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Finite element limit loads for non-idealized through-wall cracks in thick-walled pipe

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HIGHLIGHTS

- The lower bound bulging factor of thin-walled pipe can be used for thick-walled pipe.
- The limit loads are proposed for thick-walled, transition through-wall cracked pipe.
- The correction factors are proposed for estimating limit loads of transition cracks.
- The limit loads of short transition cracks are similar to those of idealized cracks.

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ABSTRACT

The present paper provides plastic limit loads for non-idealized through-wall cracks in thick-walled pipe. These solutions are based on detailed 3-dimensional finite element (FE) analyses which can be used for structural integrity assessment of nuclear piping. To cover a practical range of interest, the geometric variables and loading conditions affecting the plastic limit loads of thick-walled pipe with non-idealized through-wall cracks were systematically varied. In terms of crack orientation, both circumferential and axial through-wall cracks were considered. As for loading conditions, axial tension, global bending, and internal pressure were considered for circumferential cracks, whereas only internal pressure was considered for axial cracks. Furthermore, the values of geometric factor representing shape characteristics of non-idealized through-wall cracks were also systematically varied. In order to provide confidence in the present FE analyses results, plastic limit loads of un-cracked, thick-walled pipe resulting from the present FE analyses were compared with the theoretical solutions. Finally, correction factors to the idealized through-wall crack solutions were developed to determine the plastic limit loads of non-idealized through-wall cracks in thick-walled pipe.

1. Introduction

In the design of nuclear piping, if it is demonstrated that the rupture probabilities of nuclear piping are extremely low under conditions consistent with the design basis for the nuclear piping system, a local dynamic effect associated with the postulated pipe ruptures in the nuclear piping system can be excluded from the design basis (USNRC, 2013). Accordingly, to ensure and satisfy this criterion, the Leak-Before-Break (LBB) concept has been widely applied to nuclear piping design as a deterministic approach (USNRC, 1987). In addition, conservative crack tolerance assessment procedure to satisfy this extremely low rupture condition has been developed (USNRC, 1984). According to existing screening criteria for LBB assessment, it is specified that a nuclear piping system that is exposed to active degradation mechanism (e.g., primary water stress corrosion cracking; PWSCC) should not be designed based on the LBB concept (USNRC, 1987, 1984).

However, during the last two decades, several cracking incidents due to PWSCC have been observed in the nuclear components, even in piping systems that have been approved for LBB prior to operational PWSCC experiences. Based on the current LBB specifications, this means that these piping systems no longer satisfy the existing deterministic LBB assessment procedure (Electric Power Research Institute, 2010; Nana and Yoon, 2006). To resolve this issue regarding LBB design of piping related to PWSCC, there are on-going efforts that are attempting to directly demonstrate full compliance with the current design criteria (USNRC, 2013), i.e. the condition of extremely low probabilities of rupture of nuclear piping. These efforts have been made by using the probabilistic assessment approach for piping system with active degradation

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mechanism. One of the well-known work is the xLPR (eXtremely Low Probabilities of Rupture) program (Rudland and Harrington, 2012). Related to this work, it was demonstrated that a subcritical surface crack can transition to a through-wall crack with significant differences between the inner diameter (ID) and outer diameter (OD) crack lengths (Rudland et al., 2010). In the present work, such a crack is referred to as a non-idealized through-wall crack, whereas an idealized through-wall crack has a crack front that is parallel to the radial direction. Moreover, it has been shown that more accurate predictions (e.g., leak rate) can be made when non-idealized through-wall cracks are used in the LBB assessment (Shim et al., 2011). Thus, in order to evaluate piping rupture probabilities more accurately, it is necessary to characterize the fracture behavior of non-idealized through-wall cracks.

For typical fracture mechanics assessment, relevant fracture mechanics parameters are needed. In terms of fracture mechanics parameters, the elastic stress intensity factor is needed to predict subcritical crack growth behavior and elastic-plastic J-integral (Rice, 1968) and plastic limit load are required for prediction of unstable fracture (or instability). For leak-rate estimates, solutions for crack opening displacement (or crack opening area) are needed. For both surface and idealized through-wall cracks, the engineering estimates of these fracture mechanics parameters have been well established during the last three decades (Zahoor, 1991; Kumar and German, 1988; Rahman et al., 1998a,b; France et al., 1997; Kim et al., 2001; Miller, 1988; Huh et al., 2007). However, fracture mechanics parameters for non-idealized through-wall cracks are still limited (Huh et al., 2008a,b, 2010). Thus, there is a need to develop fracture mechanics parameters for non-idealized through-wall cracks (both in axial and circumferential directions) to support the rupture probability calculations of nuclear piping. In addition, since several crack indications have been found in a thick-walled piping (e.g., pressurizer nozzle of a light water reactor (Materials Reliability Program, 2004)), the development of fracture mechanics parameters for non-idealized through-wall crack should be extended to thick-walled components as well.

