Effect of Strength Mismatch on Crack Tip Stress Fields of HAZ-notched Joints Subjected to Bending and Tension

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Summary

A numerical investigation for a crack located in the boundary between the weld metal and the heat affected zone (HAZ) of a welded joint is presented. Three-dimensional finite element analyses are performed on a center cracked panel (CCP) subjected to tension and single edge notch bend (SENB) specimens. The numerical results show that the stresses that develop in the HAZ region of the overmatched welded joint are more intense than those in the undermatch and evenmatch cases. It is noted that highly stressed near-tip zones are detrimental to fracture resistance of HAZ regions containing local brittle zones. A discussion also follows on the significance of weld strength overmatch on fracture behavior of HAZ-notched welded joints, which is based on the local approach. The analyses indicate that the relative load-carrying capacity of an overmatched joint may be reduced, especially in the case of the high constrained deep notch bend specimen. Such features may be particularly deleterious to cleavage fracture resistance of welded joints containing cracks close to the HAZ region.

1. Introduction

Assessment of structural integrity of steel weldments generally poses a complex problem due to variation in mechanical properties and fracture resistance near the weld. For a crack located near bimaterial interfaces, like the boundary between the weld metal and the base metal, the crack tip fields may be quite different than those that develop in the corresponding homogeneous media when compared at the same load level. To the extent that deformation behavior in the vicinity of crack tip is governed by the mechanics characteristics of the bimaterial medium, fracture toughness values obtained by conventional testing (e.g., CTOD testing) are dependent on the strength mismatch between the weld and the base metals. Such features further complicate the problem of transferability of fracture mechanics parameters from laboratory specimens to structures as there is a combined effect of strength mismatch and crack size.

As the weld metal generally exhibits lower fracture resistance than the base metal, conventional engineering approaches to provide sufficient structural integrity to welded joints have long been adopted as the use of strength overmatch between the weld and the base metals, where the weld metal strength is higher than the base metal strength (see, e.g., 2)). For this case, strength overmatch causes low plastic strains in the weld region with consequent reduction in the crack tip driving force. However, for multipass welds of high strength structural steels, very embrittled regions frequently occur in the heat affected zone (HAZ) close to the fusion line. Here, occurrence of local brittle zones (LBZ) causes sharp decrease in the cleavage fracture resistance of the HAZ region. In such cases, strength overmatching of the weld metal may substantially reduce the load-carrying capacity of the welded joint as zones of large stresses will develop in the HAZ region.

In view of the importance of effects of strength mismatch on fracture behavior of welded joints, the present work addresses the problem of a crack located on the boundary between the HAZ region and the weld metal. The objective of the study is essentially the assessment of the effect of weld strength mismatch on near-tip stresses of HAZ-region for different specimen geometries and different degrees of strength mismatch. Primary attention is given to three-dimensional finite element analyses of crack tip stress field and implications for fracture. In particular, a center cracked panel and a single edge notched bend specimen are treated in detail. In the light of the numerical results, a discussion follows on the significance of weld strength overmatch on fracture behavior of HAZ-notched welded joints.

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2. Constitutive Models of Materials

A J2 incremental theory of plasticity is employed throughout this study. The plastic behavior of materials employed in the analyses is described by a Ramberg-Osgood law neglecting elastic strains. In uniaxial tension the material deforms according to:

\[
\frac{\varepsilon_p}{\varepsilon_Y} = a \left( \frac{\sigma_p}{\sigma_Y} \right)^n
\]

(1)

where \(\varepsilon_p\) is the equivalent plastic strain, \(\sigma_Y\) is the yield stress, \(\varepsilon_Y = \sigma_Y/E\) is the associated yield strain, \(a\) is a material constant which was assumed to be 1.0 in this study and \(n\) is the strain hardening exponent. Under multiaxial stress states, the equivalent stress \(\sigma_e\) is given by von Mises yield conditions as

\[
\sigma_e = \left( \frac{3}{2} S_{ij} S_{ij} \right)^{1/2}
\]

(2)

where \(S_{ij}\) is the stress deviator

\[
S_{ij} = \sigma_{ij} - \frac{1}{3} \delta_{ij} \sigma_i
\]

(3)

Here \(\sigma_{ij}\) is the stress tensor, \(\delta_{ij}\) is the Kronecker delta. Yet in Eq. (3), the tensor notation and summation convention are employed so that subscripts \(i\) and \(j\) range from 1 to 3 and \(\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}\).

