ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ANALYSIS FOR FLEXIBILITY IN THE OVALITY AND THINNING LIMITS OF PIPE BENDS

A. R. Veerappan[1] and S. Shanmugam[1]
[1]Department of Mechanical Engineering, National Institute of Technology Tiruchirappalli-620015, Tamilnadu, India
E-mail: aveer@nitt.edu

ABSTRACT

Pipe bends are critical components in piping systems. In the manufacturing process of pipe bends it is difficult to avoid thickening on the intrados and thinning on the extrados. The cross section of the bend also becomes non circular due to bending process. The acceptability of pipe bends is based on the induced level of these shape imperfections. Ovality and thinning are the shape imperfections considered for the analysis. It is observed that thinning and ovality are to be taken into account together to decide the acceptability of these bends. The possible flexibility that can be introduced in the selection of ovality and thinning limits of pipe bends to reduce rejection has been suggested. A general mathematical expression relating internal pressure, shape imperfections and bend geometry is also presented.

Keywords: pipe, bends, manufacturing, ovality, thinning**,** acceptability**.**

INTRODUCTION

Pipe bends are used to convey fluid and to change the direction of the fluid flowing inside. The bend section may be a potential source of damage during service, particularly in the cases where significant ovality and wall thickness variation (thinning/thickening) exist, which are introduced during the manufacturing process. Hence the acceptability of pipe bends depends on the magnitude of these shape irregularities induced during the manufacturing process. In this paper a non dimensional parameter defining the ratio of internal fluid pressure to allowable stress is computed for tube ratio ranging from 5 to 40 and bend ratio from 1 to 5 to decide the acceptability of pipe bends. The thinning and ovality are each varied from 0% to 20% in steps of 5% in the analysis. Two specific reports of pipe bending, from an industry actively engaged in the manufacture of boiler components are analysed for their acceptability as per the codes mentioned. The allowable levels of ovality and thinning as followed by the industry in accepting the pipe bends is compared with those obtained from the present finite element analysis and the tolerance that can be allowed is presented.

DEFINITIONS

Percent ovality C_o, thinning C_t, and thickening C_{th}, are defined as follows:

$$C_o = \frac{(D_{\max} - D_{\min})}{(D_{\max} + D_{\min})/2} \times 100 \quad (1)$$

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

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

ASSUMPTIONS

The following assumptions are made in the analysis: Linear behavior, homogeneous isotropic material, and steady static state loading. The effects of the following are not considered in the present evaluation: Bourdon's effect, external pressure, external forces, external moments, centrifugal forces due to change of fluid flow direction, effects of friction between the pipe inside fluid and the pipe bend inner surface, fluid turbulence, interfaces between the straight pipe and pipe bend, tolerances and deviations of the straight pipe before fabricating into pipe bend and pipe bend surface roughness. The cross section of a pipe bend is assumed to become a perfect ellipse after bending as shown in the Figure-1 [1].

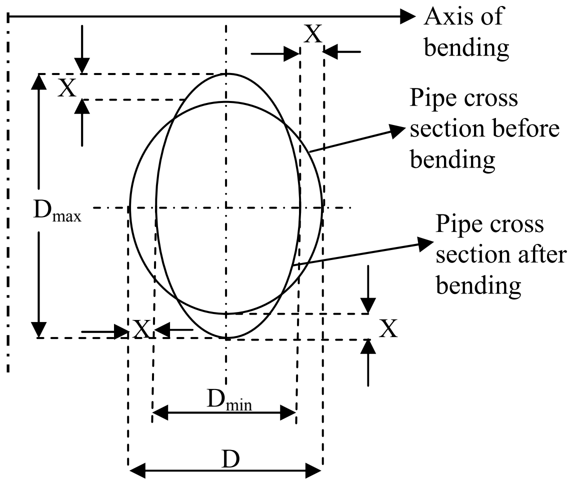

Figure-1. Pipe bend cross section before and after bending.

The major axis of the elliptical shape of pipe bend is assumed to be perpendicular to the plane of bending of the pipe bend. The minor axis of the elliptical shape of pipe bend is assumed to be in the plane of pipe bend. The pipe bend is assumed to be smooth, without ripples and flattening.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MODELING

Previous study of pipe bends has shown that when internal pressure is the only load in a 90° pipe bends, axisymmetric models provide accurate stress results, compared with those obtained from 3D models [2, 3]. Hence in the present study, an axisymmetric model is used for the FE analysis.

