International Journal of Solids and Structures 46 (2009) 2629–2641

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Effect of residual stresses on the crack-tip constraint in a modified boundary layer model

X.B. Ren [a], Z.L. Zhang [a,*], B. Nyhus [b]

[a] Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), N-7491 Trondheim, Norway
[b] SINTEF Materials and Chemistry, N-7465 Trondheim, Norway

ARTICLE INFO

Article history:
Received 26 May 2008
Received in revised form 26 January 2009
Available online 26 February 2009

Keywords:
Residual stresses
Crack-tip constraint
Cleavage fracture
Failure assessment

ABSTRACT

Residual stresses play a crucial role in structural integrity assessment. In this study, a large cracked cylinder with a weld in the center is applied to investigate the effect of residual stresses on the crack-tip constraint. A modified boundary layer model with a remote displacement-controlled elastic *K-field* and *T-stress* under small scale yielding has been used to simulate the problem. A two-dimensional tensile residual stress field due to the weld is introduced into the model by the so-called eigenstrain method. It has been shown that the residual stresses can significantly elevate the crack-tip constraint and thus increase the probability for cleavage fracture. The constraint parameter R introduced by the authors can be used to rank the crack-tip constraint induced by the bi-axial residual stresses. The R value decreases with the increase in the applied *J-integral*. The residual stress-induced constraint is also coupled with the *T-stress*. The R value becomes smaller with larger *T-stress*.
© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Process-induced residual stresses are inevitable for most mechanical or thermal operations used in processing engineering materials. Residual stresses have a significant effect on structural integrity assessment of welded structures. The proper treatment of the welded residual stresses in integrity assessment is becoming an increasing important safety factor when high strength steels are utilized more widely in the offshore industry. In practice, it has been demonstrated that the residual stresses are either overestimated in most cases or underestimated in others (Dong and Brust, 2000).

Significant progress has been made in the prediction of the welding residual stresses, and several commercial finite element codes are available on the market (WeldsimS, SYSWELD). The study of the effect of residual stresses on the crack-tip driving force, constraint, failure mechanisms and integrity assessment has also received attention recently. The studies carried out by Panontin and Hill (1996) and Hill and Panontin (1998) confirm that the residual stresses contribute to both the crack driving force and the crack-tip constraint. Xu and Burdekin (1998) investigated the effect of residual stresses on the crack-tip constraint and found that the tensile residual stresses parallel to the crack flank increase the constraint at the crack tip while compressive residual stresses in this direction have the opposite effect, but a biaxial nonlinear residual stress state may also increase the crack-tip constraint despite the residual stress component parallel to the crack flank being compressive. Lei et al. (2000) observed that the standard Rice's *J-integral* (Rice, 1968) becomes path dependent in the presence of a residual stress field. They suggested a modified *J-integral* that is path-independent for both a pure residual stress field and a combination of residual stress field and the applied load. Residual stresses were also shown to affect fracture mechanisms, such as brittle fracture, plastic collapse, fatigue, creep, stress corrosion cracking (Withers, 2007) as well as hydrogen embrittlement (Toribio and Elices, 1991). Understanding how residual stresses along with the presence of known or worst case defects affect the limit life without unnecessary conservation is crucial for the industry. Most recently, the residual stress-induced crack-tip constraint has been investigated by Liu et al. (2008) by using single edge notched bending specimens and a one-dimensional residual stress field. A new parameter R was proposed. By combining the *CTOD* (Crack Tip Opening Displacement) and *Q-stress* (O'Dowd and Shih, 1991, 1992), a so-called *CTOD-Q-R* three-parameter formulation is proposed to describe the near-tip stress field.

In this study, a modified boundary layer (MBL) model has been used to investigate the effect of a two-dimensional residual stress field on the crack-tip constraint. An ideal problem, a large round cylinder with a "spot" weld in the center, was studied, see Fig. 1. A rigid analytical surface was placed on the symmetrical line to model the contact of the crack surfaces. The cylinder was simulated by an MBL model with a remote boundary controlled by the elastic *K-field* and *T-stress*, and with a crack located at the weld

* Corresponding author. Tel.: +47 73 59 25 30; fax: +47 73 59 47 01.
E-mail address: zhiliang.zhang@ntnu.no (Z.L. Zhang).

0020-7683/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2009.02.009

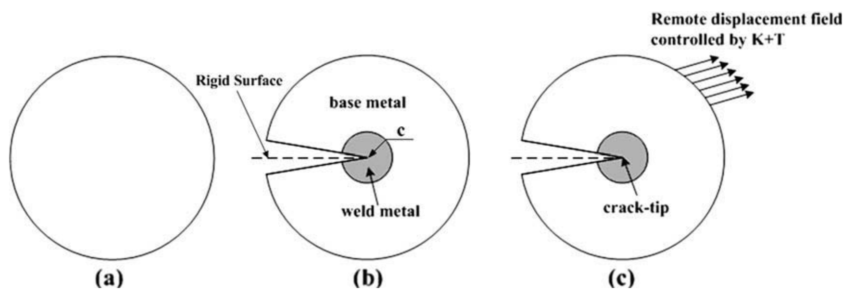

Fig. 1. Illustration of the problem. (a) The round cylinder; (b) "spot" welding with radius of c in the center and one sharp crack is introduced; (c) applied load.

metal. Material property mismatch between the weld metal and the base metal has not been taken into consideration.