The numerical analyses were conducted for a typical welded joint of a structural steel having Young's modulus \(E=206\) GPa and Poisson's ratio \(\nu=0.3\). The base metal is assumed to be a high strength steel with yield strength \(\sigma_{Y}=460\) MPa and hardening exponent \(n=15\). The overmatched weld metal is modeled by a plastically more compliant material having yield stress \(\sigma_{YW}=575\) MPa (25% overmatch) and hardening exponent \(n=20\), while the undermatched weld metal is modeled by a plastically stiffer material having yield stress \(\sigma_{YW}=345\) MPa (25% undermatch) and hardening exponent \(n=10\). The HAZ is assumed to have yield stress \(\sigma_{HAZ}=400\) MPa and hardening exponent \(n=12.5\). The true stress-true strain curves of materials employed in the analysis are illustrated in Fig. 1.

3. Finite Element Model

Three-dimensional elastic-plastic finite element analyses were performed on a center cracked panel (CCP) and three-point single edge notch bend (SENB) specimens, both with thickness \(B=30\) mm, which are schematically presented in Figs. 2 and 3, respectively. The SENB specimens have two different crack length to width ratios \((a/W)\), namely \(a/W=0.1\) and \(a/W=0.5\), while the CCP has \(a/W=0.5\). The NIKE3D finite element code \(^4\) was used in all numerical computations. All meshes used in the numerical analyses employed 8-node isoparametric elements with selective/reduced quadrature \((2\times2\times2)\). Near incompressible behavior that arises in plasticity problems is accounted for in the element formulation to preclude mesh lock-ups and

Fig. 1  True stress-true strain curves of materials employed in the analysis.

Fig. 2  Center cracked panel (CCP) with an interface crack between the weld metal and the HAZ.

Fig. 3  Single edge notch bend (SENB) specimen with an interface crack between the weld metal and the HAZ.
associated anomalous states.

The crack tip in all meshes was modeled by degenerating the 8-node hexahedron into triangular prisms arranged in a ring of 12 elements, so as to simulate blunting of crack tip. The edge size of the crack tip element in the in-plane mesh ($x-y$ plane) is 0.1 mm. The finite element model for the CCP specimen contains 1872 elements and 2600 nodes. The finite element model for the SENB specimens are constructed using 1776 elements and 2500 nodes. Figure 4 shows the core near the crack tip region in the $x-y$ plane, which is common to all models. Due to symmetry, only half of SENB specimens and one quarter of the CCP were simulated, with appropriate boundary conditions imposed on the planes of symmetry. The meshes for all configurations consist of four layers through half the thickness of the plate. The layer interfaces are located at $z/B = 0.5, 0.8, 0.9$ and $1.0$.

While no attempt was made to resolve the structure of near-tip fields, the analysis was sufficiently detailed to allow comparisons of the fields ahead of the crack tip over distances significantly larger than the crack tip opening displacement (CTOD). In the present study, the concept of total CTOD, $\delta_T$, as defined by the 90° intercept procedure to the deformed crack flanks is used as the loading parameter.

4. Effect of Strength Mismatch on Crack Tip Fields in the HAZ Region

Equivalent plastic strain contours for $\varepsilon_p = 0.05, 0.1, 0.2$ at $\delta_T = 0.10$ mm are shown in figure 5 for the center cracked panel. Very similar patterns were obtained for the deep and shallow notch bend specimens. The even-matched welded joint develops almost symmetrical strain distribution at the crack tip, which indicates only a small effect of the narrow HAZ on the strain fields. For the overmatched and undermatched welded joint, the spatial extent of the plastic zones is significantly unsymmetrical.

Figure 6 provides a comparison of the dimensionless opening stress $\sigma_{yy}/\sigma_{yy}$ along the first ray of elements in the HAZ (see Fig. 4) for all specimen geometries. As it might be expected, the intensification of the opening stress in the HAZ region is more pronounced in the case of 25% overmatch. Here the peak stresses for the CCP and SENB with $a/W = 0.1$ are essentially similar while the peak stress for the SENB with $a/W = 0.5$ is significantly larger. By contrast, in the case of 25% under-
match, the maximum opening stresses for the SENB with \(a/W=0.1\) and \(a/W=0.5\) are in close agreement. Here the maximum opening stress for the CCP decreases by a large amount to the value of only 2.6 times the yield point of the HAZ material.

Figure 7 presents the contours of hydrostatic stresses (or average stress \(\sigma_H=(\sigma_1+\sigma_2+\sigma_3)/3\), where \(\sigma_1, \sigma_2\) and \(\sigma_3\) are principal stresses) defined by the loci \(\sigma_H=1.5\sigma_y\), where \(\sigma_y=\sigma_{yw}\) in the weld metal side and \(\sigma_y=\sigma_{yH}\) in the HAZ. The zone of high hydrostatic stress in the HAZ for the overmatched and evenmatched welded joint spreads well beyond the interface HAZ/Weld Metal \(\gamma/(10\delta_t)=-2\), especially in the case of SENB specimens with \(a/W=0.5\). By contrast, the zone of high hydrostatic stress in the weld metal for the undermatched welded joint is contained within distances about \(4-6\gamma/(10\delta_t)\) for all specimen geometries.