The cross section of the pipe before and after bending is schematically shown in Figure-1. To model the pipe bend cross section the value of X is required which can be determined as follows:

$$D_{\max} = D + 2X \quad (4)$$

$$D_{\min} = D - 2X \quad (5)$$

Substituting equation (4) and equation (5) in equation (1)

$$C_o = \frac{400X}{D} \quad (6)$$

The deviation of the pipe bend cross section for circularity can be calculated for any ovality using equation (6) and hence the maximum and minimum pipe bends diameters. Thinning at the extrados is assumed to be equal to thickening at the intrados, and accordingly the dimensions of the geometry are calculated and created in a major commercial finite element analysis [4] software code.

ANALYSIS

The following summarize the acceptability criteria [5] used to evaluate the results of finite element stress analysis:

$$P_m < k\,S_m \quad (7)$$

$$P_m + P_L < 1.5\,k\,S_m \quad (8)$$

$$P_m + P_L + P_b < 1.5\,k\,S_m \quad (9)$$

$$P_m + P_L + P_b + Q < 3\,S_m \quad (10)$$

$$P_m + P_L + P_b + Q + P_F < 2\,S_a \quad (11)$$

In the case of pipe bends with internal pressure, the local membrane stress P_L is absent. Hence equation (8) is not applicable. As the stresses induced due to internal pressure in pipe bends is primary in nature, the stress Q is absent. Hence equation (10) is not applicable. As the pipe bend considered is subjected to 10 000 fatigue load cycles, the allowable range of fatigue stress intensity = 2 x S_a = 2 x 275 = 550 MPa. This is never governing in the present stress analysis. Hence equation (11) is not governing.

Hence in the present analysis it is required to consider equation (7) and equation (9) only.

Using the above acceptability criteria, the non-dimensional parameter - P/S_m are calculated as illustrated below for different tube ratio ranging between 5 and 40 and bend ratio from 1 to 5.

Since k = 1 for normal loads, from equation (7),

$$P_m < S_m \quad (12)$$

Multiplying equation (12) by P and then rearranging it to obtain

$$\frac{P}{S_m} < \frac{P}{P_m} \quad (13)$$

Substituting P_L = 0 into equation (9),

$$P_m + P_b < 1.5 S_m$$

$$S_m > \frac{(P_m + P_b)}{1.5}$$

$$\frac{P}{S_m} < \frac{1.5P}{(P_m + P_b)} \quad (14)$$

A program is written which creates the models with various combinations of and thinning/thickening from 0% to 20 % in steps of 5%, constraint the models in the Y-direction, applies the internal pressure load and solves the problem. The data obtained such as membrane, bending and peak stress intensity values at intrados, neutral and extrados sections are written into an Excel file. The program also calculates the P/S_m value and writes it into another Excel file. A model calculation for P/S_m is presented in the next section.

SAMPLE CALCULATION FOR COMPUTATION OF P/S_m

C_t = 10%, C_o = 10%, R/D = 1, D/t = 5

At intrados

$$\text{Ratio } R_1 = \frac{P}{P_{im}} = \frac{10}{20.85} = 0.4796$$

$$\text{Ratio } R_2 = \frac{1.5\,P}{(P_{im} + P_{ib})} = \frac{1.5 \times 10}{(20.75 + 3.78)} = 0.609$$

$$\text{Ratio } R_i = \text{ minimum}(R_1, R_2) = 0.4796$$

At neutral section

$$\text{Ratio } R_3 = \frac{P}{P_{nm}} = \frac{10}{16.97} = 0.5893$$

$$\text{Ratio } (R_4) = \frac{1.5P}{(P_{nm} + P_{nb})} = \frac{1.5 \times 10}{(16.97 + 18.78)} = 0.4196$$

$$\text{Ratio} (R_n) = \text{ minimum}(R_3, R_4) = 0.4196$$

At extrados

$$\text{Ratio} (R_5) = \frac{P}{P_{om}} = \frac{10}{17.79} = 0.5621$$

VOL. 3, NO. 1, FEBRUARY 2008 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

$$\text{Ratio}\left(R_6\right)=\frac{1.5P}{\left(P_{om}+P_{ob}\right)}=\frac{1.5\times 10}{\left(17.79+4.86\right)}=0.6623$$

$$\text{Ratio } R_o = \text{minimum}\left(R_5, R_6\right)=0.5621$$

$$\frac{P}{S_m}=\frac{P}{P_m}=\frac{1.5P}{\left(P_m+P_b\right)}=\text{minimum}\left(R_i, R_n, R_o\right)=0.4196$$

CORRELATION

Using artificial neural networks, which are the most powerful computer modeling techniques for modeling complex relationship, an end result is obtained to determine the allowable pressure in a pipe bend in terms of its ovality, thinning, tube ratio and bend ratio. The computer program was performed under MATLAB environment using the neural network toolbox. The data obtained from ANSYS for P/S_m are 1000 of which 750 data were used for training purpose while the remaining were randomly selected and used as test data. The configuration 4-9-1 appeared to be optimal for this application.

