Effect of Elliptic and Semi-oval Cross Sections on Collapse Load under In-plane Opening Moment and Internal Pressure

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***Abstract*—A comparison between pipe bends with assumed cross sections, namely elliptic and semi oval to include ovality along with wall thinning was performed to determine the plastic collapse load under in-plane opening bending moment and an internal pressure of 4 MPa using finite element limit analysis based on an elastic-perfectly plastic material considering geometric nonlinearity. Twice-elastic-slope method was used to obtain collapse load from the moment-rotation curve drawn for each pipe bend model considered. The effect of ovality on collapse load is significant and higher for elliptic cross sections for the geometry considered while the thinning effect is negligible for both the cross sections. The study concludes that the use of elliptic cross section is suitable for analyzing pipe bend with ovality.**

***Index Terms*—pipe bend, elliptic, semi-oval, twice-elastic-slope, ovality, thinning**

I. 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. Determination of collapse load in pipe bends, under bending with and without internal fluid pressure loads is important for the design of pipe bends.

Most of the existing works assume the cross section of the pipe bend to be circular with uniform thickness. In reality, the pipe bend exists with shape imperfections namely ovality and thinning/thickening as the result of the bending process. The acceptability of pipe bend depends on the magnitude of ovality and thinning [1]. "Reference [2]" provided a method to estimate plastic loads for elbows with non-uniform thicknesses. Therefore, it is more relevant to include ovality and thinning in the analysis of pipe bend. When ovality is included, the cross sections assumed, in the analysis of pipe bend, are elliptic [3] and semi oval [4]. "Reference [5]" compared the collapse loads of pipe bend modeled with elliptic and semi-oval cross sections under in-plane closing bending moment and concluded that elliptic cross section may be assumed to include ovality in the analysis. "Reference [6]" investigated the effects of thinning and ovality on collapse loads of pipe bends under in-plane closing bending moment for varying the internal pressures using elliptic cross section and reported the interaction of internal pressure with the ovality as thinning produces negligible effect on collapse load.

The present study compares the collapse loads of pipe bends modeled with elliptic and semi oval cross sections which include thinning when subjected to in-plane opening bending moment with an internal pressure of 4 MPa using finite element method.

II. OVALITY AND THINNING

A. Ovality (Elliptic cross section)

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 [3, 7-8] as in (1), it corresponds to percentage ovality.

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

Where $D = \dfrac{D_{max} + D_{min}}{D}$

B. Ovality (Semi-oval cross section)

The degree of ovality for semi oval cross section is determined by the difference between the nominal outside and minor radii divided by the nominal outside radius of the pipe. It is expressed in percentage form as in (2).

$$C_o = \frac{r_o - r_{min}}{r_o} \times 100 \quad (2)$$

C. Thinning

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 [1, 8] as given in (3).

$$C_t = \frac{t - t_{min}}{t} \times 100 . \quad (3)$$

D. Thickening

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. The percentage thickening is given in (4).

$$C_{th} = \frac{t_{max} - t}{t} \times 100. \quad (4)$$

III. Finite Element Limit Analysis

The finite element modeling and the limit analysis were carried out using ABAQUS [9], a general nonlinear finite element package. A scripting language Python was used to develop the program which in turn created the pipe bend geometry, input material property, meshed the model, applied boundary and loading conditions and created input files. The input file was created adopting the method used in example 1.1.2 of ABAQUS example problems manual [9].