The overall aim is to study the structure of the near-tip stress field in the presence of two-dimensional residual stresses and the relationship of this field to the applied *J-integral* and *T-stress*. The paper is organized as follows: the studies of crack-tip constraints including the geometry constraint, mismatch constraint, prestrain history-induced constraint are reviewed first. The numerical procedure for this study is briefly discussed in Section 3. The findings and results are discussed in detail in Section 4. Finally, the paper ends with the concluding remarks.

2. Crack-tip constraint

In a weldment there are basically four factors which influence the level of a crack-tip constraint. Constraint in fracture mechanics is a term that is widely used but vaguely defined or understood. In the present context we prefer to understand the level of constraint as an indicator of the near-tip stress state, and the constraint is regarded as the factors or conditions which influence the transferability and invalidate the one-to-one relation between the crack driving force and near-tip stress field. The geometry constraint is caused by crack size, specimen dimensions and loading mode; inhomogeneous material properties can induce the mismatch constraint at the crack tip (Zhang et al., 1996; Betegón and Peñuelas, 2006; Burstow et al., 1998); both the prestrain history (Eikrem et al., 2007) and the welding residual stresses influence the crack-tip constraint as well. In recent decades, a series of studies has been carried out to characterize the different crack-tip constraints.

According to William's solution, the first two terms of small-strain linear elastic expansion of the crack-tip stress field possess the following form (Williams, 1957),

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

where K_I is the mode I elastic stress intensity factor and T is a stress parallel to the crack. Larsson and Carlsson (1973) demonstrated that the second term in the series was important to modify the boundary solution to fit the real crack problem, and the *T-stress* has a significant effect on the plastic zone size and shape. Du and Hancock (1991) studied the effect of *T-stress* on the small scale yielding field of a crack in plain strain conditions and found that a positive *T-stress* causes plasticity to envelop the crack tip and exhibits a Prandtl field. This corresponds to the limit solution of the HRR field (Hutchinson, 1968; Rice and Rosengren, 1968) for a non-hardening material, while a compressive *T-stress* reduces the stress triaxiality state at the crack tip. Betegón and Hancock (1991) suggested a two-parameter framework *J-T* to characterize the effect of the constraint induced by the geometry. But, *T-stress* is only valid in an elastic regime.

O'Dowd and Shih (1991, 1992) developed the *J–Q* two-parameter theory and gave a precise meaning to the term constraint caused by the geometry and loading mode. They showed that the full range of high- and low-triaxiality fields within the *J–Q* annulus are members of a family of solutions parameterized by Q when distances are normalized by J/σ_0, where σ_0 is the yield stress. The near-tip stress field can be expressed by two-term expansion:

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

where

$$\sigma_{ij}^{HRR} = \left(\frac{J}{\alpha\epsilon_0\sigma_0 I_n r}\right)^{\frac{1}{n+1}} \sigma_0\tilde{\sigma}_{ij}(\theta, n) \tag{3}$$

is the *J*-controlled HRR stress field, r and θ are polar coordinates centered at the crack tip; n is the hardening component; ϵ_0 is the yield strain ($\epsilon_0 = \sigma_0/E$), and α is a material constant.

Their study showed that $|q| \ll 1$; and when $|\theta| < \pi/2$, $1 < r/(J/\sigma_0) < 5$, the stress components $\hat{\sigma}_{rr} \approx \hat{\sigma}_{\theta\theta} \approx constant$ and $|\hat{\sigma}_{r\theta}| \ll |\hat{\sigma}_{\theta\theta}|$. Thus, Q is a hydrostatic stress parameter. In this two-parameter formulation, J sets the size scale over which large stress and strains develop, and Q characterizes the crack-tip stress distribution and the stress triaxiality achieved ahead of the crack. Q is therefore a quantitative measure of the crack-tip constraint caused by geometry. It must be noted that the *J–Q* theory fails to characterize the crack-tip fields and quantify the constraint level in a bending-dominated large deformation regime. Zhu and Leis (2006) proposed a bending modified *J–Q* theory, by which the crack-tip stress fields for bending specimens at all deformation levels can be characterized.

In welded components, the crack located at the interface between the weld metal and the heat affected zone is generally the most critical one. Because of the nature of welding, there is often a mismatch between the weld metal and the base metal. By considering the interface crack as a bi-material system, Zhang et al. (1996) carried out a numerical investigation on the near-tip stress field and found that the near-tip field in the forward sector can be separated into two parts. The first is characterized by the *J-integral* for a reference material; the second part which influences the absolute levels of stresses at the crack tip and measures the deviation of the field from the first part can be described by a mismatch constraint parameter, M (Zhang et al., 1997b):

$$\sigma_{ij} \approx \sigma_{ij}^{Ref}(J) + M\sigma_{0_{Ref}}\bar{f}_{ij}^{M}(\theta + 12\beta) \tag{4}$$

where $\beta = 0$ for overmatch and $\beta = 1$ for undermatch, $\sigma_{0_{Ref}}$ is the yield stress of reference material and $\bar{f}_{ij}^{M}$ represents the angular function of the difference fields caused by mismatch, which only depends on the reference material. The study also showed that radial dependence of *M-field* is weak. Similar studies have been car-

Download English Version:

https://daneshyari.com/en/article/279139

Download Persian Version:

https://daneshyari.com/article/279139

Daneshyari.com