i - 1} a_i \begin{Bmatrix} f_{i,\theta}(\theta) \\ f_{i,r}(\theta) \\ f_{i,r\theta}(\theta) \end{Bmatrix} \tag{1}$$

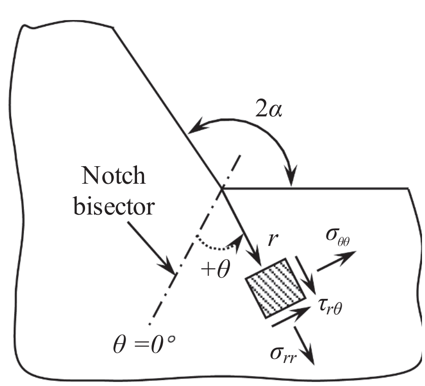


Fig. 2. Stresses are defined in a polar coordinate system at a V-shaped notch.