TABLE I.
Geometry of the pipe bends

SL.NO.	r/t	R/r	h
1	5	2	0.40
2	10		0.20

A. Geometry

The piping system considered for the analysis comprises a 90° bend and two attached equal length, L, straight pipes, L=5D, where D is the nominal outside diameter of the pipe [3]. The straight pipe attachment removes the end effects caused by the loading boundary conditions to the pipe bend. The ‘reference’ model, in this paper, corresponds to the pipe bend with circular cross section and uniform thickness. For the reference model, the mean radius and thickness of the pipe are denoted by r and t respectively, and the bend radius by R. The bend characteristic, h, is defined by

$$h = \frac{Rt}{r^2} = \frac{R/r}{r/t}. \quad (5)$$

The pipe bend geometric parameters chosen for the present analyses are shown in Table 1. The ‘irregular’ model in this paper corresponds to the pipe bend with ovality and thinning. The geometry of the pipe bend includes ovality and thinning each varied from 0% to 20% in steps of 5% [1] while the cross section of the straight pipe is circular with uniform (nominal) thickness for all the models [5-6]. The models considered have the required ovality and thinning/thickening at the bend section (center of the pipe bend), and changes linearly moving away from the bend section. At the two ends where the pipe bend is connected to the straight pipes, as shown in Fig. 1, the cross sections become circular with uniform thickness. The cross sections considered are elliptic and semi oval and it is assumed that the increase in thickness at intrados (thickening) is equal to the decrease in thickness at extrados (thinning).

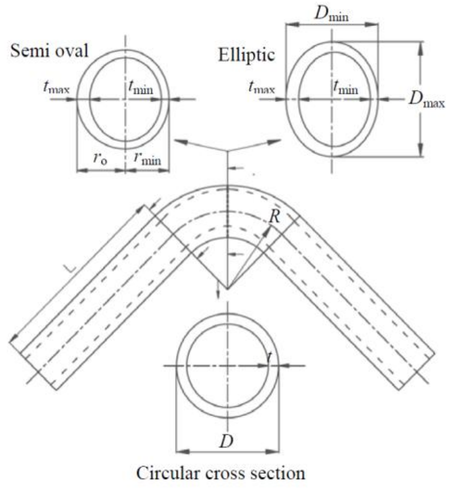
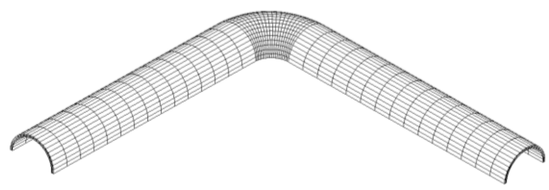


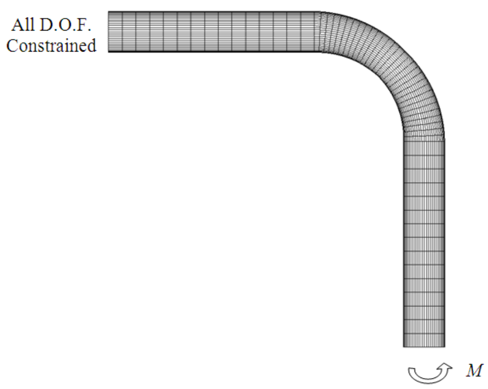
Figure 1. Pipe bend with attached straight pipe showing elliptic and semi oval cross sections.

B. Finite element analysis

The material model was assumed to be elastic-perfectly plastic, and non-hardening J2 flow theory was used. The material used was stainless steel (type 304) with Young’s modulus (E), yield stress (σo) and Poisson’s ratio (υ) respectively as 193 GPa, 272 MPa and 0.26 [10]. The C3D20R, 20-node quadratic brick, reduced integration element was preferred in order to reduce computing time. Mapped meshing was used to generate the mesh model.



(a)



(b)

Figure 2. Finite element models showing (a) half symmetry and (b) boundary and loading conditions

The number of elements and nodes for each model were chosen as 3000 and 15777 respectively, after performing mesh refinements. Three such elements were used across the thickness for all the models. One half of the model which is symmetric with respect to the assumed bending plane, as shown in Fig. 2 (a), was built and symmetry boundary condition was applied. All possible degrees of freedom (D.O.F.) at one end of the straight pipe was constrained, as shown in Fig. 2 (b), and multi-point constraint was applied to the other end in which the end surface nodes were attached to a single node where rotation boundary condition was specified. Increments of rotation were prescribed at the free end rather than increments of moment since it is anticipated that the collapse will be unstable [10]. Internal pressure was applied at the inner surface of the models as distributed load together with an axial tension equivalent to the internal pressure at the end of the pipe to simulate closed end. The RIKS option within the package was invoked to avoid problems associated with convergence in elastic-perfectly plastic calculations.

