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Residual stress induced crack tip constraint

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ABSTRACT

This paper studies the effect of welding residual stresses on the near tip stress field in single edge notched bending and tensile specimens. A combined effect of mechanical stresses by the applied load and residual stress on the crack tip constraint is analyzed. Three initial residual stress distributions were considered. It has been shown that the crack tip stress field is strongly influenced by the residual stresses and a new parameter, R, is proposed to characterize the residual stress induced crack tip constraint. The results therefore suggest a three-parameter approach ($CTOD$, Q and R) to characterize the crack tip stress field in the presence of residual stress where $CTOD$ sets the size scale over which large stresses and large strains develop, and the geometry constraint parameter Q and the new residual stress induced constraint parameter R control the actual crack tip constraint level. For the cases analyzed, R is in general positive, which indicates that residual stress can enhance the crack tip constraint. However, the results also indicate that the R decreases towards zero and the effect of residual stress on crack tip constraint can be neglected when a full plastic condition is approached in the specimen.

1. Introduction

Welded joints are common in engineering structures and often the strength of the joints controls the strength of a structure. Over the last decade, there has been an increased interest in understanding weld metal strength mismatch effects on fracture behaviour of welded structures. As a result, a large number of publications on this subject have appeared in literature on the effect of weld strength mismatch on crack driving forces and crack tip constraint [1–8]. It is known that welding residual stresses can play an important role in the fracture behaviour of welded structures. However, detailed studies on the effect of residual stress on crack driving force and constraint parameters are scarce in the literature [9]. Constraint-based approaches to fracture assessment are now becoming well established and have, for example, been included in the R6 [10], BS7910 [11] procedures. However, it is common to assume the residual stress is as high as yield stress. Although this is generally safe, it can lead to highly conservative estimates of the remaining life of components, which can result in unnecessary and expensive withdrawal from service of a component for repair or replacement. Some practical issues such as the influence of residual stress on calculation of crack driving force and constraint parameters remain. Therefore, the ability to understand the residual stress effects is important for an analysis of the continued fitness-for service of welded structure.

In the present work, the residual stress problem is treated as an initial stress problem. The methods used by O'Dowd and Shih [12] and Zhang et al. [5] are adopted to extend the two parameters fracture mechanics (J,Q) theory. A new constraint parameter R is proposed to characterize the residual stress induced crack tip constraint and a three-parameter approach ($CTOD$–Q–R) has been suggested to describe the crack tip stress field. The effect of specimen and load conditions, load level

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as well as residual stress patterns on the validity of the three-parameter approach has been investigated. In the following, the development of the crack tip constraint concepts in a welded component is reviewed first. And then the methodology of extending the *CTOD–Q* theory to include the residual stress influence is described. Details of the numerical analyses, results and discussion are included in Sections 4 and 5. The paper is ended with a summary and conclusions.

2. Crack tip constraint in a welded component

It is well recognised that crack tip constraints due to geometry, loading and material strength mismatch affect the distribution of stresses around a crack and consequently preclude the use of a single parameter characterization of the crack tip stress field. These constraint effects have been the subject of extensive investigation in the last decade, in the hope that the fracture data obtained from small specimens can be transferred to predict the fracture behaviour in large scale components.

Williams [13] showed that in a cylindrical coordinate system (r, θ) the first two terms of the expansion of the crack tip stress field possesses the following form:

$$\sigma_{ij} = \frac{K_{\mathrm{I}}}{\sqrt{2\pi r}} f_{ij}(\theta) + T\delta_{1i}\delta_{1j}, \tag{1}$$

where K_{I} is the model I elastic stress intensity factor and T is a stress parallel to the crack. Larsson and Carlsson [14] demonstrated that the second term, controlled by T was able to describe the differences in crack tip stress fields between different specimens (geometry and loading conditions) when loaded to the same stress intensity factor K_{I}.

