International Journal of Pressure Vessels and Piping 123-124 (2014) 1–9

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

Determination of collapse loads in pipe bends with ovality and variable wall thickness under internal pressure and in-plane opening moment

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ARTICLE INFO

Article history:
Received 10 May 2014
Received in revised form
30 July 2014
Accepted 31 July 2014
Available online 19 August 2014

Keywords:
Plastic collapse load
Ovality
Thinning
Pipe bend

ABSTRACT

The combined effect of ovality and variable wall thickness on collapse load of pipe bends under in-plane opening bending moment with internal pressure was investigated using finite element limit analysis considering large geometric change effect. The material was assumed to be elastic–perfectly plastic. The collapse moments were obtained from moment-rotation curves drawn for each bend using twice-elastic-slope method. Thickening/thinning effect on collapse load is very minimal and can be neglected. The effect of ovality is significant with the reduction of collapse load by a maximum of 39.1% for the maximum internal pressure and ovality considered. Based on the finite element results, a mathematical expression is proposed to determine collapse load of the pipe bends with ovality and this equation has been verified with experimental collapse loads.

1. Introduction

Pipe bend design requires determination of collapse load under various loads, namely in-plane opening and closing moments and out-of-plane bending moment with or without internal fluid pressure acting on them [1–10]. Analytical studies [1–4] were carried out earlier followed by experimental work [5–8] in pipe bends to predict the moment at which the failure occurs. After much advancement in computer technology and the ensured reliability of finite element analysis packages, numerous research works have been performed to determine the collapse load of pipe bends using finite element methods [11–15]. Most of the studies on pipe bend assume the cross section to be circular with uniform thickness [9,10]. The cross section of the pipe deviates from circularity and the thickness also varies at the bend section due to the bending processes. The deviation from circularity is called as ovality and the variation in thickness is thinning/thickening. The acceptable limit of these shape imperfections is prescribed by various codes [16,17]. To obtain more realistic collapse load results, one must include the effect of these shape imperfections in the analysis and design of pipe bends.

Few research works have included the effect of these shape imperfections in the analysis of pipe bends. Spence and Boyle [18] studied pipe bends analytically considering the cross section to be semi-elliptic under internal pressure and proposed an equation to obtain circumferential and longitudinal stresses. Veerappan and Shanmugam [19] performed finite element stress analysis on pipe bends under internal pressure considering the combined effect of ovality and thinning and suggested that flexibility in the accepting limit of the shape imperfections may be possible. Dan [20] carried out nonlinear cyclic analysis on pipe bends using finite element method and compared the induced stresses of pipe bends with 8% ovality and with no initial ovality. Under internal pressure, the presence of ovality has significant effect on the stress distribution while it has little effect on circumferential stress distribution under in-plane bending moment.

Kim et al. [11] provided a method to estimate plastic loads for elbows with non-uniform thicknesses when subjected to in-plane bending and under internal pressure based on finite element limit analysis. From this study, they recommended the use of straight pipe thickness to estimate plastic loads for elbows with non-uniform thicknesses. Christo Michael et al. studied the combined effect of ovality and thinning on plastic loads of pipe bends under in-plane closing bending [12] and combined in-plane closing moment and internal pressure [14] and found that the effect of ovality is significant while the thinning produces negligible effect. They proposed closed-form solutions to determine collapse load of

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http://dx.doi.org/10.1016/j.ijpvp.2014.07.009
0308-0161/

pipe bends with ovality. Christo Michael et al. [13] compared the limit based on small displacement analysis and collapse loads based on large displacement analysis of pipe bends with ovality and thinning under combined internal pressure and in-plane closing moment and concluded that the determination of collapse load is suitable rather than limit load when ovality is present in pipe bends. Buckshumiyan et al. [15] determined collapse load of pipe bends with ovality when the bends are subjected to in-plane opening moment and found that the effect of ovality is significant and proposed a mathematical expression to include the effect of ovality in the determination of collapse load of pipe bends. The present work determines the effect of ovality and thinning on collapse loads of pipe bends subjected to in-plane bending and internal pressure loads. The finite element limit analysis assumes elastic-perfectly plastic material considering large displacement effect.

