Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, 2003

The *J* Estimation Scheme of Fracture Toughness of Zr-2.5Nb Tubes

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Abstract

Influence of specimen configuration on the material's fracture toughness due to the constraint effect has been discussed. A concept of constraint-corrected fracture mechanics specimens has been employed to prove specimen configuration and type of loading and simulate the fracture toughness of Zr-2.5Nb pressure tube. Sizes of curved center cracked panel specimen and specimen-fixture assembly were suggested. The *J* estimation procedure for the specimen has been considered.

1. Introduction

The standard *J–R* curve is a plot of the *J*-integral versus crack extension within the region of *J*-controlled growth, and is size-independent, as specified in ASTM fracture test standard E 1820-99. But for nonstandard fracture specimens, the *J–R* curves could be size-dependent due to the loss of *J*-control. Generally speaking, the fracture toughness J_{IC} and *J–R* curve of a material could be functions of test specimen geometry, size, thickness and loading configuration. To investigate the crack-tip constraint effects on the elastic-plastic fracture toughness, a large number of nonstandard specimens (single edge-notched bending (SENB), compact tension (CT), center cracked panel (CCP), single edge-notched tensile (SENT) specimens, double edge-cracked plate (DECP)) have been analyzed [1-4].

All above experimental data have suggested that the test data of J_{IC} and $J-R$ curves are generally geometry dependent. The values of *J*-integral on the *J–R* curve for high constraint specimens are lower than those for low constraint specimens. In other words, the slope of *J–R* curves after crack initiation steadily decreases with increasing crack-tip constraint.

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Therefore, the constraint effects on the fracture toughness due to specimen geometry must be corrected so that the fracture toughness determined in laboratory can be applied to real cracked structures. Furthermore, the constraint effects in the real cracked structures should be also evaluated and accounted for in order to solve the transferability problem.

The objective of the paper is to suggest the J estimation scheme of the fracture toughness of Zr-2.5Nb pressure tubes.

2. A concept of constraint-corrected fracture mechanics specimen

Three primary methods to quantify crack-tip constraints are the J–T approach proposed by Betegon and Hancock [5], the J–Q theory proposed by O'Dowd and Shih [6], the J–A_2 method proposed by Chao et al. [7]. The $J-Q^*$ theory [8] has been suggested and based on a modified constraint parameter Q^* instead of Q in the J–Q theory.

A concept for failure assessment for low constraint applications [9], which reduces the conservatism of the standard failure analysis, can be also used. The method is based on the testing of constraint-corrected fracture mechanics specimens. These specimens can be fitted to give the same constraint levels as for real cracked structures. In our case, these specimens can be designed to give a constraint level comparable to that of a pipe with through-wall cracks.

The method based on constraint-corrected specimens has the following advantage. It makes the failure assessment more efficient and precise by relaxing the high conservatism of the usual procedure. The focus of this study is to find simple procedures for the computation of the fracture mechanics parameters necessary to perform failure assessment of pipes by using the new method. However, in our pursuit of engineering methodologies, a goal is to reduce the need for FEM calculations.

It is important to keep in mind that the fracture toughness derived from constraint-corrected specimens is limited to a specific geometry, and should not be applied to other geometries without first verifying that the constraint in the geometry is similar or higher that of the specimen.

3. Constraint-corrected fracture mechanics specimen to simulate pressure tube

The stress fields in the low constraint geometries, such as pipes, and in the high constraint geometries, such as SENB or CT specimens, are different. Similar stress fields can be expected in geometries under some type of loading with a comparable constraint level. The stress field ahead of the crack tip is characterised by the value of stress intensity factor. Our goal is to suggest constraint-corrected specimen with a crack tip field, which is comparable to that of axial crack in pipe.

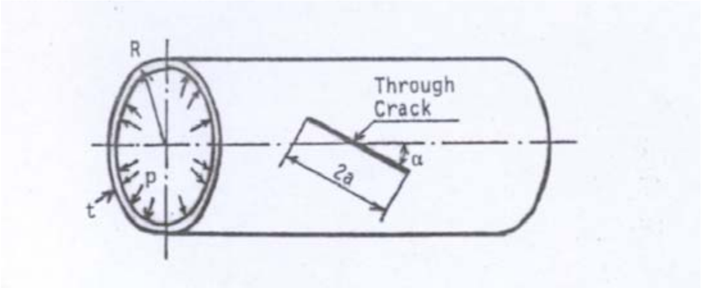
An arbitrarily through-wall cracked pipe under internal pressure p has been considered (Fig. 1a). Important non-dimensional variable is the normalized crack length parameter β, defined by formula

$$\beta = \left[12\left(1-\nu^2\right)\right]^{1/4} \frac{a}{\sqrt{8Rt}}, \qquad (1)$$

