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Characterization of near tip stresses for a plane-strain off-center crack in a strength mismatched weld

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ABSTRACT

The past two decades have seen an increasing emphasis on the development of flaw assessment procedures accounting for the state of stress (constraint) near the crack tip. In-service inspections of many nuclear power plants have revealed that cracks are most likely to occur in a weld or in the regions near the weld. In recent work, the authors have proposed a novel three-parameter scheme to characterize the crack tip opening stress, for small-scale yielding, for a crack lying at the center of a strength mismatched weld. The proposed scheme was validated with detailed finite element analyses using the modified boundary layer formulation. In the present work, the previously proposed scheme is extended to an off-center crack lying in the weld region. Apart from analyzing an off-center crack, studies are performed on an interface crack in a weld having finite width. To validate the proposed scheme, modified boundary layer analyses are carried out for a wide range of offset ratio values (ratio of the crack tip-to-weld center distance to the weld half-width), ranging from 0.33 to 0.9, and strength mismatch ratio values (ratio of yield strength of weld to yield strength of base material), ranging from 0.6 to 1.6. Our studies revealed that the proposed analytical scheme works well for all offset ratios and weld mismatch ratios. For an interface crack, crack tip stresses depend mainly on the strength mismatch ratio between the base and weld material. Practically no significant effect is observed of the weld width on the crack tip opening stress of an interfacial crack.

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1. Introduction

Existing fracture testing standards like ASTM E-1820 suggest evaluating the fracture toughness of pressure-retaining components by conducting fracture tests on high-constraint geometries like deeply cracked three-point bend, SE(B), specimen or compact tension, C(T) specimen. The fracture toughness so obtained is then used for evaluation of stability of the postulated flaws under various service loads using the flaw assessment procedures available in R6 [18], SINTAP [23], RCC-MR Appendix A-16 [19], etc. Since the level of constraint near the crack tip in an actual component may be quite different from that of deeply cracked fracture specimens, the fracture toughness obtained from specimen testing may not be readily transferable to the actual component [1]. In general, such structural integrity assessment procedures often lead to overly conservative results. As a result, there has been an increasing emphasis on the development of flaw assessment procedures accounting for the state of stress (constraint) near the crack tip. In-service inspections of many nuclear power plants and oil refineries have revealed that in comparison to base metals, weld joints are more critical. Thus, for the safe operation of a nuclear power plant or oil refinery, it is important to ensure the structural integrity of these weld joints. The existing flaw assessment procedures were essentially developed for nominally homogeneous materials. For a fracture specimen having a weld joint, strength mismatch ratio between base and weld material, weld width, and location of crack in weld are the additional variables along with magnitude of applied loading, type of loading, and geometry of specimen that affect the crack tip stresses.

The influence of weld strength mismatch and weld width on the crack tip constraint has been analyzed for the problem of weld center crack, as well as for a crack lying at the interface of base and weld material. The problem of a crack lying at the interface of two materials has been extensively examined by Fu et al. [8], Ganti et al. [9], Hyungyil et al. [10], Kim et al. [11], Ruggieri et al. [21], and Zhang et al. [25,26]. Zhang et al. [25,26] suggested a mismatch constraint parameter and an angular function which depends only on the strain-hardening property of the reference material. The proposed constraint parameter accounts for the constraint caused by the weld strength mismatch, and is practically independent of the normalized distance from the crack tip.

For a weld center crack, Burstow et al. [3,4] have accounted for the effect of strength mismatch ratio and weld width on the crack

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tip opening stress by a three-parameter scheme (J–Q–Q_M). The proposed scheme, however, cannot describe the radial dependence of crack tip opening stress along the crack plane. Ritchie et al. [22] and Ritchie and Thompson [20] have suggested that the distribution of near tip stresses over the microstructurally relevant zone (typically of the order of $1 \le r/J/\sigma_o \le 5$) controls the fracture process. Moreover, the normalized load parameter proposed by Burstow et al. [3] does not account for the effect of T-stress arising due to specimen geometry and loading condition. Very recently, a novel three-parameter scheme has been proposed by Kumar et al. [14] to describe the crack tip opening stress ahead of a crack lying at the center of a strength mismatched weld. In the present work, the scheme proposed by Kumar et al. [14] is extended for an off-center crack lying anywhere in the weld region. Apart from analyzing an off-center crack, studies have been performed on an interface crack in a weld having finite width. To validate the proposed scheme, modified boundary layer analyses were carried out for a wide range of offset ratio, ranging from 0.33 to 0.9, and strength mismatch ratio ranging from 0.6 to 1.6. Our studies revealed that the proposed analytical scheme works well for all offset ratios and weld strength mismatch ratios. For an interface crack, crack tip stresses depend mainly on the strength mismatch ratio between the base and weld material. There is practically no significant effect of weld width on the crack tip opening stress of an interfacial crack.

