The Fully Plastic Solutions of Various Matched Weldment for Plane Stress Problem

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ABSTRACT

The fully plastic plane stress solutions of elastic-plastic fracture mechanics parameters such as J-integral, the crack opening displacement, and the load-point displacement were computed for the center-cracked specimen with various matched weldment in monotonically loading with the fully plastic finite element method. Moreover, the effects of yielding stress and strain hardening exponent of the welded joint were studied and discussed on the fracture mechanics parameters.

KEYWORDS

Fracture Parameter, Weldment, Heterogeneity, FEM.

INTRODUCTION

In the development of the nuclear engineering technology the increased attention has been paid to the safety and reliability of the nuclear system, because the failure of the nuclear component would be disaster. Considering the working conditions of nuclear pressure vessels, fracture of the vessels would be ductile, and Large-scale plasticity may be developed prior to fracture initiation. After the initiation of the crack there may be a slow crack growth before the instability occurs. Elastic-plastic fracture mechanics was developed in response to needs which were not met by the linear elastic fracture mechanics. The elastic-plastic fracture mechanics technology has advanced to the point where it can be used to make a realistic assessment of the structural integrity of components containing defects like crack according to the view of the fracture mechanics. Some approaches have been developed to assess the reliability of structures in engineering (Latzko et al., 1984, Dowling et al., 1975, Kumar et al. 1981)

Welding structures are widely used in nuclear systems. It is very difficult to analyse the fracture behavior of cracked components because of the inherent characteristics of the weldments (Carlsson, 1984). A Lot of work had been done for measurement of fracture toughness of weldments (Dolby, 1974, Shi et al. 1988). Effects of the mechanical heterogeneity in welded joint were investigated on the crack opening displacement (Satoh, 1983). A concept of the local crack opening displacement was introduced to assess the fracture toughness of weldment. The detailed behavior of crack propagation in Heat Affected Zone(HAZ) of weldments in an HSLA stell was studied (Zhang, 1984). Some jobs had been done to assess the integrity of welded structures containing defects (Burdekin, 1979). The path independence of the J-integral in the weldments with mechanical heterogeneity was proved recently (Ma, 1986). The results show that the J-integral remains path-independent one in spite of mechanical heterogeneity. Based on the EPRI approach (Kumar, 1981) for estimating the fracture mechanics parameters of homogeneous materials, an equivalent yielding stress and equivalent strain hardening exponent were introduced to estimate the fracture mechanics parameters for weldment with mechanical heterogeneity (Zhang, 1989). In the present work, the fully plastic solutions of the center-cracked welded strip only consisting of weld metal and base matel were investigated. Effects of mechanical heterogeneity in the various matched weldments were computed and discussed on the fracture parameters.

MATERIALS AND COMPUTATION

In the finite element analysis, it is assumed that the weldment consists of base metal and weld metal behaving in simple tension according to the pure power hardening law

$$\varepsilon_p/\varepsilon_o = \alpha(\sigma/\sigma_o)^n \qquad (1)$$

where ε_p is the plastic strain, ε_o and σ_o the yielding strain and yielding stress, respectively. n is the strain hardening exponent, α the material constant.

The uniaxial behavior is generalized to multiaxial states using J2 deformation theory

$$\varepsilon_{ij} = (3\,\varepsilon_e/2\,\sigma_e)S_{ij} \qquad (2)$$

where ε_{ij} and S_{ij} were the strain deviator and stress deviator,respectively; ε_e the effective strain and σ_e the effective stress.

The fully plastic fracture mechanics parameters such as Jp, δp and Δcp can be written as the following equations (Kumar, 1981),

$$J_p = \alpha\,\varepsilon_o\,\sigma_o\, a(1-\frac{a}{w},n)h_1(\frac{a}{w},n)(\frac{P}{P_o})^{n+1} \qquad (3)$$

$$\delta_p = \alpha\,\varepsilon_o\, a\, h_2(\frac{a}{w},n)(\frac{P}{P_o})^n \qquad (4)$$

$$\Delta_{cp} = \alpha\,\varepsilon_o\, a\, h_3(\frac{a}{w},n)(\frac{P}{P_o})^n \qquad (5)$$

where the J_p, δ_p, and Δ_{cp} represent the plastic part of the J-integral, the crack opening displacement, and the load-point displacement respectively; a is the crack length and W the strip width, $h_{1\sim3}$ the function of a/W and n, and

$$P = 2W\sigma^{\infty}, \qquad P_o = 2(W-a)\sigma_o$$

where P is the total load per unit thickness and P_o a reference load per unit thickness, $\sigma^{\infty}$the formal stress of specimen in tension.