In the present work, plastic limit loads for thick-walled piping with non-idealized through-wall cracks are proposed based on detailed 3-dimensional (3-D) finite element (FE) analyses. In terms of crack orientation, both axial and circumferential cracks are considered. As for loading conditions, internal pressure is considered for axial crack, whereas axial tension, global bending moment and internal pressure are considered for circumferential crack. For estimating plastic limit loads, the geometric variables affecting the plastic limit loads were systematically varied. Based on the FE plastic limit loads, a correction factor to quantify the effect of the crack shape of non-idealized through-wall cracks on plastic limit loads is newly proposed.

2. Finite element analyses

2.1. Geometry

In order to accurately calculate the probabilities of rupture of nuclear piping exposed to PWSCC, the fracture behavior of a non-idealized through-wall crack should be considered. In this context, in the present work, thick-walled pipes with non-idealized axial and circumferential through-wall cracks were considered. Fig. 1 depicts the geometric variables of pipes with non-idealized circumferential and axial through-wall cracks, where R_i, R_m, R_o, and t represent the inner, mean, outer radius, and thickness of a pipe, respectively. Fig. 1(a) depicts a pipe with a non-idealized circumferential through-wall crack under axial tension, global bending, and internal pressure. The non-idealized circumferential through-wall crack is characterized by the half crack angle on the inner and the outer surface of the pipe (defined as θ_1 and θ_2). In this study, two parameters, i.e., θ_1/θ_2 (= 1, 2 and 3) and θ_1/π (= 0.125, 0.25, 0.3, 0.4 and 0.5) were systematically considered to cover various ranges of crack sizes. The parameter θ_1/θ_2, i.e., the ratio of crack angle on the inner surface of pipe to crack angle on the outer surface of pipe, represents the shape of the non-idealized circumferential through-wall crack, where $\theta_1 \geq \theta_2$ in the present study. Note that θ_1/θ_2 = 1 represents an idealized circumferential through-wall crack. The reference crack angle is defined as θ_1/π based on the crack angle on the inner surface of a pipe.

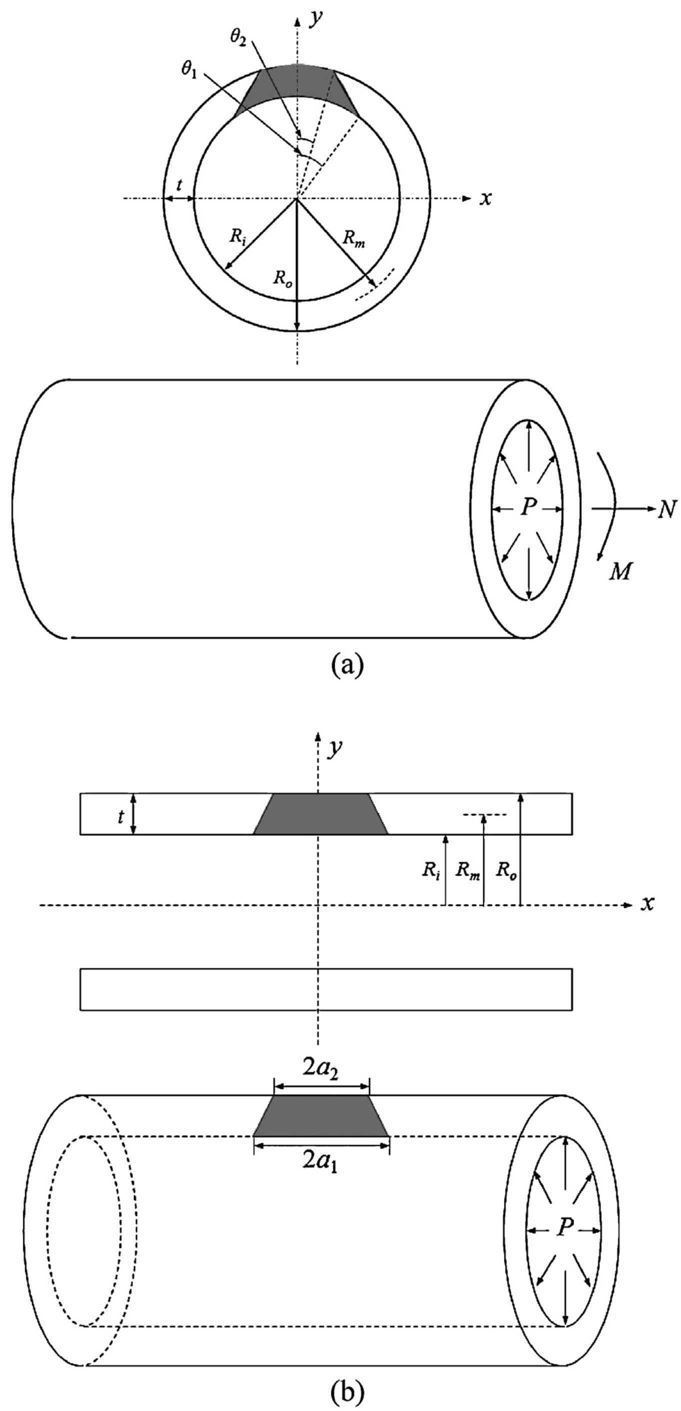

Fig. 1. Schematics of pipes with (a) a non-idealized circumferential through-wall crack under internal pressure, axial tension and global bending moment and (b) a non-idealized axial through-wall crack under internal pressure.