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Finite Element Stress Analysis In Shape-Imperfect Pipe Bends Under Internal Pressure

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Abstract

Pipe bends are very important and critical components in any piping system, particularly in thermal power plants. To avoid failure of piping system, utmost care is taken to design the pipe bends under various loads. Many analytical and numerical studies on pipe bends assume the cross section to be circular, but in practice the cross section exists with ovality and thinning/thickening.In this paper, the effect of ovality and thinning on the induced hoop stress is investigated using finite element method when the pipe bend is subjected to internal pressure. The cross section, to include ovality and thinning, is assumed to be elliptic as prescribed by ASME.The ovality and thinning were varied from 0 to 20 percent with the increment of 5 percent. The pipe bend geometry chosen for the paper is r/t=5, 10, 15 and 20 and R/r= 2 and 3. The internal pressure was varied up to 12 MPa for each model in steps of 2 MPa. It is found that the ovality and thinning have significant effect on stresses induced and hence any numerical analysis must include the effect of these shape imperfections for the proper design of pipe bends.

Keywords: Pipe bends, Ovality, Thinning, Thickening, Hoop stress,Elliptic

Introduction

Pipelines are being used by different industries to convey chemicals, crude oil, gases, vapours, hazardous and toxic substances etc. Thermal power plantsextensively use the pipelines to carry high-pressure and high-temperature steam and other fluids. Failure of the piping systems may cause catastrophic effect to humans at work and the environment. Pipe bends are critical components in piping systems and generally are the most economical means of changing directions. The bend section may be a potential source of damage during service, due to internal pressure and other loads.

Investigation on induced stress in pipe bends is very important for the design of pipe bends in any piping system. Several analytical [1-6], experimental [7-8] and numerical [9-16] studies have been performed by many researchers to avoid failure of pipe system during service.

Almost all analytical and numerical studies on pipe bends assume the cross sections of the bend to be circular. But in reality, the pipe bend exists with shape imperfections namely ovality, thinning/thickening, wrinkling etc. as the result of bending processes [18-21]. The acceptability of pipe bend depends on the magnitude of ovality and thinning. Therefore, it is more relevant to include ovality and thinning in the analysis of pipe bends. Few studies [14-16] have included the effects of ovality and thinning in their analysis. The effect of internal fluid pressure on the hoop stress of pipe bends can still be performed.

The study of combined effect of these shape imperfections on induced stresses will certainly be useful for the safe design of pipe bends. Therefore, the objective of this paper is to investigate the effect of ovality and thinning on the induced hoop stress of the pipe bends under internal fluid pressure using 2D finite element axisymmetric static and linear analysis [10-16].

Pipe bends with shape imperfections

Circular cross-sectioned pipes are processed into smooth bends but usually with noncircular cross sections and with variations in thickness [20-21] as shown in Figure 1. These changes from the ideal are normally referred to as ovality and thinning respectively.

(a) (b) (c)

Figure 1: Pipe bends with irregular cross sections

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 [22] recommends the manufacturing limits of PFI ES-24 [23] shall be met.

The variation in the cross section and thickness of the actual pipe bends, as shown in Figure1, for cold bent pipe bends, are not very uniform. In industries, generally the contour of the pipe bend cross sections are captured in their first off trial test (FOT), as given in Figure 2, to calculate the amount of ovality and thinning/thickening being present for the acceptance or rejection of the pipe bends.

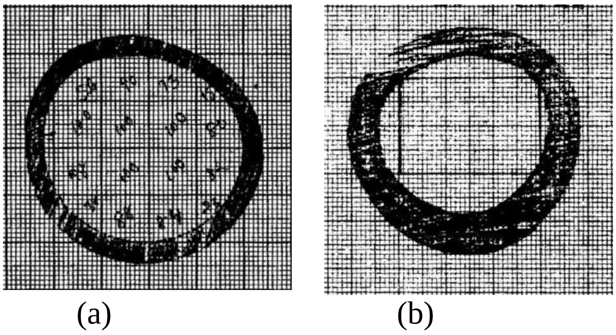

(a) (b)

Figure 2: The cross sections of the 90° cold bent pipes taken from first off trial test report (Courtesy GB Engineering, Tiruchirappalli, India.)

