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Residual stress effects on fatigue behaviour of welded T-joint: A finite fracture mechanics approach

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ABSTRACT

The effects of residual stresses on fatigue behaviour of welded T-joint are investigated based on a coupled stress and energy criterion which requires two fundamental material parameters: the fatigue threshold value and fatigue limit. Finite element analysis of the welding process determines the residual stresses. It is found that the residual stress effects on fatigue strength are significant for $R < 0.5$ and negligible for $R \geq 0.5$. The presence of residual stresses may change the crack deflection direction and lead to the decrease of ductility. The predicted fatigue strength is in good agreement with FAT value recommended by IIW.

1. Introduction

Residual stresses can have a significant influence on the structural durability of different welded joints [1–3]. Tensile residual stresses near surface usually deteriorate fatigue crack initiation and growth resistance with superimposed external cyclic loads [2]. As recommended by IIW [4], allowable fatigue stresses are conservatively determined by tests under high stress ratio for accounting for residual stresses; As recommended in BS 7910 [5], the tensile residual stress is explicitly assumed to be equal to the lesser of the room temperature yield strength of the weld or parent metal. However, it is demonstrated [3, 6] that the residual stresses are actually overestimated in most cases. Therefore, accurate prediction of residual stress effects on the structural integrity becomes more essential, especially when high strength steels are widely used in industries.

Significant progress have been made in recent years for obtaining reliable fatigue assessment of welded structures in terms of structural stress, local stress and fracture mechanics concepts. Several approaches have been used to predict the fatigue of welded joints, for instance the spot welded joints by equivalent structural stress [7] or double-Vee butt welds by the notch stress [8]. Ravi et al. [9] discussed the effects of the strength mismatch, post-weld heat treatment (PWHT) and notch positions on fatigue behaviours of steel welds. Zhao et al. [10] experimentally investigated the residual stress distribution and fatigue crack initiation in cruciform welded joints. From the point view of Fracture Mechanics, some researches [11–14] concluded that the residual stresses may contribute to the crack driving force and the crack-tip constraint. Sonsino [3] reviewed the influences of residual stresses dependent on loading mode, spectrum shape, and weld geometry among others. For well qualified welded joint, the weld toe regions are prone to fatigue crack initiation, and Lassen [15] demonstrated that 40% of fatigue life was consumed to nucleate a crack of 0.1 mm. Since arc welding processes usually result in weld toes with small values of radius, which can be modelled as a zero radius V-shape notch as shown in Fig. 1. Accordingly, fracture and fatigue has been correlated to Notch Stress Intensity Factor (NSIF), which is the asymptotic stress magnitude of Williams' solution for re-entrant corner [16–18].

Recently, Taylor et al. [19] proposed finite fracture mechanics (FFM) assuming a finite amount of crack extension (Δa) instead of an infinitesimal extension (da) to predict the facture and fatigue. However, when applying the average stress criterion, the energy balance in the crack extension is violated. On the other hand, when applying the energetic criterion, the stress criterion cannot be satisfied. Subsequently, Cortnetti et al. [20] have assumed that the value of the finite crack extension is not a material constant but a structural parameter, which is determined by the contemporaneous fulfilment of stress and energy criteria. Carpinteri et al. [21–23] have applied the coupled criterion to structures with sharp V-notches, and demonstrated that the generalized fracture toughness is a function of material tensile strength, fracture toughness and

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Nomenclature

a	crack length
da	infinitesimal crack length
Δa_s, Δa_e, Δa_{se}	critical finite crack length for stress criterion, energy criterion and the couple criterion
b	characterized dimension of the structure
E	elastic modulus
E'	equals $\frac{E}{1-\upsilon^2}$
$\mathcal{G}_I$, $\mathcal{G}_{II}$	incremental energy release rate for cracking modes I and II
$\Delta\mathcal{G}_{th}$	critical energy release rate range
$\Delta\mathcal{G}_R$	residual stress contributions to the crack driving force range
k	the function of re-entrant corner geometries and crack deflection angle
K_I^*, K_{II}^*	generalized modes I and II SIFs
ΔK_{th}	threshold stress intensity factor range
m	slope of S–N curve
n	thickness correction exponent
N	number of nodes along the crack surface
P	the applied load
P_f	the failure load
$P_{xk}^{(1)}$, $P_{yk}^{(1)}$	normal and shear nodal force along the considered crack path in the uncracked configuration
R	$\sigma_{min}/\sigma_{max}$
r, θ	polar coordinates
s	brittleness number
t_{ref}	reference thickness
t_{effe}	effective thickness
u	displacement in x direction
$u_k^{(2)+}, u_k^{(2)-}$ ($v_k^{(2)+}, v_k^{(2)-}$)	nodal displacement parallel (perpendicular) to the crack surfaces in the cracked and uncracked configuration
v	displacement in y direction
w	the width of T joint
λ_I, λ_{II}	Williams' eigenvalues
υ	Poisson's ratio
$\Delta\sigma_f$	fatigue limit
σ_R	residual stress
$\sigma_{\theta\theta}$	circumferential stress in polar coordinate
$\tau_{r\theta}$	shear stress in polar coordinate
φ	initial crack deflection angle
ω	notch angle
$(.)^{(1)}$	uncracked configuration
$(.)^{(2)}$	cracked configuration
$(.)_{max}$, $(.)_{min}$	maximum/minimum
SIF	stress intensity factor

