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Technical Note

A simplified approach for assessing the leak-before-break for the flawed pressure vessels

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ABSTRACT

Surface cracks or embedded cracks in pressure vessels under service may grow and form stable through-thickness cracks causing leak prior to failure. If this leak-before-break phenomenon takes place, then there is a possibility of preventing the vessel failure. This paper presents a simplified approach for assessing the leak-before-break or failure of the flawed pressure vessels. This approach is validated through comparison of existing test data.

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1. Introduction

Part-through cracks in pressure vessels under service loads may grow and form stable through-thickness cracks causing leak prior to failure known as the leak-before-break (LBB) phenomenon. If this phenomenon happens, then there is a possibility of preventing the vessels from failure. If the part-through cracks under service loading conditions grown to critical size, then the vessel may fail catastrophically prior to the formation of the through-thickness crack. The significant parameters affecting the critical crack size in a pressure vessel are the applied stress levels, the location of the crack and its orientation, and the strength as well as the fracture toughness of the material.

For safe design of pressure vessels, LBB is one of the important criteria (Pacholkova and Taylor, 2002). Designers apply LBB criterion to structural components (which are subjected to high or low fatigue loads) in nuclear power plants, liquid nitrogen tankers and chemical plants. The LBB concept is applied to high pressure vessels and related plant equipments (Nam and Abn, 2002). Kawaguchi et al. (2004) have examined the LBB behavior for axially notched X65 and X80 gas pipelines. Drubaya et al. (2003) have provided a guide for defect assessment at elevated temperature. Toughry (2002) has developed an acceptance/rejection criterion for high pressure steel and aluminum cylinders. Zhou and Shen (1996) have discussed on the LBB assessment methods. The concept of LBB was initially introduced by Irwin. An analogous method later on was developed by Irwin and Hood. These two methods are very simple and provide conservative estimates. Wilkowski (2000) states that Irwin has performed the linear elastic fracture mechanics (LEFM) analysis on pressure vessels specifying the axial crack length less than twice the shell thickness, and observed greater crack driving force in radial direction than in the axial direction of the vessel.

Experiments of Rana (1987) on gas cylinders containing a surface crack (whose length is four times the shell wall thickness) indicate the validity of LBB criterion. Sharples and Clayton (1990) have generated crack depth versus crack length curves for assessing leakage or break of the flawed pressure vessels. Kim (2004) has performed LBB analysis on through-thickness cracked pipes. Kim et al. (2005) have proposed an elastic–plastic *J*-integral approach to carryout LBB analysis for circumferential through-thickness cracked pipes. The plane strain fracture toughness (K_{IC}) of the material can be evaluated from the Compact Tension (CT) specimens following the ASTM E399 standards (ASTM, 2013a), whereas the crack growth resistance curve (*R*-curve) of the material can be generated following the ASTM E561 standards (ASTM, 2013b). The fracture toughness (K_C) where plane strain conditions are not fully met can be determined from the point of tangency between the *R*-curve and the crack driving force curve appropriate for the loading geometry. The crack growth observed in K_{IC} specimens after failure is very small whereas it is appreciable in K_C specimens. Failure load estimates based on the lower bound K_{IC} values will be conservative and

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Nomenclature

a	depth of a surface crack
$2c$	length of a surface crack
$2c^*$	through-thickness crack
K_C	plane-stress fracture toughness
K_I	stress intensity factor
K_{IC}	plane-strain fracture toughness
K_F, m and p	fracture toughness parameters in $K_{\max} - \sigma_f$ relation (1)
$K_{\max}$	stress intensity factor corresponding to the failure stress (σ_f)
P	internal pressure
P_b	bursting pressure of unflawed cylindrical vessel
P_f	failure pressure of flawed cylindrical vessel
R_i	inner radius of the cylindrical shell
t	thickness
β_C, β_{IC}	dimensionless parameters (ratio of plastic zone size to thickness) for plane-stress and plane-strain situations
Δa	incremental flaw growth
ΔK	stress intensity range
$\Delta\sigma_b$, $\Delta\sigma_m$	increment in bending and membrane stresses
ϕ	crack shape parameter
σ_f	hoop stress at failure pressure of flawed vessel
σ_{ys}	yield strength or 0.2% proof stress ($R_{P0.2}$)
σ_u	hoop stress at failure pressure of unflawed pressure vessel
σ_{ult}	ultimate tensile strength (Rm)

design based on K_{IC} requires unreasonably thick panels in normally thin sectioned structural members as in aerospace industry.