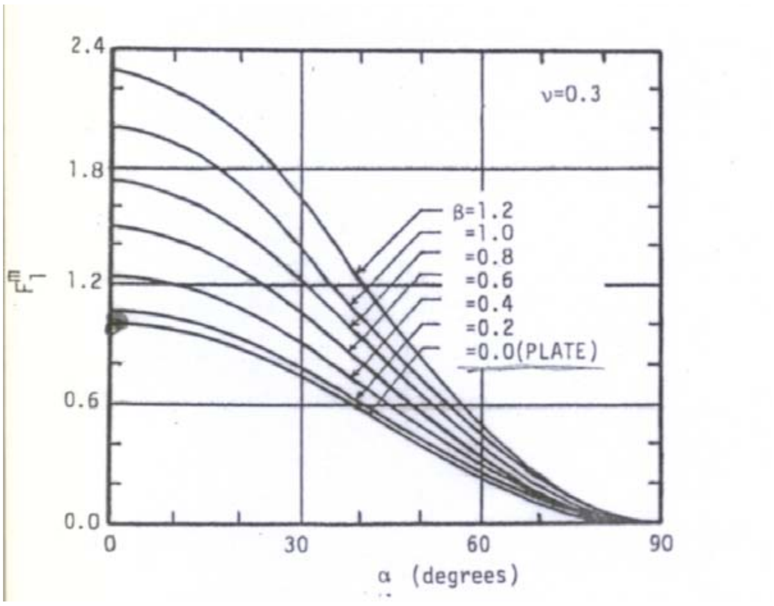
where ν is Poisson's ratio. The stress intensity factor for an arbitrarily oriented crack subjected to internal pressure is written as

$$K_I = \sigma_{app} a\left(F_I^m\right), \tag{2}$$

where $\sigma_{app} = pR/t$ is the applied stress, F_I^m is the stress intensity correction factor which is graphically given in Fig. 1*b* [10].



a)



b)

Figure 1. An arbitrarily through-wall cracked pipe under internal pressure (*a*) and the stress intensity correction factor (*b*).

For an axial crack ($\alpha = 0$), the correction factor decreases with the increase of the pipe radius (or normalized crack length parameter β) tending to its limiting value at $R \rightarrow \infty$, i.e. the correction factor of through-wall central crack $2c$ in an infinite plane under tension (Fig. 1*b*). In this case, an infinite plane with through-wall central crack under tension can be considered as an axial through-wall cracked pipe under internal pressure p with the radius of an infinite value. So, through-wall central crack in a plane under tension (central cracked panel specimen) can be fitted to give the same constraint levels as for pipe with through-wall axial crack. It is suggested that the present conclusion will be valid in the case of plastically deformed tube.

4. Specimen sizes and specimen-fixture assembly

The specimen width $2W$ can be obtained from specimen size limits analysis based on fracture toughness test procedure ASTM E 1820 "Standard Test Method for Measurement of Fracture Toughness". The maximum crack extension capacity for a specimen is given by the following

$$\Delta a_{max} = 0.25 b_0 , \tag{3}$$

where $b_0 = W - a_0$ is initial ligament. From another point of view, to determine J_{1C} according to ASTM procedures E 813-87 and E 1820, crack extension must be expected more than 1.5 mm, i.e. $\Delta a \geq 1.5$ mm. It means that minimum initial uncracked ligament is given by formula

$$b_0 \geq 4\Delta a_{max} = 4 \times 1.5 \text{mm=6mm}. \tag{4}$$

The specimen ratio a_0 / W is assumed to be 0.4. Thus, taking into account relation (4), the specimen width $2W$ will be equal to 20 mm.

It is also necessary to calculate the gage length L_G to specimen width $2W$ ratio. For example, Landes and Begley's original experimental work used a ratio of 2.25:1 [11]. In the current work, the ratio is suggested to be 2:1. In this case, all of the plastic displacement due to the crack is included in the load-line load-displacement curve.

