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Engineering estimates of crack opening displacement for non-idealized circumferential through-wall cracks in pipe

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ABSTRACT

The present paper provides the engineering estimates of non-linear crack opening displacement (COD) for a circumferential non-idealized through-wall crack in a pipe based on both the GE/EPRI and the enhanced reference stress methods. For the GE/EPRI-type solution, the h_2 values are newly calibrated based on the elastic–plastic finite element analyses. Also, elastic COD and the reference load solutions are proposed. Then, the proposed engineering estimates are validated against the FE results using actual tensile data of SA312 Type 316 stainless steel. From these comparisons, it is revealed that the enhanced reference stress method provides the best and overall satisfactory results.

1. Introduction

Over the last few decades, in accordance with the U.S. Nuclear Regulatory Commission (USNRC) Standard Review Plan (SRP) 3.6.3 [1], the Leak-Before-Break (LBB) concept has been widely used in a nuclear piping design to exclude the dynamic effect due to postulated high-energy pipe ruptures from the design basis of primary nuclear piping systems. The LBB concept can be applied to nuclear piping design on condition that a crack length corresponding to a detectable leak rate determined through a calculation of a crack opening displacement (COD) would remain stable, that is, this detectable leakage crack length is smaller than a critical crack length that can cause an unstable pipe rupture. In this basic premise, a circumferential through-wall crack (TWC) is typically employed considering dominant stress components acting on a nuclear piping. In this context, an accurate estimation of relevant fracture mechanics parameters, i.e., COD and J-integral, for a circumferential TWC is important in a LBB analysis.

Recently, in order to calculate these parameters, finite element (FE) analysis has been popularly adapted. Since a LBB analysis or a structural integrity assessment for defective components, however, often involves numerous parametric and sensitivity analyses, FE analyses sometimes has limitation in calculating fracture parameters for an actual structural integrity assessment. In this respect, the engineering methods to estimate a COD and a J-integral are typically required for a pipe with a circumferential TWC [2–4].

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Nomenclature

a_1	reference half crack length at inner surface
a_2	reference half crack length at outer surface
$h_2(n)$	plastic influence function for δ_p in the GE/EPRI method
$h_2(n=1)$	value of h_2 for the elastic case($n = 1$)
M	global bending moment
M_L	global limit bending moment
M_{oR}	optimized reference bending moment
n	strain hardening index for Ramberg-Osgood model
p	internal pressure
p_L	Internal limit pressure
p_{oR}	optimized reference internal pressure
Q	generalized load (tension, bending moment or internal pressure)
Q_L	generalized limit load
Q_{oR}	optimized reference load (General)
r	perpendicular distance from the inner surface to the outer surface at the center of crack
R_i	inner radius of a pipe
R_m	mean radius of a pipe (=$(R_i + R_o)/2$)
R_o	outer radius of a pipe
t	wall thickness of a pipe
T	tensile load
T_L	limit tensile load
T_{oR}	optimized reference tensile load
V_Q	shape factor of the elastic COD for idealized TWC under generalized loading
α	coefficient of Ramberg-Osgood model
γ_Q	non-dimensional factor of optimized reference load for non-idealized circumferential TWC under generalized loading
δ_e	elastic component of crack opening displacement
δ_p	plastic component of crack opening displacement
ε_{ref}	reference strain at the reference stress σ_{ref}
θ_1	half crack angle at inner side in the circumferential cracked pipe
θ_2	half crack angle at outer side in the circumferential cracked pipe
ν	Poisson's ratio
σ_{ref}	reference stress
σ_y	yield strength
φ	non-dimensional correction factor of elastic crack opening displacement for circumferential non-idealized TWC in pipe

Among several engineering estimates for predicting a COD and a J-integral, most popular ones are the GE/EPRI method [5,6] using the Ramberg–Osgood (R–O) fit to tensile data and the reference stress (RS) method [7] using actual tensile data of material of interest. Firstly, although the GE/EPRI method [5] has been widely used for practical applications, it has known that the results are very sensitive to how to characterize the stress–strain data of material based on the R–O model [8,9]. On the other hand, the RS method can either reduce a sensitivity associated with a material characterization or give a robust result since this method does not require material idealization, and then this method has been utilized in many structural integrity assessment methods, for instance, R6 code [7]. In the RS method, the reference stress is defined by the plastic limit load of the cracked components. Although, the plastic limit loads are widely available even for complex geometry and loading conditions, this method also suffers from inaccuracy associated with the definition of the reference stress. Thus, to improve the accuracy of the RS method, the Enhanced Reference Stress (ERS) method has been proposed by Kim and Budden [10] for a pipe with a circumferential TWC. The underlying idea of the ERS method is introducing new reference load, called optimized reference load based on the limited FE analyses instead of plastic limit load in the typical RS method. The validity of ERS method has been confirmed by comparing with 19 pipe experimental data, extracted from Kishida and Zahoor [11] and the Pipe Fracture Encyclopedia [12], where the results showed the overall excellent agreement [8].

At this point, it should be pointed out that, although, the value of the COD at the outer surface can be different from that at the inner surface of a pipe, the existing solution [10] gives only the value of COD at the mid-thickness. For this reason, when the detectable leak rate is calculated during the crack growth, the initially penetrated crack is assumed as fully penetrated crack (referred to as idealized TWC in Fig. 1) based on average crack angle concept for conservative LBB analysis [13].

However, it has been reported by Shim [14] that the equivalent area method based on the average crack angle would lead to excessively conservative result for a LBB analysis. Besides, this average crack angle concept does not physically simulate a realistic crack shape development. Note that, as shown in Fig. 1, during an actual crack growth resulting from a fatigue or a