Definitions

The degree of ovality for elliptic cross section, as shown in Figure 3, is determined by the difference between the major and minor diameters divided by the nominal diameter of the pipe. When expressed in percentage form as in Eq. (1), it corresponds to percentage ovality.

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

where

$$D = \frac{(D_{\max} + D_{\min})}{2}$$

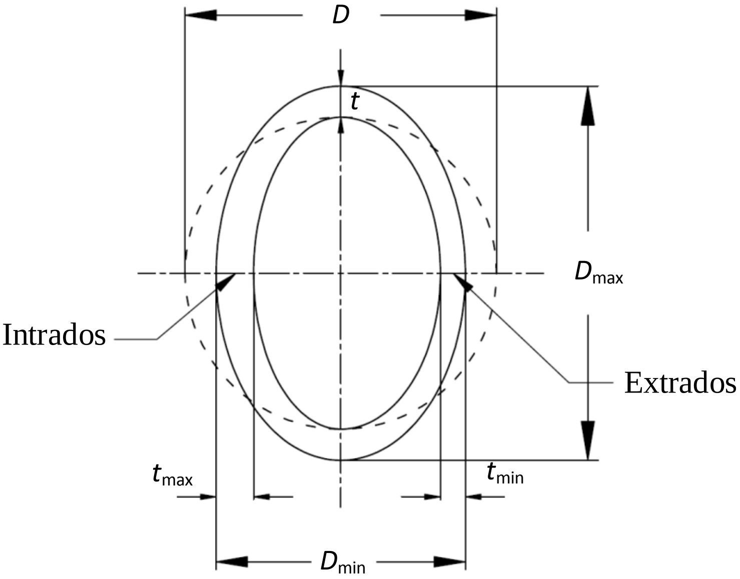


Figure 3: Elliptic cross section

Thinning, as given in Eq. (2), 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 as

$$C_{\mathrm{t}} = \frac{(t - t_{\mathrm{min}})}{t} \times 100 \qquad (2)$$

Thickening, as given in Eq. (3), 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 expressed as

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

Finite Element Analysis

The hoop stresses induced in pipe bends when subjected to internal fluid pressure is obtained using finite element analysis. The finite element method has become reliable, due to its versatility, and the results obtained are acceptable provided the analysis is performed well by bringing in the realistic boundary and loading conditions. In this work, proper validation is carried out in order to check the reliability. ANSYS [23], a general finite element software package, is used to analyze the pipe bends. In order to avoid repeating the modelling and solving of the models, a program is developed using APDL (Ansys Parametric Design Language) which can perform a complete analysis of a model starting from building of pipe bend cross section with shape imperfections to solving of the same. The flow chart shown in Figure 1 explains the methodology of the pipe bend analysis to obtain the induced hoop stress.

Geometry

The geometry parameters chosen for the project work is given in Table 1. The percent ovality and thinning is each varied from 5% to 20% in steps of 5% .The definitions of ovality and thinning are used to model the cross section with shape imperfections. The cross section assumed to include ovality is elliptic, as shown in Figure 3, and it is also assumed that the increase of thickness at intrados is equal to the decrease of thickness at extrados. One half of the cross section is modelled as shown in Fig to utilize the symmetry of the geometry. The model is moved in positive x-direction to include bend radius.

Material

The material chosen is Type 304 Stainless Steel with Young’s modulus=193 MPa, Poisson’s ratio=0.26 and yield stress=272 MPa. The material is assumed to be isotropic and homogeneous and behave linearly.

Table 1: Geometry parameters of the pipe bends

Sl. No.	Input Parameters	Specification
1	Pipe mean radius, *r*	50 mm
2	Pipe ratio, *r*/*t*	5, 10, 15 and 20
3	Bend ratio, *R*/*r*	2 and 3
4	Bend characteristic, *h*	0.1 to 0.6
5	Ovality	0% to 20% in steps of 5%
6	Thinning/thickening	0% to 20% in steps of 5%

Meshing

Mapped meshing is performed on the pipe bend cross section using plane 183 quadratic elementswith axis symmetric option invoked. The advantage of using mapped meshing is that the analyst can control the number of elements. Across the thickness three elements are chosen and the number of elements is varied on the circumference to finalize the optimum number of elements. The number of elements through the circumference was varied from 120 to 300 with the increment of 30 keeping the aspect ratio under 5 and there is no variation in the induced hoop stress as shown in Figure 4. Hence, the number of elements chosen for all analyses is 120.

