AN ENGINEERING ANALYSIS PROCEDURE FOR CRACK DRIVING FORCE IN WELDS

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ABSTRACT

In the present studies, an EPRI elastic–plastic fracture analysis procedure is modified to estimate the crack driving force in welds with mechanical heterogeneity. By using the conception of equivalent parameters, it is convenient to estimate the crack driving force in welds with various matching.For the single–edge crack specimen in tension, it is indicated that the crack driving force estimated by the proposed procedure is in agreement with the experiments, in which the welded specimen is overmatched.

KEYWORDS

Crack driving force, engineering analysis procedure, welded joint

INTRODUCTION

Welded joint usually contains weld metal, heat affected zone and base metal. During welding a complex metallurgical and heat processes occurs in the welds. Previous results(Ma and Tian, 1986; Toyoda, 1989; Zhang, Shi, and Tu, 1989a,b) indicate that the mechanical heterogeneity gives obvious influence on crack driving force in welds.

For Homogeneous materials there are many methods to evaluate the crack driving force. Especially the proposed EPRI engineering analysis procedure for elastic–plastic fracture makes the evaluation of crack driving force more convenient for engineer(Kumar, German, and Shih, 1981).

A modification for the EPRI procedure is given in the present study. The modification is not only available for the structure made of homogeneous materials, but also for the welds with mechanical heterogeneity. By using the experiments on a single–edge cracked welded plate under remote uniform tension, the proposed engineering analysis procedure for evaluating crack driving force in welds has been verified. It is indicated that the evaluating procedure is in agreement with the experiment very well.

ESTIMATION OF CRACK DRIVING FORCE

Structure with homogeneous material Most crack problems of practical structures are in the elastic–plastic regime. For a Ramberg–Osgood material the fundamental formulae of crack driving force is the interpolation of the linear elastic and the fully plastic solutions, and are of the form

$$J = J_e + J_p$$
$$\delta = \delta_e + \delta_p$$
$$\Delta_c = \Delta_{ce} + \Delta_{cp} \qquad (1)$$

where J, δ, and Δ_c are the J–integral, crack mouth opening displacement, and load point displacement, respectively. J_e, δ_e, and Δ_{ce} are the elastic contributions based on the stress intensity factor handbook, and Irwin's effective crack length. J_p, δ_p, and Δ_{cp} are the plastic contributions based on the EPRI fully plastic solutions. For a single–edge cracked plate in uniform tension, the fully plastic solutions are given by the following expressions:

$$J_p = \alpha\sigma_o\varepsilon_o c(a/b)h_1(a/b,n)(P/P_o)^{n+1}$$
$$\delta_p = \alpha\varepsilon_o a h_2(a/b,n)(P/P_o)^n$$
$$\Delta_{cp} = \alpha\varepsilon_o a h_3(a/b,n)(P/P_o)^n \qquad (2)$$

where a is the crack length. b is the plate width. Uncracked ligament c = b–a. h_1, h_2, and h_3 are function of a / b, and stain hardening exponent n. σ_o and ε_o are the yield stress and yield strain. α is the material constant. P is the total load per unit thickness, and P_o is the limit load per unit thickness, and given by

$$P_o = \lambda\eta c\sigma_o$$

$\lambda = 1.072$(plane stress), $\lambda = 1.455$(plane strain)

where η is difined as

$$\eta = [1 + (a/c)^2]^{1/2} - a/c\ .$$

Welded joint with heterogeneous material For a welded joint with crack, the crack driving force is affected by the heterogeneity of materials at the crack tip. It may be assumed that there exist the equivalent yield stress and the equivalent strain hardening exponent in the material ahead of crack tip in the welds.

For the single–edge cracked welded plate under remote uniform tension, as shown in Fig.1, the fully plastic part of fracture mechanics parameters such as the J–integral, J_{pJ}, crack opening displacement, δ_{PJ}, and the load point displacement, Δ_{CPJ}, can be written by

$$J_{PJ} = \alpha\sigma_{oe}\varepsilon_{oe}\, c(a/b)h_1(a/b,n_e)(P/P_{oe})^{n_e+1}$$
$$\delta_{PJ} = \alpha\varepsilon_{oe}\, a h_2(a/b,n_e)(P/P_{oe})^{n_e}$$
$$\Delta_{CPJ} = \alpha\varepsilon_{oe} a h_3(a/b,n_e)(P/P_{oe})^{n_e} \qquad (3)$$

where σ_{oe} and ε_{oe} are the equivalent yield stress and the equivalent yield strain, $h_{1\sim3}$ the function of a / b, and equivalent strain hardening exponent, n_e. P_{oe} is the limit load per unit thickness, and given by

$$P_{oe} = \lambda\eta c\sigma_{oe}$$

In order to determine the equivalent parameters it is assumed that the welds consist of base metal and weld metal only. For the finite element analysis, the element mesh of the welded plate with single–edge crack is shown in Fig.2.