1.1. Relationship between K_{max} and σ_f

Kannan et al. (2013) have examined the applicability of a modified two-parameter criterion (Christopher et al., 2004a, 2005a) while assessing the fracture strength of structural components. They utilized a relation between the stress intensity factor ($K_{\max}$) and the corresponding stress at failure (σ_f) as

$$K_{\max} = K_F \left\{ 1 - m\left(\frac{\sigma_f}{\sigma_u}\right) - (1-m)\left(\frac{\sigma_f}{\sigma_u}\right)^p \right\} \tag{1}$$

Here, σ_f is the hoop stress at the failure pressure of the flawed vessel and σ_u is the hoop stress at the failure pressure of the unflawed vessel. For uniaxial tensile specimens, σ_u is equal to the ultimate tensile strength (σ_{ult} or Rm) of the material. K_F, m and p are fracture parameters to be determined from the test data of cracked configurations. The fracture parameter, K_F has the units of the fracture toughness (MPa$\sqrt{}$m), whereas the second parameter $0 \le m \le 1$ and to account for plasticity the third parameter, p dependent on m is given by

$$p = \frac{1}{\ln\left\{\frac{1}{2}(1+\zeta)\right\}} \ln\left[\frac{1}{(1-m)}\left\{1 - \frac{1}{2\sqrt{2}}(1+\zeta)\left(\frac{1}{\zeta} + \left(\sqrt{2}-1\right)m\right)\right\}\right] \tag{2}$$

and ζ in Eq. (2) is

$$\zeta = \frac{4}{3+\sqrt{9-8m}} \tag{3}$$

If the fracture data corresponds to the plane strain fracture toughness (K_{IC}) of the specimens, then the fracture parameters in Eq. (1) are: $K_F = K_{IC}$ and $m = 0$. When the stress intensity factor (K_I) of the through-thickness cracked vessel under service loads is less than the plane strain fracture toughness (K_{IC}), the vessel leaks initially, grow gradually to the critical size and fail. Detection of leaking at the initial stage will be helpful in preventing the failure of vessel. To assess the life of the flawed vessel, it is essential to know the path of the part-through crack grown to the through thickness crack. If the stress intensity factor (K_I) of the through-thickness cracked vessel for the stress levels falls below the failure assessment diagram, then the vessel leaks. For $K_I \le K_{IC}$, the crack growth will be slower. Crack propagation will result if $K_I \ge K_{IC}$ of the material.

1.2. Relationship between K_C and K_{IC}

The ratio of plastic zone size to thickness (β_C) is a convenient measure of the degree of shear-lip. The dimensionless parameters β_C and β_{IC} for plane-stress and plane-strain situations defined by Irwin are (Irwin, 1962; Irwin and de Wit, 1983):

$$\beta_C = \frac{1}{t}\left(\frac{K_C}{\sigma_{ys}}\right)^2; \quad \text{and} \quad \beta_{IC} = \frac{1}{t}\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2.$$

Here σ_{ys} is the yield strength or 0.2% proof stress ($R_{P0.2}$) and t is the thickness. An approximate empirical relationship between β_C and β_{IC} (valid for $\beta_C < 2\pi$) proposed by Irwin is (Subhananda Rao et al., 2005)

$$\beta_C = \beta_{IC}(1 + 1.4\beta_{IC}^2) \tag{4}$$

1.3. Background of LBB studies

In the 1960s, Battelle had initiated the development of LBB methodologies by performing nonlinear fracture analysis for axial flaws in gas pipelines. The axial flaw equations for nuclear piping have been implemented in Appendices C and H of section XI of the ASME Boiler and Pressure Vessel code. Various researchers have made LBB studies applicable to nuclear piping (Bryan et al., 1982; Proc IAEAP, 1983; Moan et al., 1990), gas and oil pipelines (Wilkowski and Eiber, 1981; Roos et al., 1989), pressure vessels (Pellini, 1969; Kiefner et al., 1973; Rintamaa et al., 1988; Setz and Gruter, 1990), missile casings (Pierce, 1970), etc. Pacholkova and Taylor have highlighted the proposals of regulatory procedures by various research organizations (USA, UK, Germany, France, Italy, Spain, Czech Republic, Russia and Japan) to accommodate LBB for pressure vessels and pipework in nuclear design (Zdarek et al., 1995; Bergman and Brickstad, 1995, 1997; Arzhaev et al., 1996; Bartholome and Wellein, 1995).

Sharples (2012) has reviewed the LBB methodologies of the Europe nuclear industries and reported that all the LBB procedures share the same basis of specifying the flaw size in such a way that the loss of fluid escaping the through wall crack can be detected. Yoo and Huh (2013) have proposed a methodology for LBB assessment of piping systems in fast breeder reactors. Their emphasis is on assessment of leakage under low pressure situation, failure under crack growth, and buckling of thin-walled and large-diametric elbow structures. Wakai et al. (2014) have demonstrated their LBB procedure with sufficient margin on Japan sodium cooled fast reactor steel pipes. In a recent review, Bourga et al. (2015) have indicated the requirement of adequate margin between the smallest detectable leak size and the critical crack size to support LBB. It is noted from their review that most countries use a safety factor of 10 on leak detection and 2 on crack length (or applied stresses). Japanese recommend a safety factor 5 on leak detection and 1 on crack length. In contrast, the UK procedures do not provide explicit guidance on the safety factor (Bourga et al., 2015). It is a continuous process of improving the LBB procedures in order to

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