Special fixtures are necessary for curved CCP specimens to avoid specimen buckling under tension. The fixture of specimen consists of two halves, which when placed together form the specimen holder (Fig. 2). The fixture halves parts contacting with specimen surface has a diameter, which allows it to be inserted into the curved specimen, while maintaining a minimal interfacial gap. The fixture halves are loaded in tension through the pins.

5. Calculation of J-integral for the center cracked tension specimen

Fracture toughness in the elastic-plastic regime is often characterized using the J-integral. The J-integral for CCP specimen is calculated by splitting J into elastic J_{el} and plastic J_{pl} components $J = J_{el} + J_{pl}$, where

$$J_{el} = \frac{K^2}{E'} \quad \text{and} \quad J_{pl} = \eta_{pl} \frac{A_{pl}}{2t(W-a)} . \tag{5}$$

The parameter J_{pl} is calculated from the area under the load P versus load-line plastic displacement v_{pl} curve $A_{pl} = \int_0^{v_{pl}} P dv_{pl}$ and the cross-sectional area of the uncracked ligament $2t(W-a)$. Load-line displacement is typically measured using a gage length L_G.

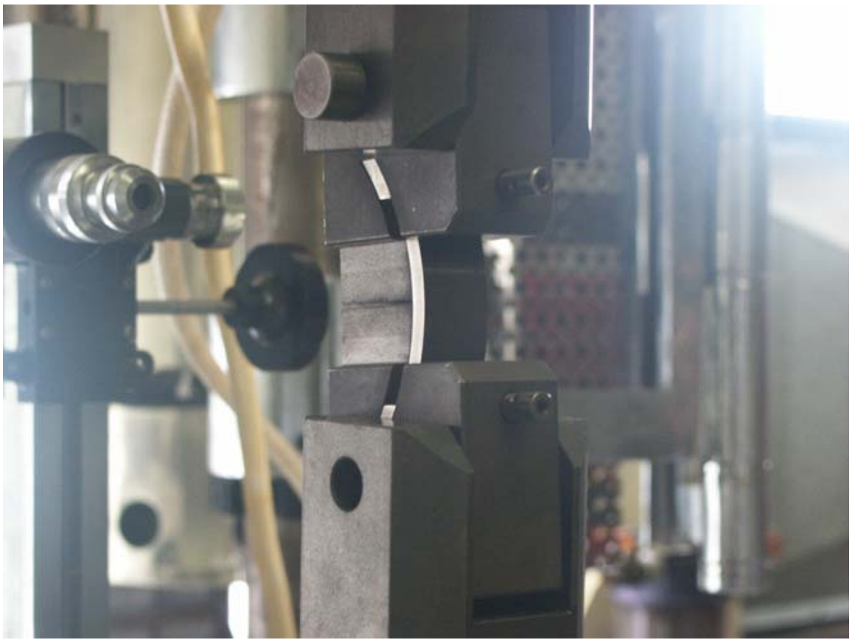


Figure 2. Curved center cracked tension specimen and specimen-fixture assembly.

The η_{pl} plastic factor (Eq. (5)) can be determined for shallow and deep cracks using the EPRI Handbook solution [12] and taking into account that the load-line plastic displacement includes both the cracked and the uncracked part [13], i.e.

$$\eta_{pl} = \frac{\sqrt{3}}{2}\frac{n+1}{n}\frac{h_1(a/W,n)}{h_3(a/W,n)+h_{30}(L_G,a/W,n)}\left(1-\frac{a}{W}\right), \tag{6}$$

where h_1, h_2, h_3 are tabulated functions for the EPRI plastic solutions. In contrast to the gauge length reported by Wu et al. [13], the gauge length is assumed to be constant value of $L_G = 4W$. It is because of the value of L_G to specimen width ratio in the *J*-integral test is ibdependent on crack sizes. The strain hardening exponent for Zr-2.5Nb alloy in Eq. (6) can be estimated through the knowledge of yield and ultimate tensile strength (e.g. [14, 15]).

The *J* estimation scheme can be adopted for the curved CCP specimen as reported by Davies et al. [16].

6. Conclusions

Concept of constraint-corrected fracture mechanics specimens has been employed to prove specimen configuration and type of loading. Sizes of curved central cracked panel specimen and specimen-fixture assembly were suggested to simulate the fracture toughness of Zr-2.5Nb pressured tube. The modified EPRI solutions could be recommended to estimate the realistic plastic factor η_{pl} for the curved CCP specimen and calculate the fracture toughness.

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