The previous results indicate that development of stress fields in the HAZ region for evenmatched and 25% overmatched welded joints is much more pronounced that the corresponding fields for the 25% undermatched welded joint. High constrained configuratious, such as deep notch bend specimens, exhibit high opening stresses and zones of high hydrostatic stresses near the crack tip. Further, the fields for the shallow notch bend specimen are essentially similar to those of the center cracked panel. While only a few combinations of strength mismatch have been explored in the present work, such a behavior is suggestive of a combined effect of strength mismatch, crack size and loading type on stress fields.

5. Significance of Weld Strength Overmatch/Mismatch on Fracture Behavior

The numerical results have shown that the stresses that develop in the HAZ region of the overmatched welded joint are more intense than those in the undermatch and evenmatch cases. As noted before, such highly stressed near-tip zones are particularly detrimental to fracture resistance of HAZ regions containing local brittle zones. Figure 8 presents contours of the maximum principal stress in the crack ligament for three load levels, \(\delta_t=0.05, 0.10\) and 0.20 mm. Though the contours are defined by the loci \(\sigma_1=2.5\sigma_{yw}\) for the entire region near the crack tip, attention is focused on the HAZ side. It can be seen that the spatial extent of zones of high principal stress is much larger for the deep notch bend specimen than for other geometries. This behavior is consistent with that presented in Fig. 7 where the HAZ region in the overmatch condition sustains the higher hydrostatic stresses. While the relative size of the zones of high principal stress becomes smaller with increasing load level \(\delta_t\) (as plots were made on nondimensionanalyzed axes) almost in the same manner for all specimen geometries, deep notch bend specimens continue to sustain very high stresses well beyond the HAZ region.

It is important to note that such results imply additional considerations on fracture behavior of overmatched welded joints. Under conditions pertaining to stress controlled fracture, a local approach based on
weakest link statistics\(^6\) can be used to describe effects of weld strength mismatch on cleavage fracture of the HAZ region. According to this model, one can show that the failure probability \(P_f\) for a cracked body under an arbitrary stress state \(\sigma\) is expressed by

\[
\sigma_{f} = 2.5\sigma_{y}\text{ for } \sigma_{f} = 1.5\sigma_{y}
\]

\(\delta_{i} = 0.1 \text{ mm}\)

**Fig. 7** Contours of hydrostatic stresses defined by the loci \(\sigma_{f}=1.5\sigma_{y}\) in the weld metal side and \(\sigma_{r}=1.5\sigma_{y}\) in the HAZ side: (a) CCP, (b) SENB with \(a/W=0.1\) and (c) SENB with \(a/W=0.5\).

**Fig. 8** Contours of maximum principal stresses defined by the loci \(\sigma_{f}=2.5\sigma_{y}\) at various load levels: (a) CCP, (b) SENB with \(a/W=0.1\) and (c) SENB with \(a/W=0.5\).
\[ P_r = 1 - \exp \left[ -\left( \frac{\sigma_w}{\sigma_r} \right)^{m} \right] \]  

which is a Weibull distribution with shape parameter \( m \) and scale parameter \( \sigma_r \). Yet in this equation, \( \sigma_w \) is the Weibull stress given by

\[ \sigma_w = \left[ \frac{1}{V_0} \int_{\Omega} (\sigma_{\text{eff}})^m d\Omega \right]^{1/m} \]  

where \( V_0 \) is a reference volume, \( \Omega \) is the volume of the fracture process zone ahead of the crack and \( \sigma_{\text{eff}} \) is an effective stress related to the stress acting on the volume element \( d\Omega \).

For assessment of effects of weld strength mismatch on cleavage fracture behavior of the HAZ region, a multiaxial form of Eq. (5) is adopted in the present study. Assuming a random incidence of circular planar microcracks in the volume of the fracture process zone and using the coplanar energy release rate criterion, \( \sigma_w \) referred to spherical coordinates \((r, \phi, \theta)\) is given by

\[ \sigma_w = \frac{1}{\Omega_{\text{HAZ}}} \left[ \int_{\Omega_{\text{HAZ}}} (\sigma_{\text{eff}})^m \right]^{1/m} \sin \phi d\phi d\theta d\Omega_{\text{HAZ}} \]  

Here, the stress normal to the microcrack plane \( \sigma_n \) and the in-plane shear stress \( \tau \) are given through the usual tensor tensor transformation, \( \nu \) is the Poisson's ratio and \( \Omega_{\text{HAZ}} \) and \( m_{\text{HAZ}} \) are the volume of the fracture process zone and the Weibull shape parameter corresponding to the HAZ region. In the present analysis, the material in the weld metal does not contribute to the failure probability \( P_r \) given by Eq. (4), so that \( \Omega_{\text{HAZ}} \) is defined as the volume of the plastic zone ahead of crack tip which belongs to the HAZ region only. Numerical procedures for evaluating the Weibull stress are presented in Appendix I, which are based on the isoparametric formulation of the element used in the analyses.