$$A1=[-3.2238c_t+10.9126c_o-0.5763/R_b+1.4177/R_t+0.1301] \quad (15a)$$

$$A2=[-5.1509c_t-24.0502c_o+2.3961/R_b+40.3502/R_t-7.7964] \quad (15b)$$

$$A3=[-0.038c_t+1.1433c_o-0.4799/R_b-7.5912/R_t+1.4347] \quad (15c)$$

$$A4=[6.2865c_t+12.3355c_o-2.5642/R_b-21.1379/R_t+5.9412] \quad (15d)$$

$$A5=[0.291c_t-6.0057c_o+9.7148/R_b+17.6119/R_t-2.7595] \quad (15e)$$

$$A6=[2.4503c_t+10.9596c_o-1.6985/R_b-4.6081/R_t-0.0518] \quad (15f)$$

$$A7=[-3.2197c_t+10.8827c_o-0.5782/R_b+1.4446/R_t+0.1323] \quad (15g)$$

$$A8=[3.3709c_t+7.3663c_o-1.6223/R_b+7.7858/R_t+0.12] \quad (15h)$$

$$A9=[1.2767c_t+1.1608c_o-2.693/R_b-20.4469/R_t+4.6447] \quad (15a)$$

$$\frac{P}{S_m}=\tanh(A+B) \quad (16)$$

where

$$A=-12.705\boldsymbol{A1}+0.062\ \boldsymbol{A2}-0.285\ \boldsymbol{A3}+0.081\ \boldsymbol{A4}+0.004\ \boldsymbol{A5}$$

$$B=-0.056\boldsymbol{A6}+12.7439\boldsymbol{A7}+0.0638\boldsymbol{A8}+0.042\boldsymbol{A9}+0.1645$$

$$\frac{C_t}{100}=c_t,\ \frac{C_o}{100}=c_o,\ \frac{R}{D}=R_b,\ \frac{D}{t}=R_t.$$

The average error and standard deviation in using equation (16) are 3.33% and 3.05% respectively.

ANALYSIS OF SPECIFIC EXAMPLES

Two specific examples of pipe bending reports as specified in Table-1 were considered to evaluate the procedure that was adopted to accept these bends.

Table-1

Pipe parameters	**Example I**	**Example II**
Pipe material	SA106 Gr B	
Pipe internal pressure	10 MPa	
Pipe outside diameter	50.8 mm	60.8 mm
Pipe nominal thickness	6.35 mm	4.5 mm
Pipe bend radius	75 mm	250 mm
Bend angle	90°	
Elastic modulus	178964 MPa	
Percent ovality	6.79	5.2
Percent thinning	4.34	14.08
Poisson’s ratio	0.3	

Example 1

The ovality limit specified by the industry is 10% maximum while the allowable thinning is calculated as 5.38% maximum allowable by applying the formula

$$C_t=\frac{100}{\left(\frac{4R}{D}+2\right)} \quad (18)$$

The ovality introduced in this case is 6.79% and thinning is 4.34%. The allowable pressure ratio obtained from analysis is 0.114 which indicates that the pipe bend can allow more than 10 MPa pressure. The allowable ovality is 10% and since it is only 6.79% in the present case, 5.38% thinning allowable can always be increased as can be observed from Figure-2. When the ovality induced is 6.79%, allowable pressure ratio of 0.115 can be obtained with 5% thinning, 0.113 with 10% and 15% thinning and 0.112 with 20% thinning. Hence lesser control on thinning is sufficient since all these values of allowable pressure are greater than that for the code allowable ovality of 10% and thinning of 5.38% which is only 0.093. An allowable pressure of 0.120 can be achieved with 6.79% ovality and 5.38% thinning.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