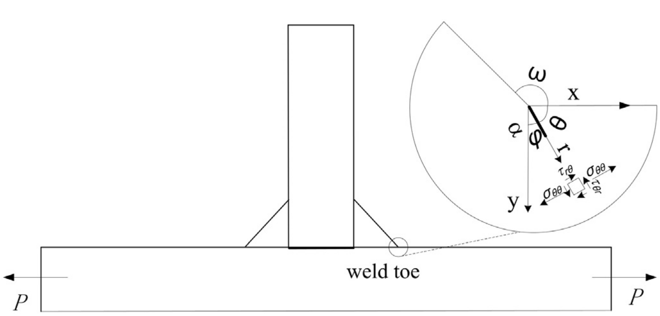

Fig. 1. V-notch around the weld toes and potential crack of length a emanating from the weld toes.

notch opening angle. In this study, the coupled stress and energy failure criterion is applied to investigate the effects of residual stresses on fatigue behaviour of welded T-joints. In the criterion for fatigue, the critical parameters are assumed to be fatigue threshold value, ΔK_{th}, and fatigue limit of material, $\Delta\sigma_f$, in addition to a finite crack extension. The analysis determines the crack initiation angle and fatigue strength. The criterion is validated by comparing its predictions with FAT values in IIW-Recommendation [4].

The paper is organized as follows: the coupled FFM criterion and its extension to fatigue are reviewed firstly. The numerical procedure for residual stress determination is briefly discussed in Section 3. The implementation of FFM is presented in details in Section 4. The results of FFM solution are demonstrated and discussed in Section 5. Finally, the paper ends with the concluding remarks.

2. Finite fracture mechanics for fatigue

The theory of FFM for fracture can be found in the literature for brittle fracture of crack and notch [19–23]. According to the coupled FFM criterion [20,21], a crack is supposed to initiate and propagate by finite crack extension, whose value is determined by the contemporaneous fulfilment of a stress requirement and an energy balance. In this section, an introduction to fatigue is given in details. Moreover, a quantitative assessment of the influence of the residual stresses on fatigue strength prediction can be made by the principle of superposition.

2.1. Strength criterion based on fatigue limit

The FFM stress criterion in the present work assumes that fatigue failure cannot occur if cyclic stress range along the potential crack path is below the fatigue limit of the base material:

$$\int_0^{\Delta a_{se}} \Delta\sigma_{\theta\theta}(r,\theta)dr \geq \Delta\sigma_f \Delta a_{se} \tag{1}$$

where Δa_{se} is the finite crack extension for the coupled criteria, $\Delta\sigma_{\theta\theta}$ is the circumferential stress range, $\Delta\sigma_f$ is the fatigue limit of material determined by smooth cylinder specimen. By referring to the polar coordinate system at the V-notch root presented in Fig. 1, the stress field $\Delta\sigma_{\theta\theta}(r,\theta)$ around the notch tip can be expressed as:

$$\Delta\sigma_{\theta\theta}(r,\theta) = \frac{K_I^*}{r^{1-\lambda_I}} f_{\theta\theta}^{I}(\theta) + \frac{K_{II}^*}{r^{1-\lambda_{II}}} f_{\theta\theta}^{II}(\theta) + \{\sigma_R\} \tag{2}$$

where K_I^* and K_{II}^* are defined as generalized SIFs by Carpinteri [18] or NSIF by Lazzin [16] with slightly difference in coefficients, and (λ_I, λ_{II}) are the Williams' eigenvalues less than 1/2; the last contribution in Eq. (2), $\{\sigma_R\}$, is due to residual stress.

2.2. Energy criterion based on crack propagation threshold

The energy criterion is invoked assuming a virtual crack emanating from the vertex of sharp V-notch. It requires that a crack of a finite extension appears once the crack onset is energetically allowed, that is, the crack driving force integrated over Δa_{se} is higher than the energy necessary to create the new fracture surfaces:

$$\int_0^{\Delta a_{se}} \Delta G(a,\theta)da \geq \Delta G_{th} \Delta a_{se}. \tag{3}$$

Considering the residual stress contribution on the crack driving force $\Delta\mathcal{G}_R$, the energy release rate under plane strain can be reformulated as:

$$\Delta G(a,\theta) = \frac{\Delta K_I^2(\Delta a,\theta)}{E'} + \frac{\Delta K_{II}^2(\Delta a,\theta)}{E'} + \Delta G_R. \tag{4}$$