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Fracture mechanics assessment of thermal aged nuclear piping based on the Leak-Before-Break concept

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HIGHLIGHTS

- The effects of thermal aging on crack unstable tearing are studied.
- The critical size of crack unstable tearing is calculated by different methods.
- The critical failure models are compared.
- The conservatism of *J–T* diagram is shown.

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ABSTRACT

The Leak-Before-Break (LBB) concept has been accepted to design the primary piping system of the pressurized water reactor (PWR). Due to thermal aging of long term operation, the cast stainless steels (CSSs) which are used for the primary piping of PWR, suffer a significant loss of fracture toughness, and as a consequence the safety margin of the thermal aged pipe decreases. Therefore, the aged piping should be analyzed and validated by the LBB concept. In this paper, elastic–plastic fracture mechanics (EPFM) assessments of the thermal aged piping are presented according to the LBB concept. The critical break size of crack unstable tearing is calculated by the EPFM method. The crack driving force diagram (*J–a* diagram), the stability assessment diagram (*J–T* diagram) and a numerical method are applied to calculate the critical crack size of crack break. The effects of thermal aging on the plastic limit load, *J–T* diagram, critical crack size of the EPFM and the critical failure mode are studied. The results show that the thermal aging effect decreases the maximum allowed *J*-integral at a certain ductile tearing modulus by more than 50% and it increases the flow stress and plastic limit load by 11.78%. The results based on the *J–T* diagram are about 40% conservative than those based on the direct numerical method for the high loading case. For the thermal aged piping, it is important to consider the competition failure modes between plastic collapse and unstable ductile tearing.

1. Introduction

The concept of Leak-Before-Break (LBB) is now widely used to design the primary piping system of nuclear power plants (NPPs) (Qian et al., 2013; Kayser et al., 2008). The LBB concept basically demonstrates by elastic–plastic fracture mechanics (EPFM) and plastic collapse analyses that there is negligible chance of any catastrophic break of piping without giving prior indication of leakage (Yang, 2010; Chattopadhyay et al., 1999). The reactor coolant piping systems are constructed of very ductile steel that is not susceptible to cleavage-type fracture in the design stage. However, the cast stainless steels (CSSs), which are usually used in the reactor coolant piping systems, suffer a loss in fracture toughness due to thermal aging after many years of service at temperature range of 280–320 °C (Lv et al., 2014; Xue et al., 2010). Thus, a detailed fracture mechanics study of the thermal aged piping system is needed, especially in the long time operation (LTO), to calculate the piping break size (EPRI, 2005; Chen et al., 2015). In the safety assessment, a through wall crack is postulated at the location of maximum stress with the most degraded material properties. The crack size is defined to ensure that the leakage can be easily detected in the plant. Finally, it is demonstrated that this crack will withstand the

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maximum credible load that may act during a safe shutdown earthquake (SSE) (Klimasauskas et al., 2003; Xie, 1999).

The LBB assessment is performed for the whole piping system which is intended to meet the design criteria (NRC, 2002). Although the toughness of weld material is significant lower than that of the base metal, the thermal aging effect is more pronounced for the base metal (NRC, 1994a, 1994b), and the inhomogeneous coarse-grain structure of the statically or centrifugally CSSs pipe makes it difficult to inspect these materials using conventional ultrasonic testing (UT) techniques (EPRI, 2009; Nageswaran et al., 2009; NRC, 1995). Therefore, from LBB point of view, the base metal may be more at risk than the weld, and both the base metal and weld are needed to be assessed. At the same time, the thermal aging effect increases the critical size for the plastic limit collapse, whereas decreases the critical size for the instable ductile tearing. Thus, the critical failure mode of the piping may be changed due to thermal aging. In order to consider the competition of plastic collapse and instable ductile tearing, the Z-factor approach is adopted in the EPFM analyses of the ASME code Section XI Appendix C (ASME, 2013a). In this approach, Z-factor is simply defined as the ratio of the plastic collapse based solution to the instable ductile tearing based solution according to EPFM method. It is expected that the Z-factor in the ASME code may be increased significantly with considering the thermal aging effects, due to the increase of tensile stress and decrease of fracture toughness. In the engineering approach, the *J*–*a* and *J*–*T* diagrams are often used to calculate the critical crack size or critical load by plotting and intersecting the curves (EPRI, 1981). However, the precision of these assessments is still problematic since it is affected by the quality of plotting. Moreover, it is a common practice in the engineering approach, e.g., ASME Code (ASME, 2013b) and the EPRI report (EPRI, 1987), to assume that the driving force curve of *J*–*T* diagram to be liner line. This linear assumption will of course bring some error, especially in the elastic–plastic materials. Therefore, in order to reduce the calculating error, the numerical method which are mathematically a combination of the information contained in the *J*–*a* or *J*–*T* diagram can be used directly based on the crack stable equations.