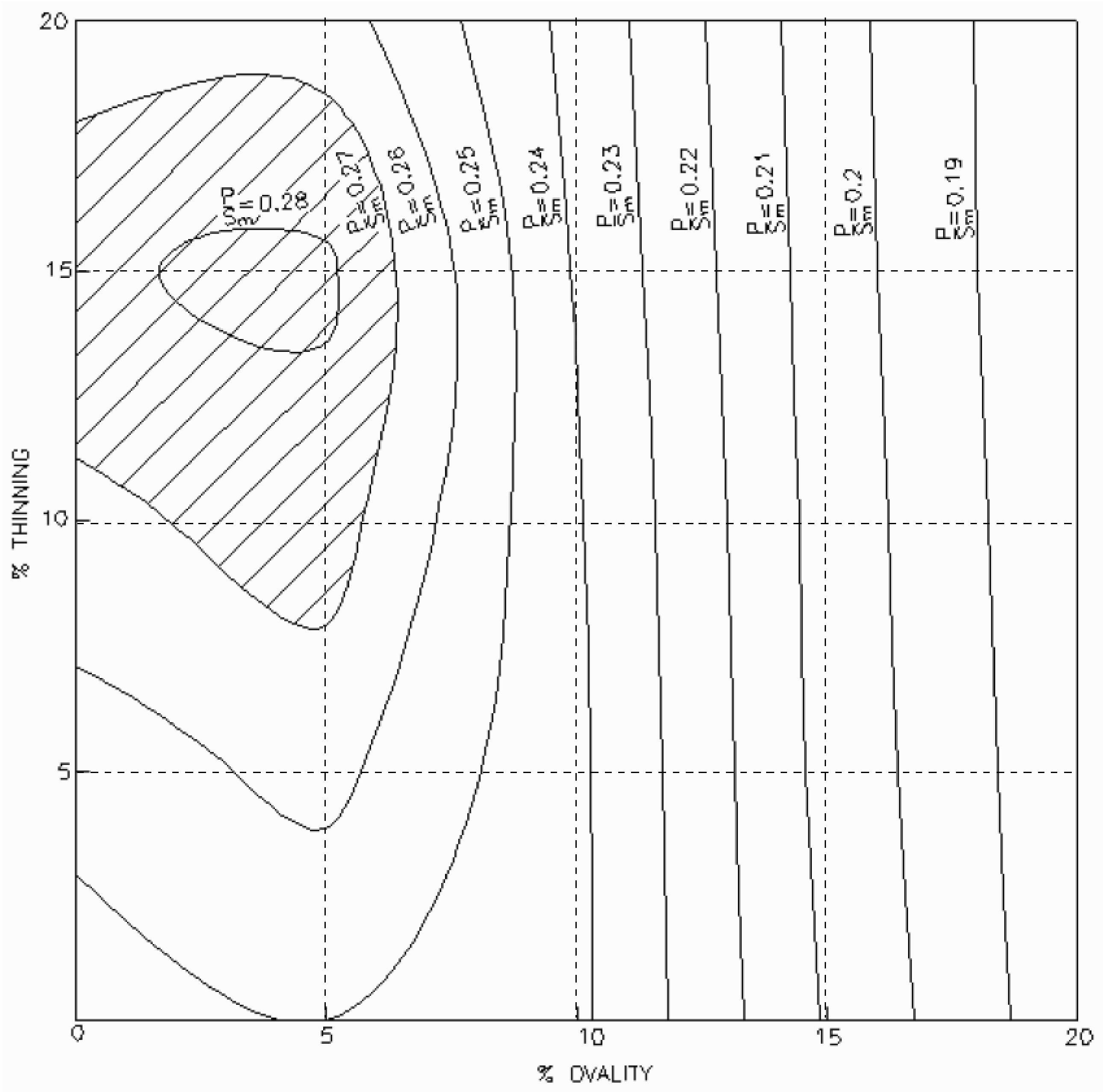

Figure-2. Variation of constant pressure ratio with shape imperfections for example-1.

Example 2

The ovality induced in the manufacturing process is 5.2% and while the induced thinning is 14.08%. The allowable pressure ratio in this case is 0.285. For 10% ovality and 12.65% thinning allowable as per the industry, the allowable pressure ratio obtained from the analysis is 0.240. Since the ovality introduced in this case is only 5.2%, the thinning allowable can be more. The limit of 0.240 allowable pressure ratio can also be achieved with ovality and thinning combinations of 10.5% and 0%, 10.3% and 5%, 10.2% and 10%, 9.6% and 15%, and 9.3% and 20% (Figure-3).

To validate equation (16) that was obtained using artificial neural network, the geometric parameters of the specific examples discussed above were substituted into equation (16) and the allowable pressure ratio obtained for 10% ovality and 10% thinning was checked with that obtained from FEM.

