International Journal of Pressure Vessels and Piping 86 (2009) 454–473

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

Improved integrity assessment equations of pipe bends

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ARTICLE INFO

Article history:
Received 31 January 2008
Received in revised form
10 December 2008
Accepted 10 December 2008

Keywords:
Pipe bend
Elbow
Limit load
Plastic collapse
J-integral
COD
J–R curve

ABSTRACT

Pipe bend or elbow is one of the important components in any piping system. Accurate integrity assessment of these pipe bends is very important for reliable operation of all types of plants including nuclear plants. While considerable research has been done in the last few decades to develop accurate integrity assessment procedures of straight pipe with or without cracks, similar efforts were missing for pipe bend or elbow. *Reactor Safety Division*, *Bhabha Atomic Research Centre* in collaboration with *MPA*, *University of Stuttgart* had embarked upon a comprehensive component integrity test program (CITP) in around 1998 to develop improved integrity assessment methods of piping components in general and elbow in particular. As a part of this program, detailed analytical, numerical and experimental investigations for so many years have generated large number of new equations for improved integrity assessment of elbows. Mainly three aspects of the integrity assessment procedure are focused – development of improved plastic collapse moment equations, proposing new elastic–plastic *J*-integral and crack opening displacement (COD) estimation schemes to simplify leak-before-break (LBB) analysis and presenting new eta and gamma expressions to evaluate *J–R* curve from test data. All these newly proposed equations have been validated with the findings of the test data, generated as a part of the CITP. A reasonably good to excellent matching between predictions of the newly proposed equations and test results have been observed in all the cases. The present paper enumerates these research findings in a consolidated yet brief manner.

1. Introduction

Integrity assessment of piping components is very essential for safe and reliable operation of all types of process power plants. It is especially important for nuclear power plants because of the application of leak-before-break (LBB) concept which involves detailed integrity assessment of primary heat transport piping systems taking into account postulated cracks. A typical piping system usually consists of various components, namely, straight pipe, elbow or pipe bend and branch tees. While considerable development has occurred worldwide in the last few decades to evolve an accurate integrity assessment procedure for straight pipes, similar effort was missing for pipe bend, one of the important piping components. Keeping this in view, a comprehensive program was initiated in 1998 in *Reactor Safety Division (RSD)* of *Bhabha Atomic Research Centre* (*BARC*), India in collaboration with *MPA*, *University of Stuttgart* to develop an improved integrity assessment procedure for pipe bends, which is consistent with the test data. Three aspects of the integrity assessment procedure have been described in the present paper – development of improved limit load equations, proposing new elastic–plastic *J*-integral and crack opening displacement (COD) estimation schemes to simplify LBB analysis and presenting new η and γ expressions to evaluate *J–R* curve from test data. All these analytical investigations have been backed by an experimental program to validate the new findings. This paper presents the outcome of these investigations. The subsequent sections will highlight each aspect of the improved integrity assessment procedure for pipe bends.

2. Development of plastic collapse moment (PCM) equations for pipe bends

Pipe bends or elbows are commonly used components in a piping system. It is important to know its plastic collapse moment (PCM) for the safe operation of the plant. The term '*limit load*' is used in this paper in a generic sense to indicate plastic collapse load. The term *Plastic Collapse Moment* indicates a load where significant plastic deformation occurs (not necessarily physical 'collapse' of the structure), determined by applying a criterion of plastic collapse (e.g. twice-elastic slope (TES) as recommended by ASME [1]) on the load-deflection curve. In this paper, plastic collapse load has always been evaluated by TES criterion. Elbows

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doi:10.1016/j.ijpvp.2008.12.005

Nomenclature

a semi-crack length
D_m, D_o mean, outer diameter of elbow cross section
E Young's modulus
$h = tR_b/R^2$ elbow factor or pipe bend characteristics
h_1 plastic influence function to calculate plastic J-integral [Eqs. (29) and (30)]
h_2 plastic influence function to calculate plastic COD [Eqs. (33) and (34)]
J J-integral
J_e, J_p elastic, plastic J-integral
M bending moment
M_o plastic collapse moment of defect-free elbow
M_L plastic collapse moment of cracked elbow
P internal pressure
$p = PR/(t\sigma_y)$ normalized internal pressure
R mean radius of elbow cross section
R_b mean bend radius at elbow crown
t wall thickness of elbow
$X = M_L/M_o$ weakening factor of throughwall axially cracked elbow plastic collapse moment due to the presence of crack