When a pipe bend is subject to in-plane opening moment, geometric strengthening is present [11], hence the GNL (Geometric Non-Linearity) was included in the analyses. The input files were created and submitted for solving the models. The reaction moments corresponding to the specified rotations at the MPC (Multi Point Constraint) node were extracted directly in Excel sheets. Using the moment and rotation data the curves were plotted. When nonlinear geometry effect is considered, the moment-rotation curves do not approach horizontal asymptote to obtain clear limiting loads. Therefore, the Twice-Elastic-Slope (TES) [12] method (in which a straight line from the origin with twice the slope of the initial elastic response of the moment-rotation curve is drawn to intersect the same curve) was used to determine the plastic collapse loads from FE moment-rotation curves.

IV. Results and Discussion

Percent difference between reference and irregular models were calculated and plotted to observe the effect of thinning and ovality on collapse load.

A. Effect of Thinning

Fig. 3 shows the effect of thinning on collapse load for the cases considered for both the cross sections, when the internal fluid pressure is 4 MPa. The maximum thinning occurs at r/t=10 and it occurs for 20% thinning, the ovality being 0% for elliptic cross section and 20% for semi-oval cross section.

Comparing the two cross sections, the thinning effect is higher for semi-oval cross section. For a particular ovality but different thinning the maximum variation is within 2.5% which indicates the thinning effect is minimal. Hence, thinning effect can be neglected.

B. Effect of Ovality

The percent difference increases as the ovality is increased for all the cases considered, as shown in Fig. 4. The percent difference is higher for elliptic cross sections for both r/t=5 and 10 indicating that elliptic cross section has to be assumed for the analysis of pipe bend.

