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Suitability of assumed cross sections to include ovality in the limit analysis of pipe bends under in-plane closing moment and internal pressure

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ABSTRACT

To include ovality in the analysis of pipe bends, elliptic and semi-oval cross sections are generally assumed. This study determines collapse load equations for semi-oval cross section using finite element analysis under in-plane bending and internal pressure and compares them with the existing collapse loads for elliptic cross sections. The comparison reveals that elliptic or semi-oval cross section may be used when the pipe bend is subjected to only in-plane bending moment. With internal pressure, though elliptic cross section is suitable for low pressures, semi-oval cross section may be preferred as it is suitable for high pressures.

1. Introduction

Ovality and thinning present in pipe bends are the outcomes of pipe bending processes. During pipe bending, stringent mechanisms are used to keep these shape imperfections within allowable limits [1,2]. American Society of Mechanical Engineers (ASME) recommends the manufacturing limits of PFI ES-24 [3] shall be met. The acceptance or rejection of pipe bends is based on these limits. The rejection rate during inspection will be more if the ovality and thinning exceed the limits prescribed by codes. However, the basis with which the codes use these limits is not clearly known when the pipe bends are subjected to in-plane and out-of-plane bending moment loads. Therefore, inclusion of variation in cross section (ovality) and thickness (thinning) in the analyses of pipe bends shall help the designers to predict the collapse load of pipe bends.

Plastic loads have been determined in pipe bends under bending and with internal fluid pressure loads by analytical [4–6], experimental [7–9] and numerical [10–15] methods. The influence of cracks on plastic loads of pipe bends have also been studied [8,16–18]. Few studies have included the shape imperfections in the analyses of pipe bends. Kim et al. [15] provided a method to estimate plastic loads for elbows with non-uniform thicknesses. Various studies [19–22] have reported the effect of local wall thinning, from flow-accelerated corrosion (FAC), on the collapse loads of pipe elbows. Christo Michael et al. [23] 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 is not significant while ovality influences the plastic loads. Comparison of plastic limit load based on small displacement analysis and plastic collapse loads based on large displacement analysis in shape-imperfect pipe bends [24] has been performed and it was concluded that the geometric nonlinearity effect has to be included in the analysis of pipe bends when ovality is present. Further, Christo Michael et al. [25] investigated the collapse behavior of bends with shape imperfections for different internal pressures and found that the ovality decreases the collapse load up to a certain pressure then increases for each case considered and this increase in collapse load is attributed to the increase of stiffening effect of internal pressure.

Elliptic and semi-oval are the assumed cross sections in the analysis of pipe bend with ovality. Elliptic cross section [23–29] has been widely assumed to include ovality. Distortion in cold bend tubes is usually limited to the outer half of the bend where flattening occurs and the distortion can be described by a semi-oval/semi-round section [30]. The bending processes mostly use cold bend methods as these methods are inexpensive when compared with hot bending processes. Since two assumed cross sections are found in literature to include ovality, it is important to analyze both to ascertain the cross section that may be assumed to carry out finite element (FE) limit analyses.

In-plane closing bending moment weakens the cross section of the pipe bends. The presence of ovality weakens the bend further. When internal pressure is also applied along with in-plane closing moment, the cross section is stiffened and the collapse load increases. But this stiffening effect produced by internal pressure varies with ovality [25]. The presence of ovality is therefore directly attributed to the variation of weakening and stiffening effects on the pipe bends under in-plane closing moment and combined loading (in-plane closing bending along

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Nomenclature

C_o^{EL}	percent ovality for elliptic cross section
C_o^{SO}	percent ovality for semi-oval cross section
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 (GPa)
h	bend characteristic
L	length of straight pipe (mm)
M^{EL}	collapse moment of bend with elliptic cross section under combined in-plane closing moment and internal pressure (kN-m)
M^{SO}	collapse moment of bend with semi-oval cross section under combined in-plane closing moment and internal pressure (kN-m)
M_o^{EL}	collapse load of a pipe bend with elliptic cross section (kN-m)
M_o^{SO}	collapse load of a pipe bend with semi-oval cross section (kN-m)
M_o^s	limit in-plane moment of a straight pipe (kN-m)
P	internal pressure (MPa)
P_o^s	limit pressure of straight pipe (MPa)
R	bend radius to neutral axis (mm)
r	mean pipe radius (mm)
r_{min}	minimum radius (mm)
r_o	nominal outside radius (mm)
t	nominal thickness of pipe bend (mm)
t_{max}	maximum pipe thickness (mm)
t_{min}	minimum pipe thickness (mm)
υ	Poisson's ratio
σ_o	limit/yield stress of an elastic-perfectly plastic material (MPa)

