Engineering Fracture Mechanics 123 (2014) 77–85

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Collapse loads for circumferentially through-wall cracked pipes subjected to combined torsion and bending moments

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ARTICLE INFO

Article history:
Available online 17 January 2014

Keywords:
Flaw evaluation
Collapse load
Combined bending and torsion moment
Circumferential crack
Cracked pipe
Through-wall crack

ABSTRACT

Pressurized piping items in power plants may experience combined torsion and bending moments during operation. Currently, there is a lack of guidance in flaw evaluation procedures for combined loading modes of pressure, torsion and bending loads. Recently, collapse bending moments for pipes under torsion moments were analyzed by finite element modelling. Equivalent moments defined as the root of the sum of the squares of the torsion and bending moments are shown to be equal to pure bending moments for various diameter pipes containing circumferentially part through cracks. This paper focuses on behaviour of plastic collapse moments for pipes with circumferential through-wall cracks using finite element analysis, and describes the behaviour of the equivalent bending moments for flaw evaluation procedures, referring the results of part through cracked pipes.

1. Introduction

Piping items in power plants may experience internal pressure, axial load, bending and torsion loads during operation. Several methods for predicting failure loads for circumferential cracked pipes under combined loadings had been developed for assessment of piping integrity [1,2]. The proposed methods for combined loads are applicable on Mode I type loading of internal pressure, axial tension and bending. That is, Mode II type of torsion moment is not included in these methods.

When cracks detected in piping items are assessed by using fitness-for-service Codes, such as ASME Boiler and Pressure Vessel Code Section XI [3] or JSME S NA1-2008 [4] Code. These ASME and JSME Codes provide evaluation procedures for predicting plastic collapse loads for cracks in pipes subjected to internal pressure and bending moment under fully plastic conditions. Currently, torsion load is also not included in these Codes. In addition, the depths of the cracks are less than or equal to 75% of pipe wall thickness for the evaluation procedures. This is because the Codes do not allow leakage from pipes.

A guidance including the torsion moment is developed for pipes with circumferential part through wall cracks. It is reported that combined bending and torsion moments at collapse can be estimated by pure bending moments, when the combined bending and torsion moments are given by the equivalent moment defined as the root of the sum of the squares of the torsion and bending moments [5–12].

On the other hand, evaluation of collapse load for circumferential through-wall crack is necessary for leak-before-break evaluation [13,14] and temporary acceptance of coolant leakage from power plant piping [15]. This paper focuses on combined torsion and bending moments at collapse for a pipe containing a circumferential through-wall crack, and shows validity of the equivalent moment at plastic collapse for circumferential through-wall crack, referring the equivalent moment for a part through wall crack.

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0013-7944/$ - see front matter © 2014 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.engfracmech.2013.12.013

Nomenclature

a	circumferential crack depth
D_0	pipe outside diameter
M_b, M_B	applied and collapse bending moments under given torsion moment
M_{B0}	collapse bending moment without torsion moment (pure bending moment)
M_{eq}	equivalent collapse moment
M_t, M_T	applied and collapse torsion moments
M_x, M_y, M_z	orthogonal moment components at a given position in a piping system
R	pipe mean radius
t	nominal pipe wall thickness
β	angle to neutral axis of cracked pipe
θ	one half of circumferential crack angle
θ_b	applied bending angle
σ_f	flow stress
σ_m	primary membrane stress in the pipe at the crack location
τ	torsion stress
ASME	American Society of Mechanical Engineers
FE	finite element
JSME	The Japan Society of Mechanical Engineers

2. Plastic collapse moment by bending and torsion

2.1. Plastic collapse bending moment by limit load criteria

In case of a circumferential part-through crack, plastic collapse bending moment for a pipe is provided by ASME B&PV Code Section XI [3] and JSME (Japan Society of Mechanical Engineers) Code on Fitness – for – Service Rules [4]. The concept of the plastic collapse moment was developed by Battelle Columbus Laboratories [16]. Fig. 1 illustrates the stress distribution at incipient plastic collapse in a pipe. The internal stress distribution in the pipe wall in the cracked section is assumed to be at plus or minus the flow stress, as depicted in Fig. 1. From the equilibrium of bending moment and axial force, plastic collapse bending moment M_{B0} is given as follows;

For more common case of $\theta + \beta \leqslant \pi$

$$M_{B0} = 2\sigma_f R^2 t\left[2\sin\beta - \frac{a}{t}\sin\theta\right] \tag{1}$$

with

$$\beta = \frac{1}{2}\left(\pi - \frac{a}{t}\theta - \pi\frac{\sigma_m}{\sigma_f}\right) \tag{2}$$

where σ_f is the flow stress, θ the half crack angle, a the crack depth, t the wall thickness, R the mean radius of the pipe, β the neutral angle, and σ_m the membrane stress. The flow stress is normally taken as the average value of the yield stress and ultimate tensile strength of the pipe material [3,4].

If the crack is long enough and both ends of the crack length are in the region of compression stress area, the plastic collapse moment M_{B0} is given as follows;

For less common case of $\theta + \beta > \pi$

$$M_{B0} = 2\sigma_f R^2 t\left(2 - \frac{a}{t}\right)\sin\beta \tag{3}$$

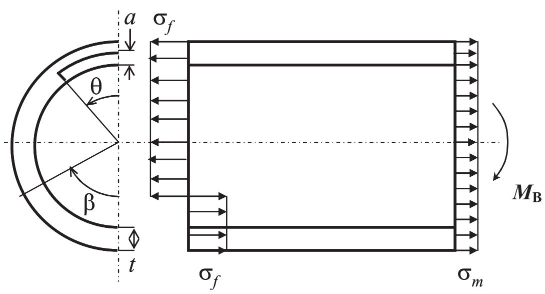

Fig. 1. Nomenclature and stress distribution of a pipe with a circumferential crack.