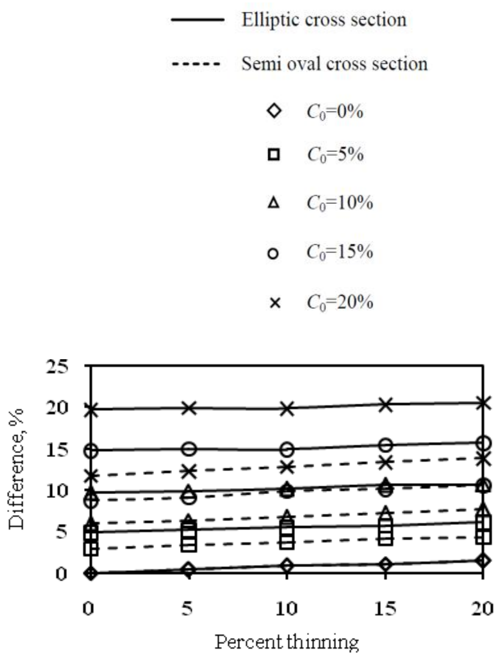


Figure 3. Effect of thinning on collapse load

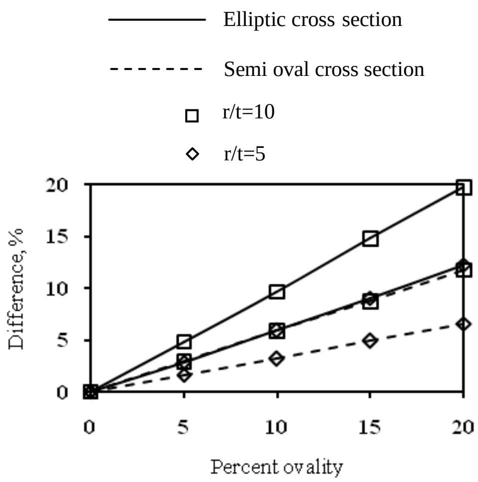


Figure 4. Effect of ovality on collapse load

When the ovality is 5%, for r/t=5 and 10, the percent difference is 2.9 and 4.8, respectively, for elliptic cross section and 1.6 and 2.9 for semi-oval cross section. For ovality of 10%, when r/t=5 and 10, the percent difference is 5.9 and 9.6, respectively, for elliptic cross section and 3.2 and 5.9 for semi-oval cross section. For r/t=5 and 10, the percent difference is 9 and 14.7, respectively, for elliptic cross section and 4.9 and 8.7 for semi-oval cross section, when the ovality is 15%. For ovality of 20%, when r/t=5 and 10, the percent difference is 12.3 and 19.7, respectively, for elliptic cross section and 6.5 and 11.7 for semi-oval cross section.

It is found that the effect of ovality, for any particular percent of ovality, increases with increasing r/t for both the cross sections considered. It is also observed that for a considered value of R/r=2, the effect of ovality is higher for the elliptical cross section for both r/t=5 and 10.

V. Conclusions

The following are the conclusions drawn from the finite element limit analysis.

- The effect of thinning on collapse load for elliptic and semi-oval cross sections is negligible and hence, the thinning need not be considered for the finite element analysis.
- The effect of ovality on collapse load increases as the ovality is increased for both the cross sections. For higher percent ovality, the effect on collapse load is significant. Hence, ovality should be included in the limit analysis.
- For the geometry considered, the ovality effect is higher for elliptic cross section. Therefore, to include the ovality effect in the analysis of pipe bends, elliptic cross section may be assumed.

References

[1] A. R. Veerappan, and S. Shanmugam, "Analysis for flexibility in the ovality and thinning limits of pipe bends," *ARPN J Engng Appl Sci,* 3(1), pp. 31–41, 2008.

[2] Y. J. Kim, N. H. Kim, C.Y. Oh, and C.S. Oh, "A method to estimate plastic loads for elbows with non-uniform thicknesses," *Fatigue Fract Engng Mater Struct,* 31, pp. 822–37, 2008.

[3] V. Dan, "The influence of the initial ovality tolerance on the nonlinear cycling analysis of piping bends," *J Pressure Vessel Technol*, 131, 041203-1– pp. 3-7, 2009.

[4] J. T. Boyle, and J. A. Spence, "Simple stress analysis for out-of –round pressurized pipe bends," *Int J Press Vessel Pip,* 9, pp. 251–61, 1981.

[5] T. Christo Michael, A. R. Veerappan, and S. Shanmugam, "Effect of ovality and variable wall thickness on collapse loads in pipe bends subjected to in-plane bending closing moment," *Engng Fract Mech,* 79, pp. 138-48, 2012.

[6] T. Christo Michael, A. R. Veerappan, and S. Shanmugam, "Effect of Internal pressure and shape imperfections on plastic loads of pipe bends under in-plane closing moment," *Engineering Fracture Mechanics*, Vol. 105, pp.1-15, 2013.

[7] A. V. Kale, and H. T. Thorat, "Effect of precompression on ovality of pipe after bending," *J Pressure Vessel Technol,* 131, 011207, pp. 1–7, 2009.

[8] A. R. Veerappan, S. Shanmugam, and S. Soundrapandian, "The accepting of pipe bends with ovality and thinning using finite element method," *J Pressure Vessel Technol,* 132, 031204, pp. 1–4, 2010.

[9] ABAQUS Version 6.9, User's manual, *Simulia*, RI, USA; 2009.

[10] M. A. Shalaby, and M. Y. A. Younan, "Limit loads for pipe elbows with internal pressure under in-plane closing moments," *J Press Vessel Technol,* 120, pp. 35–42, 1998.

[11] A. Robertson, H. Li, and D. Mackenzie, "Plastic collapse of pipe bends under combined internal pressure and in-plane bending," *Int J Press Vessel Pip,* 82, pp. 407–16, 2005.

[12] Y. J. Kim, J. H. Je, C. S. Oh, J. J. Han, and P. J. Budden, "Plastic loads for 90° thick-walled elbows under combined pressure and bending," *J Strain Anal,* 45, pp. 115–27, 2009.