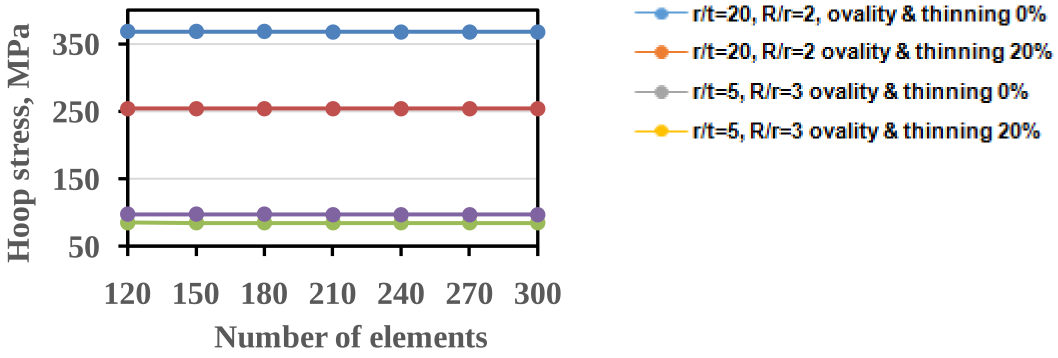


Figure 4: Hoop stress variation for different number of elements

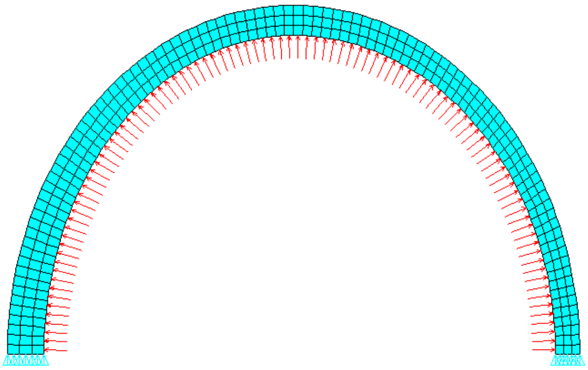


Figure 5: Boundary and loading conditions of pipe cross section

Boundary and Loading Conditions

The symmetry boundary condition is applied, as shown in Figure 5, by constraining the nodes across the thickness in y-direction. The internal fluid pressure is applied at the inner circumference of the cross section. The pressure is varied from 2 MPa to 12 MPa with an increment of 2 MPa to have wide of pressures.

Solving

The model is analyzed for various ovality, thinning and pressures. ANSYS uses sparse solver to solve the models. Since 25 models are solved, for a particular thickness and bend radius, with various combinations ovality and thinning, the APDL program uses DO loop to complete all the 25 models in one run.

Post-processing

The hoop stress values are obtained for inner and outer nodes of intrados, crown and extrados directly to the excel sheet through a macro. The maximum of the six nodes is used for the interpretation. A typical post processing result of the solved pipe bend model is shown in Figure 6.

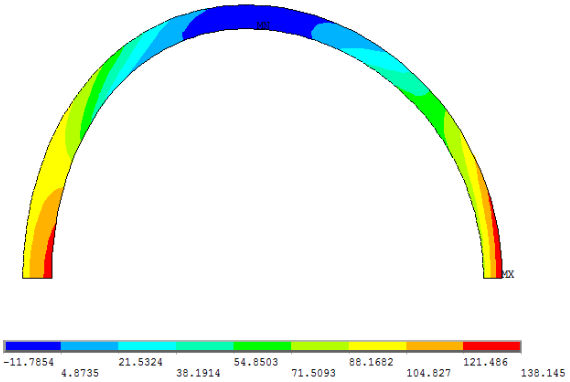


Figure 6: ANSYS model showing nodal solution for stress induced

Validation

In order to check the reliability of the finite element procedure, the finite element results of pipe bends with circular cross section having uniform thickness is compared with the analytical hoop stress formula for torus. As the present axis symmetric two dimensional finite element analyses is equivalent to3D torus, it is relevant to compare the finite element hoop stresses with the analytical hoop stress [24]. The formula for the hoop stress of torus is given in Eq. (4) as