Greek symbols

α semi-axial crack angle [Eqs. (11)–(14)]; Ramberg–Osgood coefficient [Eqs. (16), (24)–(33)]
δ maximum COD at middle of crack length
δ_e, δ_p elastic, plastic COD
ε true strain
$\varepsilon_y\ (=\sigma_y/E)$ yield strain
γ a function to correct the J-integral evaluated by 'η' function in crack growth situation
η_{pl} a function to multiply the area under the load vs. plastic load-point-deflection curve to get the plastic component of the J-integral
σ true stress
σ_y yield stress
θ semi-circumferential crack angle

Abbreviations

COD crack opening displacement
PCM plastic collapse moment
TAC throughwall axially cracked
TCC throughwall circumferentially cracked
TES twice-elastic slope

may potentially contain cracks due to manufacturing defects or service related degradation mechanisms. It is very important to know the effect of cracks on the PCM of elbows for integrity assessment of the piping system. The PCM of any cracked component is generally expressed as product of PCM of defect-free component and a weakening factor due to the presence of crack. Therefore, before studying the PCM of any cracked component, one should know the PCM of a defect-free component. In comparison to the straight pipe, the deformation characteristics of pipe bend has additional complexities due to ovalisation of elbow cross section, which makes the deformation behaviour completely different for opening and closing mode of bending moment. Additionally, bending moment induces both axial and circumferential stresses at a significant level in pipe bends, which makes it imperative to postulate both circumferential and axial crack configurations. This is unlike a straight pipe where only circumferential crack is usually postulated, because bending stress in a pipe acts along its axis only. Further, an elbow is often subjected to combined internal pressure and bending moment in actual service condition. Internal pressure affects the load carrying capacity of elbows (specially thin ones) quite significantly. Finally wall thickness and bend radius of elbows also determine its deformation characteristics. These large numbers of variables make the analysis of pipe bends quite elaborate and complex. As a part of the comprehensive program initiated by RSD, BARC, new closed-form equations have been proposed to evaluate plastic collapse moments of pipe bends considering almost all the variables mentioned above. The following cases have been studied.

Three crack configurations:

- Defect-free elbow
- Throughwall circumferentially cracked elbow
- Throughwall axially cracked elbow

For each crack configurations two in-plane bending modes:

- Closing mode
- Opening mode

For each bending mode two loadings:

- Pure in-plane bending moment
- Combined loading of internal pressure and in-plane bending moment

For each of the above geometry and load configuration, several radii to thickness ratio (R/t) and crack sizes (for cracked elbows) have been considered. The following sections describe briefly the basic methodology followed to develop these limit moment equations, results and discussion. More details may be found in Refs. [2–5].

2.1. Methodology

The finite element method is used to conduct the parametric study to develop the equation for plastic collapse moment (PCM) of pipe bends. Mostly, finite element program WARP3D [6] is used for this study. However, ANSYS [7] is also used to analyze throughwall axially cracked (TAC) elbow for contact analysis. Non-linear finite element analysis is carried out to determine the PCM of elbows for various geometric and loading combinations. Both geometric and material non-linearity are considered in the analysis. Consideration of geometric nonlinearity is very important to capture the ovalisation of elbow cross section during bending. Crack closing is observed in most of the cases of TAC elbows. To capture the crack closure effect, contact analysis is performed using ANSYS [7] where both target and contact surfaces are considered as deformable. Moment vs. end rotation curves are generated through finite element analysis. PCM is obtained by twice-elastic slope (TES) method from these curves. The following sections briefly describe the different aspects of the finite element analysis.

2.1.1. Geometry

Fig. 1a–c shows the geometry of a throughwall circumferentially and axially cracked elbow. In case of circumferential crack, the crack is centered at extrados or intrados depending on the mode of bending moment applied. The extrados crack is assumed for closing