By using a modified boundary layer (MBL) model with remote boundary governed by Eq. (1), Edmunds and Willis [15] and Bilby et al. [16] performed detailed analyses on the elastic–plastic stress fields around a crack tip. Betegon and Hancock [17] and Du and Hancock [18] investigated the effect of different T-stress levels on the near tip stress fields and the development of plasticity. It has been shown that a negative T-stress will significantly lower the crack tip stress fields, reduced the constraint and cause the plastic zone to elongate and rotate to a position ahead of the crack tip, while a positive T-stress has little effect on the stress distributions other than to raise them slightly and cause the crack tip plastic zone to move backwards. It should be noted that these results are not suited for fully yielded crack geometries since the T-stress has no relevance under fully yielded conditions.

O'Dowd and Shih [12,19] proposed an alternative method of quantifying the effect of constraint on crack tip stress fields with a so-called Q-stress parameter. Based on the work by Li and Wang [20] and Sharma and Aravas [21], they observed that the crack tip stress field can be described as

$$\sigma_{ij} = \sigma_{ij}^{\mathrm{HRR}} + Q\sigma_0 \left(\frac{r}{J/\sigma_0}\right)^q \hat{\sigma}_{ij}(\theta, n) + \text{higher order terms}, \tag{2}$$

where

$$\sigma_{ij}^{\mathrm{HRR}} = \left(\frac{J}{\alpha\varepsilon_0\sigma_0 I_n r}\right)^{1/(n+1)} \sigma_0 \tilde{\sigma}_{ij}(\theta, n) \tag{3}$$

is the J-controlled HRR stress field after Hutchinson [22] and Rice and Rosengren [23]. In the above equations, ε_0, α and σ_0 are constants in a power law plasticity constitutive equation, n is the hardening exponent. I_n is an integration constant, q is a constant. A complete theoretical equation for the higher-order asymptotic terms in Eq. (2) has been developed by Yang et al. [24].

O'Dowd and Shih [12,19] performed detailed FE analyses of the small scale yielding (SSY) case for different levels of T stress, and carefully examined the near crack tip stress fields. They found that $|q| \ll 1$ and for $|\theta| < \pi/2$ and in the range of $J/\sigma_0 < r < 5J/\sigma_0$, $\hat{\sigma}_{ij}(\theta, n) \approx$ constant for $i = j$ and $\hat{\sigma}_{ij}(\theta, n) \approx 0$ for $i \neq j$.

It means that the Q field represents an additional hydrostatic stress field ahead of the crack tip due to the geometry constraint. Thus, the near crack tip stress field can be expressed by a reference term represented by the HRR field and one term that corrects the hydrostatic stress level because of geometry constraint. The first term includes the dependence of J and scales the zone over which high stress and strains act. The HRR field was originally proposed as the reference field by O'Dowd and Shih [25], alternatively, it is possible to take the MBL solution with $T = 0$ as the reference solution.

In O'Dowd and Shih's J–Q formulation all the higher order terms are included in the second term (Eq. (2)). As a result of this approximation, the radial independence of the Q-stress term is sacrificed. O'Dowd and Shih [19] evaluated the Q parameter in different geometries. The stress fields in finite geometry are less parallel to the reference solution than the stress fields obtained in the MBL model with different T stresses. For specimens loaded in tension and bending specimens with shallow cracks the deviations were rather small, but for deeply cracked bending specimens the strong interaction with the global bending stress field makes the valid ranges of Q very small. In order to assess the validity of the Q stress, a criterion has been proposed to measure its distance dependence:

$$Q_{\Delta} = \frac{Q_{r\sigma_0/J=5} - Q_{r\sigma_0/J=1}}{4} \leqslant k, \tag{4}$$

where k is a constant. Different values have been proposed for k. Originally O'Dowd and Shih [12] suggested that $k = 0.03$ for a valid J–Q characterisation. Later, Dodds et al. [26] argued that $k = 0.1$ would be appropriate for describing the stress field in a failure assessment for cleavage fracture.