with internal pressure) respectively. This brings us the objective to analyze the pipe bends with semi-oval cross section to include ovality and to compare the results with the existing collapse loads [25] in order to determine the suitability of the two assumed cross sections. Thinning is also included in the analyses. The finite element method is employed to carry out the limit analysis considering geometric nonlinearity to determine the collapse load.

2. Shape-imperfect pipe bends

Many hot and cold bending methods are used to bend the straight pipes in to bends of different angles. During bending process the cross section and thickness of the pipes are not uniform as shown in Fig. 1. These changes are called as "ovality" and "thinning". Ovality is a main defect in all pipe bending techniques [1]. 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. For example, ASME [31] recommends the manufacturing limits of PFI ES-24 [3] shall be met. In industries, the contours of the pipe bend cross sections are captured in their first off trial test (FOT), as given in Fig. 1, to calculate the ovality and thinning/thickening present. The pipe bends cross sections in Fig. 2b and c approximate elliptic shape while that in Fig. 2a is semi-oval indicating that pipe bend cross sections are not uniform.

3. Finite element limit analyses

The geometrical parameters and the modeling of pipe bends with attached straight pipe, material properties, meshing, boundary and loading conditions and solution controls to solve the models are explained in this section. A general nonlinear finite element package [32] was used to do the above tasks with the help of a program written using the scripting language called python.

3.1. Geometry

The geometric parameters and the material details chosen are given in Table 1. To have wide range of bend characteristic, h, the thicknesses for a particular diameter [31] with different bend radii [27] were chosen. The bend characteristic is given as

$$h = \frac{Rt}{r^2} = \frac{R/r}{r/t} \tag{1}$$

where R is the bend radius of the pipe bend, r is the mean radius and t is the thickness of the pipe as given in Fig. 3a. The ends of the pipe bend are attached with straight pipes. During the finite element modeling, various assumptions [25] are made to model the pipe bends with shape imperfections. The present work assumes semi-oval cross section to include ovality. The cross section includes thinning/thickening as well. The terms ovality, thinning at extrados, and thickening at intrados for semi-oval cross section is defined below:

One half of the cross section where thickening occurs is circular and the other half where thinning exists is semi-elliptic/oval as shown in Fig. 3b. The ovality is defined as the difference between nominal outside radius and minimum radius divided by the nominal outside radius of the pipe.

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

The percent thinning [23–27] and thickening are given as

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

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

The variation of thickness and the cross section deviation due to ovality at the mid-section of the bend was explained mathematically in the previous work [25]. Similarly, the deviation of the cross section at mid-section was carried out for semi-oval cross section using ellipse

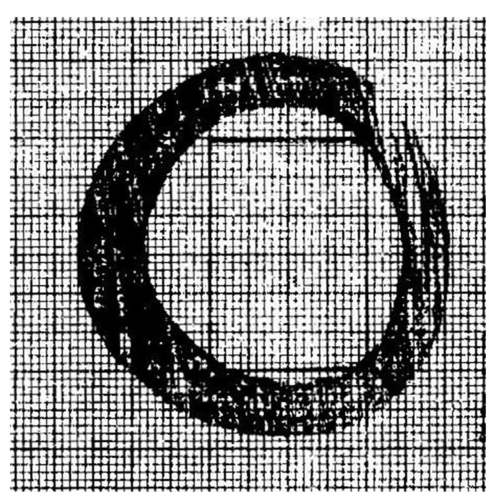

Fig. 1. The cross sections of 90° cold bent pipe taken from first off trial test report (Courtesy GB Engineering, Tiruchirappalli, India.).