$$\sigma = \frac{pr_i}{2t}\left(\frac{2R-r_i}{R-r_i}\right) \tag{4}$$

where, σ is the hoop stress of torus, r is inside radius of bend cross section,t is the thickness of the pipe,R is the bend radius of the bend and p is the internal pressure. As this formula is suitable for thin pipe, the comparison is carried out for r/t=20,15 and 10 for the lowest and highest pressures considered. The comparison is given in Table 2.

Table 2: Comparison of analytical hoop stress with numerical results

No	p, MPa	t, mm	r, mm	r_i, mm	R, mm	σ by Eq. (1), MPa	σ by FEM, MPa	% Difference
1	2	2.5	50	48.75	100	57.55	61.40	6.27
2	2	3.33	50	48.335	100	42.61	46.43	8.23
3	2	5	50	47.5	100	27.60	31.61	12.70
5	2	2.5	50	48.75	150	48.39	51.10	5.31
6	2	3.33	50	48.335	150	35.93	38.87	7.55
7	2	5	50	47.5	150	23.40	26.68	12.28
9	12	2.5	50	48.75	100	345.29	368.40	6.27
10	12	3.33	50	48.335	100	255.66	278.60	8.23
11	12	5	50	47.5	100	165.57	189.66	12.70
13	12	2.5	50	48.75	150	290.33	306.60	5.31
14	12	3.33	50	48.335	150	215.59	233.20	7.55
15	12	5	50	47.5	150	140.41	160.07	12.28

As the thickness increases, the percent difference is also increasing indicating that the equation is not suitable for thick pipe bends. The percent difference is within 12.3% and this shows good agreement with the analytical solution. Thus, the finite element procedure is validated.

Results and Discussion

The hoop stress induced due to the application of internal fluid pressure in various pipe bends chosen is discussed in this chapter. First, the hoop stress of pipe bends with circular cross section with uniform wall thickness is presented and then the ovality and thinning are included in the bend model to determine the combined effects of these shape imperfections on the induced hoop stress when the pipe bend is subjected to various internal fluid pressures. A total of 8 pipe bends with r/t=5,10,15& 20 and R/r= 2 & 3 are chosen for the present work, where, R is the bend radius, r is mean radius and t is the thickness of the pipe. Increase of r/t corresponds to decreases of thickness while increase of R/r refers to increase of bend radius. The bend characteristic ($\lambda=Rt/r^2$) is kept within 0.6. Therefore, the thickness values are calculated as 2.5, 3.33, 5, and 10 mm and the bend radius values are 100 and 150 mm. For all the eight cases, the mean pipe radius, r, is fixed as 50 mm. The internal pressure is varied from 2 MPa to 12 MPa with the increment of 2 MPa.

Pipe bends with no initial ovality and thinning

The induced hoop stress values for the pipe bends with no initial ovality and thinning are shown in Figure 7. It can be observed that the hoop stress increases with increasing the pressure for all the cases considered. When R/r=2, for any particular pressure, the increase of thickness decreases the hoop stress. It is obvious that the strength of the pipe increases with increasing the thickness as there is more material to resist the stress. The hoop stress of the straight pipe is lesser than the stress value of the torus. As the bend radius increases, the bend approaches straight pipe and hence the induced stress for smaller bend radius is higher than the higher bend radius. This could be seen from Figure 7 that the stress decreases as the bend radius is increasing for a particular pressure. For all the cases, the maximum stress occurs at the inner intrados of the cross section.

