International Journal of Pressure Vessels and Piping 111-112 (2013) 21–26

Contents lists available at SciVerse ScienceDirect

International Journal of Pressure Vessels and Piping

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

Plastic collapse loads in shape-imperfect pipe bends under in-plane opening bending moment

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ARTICLE INFO

Article history:
Received 5 January 2013
Received in revised form
28 March 2013
Accepted 24 April 2013

Keywords:
Ovality
Thinning
Pipe bend
Collapse load

ABSTRACT

The combined effect of ovality and thinning/thickening on collapse load of pipe bends under in-plane opening bending moment was investigated using finite element limit analysis considering large geometric change effect. The material is assumed to be elastic-perfectly plastic. Twice-elastic-slope method is used to obtain collapse moment from moment–rotation curves drawn for each bend. Variation of thickness due to thinning in the cross section of pipe bend produces negligible effect on collapse load. The effect of ovality is significant except for pipe ratio 20 with $\lambda = 0.5$. A new closed-form solution is proposed to determine collapse moment of pipe bends with ovality and it is validated with existing experimental data.

1. Introduction

Pipe bends are generally formed by both hot and cold bending methods. Some of the hot bending methods are furnace bending, incremental bending, and induction bending while rotary draw bending, ram bending and roll bending are cold bending methods [1]. As a result of the bending process, existence of shape imperfections namely ovality, thinning/thickening, wrinkling etc. are unavoidable. PFI ES-24 [1,2] proposed that ovality shall not exceed the ovality required by governing code. This code further extends that if there is no governing code, ovality limit shall not exceed 8% unless by mutual agreement between the purchaser and fabricator. On thinning, code gives guidelines for different bending methods to decide the minimum thickness prior to pipe bending for various bend radii. Thus, the thinning ranges from 6 to 30 percent for any bending method is followed in the present analyses.

The influence of these shape imperfections has been studied by many researchers [3–7]. Spence and Boyle [8] 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 [3] 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 is possible. Dan [9] 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 the ovality has little effect on circumferential stress distribution under in-plane bending moment.

Collapse behavior of pipe bends were studied by various researchers assuming circular cross section when subjected to different loads namely in-plane and out-of-plane moment with or without internal fluid pressure [10–13]. Determination of collapse loads of pipe bends considering shape imperfections is very limited. The effect of shape imperfections on collapse loads of pipe bends is very important to predict the failure of pipe bends under the action of in-plane and out-of-plane bending moments. Kim et al. [14] 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 to use straight pipe thickness to estimate plastic loads for elbows with non-uniform thicknesses. Christo Michael et al. [6] studied the combined effect of ovality and thinning on plastic loads of pipe bends using finite element analysis under in-plane closing bending and found that the effect of ovality is significant while thinning produces negligible effect. Christo Michael et al. [7] 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

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http://dx.doi.org/10.1016/j.ijpvp.2013.04.034

Nomenclature

C_o	percent ovality
C_t	percent thinning
C_{th}	percent thickening
D_o	outside diameter of pipe, mm
D_{max}	maximum outside diameter of pipe, mm
D_{min}	minimum outside diameter of pipe, mm
E	Young's modulus, MPa
L	length of straight pipe, mm
M_o	collapse in-plane moment of a pipe
M_s^o	limit in-plane moment of a straight pipe, kN m
r	mean radius of pipe, mm
R	bend radius to neutral axis (mm)
t	nominal thickness of pipe bend, mm
t_{max}	maximum thickness of pipe, mm
t_{min}	minimum thickness of pipe, mm
υ	Poisson's ratio
σ_0	limit/yield stress of an elastic-perfectly plastic material
λ	bend characteristic
r/t	pipe ratio
R/r	bend ratio

determination of collapse load is suitable rather than limit load when ovality is present in pipe bends.

The objective of the present study is to determine the effect of ovality and thinning on plastic collapse loads for pipe bends subjected to in-plane opening moment. The finite element limit analysis assumes elastic-perfectly plastic material considering large displacement effect.

2. Shape imperfections in pipe bends

The pipe bends exist with various shape imperfections on account of bending process. The variation of cross section from circular section is called ovality and that in thickness in the cross section is known as thinning/thickening. Thickening occurs at intrados while thinning at extrados of pipe bends. Fig. 1 shows cold bent pipes with actual cross section. The variation in the cross section is not so uniform and therefore assumptions are made in the geometry of pipe bends to include ovality and thinning in the finite element analysis of pipe bends.

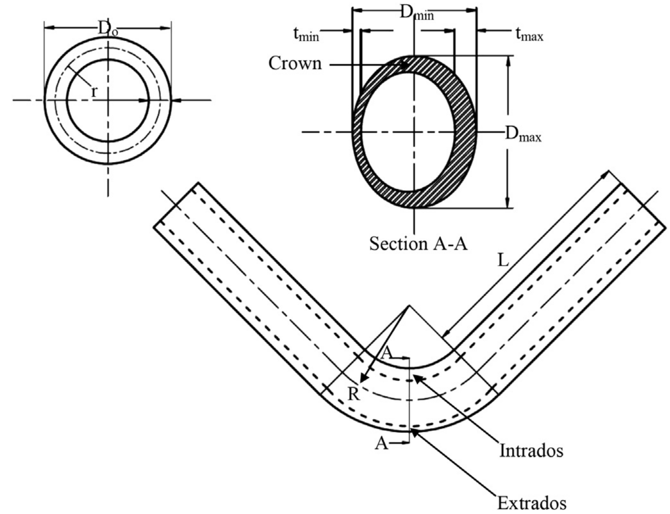

Fig. 2. Pipe bend geometry with attached straight pipe.

The assumptions made in the geometry are

- Cross section is assumed to be elliptic.
- When thinning is considered, the thickness varies linearly from intrados to extrados and the increase in thickness at intrados is equal to this 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 bend 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 finite element limit analysis assumes elastic-perfectly plastic material considering large geometric change effect. Fig. 2 shows the geometry of the pipe bend with straight pipe attachment. Referring to the figure, ovality, thinning and thickening and bend characteristics are defined as follows:

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

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

Fig. 1. Actual cold bent pipes with deviation in cross section and wall thickness (Courtesy, GB Engineering, Tiruchirappalli.).