Section 2 discusses the definition of plastic collapse load and the typical moment-rotation curve from which the collapse load is obtained using a precise method called Twice-Elastic-Slope (TES). In Section 3, the finite element analysis procedure is explained in detail which includes the geometry considered for the analyses, the assumptions in geometry, the material properties, meshing details, boundary and loading conditions, the solution controls and the post processing after solving each pipe bend model. The subsequent section discusses about the validation of finite element analysis procedure. The results and discussions are detailed in Section 5 and the proposed equations and the comparison with experimental values are presented in Section 6. Lastly, the conclusion of the present work is highlighted in Section 7.

2. Plastic collapse loads

The plastic collapse load is obtained from moment–rotation curve of each pipe bend model analyzed. A typical moment–rotation curve of a particular pipe bend model is shown in Fig. 1. The plastic collapse moment load can be obtained using Twice-Elastic-Slope (TES) method [21] in which a straight line from the origin of the moment-rotation curve with twice the slope (half elastic slope) of the initial elastic response of the curve from the ordinate axis is drawn to intersect the same curve. The point of intersection is called as collapse load. The TES method is adopted in Sections III [22] and VIII of the ASME BPVC wherein the definition of collapse moment is clear and precise, which promotes consistency in its results. This method is also convenient in its use, since only the load-deflection curve is needed. It eliminates the need for determining the first yield point, or the location of maximum strains, for each case analyzed. The collapse moment determined by this method is a more conservative estimate of the structure's load carrying capacity, compared to the instability moment. It can be used as an approximation of the instability moment in case convergence is not obtained up to instability [23].

3. Finite element analysis

The FE modeling and limit analysis were performed using a general nonlinear finite element package [24]. Python language was used to write a program to analyze the pipe bends for the various geometric parameters and internal pressure and in-plane moment loading considered.

3.1. Geometry and material

One half of the pipe bends with attached straight pipes were modeled as shown in Fig. 2 to utilize the symmetry. Geometrical parameters and material used for the present study are given in Table 1.

A typical pipe bend with shape imperfect cross section is shown in Fig. 3. The definitions [15] of ovality, thinning and thickening are presented below.

$$C_O = \frac{(D_{max} - D_{min})}{D_O} \times 100 \quad (1)$$

where $D_O = (D_{max} + D_{min})/2$

$$C_t = \frac{(t - t_{min})}{t} \times 100 \quad (2)$$

$$C_{th} = \frac{(t_{max} - t)}{t} \times 100 \quad (3)$$

The assumptions [15] to include ovality and thinning in pipe bends are.

- The cross section is elliptic.
- Increase in thickness at intrados is equal to decrease in thickness at extrados.
- The thickness at crown of the bend is the average of maximum and minimum thickness (=t).

The required ovality and thinning is supplied at the bend section of the pipe and it varies linearly in the axial direction as it moves away from the bend section to end sections where the cross section takes circular shape.

The bend characteristic is defined as.

$$\lambda = \frac{Rt}{r^2} = \frac{R/r}{r/t} \quad (4)$$

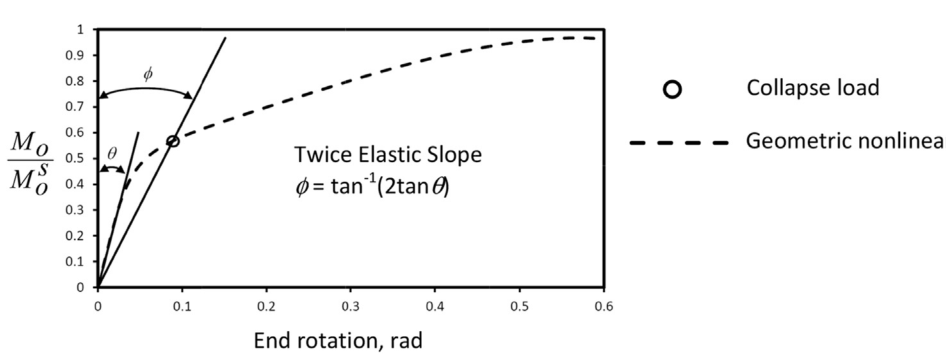

Fig. 1. Moment-rotation curve with TES method for $r/t = 5$ with $\lambda = 0.2$.