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

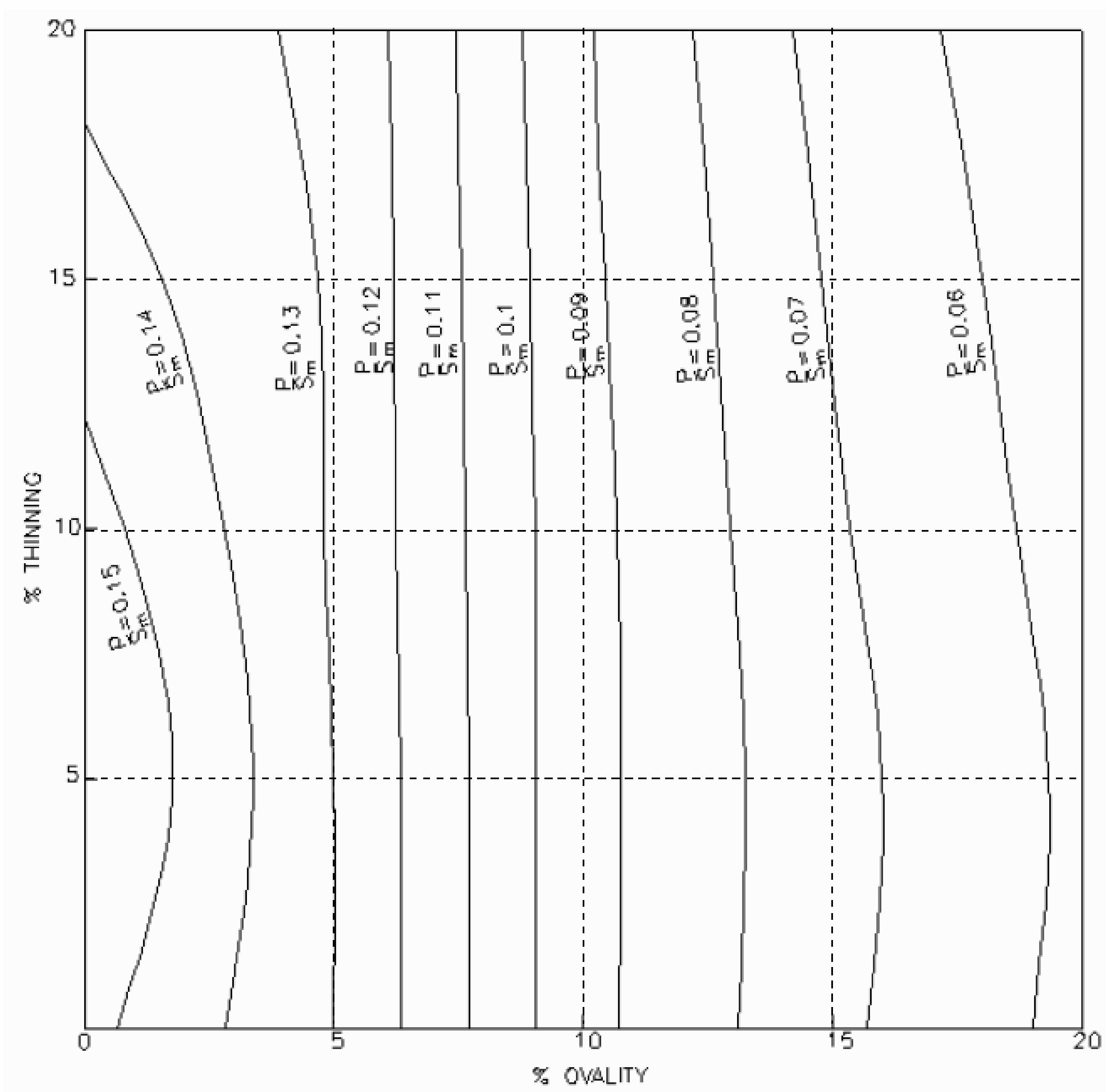

Figure-3. P/S_m curves for example-2.

Example-1

$$\frac{D}{t} = 8,\ \frac{R}{D} = 1.4764,\ C_t = 10\%,\ C_o = 10\%$$

Using Eq. (16), the values of A_1 to A_9 were obtained as

A_1	A_2	A_3	A_4	A_5
0.5952	-0.9994	0.2647	0.9979	0.99996

A_6	A_7	A_8	A_9
-0.4116	0.5966	0.7886	0.4684

These values were substituted in equation (16) and the value of allowable pressure obtained was 0.241 which is equal to that obtained using FEM (Table-2).

VOL. 3, NO. 1, FEBRUARY 2008 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

If you are interested to read about Table-2 (Allowable pressure ratio for example-1) then, please **Click here**

Blank Page

Example-2

$$\frac{D}{t} = 13.51, \ \frac{R}{D} = 4.1118, \ C_t = 10\%, \ C_o = 10\%$$

Using equation (16), the values of A_1 to A_9 were obtained as

A_1	A_2	A_3	A_4	A_5
0.69819	-1	0.699654	0.999973	0.323287

A_6	A_7	A_8	A_9
0.489211	0.699008	0.879933	0.991359

These values were substituted in equation (16) and the value of allowable pressure obtained was 0.093 which is equal to that obtained using FEM.

PRESSURE RATIO PLOT

A graph is plotted for the allowable pressure taking ovality along x-axis and thinning along y-axis. The points with same allowable pressure values are joined by smooth curve to obtain constant P/S_m curves (Figures-2 and 3). Taking the P/S_m value of 0.270 in Figure-2, a point bearing this magnitude lies between the pairs of points (0, 10) (0, 15); (0, 10) (5, 10); (5, 5) (5, 10); (5, 10) (10, 10); (5, 15) (10, 15); (5, 15) (5, 20); (0, 15) (0, 20). These points are located to a suitable scale and joined by a smooth curve to obtain the constant allowable pressure curve of magnitude 0.270. Similarly all other constant P/S_m curves are obtained. The plot of constant pressure ratio which is useful in analysing the possibility of introducing flexibility permissible levels of ovality and thinning in pipe bend is explained in the next section.

