Nuclear Engineering and Design 301 (2016) 175–182

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Effective applied moment in circumferential through-wall cracked pipes for leak-before-break evaluation considering pipe restraint effects

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HIGHLIGHTS

- Effective applied moment at pipe cracked section considering the pipe restraint effect.
- Verification of the proposed evaluation methods using finite element analyses.
- Applicability for distributed external load of the proposed methods.

ARTICLE INFO

Article history:
Received 29 November 2014
Received in revised form 11 February 2016
Accepted 20 February 2016
Available online 23 March 2016

JEL classification:
A. Engineering mechanics

ABSTRACT

In the leak-before-break (LBB) design of nuclear power plants, crack opening displacement (COD) is an essential element for determining the length of the leakage size crack. Recent researches regarding the evaluation of COD have indicated that the current practice of the LBB evaluation without consideration of the pressure induced bending (PIB) restraint overestimates COD, which in turn gives non-conservative results. Under a free-ended boundary condition, however, the applied moment at cracked section also can be overestimated, which has conservative effects on LBB evaluation. Therefore, it is necessary to evaluate pipe restraint effects on the applied moment as well as on COD to keep the constancy. In this paper, an evaluation method for the effect of the PIB restraint on COD and an effective applied moment (=crack driving force) at cracked section was developed. Both the linear elastic and elastic–plastic behaviors of the crack were considered. By comparing the behaviors with 3-D finite element analysis results from earlier studies, it was confirmed that the proposed methods make accurate estimations of the PIB restraint effect on COD. Next, the applicability of the proposed method to other types of external loading conditions was examined.

1. Introduction

In the light water reactor (LWR) design, the concept of leak-before-break (LBB) is generally adopted for nuclear piping systems to demonstrate the safety of the piping systems when protective hardware is removed (U.S. Nuclear Regulatory Commission, 2007). At a determined critical location of the pipe, the length of the leakage size crack (LSC) can be predicted, considering crack opening displacement (COD) and operating conditions. Then, based on the elastic–plastic fracture analysis, an instability moment is determined for the given LSC. An applied moment under faulted conditions at the postulated critical location needs to be less than the calculated instability moment to satisfy the LBB requirements. In the practical LBB procedure, applied loads that are calculated from the piping design are used for input in the through-wall crack analyses. Then, the value of COD and the instability moment are determined with the assumption that a free-ended cracked pipe is subjected to the calculated applied load (The Pipe Break Task Group, 1984).

Pressure induced bending (PIB) is bending displacement (rotation) caused by an axial load including the end cap force arisen from an internal pressure in the circumferential through-wall cracked (TWC) pipe (Scott et al., 2005). Under free-ended boundary conditions, PIB does not affect COD calculations because the cracked pipe model has no restraints from connected pipelines. In real nuclear piping system, however, the rotation due to PIB can be restrained

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http://dx.doi.org/10.1016/j.nucengdes.2016.02.028
0029-5493/

Nomenclature

$C_{\mathrm{Rest,LE}}$	restraint coefficient for the linear elastic analysis
$C_{\mathrm{Rest,EP}}$	restraint coefficient for the elastic–plastic analysis
E	elastic modulus of pipe material
E'	effective elastic modulus of pipe material ($=E$ for plane stress, $=E/\left(1-\nu^2\right)$ for plane strain)
F_R	reaction force
$F_{R,\mathrm{Rest}}$	reaction force induced by pipe restraint at fixed ends
G_{LE}	rotational compliance of a crack for the linear elastic analysis
G_{EP}	rotational compliance of a crack for the elastic–plastic analysis
I	moment of inertia
L	half-length of pipe ($2L=L_1+L_2$)
L_1	restraint length-1, pipe length of one side of the crack
L_2	restraint length-2, pipe length of other side of the crack
L_{N1}	normalized restraint length-1 ($=L_1/2L$)
L_{N2}	normalized restraint length-2 ($=L_2/2L$)
M_A	applied moment
M_R	reaction moment
$M_{R,\mathrm{Rest}}$	reaction moment induced by pipe restraint at fixed ends
$M_{P,\mathrm{Eq}}$	pressure equivalent moment
$M_{P,\mathrm{Eq,Eff}}$	effective pressure equivalent moment due to pipe restraint
$M_{A,\mathrm{Crack}}$	applied moment at a cracked section
$M_{A,\mathrm{Crack,Eff}}$	effective applied moment at a cracked section due to pipe restraint
$M_{A,\mathrm{CPipe}}$	applied moment distribution to a cracked pipe
$M_{A,\mathrm{UcPipe}}$	applied moment distribution to an uncracked pipe
P_A	applied axial tension load
P_{in}	pipe internal pressure
r_{COD}	ratio of the COD of a restrained pipe to the COD of an unrestrained pipe
$r_{\mathrm{COD,LE}}$	r_{COD} for the linear elastic analysis
$r_{\mathrm{COD,EP}}$	r_{COD} for the elastic–plastic analysis
R_m	pipe mean radius
R_i	pipe inner radius
R_o	pipe outer radius
t	pipe thickness
w	uniformly distributed vertical load per unit length
x	distance from the fixed end
$\delta_{\mathrm{Free,LE}}$	COD of a free-ended pipe for the linear elastic analysis
$\delta_{\mathrm{Free,EP}}$	COD of a free-ended pipe for the elastic–plastic analysis
$\delta_{\mathrm{Rest,LE}}$	COD of a fixed-ended pipe for the linear elastic analysis
$\delta_{\mathrm{Rest,EP}}$	COD of a fixed-ended pipe for the elastic–plastic analysis
ϕ	rotation of pipe
$\phi_{C,b,\mathrm{LE}}$	linear elastic rotation due to crack of a free-ended pipe caused by a bending moment
$\phi_{C,b,\mathrm{PE}}$	elastic–plastic rotation due to crack of a free-ended pipe caused by a bending moment
$\phi_{C,t,\mathrm{PE}}$	elastic–plastic rotation due to crack of a free-ended pipe caused by an axial tension load
v	deflection
θ	half-crack length of a circumferential through wall crack

