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Effect of plasticity constraint on structural integrity assessment of pressure vessel welds

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ABSTRACT

The BS 7910 Option 1 and constraint-based failure assessment diagrams (FADs) methodologies were utilized for the integrity assessment of the cracked Al alloy pressure vessel welds (PVWs). To determine the constraint-based FAD curves, finite element analyses were performed to derive the functional relationships between normalized load and Q-constraint for single-edge notched bending (SENB) specimens. The results showed that there was a significant difference between conventional and constraint-based FAD curves for shallow-cracked specimens with low Q-constraint ahead of the crack tip. However, for deeply cracked specimens with high Q-constraint, the effect of constraint-correction on the BS 7910 Option 1 was not pronounced. It was revealed that the prediction based upon constraint-modified FADs was in better agreement with the experimental results of residual strength than the BS 7910 Option 1 procedure which was proved to be conservative for the shallow-cracked vessel specimens.

1. Introduction

Engineering structures containing defects might be responsible for structural failure during the fabrication stage or during the service life. The structural significance of such imperfections, particularly crack-like flaws need to be assessed to prevent failure of the component during service [1]. In particular, welded structures require special procedure for structural integrity assessment of the welding flaws. Fracture assessment procedures for welded components containing flaws play an important role in the design, manufacture and safe operation of pressure vessels, piping and storage tanks [2].

In certain engineering structures, the failure of a structural component due to the existence of flaws is quite catastrophic, which may result in serious economic and environmental consequences. However, to determine if a structure containing flaws requires a repair, an acceptance level is required to define the size of defects. Several important standard procedures have been published for the defects assessment of welded structures in the past few years, such as the BS 7910 [3] and R6 [4]. These standard procedures are based on the failure assessment diagrams (FADs), which was initially developed from the two-criterion assessment proposed by Dowling and Townley [5]. In the FAD procedures, the integrity of cracked components is assessed by calculating the two extremes of fracture behavior separately, linear elastic and plastic collapse behavior. This is schematically illustrated in Fig. 1. In the last few years, defect assessment procedures based on the FAD concept have been widely used to assess the integrity of engineering components containing defects [6–8].

However, a conservative implication in the conventional FAD methodologies is that the assessment uses fracture toughness values obtained from tests on deeply cracked specimens according to established experimental standards and validity criteria. The validity criteria are designed to ensure plane-strain conditions and to guarantee high levels of stress triaxiality near the crack-tip. However, structural flaws in pressurized vessel systems are usually surface cracks and these crack configurations generally develop low levels of crack-tip stress triaxiality. Consequently, defect assessments in low constraint structural components using conventional FAD methodologies may be overly conservative and pessimistic. However, such conservatism may lead to unnecessary replacement or repairs of in-service components at great operational cost.

There has been considerable research [9–12] on these low constraint effects in order to quantify the geometry dependence of the fracture toughness using so-called constraint parameters. This has led to constraint-based FADs within the BS 7910 [3] and R6 [4] procedures. However, there are few investigations that discuss in

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Nomenclature

a	flaw height for surface flaw
c	half flaw length for surface flaw
m	Weibull model exponent
r, θ	the polar coordinates taken from the crack tip
B	section thickness in plane of flaw
CTOD	crack tip opening displacement
D	outside diameter of pressure vessel
E	elasticity modulus
J	J-integral
K_r	fracture ratio of applied elastic K value to K_{mat}
K_{mat}	fracture toughness
L_r	ratio of applied load to yield load
N	strain hardening exponent
Q	normalized hydrostatic stress used as a constraint parameter
Q^p, Q^s	values of Q for primary stress, secondary stress, respectively
S	specimen span
T	elastic T-stress
W	specimen width
α, k	parameter defining influence of constraint on fracture toughness
β_Q	normalized constraint parameter
σ_y	yield stress
$\sigma_{\theta\theta}$	stress field at a specific position ahead of the crack tip
SENB	single edge notched bending specimen
SE(T)	single edge notched tension specimen
SSY	small scale yielding
LSY	large scale yielding
FAD	fatigue assessment diagram
BM	base metals
HAZ	heat affected zone
WM	weld metal
PVWs	pressure vessel welds

detail the integrity assessment of cracked PVWs based on Q-constraint modification FAD procedures by comparing the outcomes with the conventional FAD procedures.