2. Background

Two parameter schemes, such as J–T [2], J–Q [17], J–A_2 [5], etc., have been widely employed to characterize the crack tip stresses in a nominally homogeneous (single) material. While the J-integral accounts for the magnitude of applied load, the second parameter T, Q or A_2 represents the crack tip constraint arising due to specimen geometry and type of loading. Williams [24] described the crack tip stresses ahead of a stationary crack in an isotropic elastic material subject to plane strain Mode-I loading as follows:

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

Here, K_I is the elastic stress intensity factor under Mode-I loading and T is a stress parallel to the crack face. T-stress being an elastic parameter has no physical meaning under large scale plasticity. To overcome the limitations of the J–T approach, O'Dowd and Shih [17] proposed to describe crack tip stresses in terms of a power series where the HRR solution is the leading term. The higher order terms of this series were grouped together and its amplitude was denoted as Q,

$$\sigma_{ij} = (\sigma_{ij})_{HRR} + Q\sigma_o\delta_{ij} \tag{2}$$

Here, $(\sigma_{ij})_{HRR}$ is the crack tip stress distribution as obtained from the HRR solution, and σ_o is the reference stress of material. Using the modified boundary layer (MBL) formulation, O'Dowd and Shih [17] studied the effect of constraint arising due to specimen geometry and types of loading on the near tip stresses. MBL analysis facilitates the characterization of the near tip stress field of an arbitrary crack geometry, under small-scale yielding, by a disk-shaped finite element (FE) model where the equivalent tractions or the equivalent displacements are applied on the disk boundary, based on the first two terms of Williams' series expansion. The displacement terms u_1 and u_2 applied on the outer boundary of the finite element mesh can be calculated as follows:

$$u_1 = K_I\frac{(1+\nu)}{E}\sqrt{\frac{r}{2\pi}}(3-4\nu-\cos\theta)\cos\frac{\theta}{2} + T\frac{(1-\nu^2)}{E}r\cos\theta,$$

$$u_2 = K_I\frac{(1+\nu)}{E}\sqrt{\frac{r}{2\pi}}(3-4\nu-\cos\theta)\sin\frac{\theta}{2} - T\frac{(1+\nu)}{E}\nu r\sin\theta, \tag{3}$$

Here, E is Young's modulus of elasticity, and ν is Poisson's ratio.

Many researchers [12,13,16] have found that, apart from specimen geometry and type of loading, the weld strength mismatch ratio, weld geometry and location of crack in the weld also affect the crack tip stresses of a fracture specimen having a strength mismatched weld. For a stationary crack lying at the interface of two materials, Zhang et al. [25,26] have suggested a two-parameter formulation for characterizing the near tip stress field. The first term represents the stress field obtained from the HRR solution for a homogeneous material. The second term consists of a mismatch induced constraint parameter M and an angular function that depends only on the strain-hardening index of the reference material. The constraint parameter M is a measure of the constraint caused by the material mismatch and is practically independent of the normalized distance from the crack tip. In reality, weld joints have a finite weld width and it remains to be established how the weld size can influence the solutions for a crack lying at the interface of two materials (say base and weld) of infinite extent [25,26]. Very recently, Fan et al. [6] have studied the variation of local fracture resistance for a crack lying at the interface or near the interface regions in dissimilar metal welds, using detailed 2-D finite element analyses. The Gurson–Tvergaard–Needleman (GTN) damage model was used in this study. It was demonstrated that the location of the crack near the interface leads to a large variation in the local fracture toughness. For the case of a crack lying at the interface of two dissimilar materials, the crack tip constraint was observed to be higher. For cases where the crack lied near the interface regions (either in soft or hard material), the crack tip constraint gets relaxed.

The problem of a stationary crack lying at the center of a strength mismatched weld was analyzed in detail by Burstow et al. [3]. These authors proposed a three-parameter formulation, J–Q–Q_M, to incorporate the effect of magnitude of applied load, weld width, and strength mismatch ratio (M) between base and weld material, on the crack tip opening stress under small-scale yielding. The effect of applied load and weld width on the crack tip opening stress was represented by a normalized load parameter $J/h/\sigma_o$ that relates the size of the plastic zone (J/σ_o), with half of the weld width (h). The constraint arising solely due to specimen geometry and type of loading was represented by the Q-parameter proposed by O'Dowd and Shih [17]. The additional constraint arising due to weld strength mismatch was represented by a third term Q_M that accounts for the strength mismatch between the base and weld material. An explicit dependence of constraint parameter Q_M on the weld mismatch ratio M was proposed. The normalized load parameter was defined for the case of $T=0$. However, it is well recognized that the T-stress has a strong influence on the plastic zone size ahead of crack tip [15]. To overcome this limitation, Kumar et al. [14] have recently proposed a more general three-parameter scheme to characterize the crack tip opening stress for a crack lying at the center of a strength mismatched weld. In the proposed scheme, the first term represents the crack tip opening stress, under small-scale yielding, in a homogeneous specimen for the case of $T=0$. The second parameter accounts for the constraint effect of specimen geometry via the Q-stress. The third term proposed by Kumar et al. [14] provides a more general framework to represent the combined effect of weld strength mismatch and applied T-stress on the plastic zone size, ahead of the crack tip, via a plastic interaction factor (I_p). Kumar et al. [14] have point out that, apart from the weld strength mismatch ratio (M) and weld geometry, the mismatch induced constraint in a weld center crack also depends on the magnitude of loading. For higher load level the depth of penetration of plastic

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