due to other connected structures or components. The PIB restraint limits the deformation of the crack and, consequently, decreases COD. Thus, it is well established that current practice of the LBB analysis without considering the PIB restraint overestimates COD and underestimates the length of LSC, which in turn gives non-conservative results of the LBB evaluation (Ghadiali et al., 1996; Scott et al., 2002; Wilkowski et al., 1998). From this point of view, a large safety factor for the LSC calculation has been applied to the LBB design.

Several studies suggested evaluation models to estimate the effect of the PIB restraint on COD (Kim, 2008; Miura, 2001) for the straight pipe model. The simple procedures for COD calculation were derived and verified by comparing it with the full-scale finite element analysis results. However, the evaluation models have a few limitations with respect to the whole procedure of the LBB evaluation.

First, the suggested models regarding the restraint effect consider only PIB as the applied load. The bending displacement can be restrained by the boundary conditions regardless of loading type and thus, an additional evaluation model is needed to account for the restraint effects of various types of loadings. Second, the suggested models only consider the effect on COD, while the piping restraints also affect the crack driving force (Smith, 1988). When the pipe is restrained, CODs and crack driving forces decrease simultaneously compared with the case of unrestrained case because the deformation of the crack is limited. Moreover, the effect on COD decreases the margin of the LBB design, but the effect on the crack driving force increases the margin. Thus, to keep the constancy of design conservatism, the reduction of the crack driving force needs to be considered if the restraint effect on COD is accounted for in the LBB design. Because the suggested model is focused only on the effect on COD, an improved evaluation model is needed to investigate the piping restraint effect on the crack driving force not only COD.

In this paper, a modified evaluation method was developed to quantify the PIB restraint effect on COD and an effective applied moment (=crack driving force) at cracked sections for the circumferential TWC pipes. Both the linear elastic behavior and elastic–plastic behavior were considered. The proposed method was verified using finite element analysis (FEA) results from earlier studies. Additionally, it was discussed that the proposed evaluation method can be applied not only to PIB but also to bending displacement induced by other types of external loads.

2. Effective applied moment at cracked section of fixed-ended straight pipe

2.1. Previous studies for PIB restraint effect

There have been several studies to develop the evaluation models for the PIB restraint. Rahman et al. (1995, 1996, 1998) used a 3D finite element analysis model of circumferential cracked pipe to investigate the effect of PIB restraint on COD. The results revealed that the PIB restraint decreases COD, and this affect calculating the length of LSC. The PIB restraint effect increases as the crack length increases and the normalized restraint length decreases, which means the distance from the crack to fixed-end normalized by the pipe diameter.

Miura (2001) developed the evaluation method for COD using the beam model including reduced-thickness section which represents the cracked section. Using this model, the simplified COD evaluation equations were derived for a fixed-ended straight pipe with circumferential TWC, considering the linear elastic material behavior in which the Paris-Tada formula (Paris and Tada, 1983) was used for the COD calculations. The Battelle Integrity of Nuclear