RESULTS AND DISCUSSIONS

It can be seen from Figure-2 that an island is obtained with a constant pressure ratio (0.280) boundary. In this case the bends made can have any value of pressure ratio in the area bounded by the pressure ratio of 0.280. The minimum and maximum ovality that a bend can have is 2% and 5.2% and the corresponding thinning are 15%. The minimum and maximum thinning are 13.6% and 15.5% and the corresponding ovality are 4.8% and 3.9%.

It can also be seen from the Figure-2 that the area enveloped by constant pressure ratio becomes larger and larger as the pressure ratio is smaller and smaller. If the pressure ratio obtained as per codes for determining permissible ovality and thinning is 0.270, the possible combination of ovality and thinning a bend can have is any point in the shaded area (Figure-2).

From the Figure-2, the constant pressure ratio line is almost straight from the pressure ratio 0.220. The area lying on the left of this curve offers as much number of combinations of ovality and thinning as the numbers of coordinate points lie in the area.

Also, as the ovality measured is less than the calculated value, it is evident from the Figure-2 the pressure ratio increases. This ovality can still be accepted provided the corresponding point of thinning should lie in the shaded area or inside the area on the left of the constant pressure ratio line.

In this case the fluid pressure can be higher. This means that the fluid can be admitted at a higher pressure than the designed one. Though the design will not be conservative yet the bend will withstand higher fluid pressure. In other words, there will be less rejection of pipe bends. In order to make the design economical, the combinations of ovality and thinning will have to be so chosen that the pressure ratio should be exactly equal to the design pressure ratio. Here, the quality control should be very stringent which will obviously lead to more number of rejections of pipe bends.

Figure-3 shows the constant pressure ratio variation with different combinations of ovality and thinning when the bend ratio is 4.1118 and tube ratio is 13.5111. The constant pressure ratio lines straighten beyond the pressure ratio of 0.140. An increase in ovality causes generally a very rapid decrease in thinning at a constant pressure ratio.

Figure-4 shows the dependence of P/S_m on thinning and ovality with varying tube ratio when bend ratio is 5. As tube ratio increases from 5 to 40 the difference in pressure ratio becomes progressively smaller. There is insignificant change in pressure ratio beyond tube ratio of 20. The pressure ratio increases as thinning is increased at a particular ovality.

Figure-5 shows the influence of bend ratio on P/S_m with a constant tube ratio of 10. When the bend radius is equal to tube diameter, the pressure ratio increases up to 10% ovality and then starts decreasing while for bend ratio of 2, the pressure ratio decreases after 5% ovality. Beyond bend ratio of 2, the pressure ratio decreases. Similar trend is observed for tube ratio of 15. When tube ratio is 5, the pressure ratio is observed to change direction at 5% ovality irrespective of percent thinning.

When tube ratio increases beyond 15, the pressure ratio increases up to 15% ovality for 0% and 5% thinning with bend radius equals pipe outside diameter (Figure-4). As thinning is further increased, after 10% ovality the pressure ratio decreases. At bend ratio of 2, the pressure ratio increases up to 5% ovality for all thinning (Figure-5). Further increase in bend ratio causes pressure ratio to decrease. This trend has been observed for tube ratio is equal to 25 and beyond.

Using the parametric relation (equation (16)), the values of P/S_m are obtained after substituting the measured values of ovality, thinning and bend radius of the pipe. This is equal to, say; Pr. The value of S_m can be taken from the material specification. Now the fluid pressure (Pc) is calculated using Pc/S_m = Pr. If $P \leq Pc$, the bend made can be accepted otherwise rejected. A wide range of Pc can be obtained as the value of Pr is different for different combinations of ovality, thinning, etc. The ovality and thinning need not be obtained from codes.

Alternatively, if the values of ovality and thinning are obtained using codes as permissible ovality and thinning, the allowable pressure ratio can be obtained

VOL. 3, NO. 1, FEBRUARY 2008 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

from these values of ovality and thinning using the equation (16). These values could lead to think that the actual value of ovality and thinning, measured after a bend is made, can lie below the permissible values. In fact this is not so for all allowable pressure ratios and bend ratios. There can be a certain case of bend whose permissible pressure ratios limit the scope of getting wider ovality and thinning.