Considering the stress-strain singularity at the crack tip and effects of mechanical heterogeneity near the crack on the crack tip behavior, it is supposed that the forms of fully plastic solutions of the weldment would take the similar forms as homogeneous material (Zhang,1989).

$$J_{pj} = \alpha\,\varepsilon_{eo}\,\sigma_{eo}\, a(1-\frac{a}{w})h_1(\frac{a}{w},n_w)(\frac{P}{P_e})^{n_e+1} \qquad (6)$$

$$\delta_{pj} = \alpha\,\varepsilon_{eo}\, a\, h_2(\frac{a}{w},n_w)(\frac{P}{P_e})^{n_e} \qquad (7)$$

$$\Delta_{cpj} = \alpha\,\varepsilon_{eo}\, a\, h_3(\frac{a}{w},n_w)(\frac{P}{P_e})^{n_e} \qquad (8)$$

where J_{pj}, δ_{pj}, and Δ_{cpj} represent the fully plastic part of the J-integral, crack opening displacement, and load-point displacement of the weldment.ε_{eo} andσ_{eo} are the equivalent strain and stress in the vicinity of the crack tip in the weldment; n_w the strain hardening exponent of the weld metal; n_e the equivalent strain hardening exponent near the crack tip in the weldment.

When the strain hardening exponent of the weld metal is equal to that of base metal. but the yielding stresses are different between weld metal and base metal. the equivalent yielding stress in the vicinity of crack tip may be obtained from Eq.(9) (Zhang, 1989),

$$\sigma_{eo} = \left\{ (\frac{EJ_{pj}W}{\alpha a c h_1(a/w,n)})(\frac{2c}{P})^{n+1} \right\}^{\frac{1}{1-n}} \qquad (9)$$

where E is the Young's modulus, and c=w-a.

When the yielding stress of weld metal equals to that of base metal, but the strain hardening exponents are different between weld metal and base metal, the equivalent strain hardening exponent near the crack tip in the welded joint may be obtained from Equation(10) (Zhang, 1989)

$$n_e = \left\{ [\log(\frac{J_{pj}W}{\alpha\,\varepsilon_o\,\sigma_o a c h_1})]/[\log(\frac{P}{P_o})] \right\} -1 \qquad (10)$$

If both the yielding stress and the strain hardening exponent are different between the weld metal and the base metal, the Eq.(9) may be used to compute the equivalent yielding stress and then the Eq.(10) to compute the equivalent strain hardening exponent in the vicinity of crack tip individually (Zhang, 1989).

In the computation the following data are input. The ratio of crack length to specimen width a/W=0.4; the yielding stress of base metal σ_{BO}= 490 MPa; the strain hardening exponent of base matel n_B =3.0. The values of yielding stress of weld metal are 390 MPa, 490 MPa, and 610 MPa, and the strain hardening exponent of weld metal varied from 1.0 to 6.0 in order to simulate the various matched weldments.

The welded center-cracked specimen configuration and the finite element mesh for the upper-right of the specimen are shown in Fig.1 and 2, respectively. In the large strain gradient zone the mesh is refined. The zone near crack tip consisted of several layers of circular rings of elements which are centered about the crack tip. The elements in the first ring are wedge-shaped, that is, one edge of the element is shrunk to a point which coincides with the crack tip location.

The numerical evaluation of the J-integral was conducted according to the reference (Shih, 1984). In the present work, six paths of the J-integral were taken. Two of the paths located within the weld metal region. The others traversed both the base metal and weld metal. The values of the J-integral computed from the paths exhibited no more than 5 percent variation. With the mesh having 124 elements and 850 nodes the computing time per an exponent or a yielding stress was about 5 min on a Honeywell DPS/8-52 computer. All the results computed in this paper were abtained with this mesh devision.

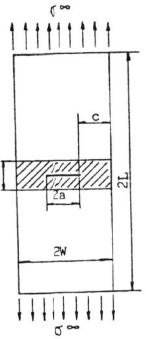

Fig.1 Configuration of welded center-cracked specimen.

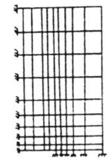

Fig.2 Finite element mesh

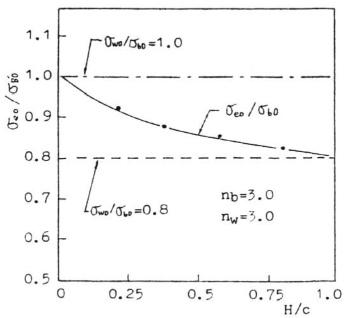

Fig.3 The equivalent yielding stress of undermatched weldment versus the width of weld metal.

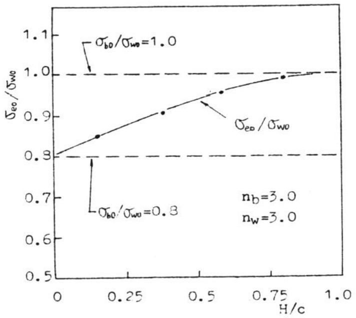

Fig.4 The equivalent yielding stress of overmatched weldment versus the width of weld metal.