The present study is focused on the EPFM analysis of the primary piping considering the thermal aging effect. The *J*–*a* diagram, the *J*–*T* diagram and numerical method are applied to calculate the critical crack size of the EPFM. The effects of thermal aging on the plastic limit load, *J*–*T* diagram, critical crack size of the EPFM and the critical failure mode are studied based on the reference material in NUREG/CR 4513 (NRC, 1994a) and NUREG/CR 6142 (NRC, 1994b). Finally, the conservatism of the *J*–*T* diagram is discussed with a case study.

2. Procedure of LBB assessments

For nuclear piping, one of the design conceptions is to ensure a LBB case by demonstrating that a crack will grow in a way to cause a stable detectable leak of the pressure boundary rather than a sudden, disruptive break. The various stages in the development of a LBB concept for a piping with a circumferential semi-elliptical surface crack are shown in Fig. 1. In the first step, the crack is characterized and the mechanism by which it grows is identified. The next step is to perform crack propagation analysis and to calculate the length of the through-wall crack with fracture mechanics method. The ligament instability line is drawn by considering plastic collapse of the ligament. Finally, it estimates the crack opening area, the fluid leak rate and the leak detection. The crack length $2c_d$ at detected leak point is calculated. The unstable crack propagation is defined by the ductile tearing analysis. It is demonstrated whether the leak will be detected before the crack grows to a critical length $2c_b$. A LBB assessment is fulfilled if it is proven that a

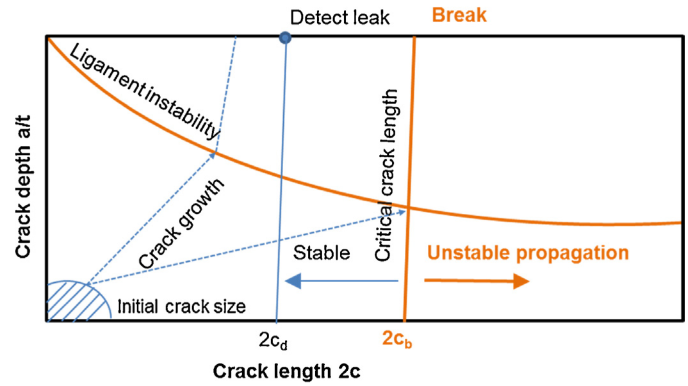

Fig. 1. Leak-Before-Break concept.

leakage can be detected before the crack leads to break. It is worth mentioning that this study aims to apply EPFM for the calculation of crack break size. The fluid leakage analysis and the calculation of the corresponding crack leakage size is our future work.

As the calculation of the critical crack size is one of the main concerns in the LBB assessment and the material toughness is obviously influenced by the thermal aging effect, this work aims to perform the EPFM analyses of the primary piping with postulated through wall cracks. The critical crack size of a cracked structure is calculated in two ways according to the engineering EPFM method: one using the *J*–*a* diagram and the other using the *J*–*T* diagram. Both methods are firstly reviewed in this paper. Then a numerical method is presented based on the information contained in the *J*–*a* or *J*–*T* diagram. The plastic collapse limit load is calculated to check whether plastic collapse precedes the onset of unstable ductile tearing.

2.1. *Fracture mechanics analyses for unstable ductile tearing*

In the LBB assessment, a through wall crack is postulated in the pipe of the highly stressed zone and is demonstrated to be stable under the maximum credible loading condition. Axial cracks are usually not considered because it has been shown that more safety margin is demonstrated for axial cracks than for circumferential ones. NUREG-0800 SRP 3.6.3 (NRC, 2007) implicitly endorses this approach since no limit load equations are provided for axially-oriented cracks. Maximum credible load generally acts during accident condition owing to improbable SSE. Stability analysis of the crack involves the determination of critical load at which crack will extend in an unstable manner. This is carried out by performing the EPFM or plastic collapse assessment of the cracked component with a circumferential through-wall crack.

2.2. *Critical crack size determined by EPFM*

2.2.1. J–a *diagram*

J–*a* diagram is basically a plot of the *J*-integral versus crack length and applied load. The crack driving force *J*-integral for a given flawed body can be obtained by superposing the elastic and fully plastic solution according to the estimation procedure. By comparing the crack driving force with the material resistance to crack growth, one can predict various quantities of interest associated with the fracture behavior. As shown in Fig. 2, one can translate the *J*–*R* curve to get the critical location under a certain level load, and the critical crack size is obtained in the *J*–*a* diagram.

2.2.2. J–T *diagram*

According to the *J*–*T* diagram method, the "applied" and "material" *J*-integrals and tearing modulus are calculated and compared