Figure 9 shows the variation of the Weibull stress with load level for all specimen geometries in the even-match and overmatch conditions. Without loss of generality, the \( m_{\text{HAZ}} \)-value was assumed to be 20 in the light of \( m \)-values reported in previous analyses. It can be seen that weld strength overmatch promotes elevation of the Weibull stress in the HAZ region. In particular, increase of the Weibull stress is much more pronounced for the deep notch bend specimen. In the context of the local approach employed, this behavior implies that fracture initiation in the HAZ is promoted by increasing the strength level of the weld metal.

The previous results clearly indicate that the relative load-carrying capacity of the overmatched joint is reduced, especially in the case of the high constrained deep notch bend specimen. It is important to note that though these results are expected to describe the phenomenological characteristics of HAZ-notched joints, effects of strength mismatch on fracture behavior should be further analyzed. For example, large differences in strain hardening properties of the bimaterial medium may alter the deformation patterns from those observed in this work. Nevertheless, the present study has indicated that there are important implications for fracture behavior of HAZ-notched joints when a crack is located near the interface of the embrittled HAZ.

6. Concluding Remarks

Effects of weld strength mismatch on crack tip stress fields of HAZ-notched welded joints were numerically investigated by a three-dimensional finite element analysis. A center cracked panel (CCP) subjected to tension and single notched edge bend (SENB) specimens were treated in detail. It was demonstrated that the stress fields that develop in the HAZ region of overmatched joints are significantly larger that those that develop in evenmatched and undermatched joints. Such features may be particularly deleterious to cleavage fracture resistance of welded joints containing cracks close to the HAZ region.
References


Appendix I

Numerical Evaluation of the Weibull Stress

In Eq. (5), the integration of a local effective stress over the volume of the plastic zone ahead of the crack tip defines the fracture controlling parameter for the present model. Once an accurate finite element solution to the continuum near-tip stress distribution is obtained, the integral can be split up into a sum of integrals over the yielded elements. Then Eq. (5) can be rewritten in multiaxial form as

$$\sigma^w = \frac{1}{4\pi V_0} \sum_{i=1}^{n_e} \int_{\Omega_i} \int_{x_i}^{x_f} \sigma_{ij} \sin \theta \, d\theta \, d\varphi \, d\Omega_i \quad (I.1)$$

where $n_e$ and $\Omega_i$ are the number and volume of elements included in the fracture process zone, respectively. Evaluation of this equation can be accomplished by taking the transformation of Cartesian coordinates $(x_i, x_2, x_3)$ of the deformed elements into natural coordinates $(\eta_1, \eta_2, \eta_3)$, $(-1 \leq \eta_i \leq 1, i=1, 2, 3)$. Since $d\Omega_i = \det J d\eta_1 d\eta_2 d\eta_3$, where $\det J$ is the determinant of the Jacobian matrix of the transformation, Eq. (I.1) yields

$$\sigma^w = \frac{1}{4\pi V_0} \sum_{i=1}^{n_e} \int_{-1}^{1} \int_{-1}^{1} \int_{-1}^{1} \sigma_{ij} \sin \theta \, d\eta_1 \, d\eta_2 \, d\eta_3 \quad (I.2)$$

In this work, an isoparametric hexahedron element with 8 nodes is employed for the finite element solution of the crack tip fields. The Cartesian coordinates $x_i$ of any point inside the element are related to the natural coordinates $\eta_i$ through the relationship

$$x_i = \sum_{k=1}^{8} N_k x_{ik}, \quad i=1, 2, 3 \quad (I.3)$$

where $N_k$ are the shape functions corresponding to the node $k$ and $x_{ik}$ are its nodal coordinates. These shape functions can be expressed as

$$N_k = \frac{1}{8} \prod_{i=1}^{3} (1 + \eta_i \eta_1), \quad k=1, \ldots, 8 \quad (I.4)$$

where $\eta_{ik}$ are the natural coordinates of node $k$. Yet in (1.2) $J$ is a square matrix of order $3 \times 3$ given by

$$J_0 = \sum_{k=1}^{8} \frac{\partial N_k}{\partial \eta_i} x_{ik}, \quad i,j=1, 2, 3 \quad (I.5)$$

where $J_0$ is the $i$th element of the $j$th row. Upon combining these expressions, we then arrive at a set of equations that can be directly evaluated by numerical quadrature and from which the Weibull stress can be determined.

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