RESULTS AND DISCUSSION

The equivalent yielding stress in the vicinity of the crack tip is changed with the width of the weld metal, as shown in Fig.3 and 4. Fig.3 gives a relation between the ratio, σ_{e0}/σ_{b0}, versus dimensionless parameter, H/c, in under-matched weldment, and Fig.4 a relation between the ratio, σ_{e0}/σ_{w0}, versus parameter, H/c, in overmatched weldment. In the undermatched weldment the ratio of the equivalent yielding stress to the yielding stress of base metal will be decreased with the increase of weld metal width(Fig.3). However, in the overmatched weldment the ratio of equivalent yielding stress to yielding stress of weld metal will be increased with the increase of the weld metal width, as shown in Fig.4. The difference between the equivalent yielding stress and the yielding stress of weld metal is diminished in either overmatched or undermatched weldments with the increase of the weld metal width. When the ratio of the weld metal width ,H, to the ligament length ,c, is larger than 1.0, the mechanical properties of the base metal has no effects on the fracture parameters of weldment. In the undermatched weldment the yielding stress of the weld metal near the crack tip increases because of the strengthening of the base metal. In the opposite the yielding stress of weld metal in the vicinity of crack tip will decrease in overmatched weldment because of the softening of base metal.

Fig.5-7 give the relations between the equivalent strain hardening exponent and parameter, H/C, of the various matched weldments. It can be seen that the equivalent strain hardening exponent, n_e, gradually closes to the exponent of weld metal with the increase of the weld metal width. If the value of the ratio, H/c, is more than 1.0 , the equivalent strain hardening exponent is very close to the exponent of weld metal. When the hardening exponent of weld metal is lower than that of the base metal, the equivalent hardening exponent will be larger than that of weld metal. If the strain hardening exponent of the weld metal is larger than that of the base metal, the equivalent hardening exponent will be lower than the

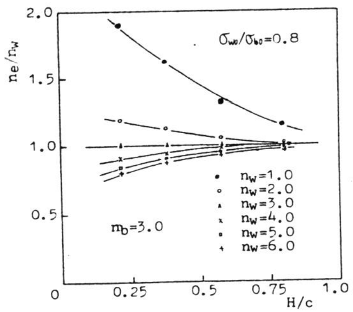

Fig.5 The equivalent strain hardening exponent of undermatched weldment versus the weld metal width.

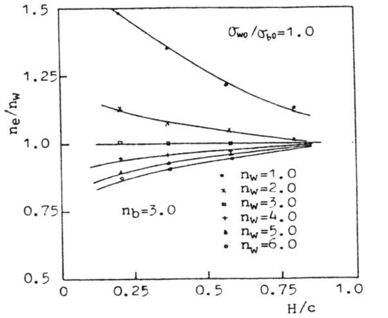

Fig.6 The equivalent strain hardening exponent of evenmatched weldment versus the weld metal width.

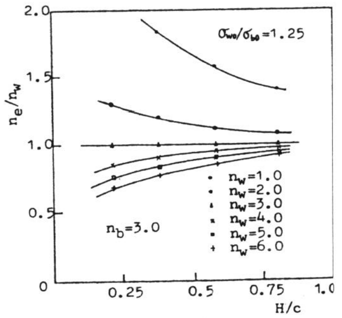

Fig.7 The equivalent strain hardening exponent of overmatched weldment versus the weld metal width.

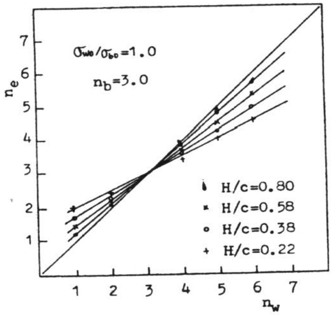

Fig.8 The relation among equivalent strain hardening exponent, strain hardening exponent of weld metal, and parameter H/c.

hardening exponent of the weld metal. The similar results can be found in any matched weldments. That is to say the equal driving force can be obtained in the given load whether the weldment is overmatched, evenmatched or undermatched. In the condition of various matched weldments the width of the weld metal will have great effect on the fracture mechanics parameters. The fracture behavior of weldment depents on the weld metal when the value of the H/C is larger than 1.0.

Fig.8 shows the relation between the equivalent hardening exponent and the weld metal hardening exponent. In fact, that is another arrangement of the results shown in Fig.6. It is clear that the equivalent hardening exponent is gradually close to the hardening exponent of weld metal with the increase of the width of the weld metal.

CONCLUSIONS

The fully plastic finite element method in plane stress condition is used to calculate the fully plastic fracture mechanics parameters of various matched weldment for a center-cracked specimen. The equivalent yielding stress and equivalent strain hardening exponent near the crack tip are obtained for various matched weldments.

The width of the weld metal has strong effect on the evaluation of fracture mechanics parameters of weldment. The narrower the width of the weld metal, The stronger the effect. The values of fracture mechanics parameters of weldment reach to those of weld metal when the width of the weld metal is larger than the ligament of specimen.

When the yielding stress of weld metal is larger or smaller than that of base metal, the equivalent yielding stress near the crack tip will be smaller or larger than that of weld metal because of the softening or strengthening of the base metal.

The equivalent strain hardening exponent near crack tip will be gradually close to strain hardening exponent of weld metal with the increase of the weld metal width in spite of undermatched, evermatched, or overmatched weldment.

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