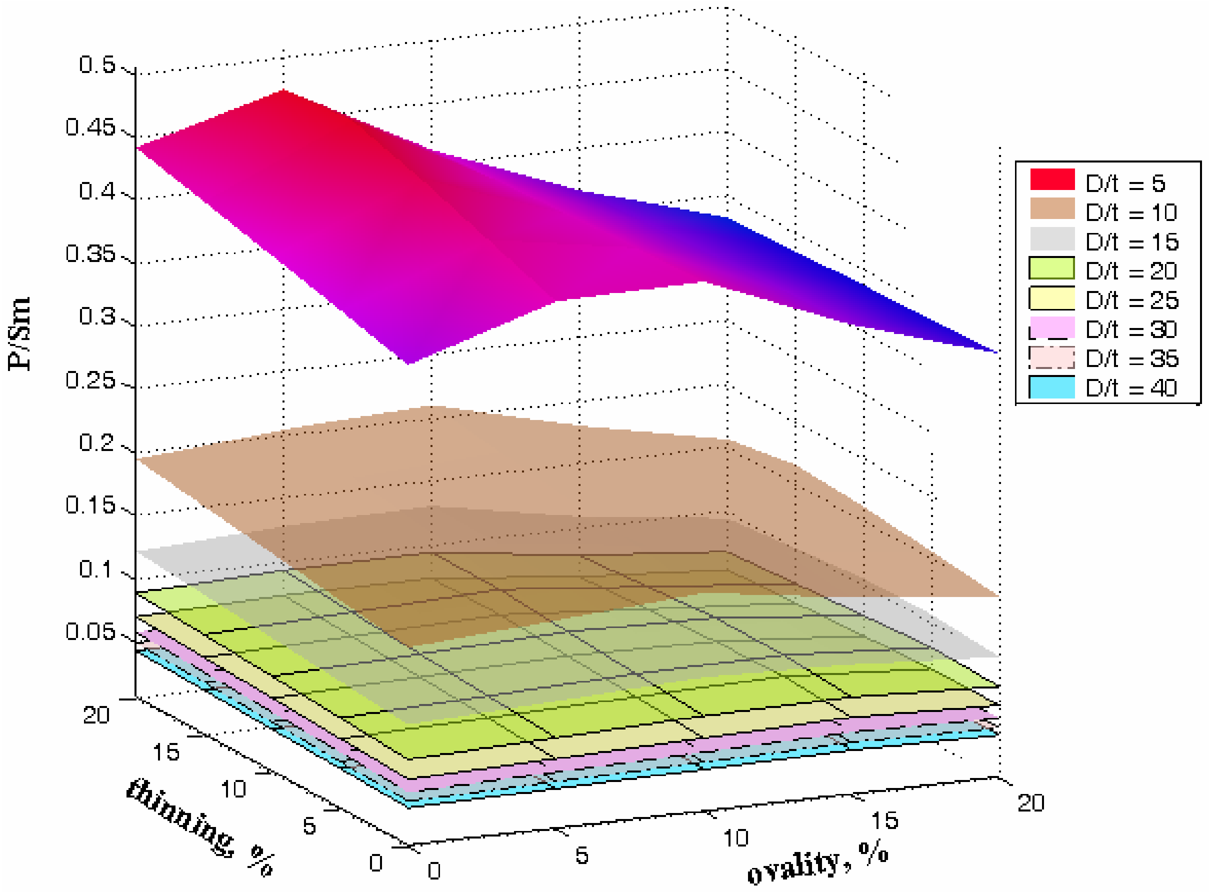

Figure-4. Dependence of allowable pressure on shape irregularities.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