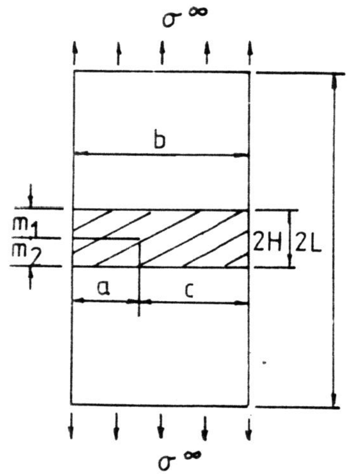

Fig.1 Configuration of single–edge cracked welded specimen

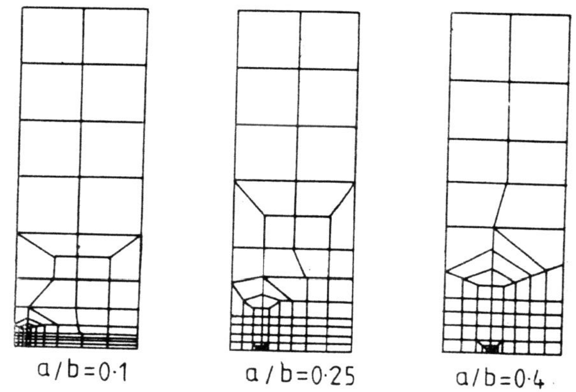

Fig.2 Finite element mesh

If the strain hardening exponent of the welds is equal to that of the base metal, but the yield stress is different between the weld metal and the base metal, the equivalent yield stress in the vicinity of crack tip may be expressed by

$$\sigma_{oe} = \left\{ \left[\frac{EJ_{PJ}}{\alpha c(a/b)h_1} \right] \left(\frac{\lambda \eta c}{P} \right)^{n_e+1} \right\}^{\frac{1}{1-n}} \quad (4)$$

where J_{PJ} is determined by the fully plastic finite element solution. If the yield stress of the welds is equal to that of the base metal, but the strain hardening exponent is different between the base metal and the weld metal, the equivalent strain hardening exponent in the vicinity of crack tip may be expressed by

$$n_e = \left\{ \log\left(\frac{J_{PJ} b}{\alpha \sigma_o \varepsilon_o a c h_1} \right) / \log\left(\frac{P}{P_{oe}} \right) \right\} - 1 \quad (5)$$

If both the yield stress and the strain hardening exponent are different between the base metal and the weld metal, the above equations (4) and (5) are still avaiable.

By means of the conception of equvialent properties in the welds, the estimation of the fracture mechanics parameters of welds can keep the similar form as that of homogeneous materials. Large number of computations indicate that the equivalent yield stress is independent on the equivalent strain hardening exponent. This is very helpfull for determining the equivalent parameters independently. In addition the effect of stress state on the equivalent parameters can be neglected. Thus, the results obtained from plane stress condition can be used for plane strain condition. It should be noted that the equivalent parameters are not actual material constants, but related with several factors.

The main factors affecting the equivalent yield stress and the equivalent strain hardening exponent are the weld width, crack size, matching property, material constant, and the relative location of crack in welds. Thus, the following expressions may be used to correlate the equivalent parameters(Zhang, Shi and Tu, 1991):

$$\frac{\sigma_{oe}}{\sigma_{ob}} = f_1\left(\frac{H}{a}, \frac{m_1}{m_2}, \frac{a}{b}, \frac{\sigma_{ow}}{\sigma_{ob}} \right) \quad (6)$$

$$\frac{n_e}{n_b} = f_2\left(\frac{H}{a}, \frac{m_1}{m_2}, \frac{a}{b}, \frac{\sigma_{ow}}{\sigma_{ob}} \right) \quad (7)$$

