International Journal of Pressure Vessels and Piping 99-100 (2012) 23–33

Contents lists available at SciVerse ScienceDirect

International Journal of Pressure Vessels and Piping

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

Comparison of plastic limit and collapse loads in pipe bends with shape imperfections under in-plane bending and an internal pressure

T. Christo Michael*, A.R. Veerappan, S. Shanmugam

Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli 620 015, Tamilnadu, India

ARTICLE INFO

Article history:
Received 7 June 2012
Received in revised form
25 July 2012
Accepted 28 July 2012

Keywords:
Collapse load
Limit load
Ovality
Pipe bend
Thinning

ABSTRACT

The comparison of limit load based on small displacement limit analysis and collapse load based on large displacement analysis for shape-imperfect pipe bends, under combined in-plane closing bending and an internal pressure, were carried out using finite element method. The limit and collapse moments were obtained from moment–rotation curves drawn for each model. Twice-elastic-slope method was used to obtain collapse load. The effect of thinning on limit and collapse moments are minimal and hence thinning need not be considered for the analysis of pipe bends. The influence of ovality on both limit and collapse loads for most of the cases considered are significant. Comparison of effect of ovality on limit and collapse loads reveals that the determination of collapse load is preferable when ovality is included in the analysis of pipe bend. A closed-form solution is presented to include ovality in the determination of the collapse load of pipe bends.

1. Introduction

Pipe bends are critical components in piping systems and generally are recognized to be the most economical means of changing directions while providing flexibility and end reactions to piping systems within the allowable limits [1]. Due to their increased flexibility in comparison to straight pipes, they allow a reduction of the reaction forces and moments within the system as a whole by virtue of their elastic deformations. When exposed beyond elastic limit, plastic collapse occurs which must be avoided. Plastic limit analysis concepts are used for establishing the allowable limits of these plastic loads [2].

The research in the determination of plastic loads in pipe bends comprises analytical works [3–5], experimental works [6–14] and numerical works [2,15–24]. Major loads considered for finding out the plastic loads of pipe bend are in-plane closing/opening bending moment and out of plane moment with and without internal fluid pressure. A systematic investigation of pipe bend requires large number of data. Generating the data by experiments has limitations and expensive, though the results are extremely useful. In this respect, a numerical approach using finite element (FE) method is quite useful [22].

Theoretical limit analysis assumes elastic-perfectly plastic material model and small deformation theory [17]. The ASME [25] guidelines to finite element limit analysis also prescribe use of small geometric change effect in the analyses. When the pipe bend is subjected to closing bending moment, the cross section largely deforms (ovalize) which in turn weakens the geometry while the geometry is strengthened under opening moment [16]. This behaviour of the pipe bend can be accounted when geometric nonlinearity is included in the analyses. When internal pressure is applied along with bending loads, the internal pressure counteracts the cross section ovalization and tends to keep the cross section circular, hence increases the stiffness of the pipe bend and thereby, increases the plastic collapse loads [2].

The studies in pipe bends generally assume the cross section of the bend to be circular. In reality, the cross section deviates from circularity during bending in the manufacturing process and exists with ovality and thickness variation [26,27]. The acceptability of pipe bend depends on the magnitude of ovality and thinning [28–30]. Few works [28–32] have included the effects of these shape imperfections in the analyses of pipe bends. Kim et al. [31] provided a method to estimate plastic loads for elbows with non-uniform wall thicknesses using FE limit analysis. Dan [32] carried out linear and nonlinear cyclic analysis on pipe bends with circular cross section and cross section with 8% ovality and compared the finite element (FE) results. Christo Michael et al. [33] have studied the combined effect of ovality and thinning on plastic collapse loads in pipe bends modelled with elliptic cross section under in-plane closing moment and found that the effect of thinning on plastic loads are not significant whereas the ovality influences the plastic loads.

* Corresponding author. Tel.: +91 (0)431 2503416; fax: +91 (0)431 2500133.
E-mail address: christomic74@gmail.com (T. Christo Michael).

