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Assessment of plastic loads of critical throughwall circumferentially cracked pipe bends with structural distortions under in-plane bending

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ABSTRACT

A comparative evaluation of limit moments based on small displacement and collapse moments based on large displacement for structurally distorted throughwall circumferentially cracked pipe bends, under in-plane closing bending were carried out using finite element analysis. The moments were obtained employing the twice-elastic-slope method. Results indicate the influence of thinning is minimal whereas the effects of ovality on both limit and collapse moments for the cases considered are significant and therefore thinning need not be considered in the analysis. Moreover determination of collapse moments is preferred when ovality is incorporated in the analysis of pipe bends with the geometries considered.

1. Introduction

Pipes with circular cross sections are shaped into even bends of required configurations but with non-circular cross sections and varied thickness [1]. The acceptability of these pipe bend depends on the degree of ovality and thinning [2–4]. Few works [2–6] have included the effects of these shape imperfections in the analyses of pipe bends. Kim et al. [5] presented a procedure to estimate plastic moments for pipe bends with non-uniform wall thicknesses using finite element limit analysis. Dan [6] conducted finite element (FE) linear and nonlinear analysis on pipe bends with circular cross section and cross section with 8% ovality and compared the results. Christo Michael et al. [7] have carried out limit analysis to study the combined effects of ovality and thinning on plastic collapse moments in pipe bends with elliptic cross section under in-plane closing moment and noted that the effect of thinning on plastic moments is not remarkable whereas the ovality influences the plastic moments.

When piping system components are 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 moments [8]. Theoretical limit analysis presume elastic-perfectly plastic material model and small deformation theory [9]. The ASME [10] recommendations to finite element limit analysis also stipulate use of small geometric change effect in the analyses. Crack-like defects develop on pipe bends not only during various stages during manufacturing and installation, but can also appear with cyclic loading and material deterioration as a result of continued operation [11]. Large throughwall circumferential crack could significantly reduce the load carrying capacity of pipe bends [12]. The studies on cracked pipe bends generally assume the cross section of the bend to be circular. Existing theoretical solutions, have not examined the weakening effect on plastic moments due to the presence of postulated circumferential throughwall crack in pipe bends with distorted cross sections due to ovality and thinning.

The present study mainly focuses on the evaluation and comparison of limit moments based on small displacement analysis and collapse moments based on large displacement analysis of critical throughwall circumferentially cracked 90 degree pipe bends with ovality and thinning using finite element limit method. As opposed to existing works on determination of limit and collapse moments assuming the cross section of the cracked pipe bend to be circular, this work will be the basis for determination of limit or collapse moments when a critical throughwall circumferentially cracked pipe bends exist with structural distortions.

2. Shape imperfections

In reality, the pipe cross section deviates from circularity during

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Nomenclature

C_o	percent ovality
C_t	percent thinning
D	pipe outside diameter, mm
D_{max}	maximum outside pipe diameter, mm
D_{min}	minimum outside pipe diameter, mm
t	nominal thickness of pipe bend, mm
t_{max}	maximum pipe thickness, mm
t_{min}	minimum pipe thickness, mm
R	bend radius to neutral axis, mm
r	mean radius of pipe, mm
L	length of attached straight pipe, mm
h	bend characteristic
σ_0	yield stress of an elastic-perfectly plastic material, MPa
E	Young's modulus, MPa
M_L	plastic in-plane moment of cracked pipe bend given by [12], kN-m
M_O	plastic in-plane moment of un-cracked pipe bend, kN-m
M_R	plastic in-plane moment of cracked pipe bend with circular cross section, kN-m
M_I	plastic in-plane moment of cracked pipe bend with irregular cross section, kN-m
Z	percent difference of plastic moments between circular and irregular models
θ	semi-circumferential crack angle
θ/π	relative crack length

bending in the manufacturing process. These changes from the ideal are generally 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. In industries, normally the profile of the pipe bend cross sections are captured 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

(i) The cross sections of the bend that includes ovality are perfectly elliptic [7] as shown in Fig. 1.
(ii) The increase in thickness at intrados (thickening) is equal to the decrease in thickness at extrados (thinning).
(iii) 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. 1, from extrados to intrados.
(iv) 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 [7].

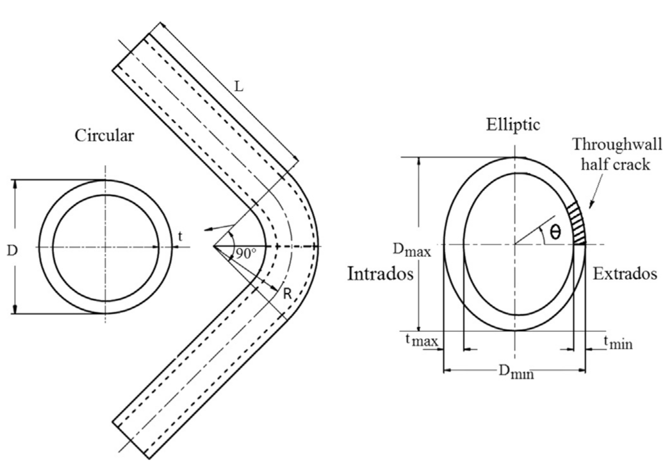

Fig. 1. 90° Pipe bend with attached straight pipe showing assumed elliptic cross section with circumferential throughwall crack.

The terms ovality, thinning at extrados, and thickening at intrados [2,3] are defined as follows.

The magnitude of ovality is calculated by taking the difference between the major and minor diameters and dividing by the nominal diameter of the pipe. When expressed in percentage form, it corresponds to percentage ovality.

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

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

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.

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

3. Limit analyses

ABAQUS [13], a general nonlinear finite element package, was used to carry out limit and collapse moment analyses of pipe bends with distorted cross sections and circumferential through-wall cracks.

3.1. Geometry

The geometry parameters and material properties for the cracked pipe bends from published works [7,12,14] were chosen for the present study as given in Table 1. Fig. 1 illustrates the cracked pipe bend model with the postulated elliptic cross section used in the present study. The bend characteristic is defined as

$$h = \frac{Bend\ ratio}{Pipe\ ratio} = \frac{R/r}{r/t} = \frac{Rt}{r^2} \tag{3}$$

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 [12]. The end effects due to the boundary conditions have been eliminated by connecting straight pipes to the ends of the pipe bend. The crack is assumed to be located in the center of the pipe bend at the extrados. The circumferential throughwall crack is characterized by its relative crack length, θ/π, where θ represents the half-crack angle. Three cases of relative crack lengths corresponding to threshold crack angles on cracked pipe bends for three bend ratios