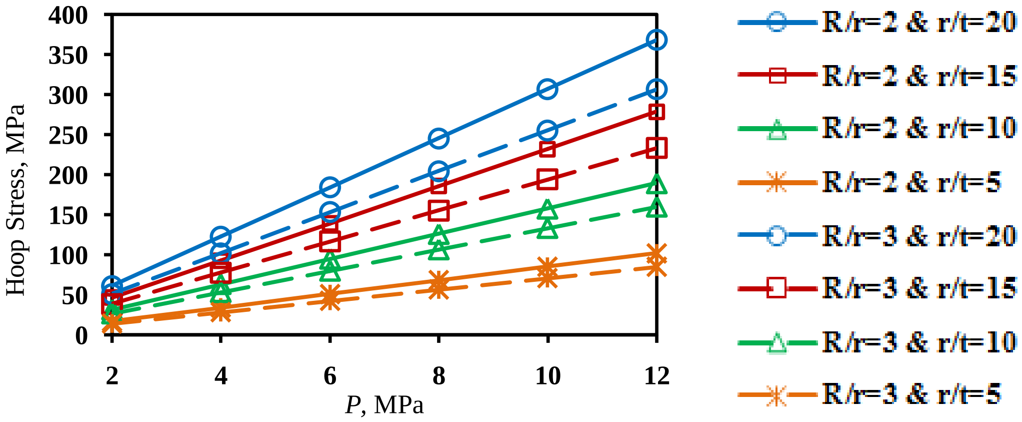


Figure 7: Hoop stress of pipe bends with circular cross section for various pressures

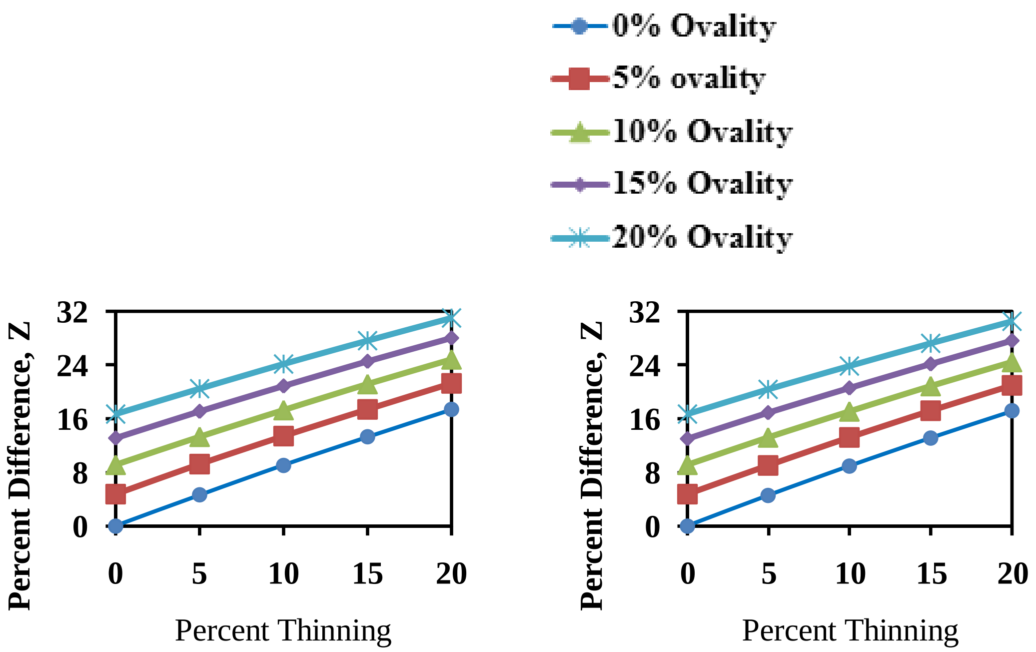
Effect of Ovality and Thinning on Hoop Stress

The effect of ovality and thinning on induced hoop stress can be observed from Figures 8 and 9. The circular cross section with uniform thickness can be termed as reference model and the models with ovality and thinning are termed as irregular models. The effects are obtained by calculating the percent differencebetween the hoop stresses of circular cross section and the cross sections with ovality and thinning as given in the formula belowin Eq. (5):