where sub b and sub w express the material constants of base metal and weld metal separately. m_1/m_2 expresses the relative crack location in the welds. For the single–edge cracked welded plate in tension, the following data are input in the computation: $a/b=0.1$, 0.25, 0.4; $m_1/m_2=1$; $H/a=0$, 0.3, 0.6, 0.9, 1.2; $\sigma_{ow}/\sigma_{ob}=0.8$, 1.0, 1.2; $n_w/n_b=0.5$, 0.75, 1.0, 1.25, 1.5. Regressing the computed results by the least square fitting method, the equivalent parameters can be written by

$$\frac{\sigma_{oe}}{\sigma_{ob}} = b_2\left(\frac{\sigma_{ow}}{\sigma_{ob}} - 1 \right)\left(\frac{H}{a} \right)^2 + b_1\left(\frac{\sigma_{ow}}{\sigma_{ob}} - 1 \right)\left(\frac{H}{a} \right) + b_o \quad (8)$$

$$\frac{n_e}{n_b} = b_3\left(\frac{n_w}{n_b} - 1 \right)\left(\frac{H}{a} \right)^3 + b_2\left(\frac{n_w}{n_b} - 1 \right)\left(\frac{H}{a} \right)^2 + b_1\left(\frac{n_w}{n_b} - 1 \right)\left(\frac{H}{a} \right) + b_o \quad (9)$$

where the coefficients, b_o, b_1, b_2 and b_3 are the function of crack length to the specimen width, a/b. Then, the equivalent parameters can be calculated from Eqs.(8) and (9). Finally the determined equivalent parameters may be input to the Eq.(3) to estimate the fully plastic fracture mechanics

parameters.

EXPERIMENT ON CRACK DRIVING FORCE

It is assumed that the welded joint consists of base metal and weld metal only. Two pipeline steels API X52, and API X65 are welded by the electron beam welding process to prepare the model welds, as shown in Fig.1. In the welds API X52 steel is used as the base metal and API X65 steel is used as the weld metal. The electron beam welding with high energy density leads to very narrow welded zone, which is less than 1mm, so the welded joint prepared by this process is very similar with the finite element model.

Table 1 gives the chemical compositions and mechanical properties of the test steels. Based on the Ramberg–Osgood relation, the material constants α and n are shown in the followings:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + 1.103\left(\frac{\sigma}{\sigma_o} \right)^{7.99} \quad \text{(API X52 steel)} \quad (10)$$

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + 1.078\left(\frac{\sigma}{\sigma_o} \right)^{14.01} \quad \text{(API X65 steel)} \quad (11)$$

Table 1 Chemical composition (w.t,%) and mechanical properties

	C	Mn	Si	P	S	Cu	Nb	Ti	σ_Y(MPa)	σ_{UTS}(MPa)
API X52	0.11	1.33	0.28	0.023	0.015			0.046	358	515
API X65	0.13	1.32	0.23	0.025	0.017	0.03	0.009		533	575

The size of the specimen is that length $2L=200$mm, weld width $2H=8,15,21$mm, specimen thickness $B=4$mm, specimen width $b=30$mm. Moreover, when $a/b=0.25$, $H/a=2.05$; When $a/b=0.4$, $H/a=0.67$ and 1.75. Specimen number is given in Table 2.

Table 2 Specimen number and correspondent equivalent parameters computed

Specimen No.	a / b	H / a	σ_{ow}/σ_{ob}	n_w/n_b	σ_{oe}/σ_{ob}	n_e/n_b
A	0.4	0.67	1.49	1.75	1.13	1.30
B	0.4	1.75	1.49	1.75	1.30	1.54
C	0.25	2.05	1.49	1.75	1.20	1.58

Tensile test is carried out in an Instron 1342 testing machine with a crosshead speed of 0.5mm / min at the room temperature. During the testing, the load vs crack mouth opening displacement is recorded. When the loading is attained to the maximum, the specimen is unloaded. Then, the specimen is broken up at the temperature of liguid nitrogen. Original crack length and crack length increment are measured.

RESULTS AND DISCUSSION

Fig. 3 shows the results of the single–edge cracked specimens. It is indicated that the δ–P curves of the model welds are located between the two parent steel specimens, and the δ–P curve of specimen B more approaches to that of X65 parent steel specimen. That is , when the width of the weld is increased such as the specimen B in comparison with the specimen A, the effect of the parent steel on the crack driving force of weld metal is reduced.