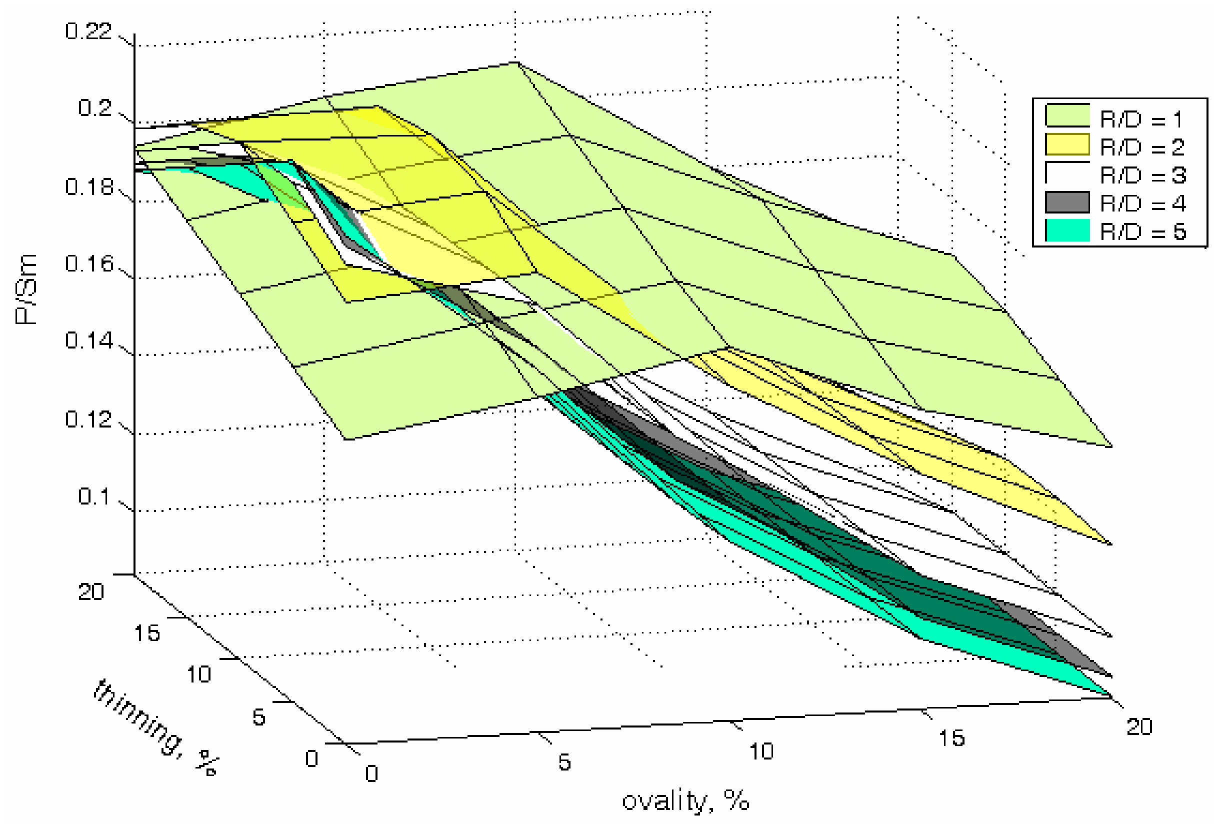

Figure-5. Variation of allowable pressure with D/t = 10 for different bend ratios.

CONCLUSIONS

The following are the major conclusions that could be drawn from the analysis of dependence of allowable pressure ratio of the pipe bend on bend ratio, tube ratio, ovality and thinning:

- There are more than one values of ovality and thinning for a pipe bend manufactured, which would reduce rejection of pipe bends after they have been made.
- Given the values of ovality and thinning of pipe bend, it can be checked whether the bend can withstand the designed pressure.
- A mathematical relationship among the pressure ratio, ovality, thinning, tube ratio and bend ratio is presented which simplifies the problem of solving complex differential equations.

NOMENCLATURE

C_o	: per cent ovality
C_t	: percent thinning
C_{th}	: percent thickening
D	: pipe outside diameter, mm
D_{max}	: maximum outside pipe diameter, mm
D_{min}	: minimum outside pipe diameter, mm
E	: elastic modulus, MPa
k	: occasional load factor
N	: number of fatigue load cycles during the plant life
Nu	: Poisson's ratio
P	: pipe internal pressure, MPa (g)
P_b	: average bending stress intensity across the thickness, MPa
P_F	: peak stress intensity, MPa
P_L	: local membrane stress intensity across the thickness, MPa
P_m	: average membrane stress intensity across the thickness, MPa
Q	: secondary stress intensity, MPa
R	: bend radius to neutral axis, mm
S_a	: allowable amplitude of stress intensity for *N* fatigue load cycles, MPa
S_m	: allowable stress intensity, MPa
Suffix i	: intrados
Suffix n	: neutral section
Suffix o	: extrados
T	: pipe design temperature, ° C
t	: nominal thickness of pipe bend, mm
t_{max}	: maximum pipe thickness, mm
t_{min}	: minimum pipe thickness, mm
θ	: pipe bend angle, degrees

REFERENCES

Mohindar L. Nayyar. 2000. Piping Handbook, 7th Ed., McGraw-Hill. p A 269.

Hyde, T.H., Yaghi, A., Becker, A.A. and Earl, P. G. 1999. Comparison of toroidal pipes and 90° pipe bends during steady state creep analysis. Proceedings of the Fifth International Colloquium on Ageing of Materials and Methods for the Assessment of Lifetimes of Engineering Plant, Cape Town. pp. 305-317.

Hyde, T.H., Becker, A.A., Sun, W., Williams, J.A. 2005. Influence of geometry change on creep failure life of 90° pressurised pipe bends with no initial ovality. International Journal of Pressure Vessels and Piping. 82: 509-516.

ANSYS Inc. 2003. Theory reference. Canonsburg, PA.

ASME. 2004. ASME Boiler and Pressure Vessel Code: Rules for Construction of Pressure Vessels, Section VIII, Division 2-Alternative Rules, ASME, New York. p. 266.