$$Z = \frac{\sigma_R - \sigma_I}{\sigma_R} \times 100 \quad (5)$$

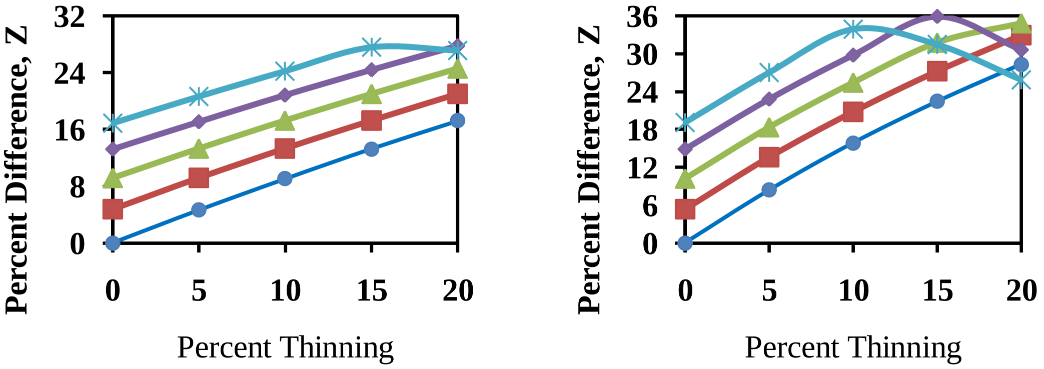
where$Z$ is the percent difference, σ_R is the hoop stress of reference model and σ_I is the hoop stress of the irregular models. The percent difference is positive when the stress value of the reference model is higher than the irregular models and vice-versa.

An interesting finding is made that there is significant effect of ovality and thinning on stress for a particular low pressure (2 MPa) and the increase of pressure does not alter the effects of ovality and thinning. Hence, the results presented in the Figures 8 and 9 are for the maximum pressure of 12 MPa.