The purpose of this study is to assess the application capability of the BS 7910 Option 1 and constraint-based FAD procedures in integrity assessment analyses of PVWs with different crack configurations and to broaden current understanding on the effect of Q-constraint on defect assessment procedures for these components. A finite element analysis is adopted in order to obtain the relationship of normalized load and Q-stress for the SENB specimens. Specifically, the present study compares the residual strength predictions of cracked PVWs using BS 7910 Option 1 and constraint-based FADs with experimental values.

2. Constraint-based failure assessment diagrams

2.1. J–Q characterization of near tip fields

There are many studies indicating that the material resistance to fracture was increased when the crack length of specimens decreased [13–15]. The improvement of material toughness is related to loss of crack tip constraint, which has potential benefits when assessing the safety of components containing shallow defects. In general, it was found that Q-constraint can provide a good characterization for crack front stress fields [16]. Based on the Q-constraint parameter, the resistance to fracture for different geometries can be quantified and thus providing a more realistic basis for fracture assessments.

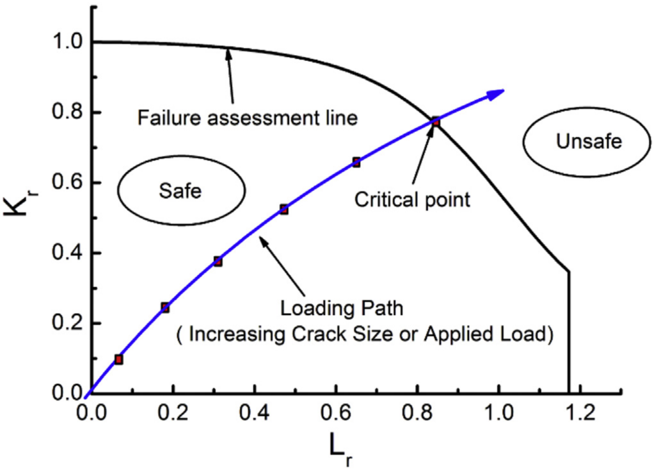

Fig. 1. Failure assessment diagram for defected structure.

The Q-stress that is derived from the HRR stress field proposed by Hutchinson [17] as well as by Rice and Rosengren [18] was adopted to develop the degree of constraint for cracked specimens and structures. A second term was incorporated into elastic–plastic fracture mechanics and the HRR theory to accommodate the constraint effects in fracture mechanics [19]. The Q-stress is normalized by the yield stress and defined by the Eq. (1) as follows:

$$\sigma_{ij} = (\sigma_{ij})_{HRR} + Q\sigma_y\delta_{ij} \tag{1}$$

where $(\sigma_{ij})_{HRR}$ is the HRR field, σ_{ij} is the stress field ahead of the crack tip, and δ_{ij} is the Kronecker delta. O'Dowd and Shih [20,21] proposed that the first HRR term was replaced by a small-scale yielding solution obtained from modified boundary layer analyses with T = 0. Here, T is the elastic T-stress. Then the equation (1) is represented by

$$\sigma_{ij} = (\sigma_{ij})_{SSY;T=0} + Q\sigma_y\delta_{ij} \tag{2}$$

$$\text{where } (\sigma_{ij})_{SSY;T=0} = \left[\sigma_{ij}\left(\frac{r}{J/\sigma_y},\theta\right)\right]_{T=0} \text{ for } |\theta| \le \frac{\pi}{2} \text{ and } 1.5 \le \frac{r\sigma_y}{J} \le 5 \tag{3}$$

Based on the Eqs. (2) and (3), Q may be evaluated as the difference between the actual stress field and the small-scale yielding reference solution, as follows:

$$Q = \frac{\sigma_{\theta\theta} - (\sigma_{\theta\theta})_{SSY;T=0}}{\sigma_y}, \text{ at } \theta = 0, \ \frac{r}{J/\sigma_y} = 2, \tag{4}$$

where $\sigma_{\theta\theta}$ is the opening stress component, and the difference field is evaluated at the microscale distance $r = 2J/\sigma_y$, which is the