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http://dx.doi.org/10.1016/j.ijpvp.2012.07.013

Nomenclature

C_o	percent ovality
C_t	percent thinning
C_{th}	percent thickening
D	pipe outside (nominal) diameter (mm)
D_{max}	maximum outside pipe diameter (mm)
D_{min}	minimum outside pipe diameter (mm)
E	Young's modulus (MPa)
h	bend characteristic
L	length of straight pipe (mm)
M	collapse moment under combined internal pressure and in-plane bending moment (kN-m)
M_0	collapse in-plane moment of a pipe bend given by [18] (kN-m)
M_0^C	collapse in-plane moment of a pipe bend given by [33] (kN-m)
M^I	limit/collapse moments of the irregular models (kN-m)
M^R	limit/collapse moments of the reference models (kN-m)
M_0^s	limit in-plane moment of a straight pipe (kN-m)
P	internal pressure (MPa)
R	bend radius to neutral axis (mm)
r	mean pipe radius (mm)
t	nominal thickness of pipe bend (mm)
t_{max}	maximum pipe thickness (mm)
t_{min}	minimum pipe thickness (mm)
Z	percent difference of limit/collapse moments between reference and irregular models
υ	Poisson's ratio
σ_0	limit/yield stress of an elastic-perfectly plastic material (MPa)

The present study mainly focuses on the comparison of limit load (based on small displacement analysis) and collapse loads (based on large displacement analysis) of pipe bends with shape imperfections namely ovality and thinning using finite element limit analyses. As opposed to existing works on determination of limit and collapse loads assuming the cross section of the pipe bend to be circular, this work will be the basis for determination of limit or collapse loads when the pipe bends exists with shape imperfections. The combined effect of these imperfections on limit and collapse loads are quantified and compared.

2. Shape imperfections

Circular cross sectioned pipes are processed into smooth bends but usually with noncircular cross sections and with variations in thickness [26]. These changes from the ideal are normally referred to as "ovality" and "thinning". The main objective of any bending method is to control ovality and thinning since the acceptance/rejection of the pipe bends are based on the limits of these shape imperfections prescribed by the governing codes. For example, ASME [34] recommends the manufacturing limits of PFI ES-24 [35] shall be met. In industries, generally the contour of the pipe bend cross sections are captured in their first-off-trial test (FOT), as given in Fig. 1, to calculate the amount of ovality and thinning/thickening present for the acceptance or rejection of the pipe bends.

Since the cross section of the bend is irregular and the thickness is not uniform, initial assumptions made in the geometry of the pipe bends to include ovality and thinning/thickening are,

- The cross sections of the bend that includes ovality are perfectly elliptic [28–30,32] as shown in Fig. 2.
- The increase in thickness at intrados (thickening) is equal to the decrease in thickness at extrados (thinning) [28–30,32].
- The thickness at the crown is the average of maximum thickness (at intrados) and minimum thickness (at extrados) and is equal to the nominal thickness of the straight pipe. The thickness varies with respect to θ, as shown in Fig. 2, from extrados to intrados.
- The required ovality and thickness variation is given at the bend section and it is assumed to vary linearly moving away from the bend section. At the two ends of the pipe bend where the straight pipes are connected, the cross sections become circular [32].

The terms ovality, thinning at extrados, and thickening at intrados [28–30] are defined as follows.

The degree of ovality is determined by the difference between the major and minor diameters divided by the nominal diameter of the pipe. When expressed in percentage form, it corresponds to percentage ovality.

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

where $D = \dfrac{D_{max} + D_{min}}{2}$

Thinning, which occurs at extrados of the pipe bend, is defined as the ratio of the difference between the nominal thickness and the minimum thickness to the nominal thickness of the pipe bend and is expressed in percentage.

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

Thickening occurs at intrados and is defined as the difference between the maximum thickness and the nominal thickness divided by the nominal thickness of the pipe bend.

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

3. Limit analyses

ABAQUS [36], a general nonlinear finite element package, was used to carry out limit and collapse load analyses of pipe bends.

3.1. Geometry

The geometry parameters of the pipe bend chosen for the present study are given in Table 1. Three bend radii [29] are selected to have wide range of bend characteristic, h, ranging from 0.105 to 1.275. The bend characteristic is defined as

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

where R is the bend radius of the pipe bend, r the mean radius and t the thickness of the bend. The angle of the bend is chosen as 90° and straight pipe length equal to five times the outside diameter of the pipe are attached at the two ends of the bend [32]. The end effects caused by the boundary conditions have been removed by connecting straight pipes to the ends of the pipe bend. Ovality and thinning were included in the pipe bend geometry and were each