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EFFECT OF RESIDUAL STRESS ON THE BRITTLE FRACTURE BY COHESIVE ZONE MODELING NSCM-21

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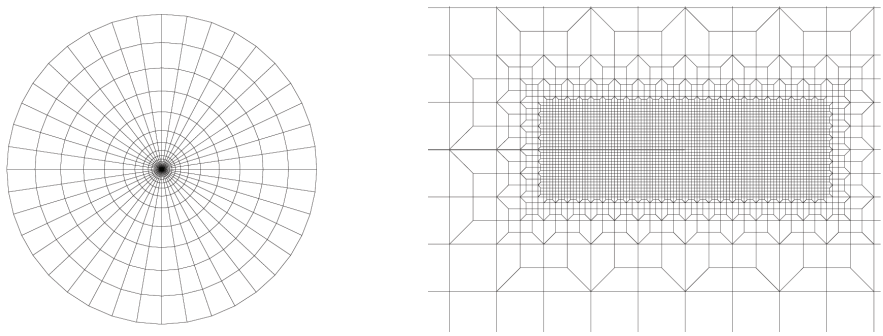
Summary. In this work, the effect of residual stress on the brittle fracture is studied under mode I, plane strain conditions. The modified boundary layer simulations are performed with the remote boundary conditions controlled by the stress intensity factor K. The eigenstrain method is used to introduce a two-dimensional tensile stress field near the crack tip. A layer of cohesive elements are placed ahead of the crack tip to simulate the crack propagation. The bi-linear traction-separation-law is used to describe the behavior of the cohesive zone elements. The result indicates that the residual stress influences the initiation of the crack significantly. Higher level residual stress field causes lower fracture toughness.

1 INTRODUCTION

Residual stresses have significant effect on the crack-tip constraint[1,2], which can further influence the fracture toughness of the brittle materials. Understanding how residual stress influences the brittle fracture behavior becomes more and more important when high strength steels are increasingly utilized in offshore industry.

Panontin and Hill[3] analytically investigated the effect of residual stress field on the micromechanics of fracture initiation and found that the residual stress reduced the brittle fracture toughness significantly. They also pointed out that the reduction of brittle fracture toughness is due to the change of the crack-tip constraint conditions caused by the residual stress. Hill and Panontin[4] employed the RKR[5] failure theory to predict the brittle fracture loads for three-point bending samples with and without residual stress. Their results showed that the residual stress affects both the crack driving force and the crack-tip constraint, and together these effects decrease the fracture toughness. In this work, we focused on the effect of residual stress on the fracture behavior caused by the crack-tip constraint changing.



(a) (b)

Figure 1: Modified boundary layer model, (a) global mesh; (b) crack-tip mesh.

2 NUMERICAL PROCEDURE

The modified boundary layer (MBL) model used for this study consists of a round shape weld metal region located at the center of the model and an outer base metal region. The problem considered is a plane strain formulation with an assumed sharp crack in the center of the weld metal. The load was applied to the remote edges of the model through a displacement field (u, v) controlled by the elastic asymptotic stress field of a plane strain mode I crack:

$$u(r,\theta) = K_I \frac{1+\nu}{E}\sqrt{\frac{r}{2\pi}}\cos(\frac{1}{2}\theta)(3-4\nu-\cos\theta) \tag{1}$$
$$v(r,\theta) = K_I \frac{1+\nu}{E}\sqrt{\frac{r}{2\pi}}\sin(\frac{1}{2}\theta)(3-4\nu-\cos\theta)$$

where $K_I = \sqrt{EJ/(1-\nu^2)}$ under plane strain condition; E is Young's modulus, ν is Poisson's ratio; r and θ are polar coordinates centered at the crack tip with $\theta = 0$ corresponding to the crack tip.

ABAQUS/CAE was used for the analyses. The crack is assumed to be a sharp crack without initial radius and the radius of the MBL model was taken as 4000 mm to ensure that the small scale yielding condition is fulfilled. A layer of cohesive element is placed on the central line behind the crack tip to simulate the crack initiation and propagation. The weld- and base-metal region of the model was meshed by standard four-node elements with reduced integration, CPE4R, with finer mesh in the crack-tip region. The cohesive zone is meshed by standard cohesive element COH2D4. The behavior of the cohesive elements is characterized by a bi-linear traction-separation law, which is characteristic of brittle materials [6]. The finite element model has 5397 elements and the meshes are shown in Fig.1.