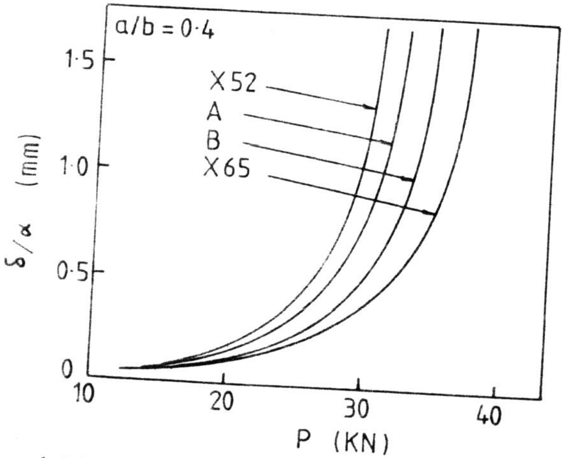

Fig. 3 COD crack driving force diagram for the single–edge cracked specimens of parent steels and with overmatched welds in tension.

As the tested specimen is in an intermediary state between the plane stress and the plane strain state, the parameter in Eq. (2) can be well estimated by the experimental curve. When $P/P_o = 1$, the $h_2$value can be determined by the measured $\delta_p$value. Any value in the curve can be used to determine the λ value in the expression on P_o, and this λ value represents the stress state of the practical specimen.

Fig. 4 gives the calculated curves of parent steel specimens, and the measured points. It is indicated that the experimental results are in agreement with the calculating results well. However, when the load increases, error becomes increasing. Due to the large load, the larger deformation of the specimen and local crack growth may cause error in calculating which is based on the small–scale yield theory.

For the welded joint, the equivalent parameters are given in Table 2. The calculated curves given by using the present procedure are in ageement with the experimental results, as shown in Fig. 5.

CONCLUSIONS

1) Experiments and computation indicate that the effect of the mechanical heterogeneity on crack driving force of welds is essential.

2) By means of the conception of equivalent parameters, it is convinient to estimate the crack driving force in welds with various matching .

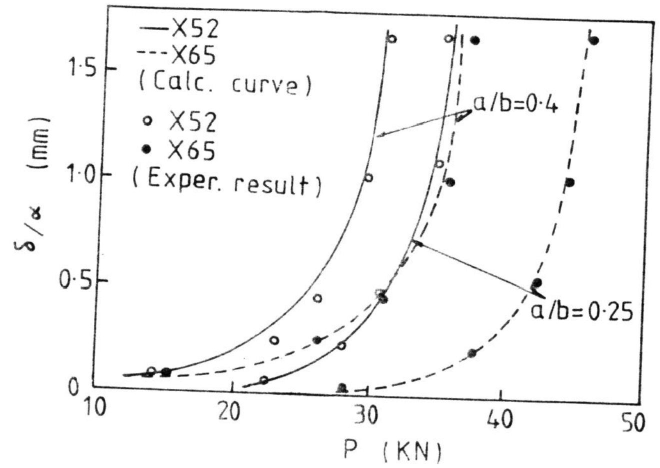

Fig. 4 Comparison between the calculated curves and the experimental results for parent steels.

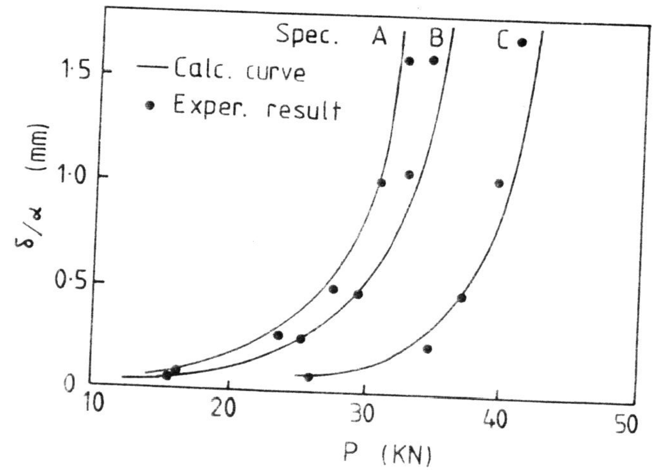

Fig. 5 Comparison between the calculated curves and the experimental results for welds.

3) For the single–edge crack specimen in tension, the calculated results given by using the present analysis procedure are in agreement with the experiments .

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