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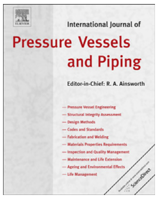

Review

Leak-before-break: Global perspectives and procedures

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ABSTRACT

Structural integrity of components containing fluids is critical for economic, environmental and safety issues. Any risk of catastrophic failure, in the form of either brittle or ductile manner, is not acceptable across the industries. Consequently, many efforts have been invested in the structural integrity aspect to improve the assessment methodologies. One of the ways to aid the decision whether or not to live with the defect is through the demonstration of Leak-Before-Break (LBB). LBB which is a well-established practice in the nuclear industry, albeit as a defence-in-depth argument or to justify the elimination of pipe whip restraints, also finds its applicability in other industries. A review of the available procedures, their associated limitations and the research carried out in the last thirty years is presented in this paper. Application of this concept within non-nuclear industries is also discussed.

1. Background

Since 1950, numerous investigations have been performed to assess the mechanical and structural behaviour of pressurized components, such as loading capacity and failure behaviour of piping. One of the first few cases associated with LBB was presented by Irwin [1] in the 1960s. According to his work, leakage was predicted to occur due to an axial flaw if the defect length was less than twice the thickness of the pressure vessel. In that case, the crack driving forces in the radial direction exceed those in the axial direction resulting in a through-wall crack which could exist up to a significant size without any risks of pipe burst.

After that, most research on LBB has been carried out for nuclear applications. Historically, an instantaneous double-ended guillotine break (DEGB) of the largest heat transport pipe was used as the design basis in nuclear power plant, assuming that the pipe would break in a brittle manner [2]. This led to the installation of numerous pipe-whip restraints to hold ruptured pipes in place. However this criterion was restrictive [3], due to the risk of loose pipe ends jamming under certain conditions and the difficulties of carrying out inspection. Advances in fracture mechanics allowed a better understanding of piping behaviour and it has been demonstrated that postulated small through-wall flaws could be detected by leakage long before the flaws could grow to unstable sizes which might cause a DEGB [2]. For this reason, developing an alternate design criterion was necessary [4,5]. Further studies have expanded the elaboration of LBB procedures, which were adopted in 1986 by the United States Nuclear Regulatory Commission (USNRC), for the assessments of high energy pipes in Pressurized Water Reactors (PWRs), which provided guidelines (revised in 2007 [6]) for safety evaluation of the operating and design of Nuclear Power Plant.

LBB assessment methods have contributed to a new approach of pressure equipment design. Details about guidance for the implementation, limitations and acceptance criteria for LBB were provided in the late 1980s by the American regulatory authority [6–8]. Nowadays, this criterion is widely used in the nuclear industry as either validation to remove pipe-whip restraints and jet-impingement shields or as defence-in-depth argument. Outside of the nuclear industry, LBB arguments are sometimes included as part of Fitness-for-Service (FFS) assessments.

2. Definitions

The European Commission [9] defines LBB as “a failure mode of a cracked piping leaking through-wall crack which may by timely and safely detected by the available monitoring systems and which does not challenge the pipe's capability to withstand any design

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loading". Although inelegantly described, this concept is related to pipe failures and their safety implications and it has been presented as a way to partially relax the common requirements to the postulated DEGB failure. Fracture mechanics principles are used to demonstrate that a flaw will develop through-wall allowing sufficient and stable leakage that it can be detected before catastrophic rupture of the component occurs. This concept may therefore be applied to structures containing a fluid such as pipes or pressure vessels.

LBB is applicable to ductile materials which exhibit high toughness and are fracture resistant [9]. These material properties permit a through-wall defect of a certain length to be stable under specified conditions and allow sufficient time for the detection of the resulting leak. A combination of ductile material, benign fluid environment and a reliable leak detection system is therefore necessary.