(a) *r*/*t*=20

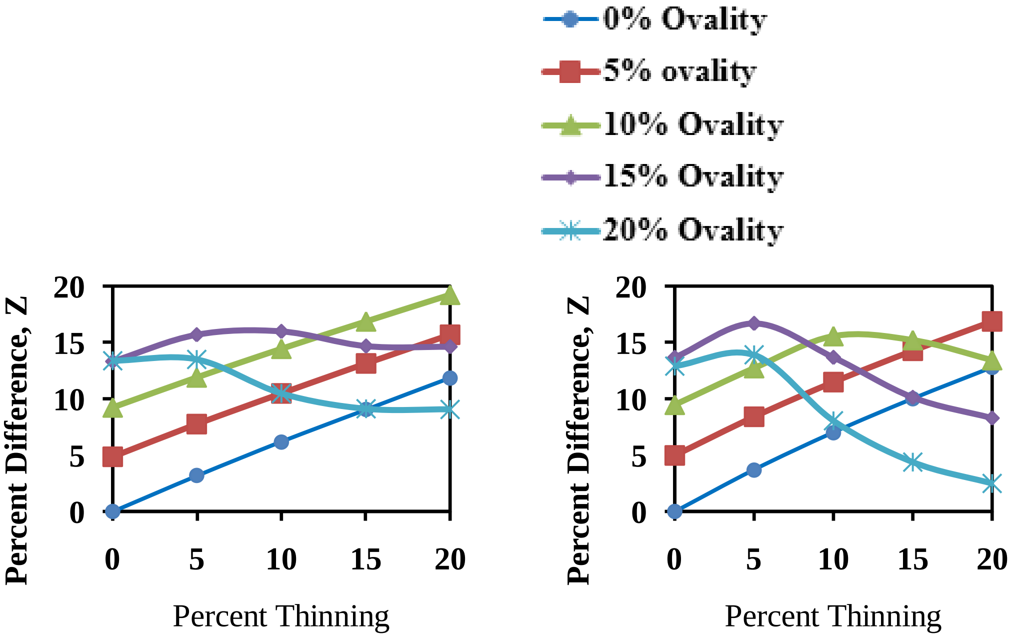
(b) *r*/*t*=15



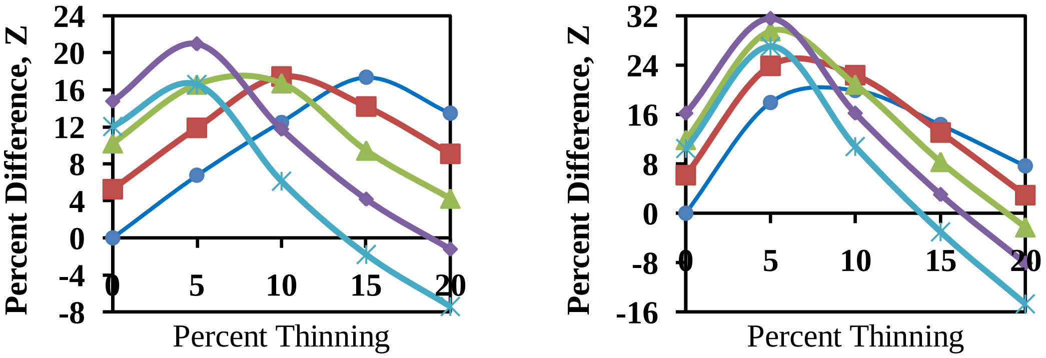
(c) *r*/*t*=10 (d) *r*/*t*=5

Figure 8: Effect of ovality and thinning on hoop stress of bends with R=100 mm for any pressure.

Figure 8 shows the combined effect of ovality and thinning on hoop stress for *R*/*r*=2, i.e., *R*=100 mm. For thin pipes, *r*/*t*=20 and *r*/*t*=15, the percent difference increases as the thinning percent is increased for any particular ovality. The percent difference is also increasing when the ovality percent is increased. But as the thickness increases, for higher ovality, the percent difference starts decreasing as the thinning is increased. The reason for the variation is that the location of the maximum hoop stress shifts from inner intrados to outer extrados as the thickness of the bend at extrados is becoming thin.



(a) *r*/*t*=20 (b) *r*/*t*=15



(c) r/t=10 (d) r/t=5

Figure 9: Effect of ovality and thinning on hoop stress of bends with R=150 mm for any pressure.

When bend radius is increased to 150 mm, for r/t=20 as shown in Figure 9a, the percent difference increases as thinning increases for up to 10 percent ovality. For 15% ovality, up to 10% thinning, the percent difference increases and then decreases. When ovality is maximum, the percent difference increases up to 5% ovality and then starts decreasing. When r/t=15 as shown in Figure 9b , the percent difference increases as the thinning is increased for up to 5% ovality, beyond which the percent difference starts decreasing as the thinning is increasing beyond 10% when ovality is 10% and it decreases as the thinning is increased beyond 5% when the ovality is increased beyond 10%. For r/t=10 and 5, as the thickness increases, for any ovality, the percent difference increases up to 5% thinning, beyond which the percent difference decreases and for few cases of higher ovality and thinning, the percent difference reaches negative value, as shown in Figs 9c and d, indicating that the hoop stress of those irregular models are higher than the reference model. Care must be taken for these cases as the percent difference exceeds the reference models. The shift of maximum hoop stress from the inner intrados to the extrados is the reason for the variation.

As per analytical formula of hoop stress, when the pipe bend is considered as torus, the maximum occurs at inner intrados for thin pipes. The finite element results of reference models agree the analytical location. But it is the effects of ovality and thinning along with the increase of bend radius and thickness causes the shift of maximum hoop stress to extrados.

Conclusions

The following are the findings of the present work:

- The effect of ovality and thinning on hoop stress of pipe bends is significant and the presence of these shape imperfections decrease the induced stress for lower bend radius and thicknesses considered indicating that the accepting limit prescribed by different codes may be reconsidered as the ovality and thinning produce positive effect.

- On the other hand, for higher bend radius and thicknesses, the presence of ovality and thinning increases the hoop stress than the circular cross section with uniform thickness indicating that care must be taken to accept the pipe bends.
- An interesting finding is that the effects of ovality and thinning are significant for a particular lower value of internal pressure and those effects are unaltered as the internal pressure is increased.
- The maximum hoop stress occurs at the inner intrados of the bend cross section for the thin pipe without initial ovality and thinning. The finite element results comply with that of the analytical hoop stress of torus bend. When ovality and thinning are included, the maximum stress shifts from intrados to extrados. This is happening for the higher thickness and higher bend radius bends.
- A general observation is that the hoop stress increases with increasing the thickness. The same is decreasing as the bend radius approaches the straight pipe. The increase of internal pressure is also increasing the hoop stress of the pipe bend.

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