The base- and the weld-metal were assumed to have the same elastic properties ($E = 2\times10^5$ MPa, ν=0.3) and plastic properties but different thermal expansion coefficients. The rate-dependent power law strain hardening materials were assumed which have the form of

$$\sigma_f = \sigma_0(1+\frac{\bar{\epsilon}^p}{\epsilon_0})^n \tag{2}$$

where σ_f is the flow stress; $\bar{\epsilon}^p$ is the equivalent plastic strain, $\sigma_0 = 400$ MPa the yield stress, $\epsilon_0 = \sigma_0/E$ the yield strain and n is the plastic strain hardening exponent.

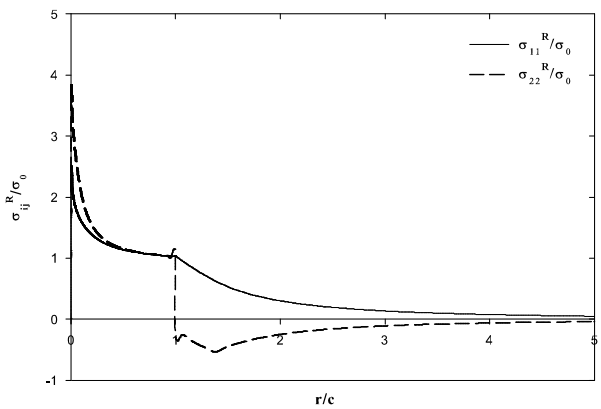


Figure 2: Residual stress field introduced by the eigenstrian method. $E/\sigma_0 = 500, \mu = 0.3; n = 0.1; \alpha_w = 0.002, \alpha_b = 0; c = 20mm.$

The residual stress field was introduced into the model by so-called eigenstrain method that was also called "inherent strain" method when first introduced by Ueda[7]. The basic idea of eigenstrain method is that the source of residual stress is an incompatible strain field caused by plastic deformation, thermal strains and phase-transformation etc. Thus, if the distribution of the eigenstrain is known, the distribution of residual stresses can be obtained through linear elastic calculation by using the finite element method. In this study, the isotropic distribution of eigenstrain in both the base metal and weld metal regions was assumed. The eigenstrain values were set to be equal to the thermal expansion coefficients of two regions(α_w and α_b), respectively. The residual stresses were then introduced by loading the model with a unit temperature change. Fig.2 presents the redistributed residual stress after the crack was introduced for the case with eigenstrain $\alpha_w = 0.002$ and $\alpha_b = 0$. The stress components were normalized by the yield stress, and the distance from the crack tip was normalized by the radius of the weld metal region c.

3 RESULTS AND DISCUSSION

Brittle fracture is sensitive to the near tip stress field, and there is no or negligible plastic deformation before failure. The effect of residual stress on the brittle fracture toughness was investigated in this study. The fracture resistance curve without residual stress effect is compared with the cases with the effect of residual stress in Fig.3.

It can be seen that the residual stresses influence the initiation of the crack propagation significantly. Also, the influence of residual stress on the fracture resistance is stronger at the early stage of the crack propagation. The effect of residual stresses on the brittle fracture toughness also depends on the residual stress field itself. The residual stress field of $\alpha_w = 0.002$ causes lower fracture toughness than the residual stress field of $\alpha_w = 0.002$ does.

4 CONCLUSIONS

1. Cohesive zone element with a bi-linear traction-separation-law can be used to simulate the brittle fracture.

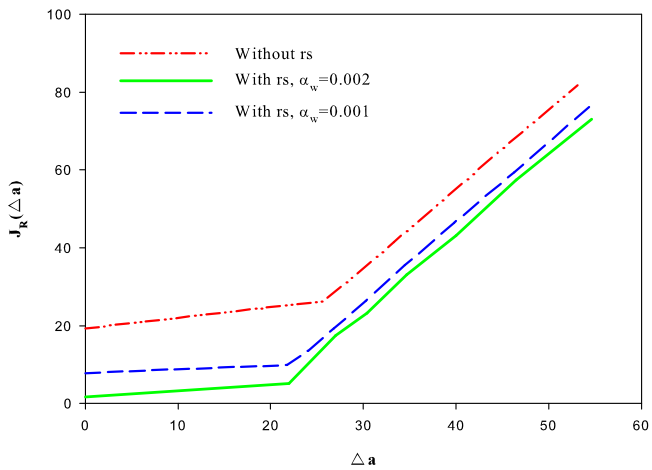


Figure 3: Effect of residual stress on the fracture resistance curve. $E/\sigma_0 = 500, \mu = 0.3; n = 0.1; \alpha_b = 0; c = 20mm$.

2. Residual stress reduces the crack initiation toughness significantly. The influence of residual stress on the fracture resistance is stronger at the early stage of the crack propagation. Higher level residual stress field causes lower fracture resistance curve.

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