2.1. Basic design analysis

A basic analysis to show the balance of leak conditions and break conditions is presented in Ref. [10]. These formulations are used for the design of pressurized thin-walled structures. For example, a thin-walled cylindrical pressure vessel of radius R and thickness t is subject to an internal pressure P. In the basis of design, the maximum hoop stress cannot exceed the yield strength of the material $(\sigma_h \leq \sigma_{ys})$, and therefore the thickness t to preclude yielding has to be:

$$t \geq \frac{PR}{\sigma_{ys}} \tag{1}$$

In the case of a through-wall crack $(2a_c = t)$ where a leak may be detected, the crack will remain stable if:

$$\sigma_h \leq \frac{K_{IC}}{\sqrt{\pi \frac{t}{2}}} \tag{2}$$

Where K_{IC} is the plane strain fracture toughness. These two equations lead to a limiting pressure:

$$P \leq \frac{2}{\pi R}\left(\frac{K_{IC}{}^2}{\sigma_{ys}}\right) \tag{3}$$

These basic conditions (more detailed procedures will be discussed in Section 2.2) are used at the design stage to select materials and they may also be used to ensure that a leak-before-break condition can be feasibly reached. Design engineers select the material's yield strength and thickness according to conventional formulae of stress analysis so that the wall thickness is sufficient to withstand the internal pressure. The next step is the selection of the minimum required fracture toughness to meet the leak-before-break criterion. This is followed by the evaluation of cost of material, fabrication, certification, and other technical and economic decisions [11].

2.2. Detailed procedures

In a detailed LBB assessment a number of different calculations is required, including those of the limiting length of a through wall defect and those of crack opening area. Validation of methods for the calculation of the limiting length of a through wall defect is included in the validation of flaw assessment procedures [12]. The formulation of a Leak-Before-Break argument can be explained with the aid of the following diagram (see Fig. 1) where (1) and (2) represent the margins applied on leak detection and crack length and flowchart (see Fig. 2). During stable crack growth (Crack length < Critical crack length) the penetrating crack will grow to a through-wall crack and form a leak until it reaches the critical length. Catastrophic failure occurs when the crack length reaches its critical length leading to unstable crack growth assuming stresses are load-controlled (generally true for pipes containing high energy fluids). Under fatigue crack growth, defects will grow under the action of cyclic stress mainly due to changes in internal pressure or due to thermal transient load cycles. For example, circumferential defects will grow under cyclic axial stresses and are subject to axial pipe end load, internal pressure and external pipe bending moments [13].

Typical inputs for LBB evaluation include pipe geometry, material properties, crack morphology, cyclic loads, operating pressure and temperature. The different procedures available are explained in the next part of this paper. However, having a common origin, some major steps can be summarized as follows (from Refs. [14–16]):

i. Characterise/postulate the initial flaw

Flaw dimensions have to be defined for surface or through-wall flaws. Depending on the procedure used, surface defects may be assessed in addition to through-wall defects taking crack growth into account.

ii. Determine critical length of the through-wall flaw

This refers to the length at which the through-wall defect becomes unstable, based on fracture mechanics calculations, assuming stresses are load-controlled.

iii. Estimate the flaw length at breakthrough

This is carried out by calculating the surface flaw length at which ligament failure is predicted to occur and re-characterising this flaw as a through-wall flaw.

iv. Determine detectable leakage length of the through-wall flaw

This includes calculation of the Crack Opening Area (COA) associated with the crack length and calculation of the resulting detectable leak rate appropriate to the leak detection system capabilities. Time to detect the leak should be taken into account. The leak rate may be estimated from relevant experimental data if available or computer codes which predict leakage rates for single- or two-phase flows for a wide range of through-wall defects that appropriately account for the surface roughness, number of turns, etc for the crack mechanisms of interest.

v. Assess the results:

A case for LBB is established provided the calculations in previous steps show that:

- The flaw length at breakthrough is less than the critical length of the through-wall flaw.
- The time to detect the leak is less than the time for the flaw to grow to the critical length.

Guidance and established procedures are given in different standards and procedures to resolve each of these steps. Depending on the procedure used, different methodologies can be found with