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COLLAPSE LOAD OF PIPE BENDS WITH ASSUMED AND ACTUAL CROSS SECTIONS UNDER IN-PLANE AND OUT-OF-PLANE MOMENTS

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ABSTRACT

The finite element nonlinear limit analysis compares the four cross sections to include the effect of ovality and thinning on collapse load of pipe bends when subjected to in-plane and out-of-plane bending moments with and without internal pressure. The assumed cross sections namely elliptic and semi-oval and the actual cross sections are compared with circular cross sections. A new methodology is proposed to use actual cross section in the finite element analyses. The comparison reveals that the actual cross section produces a positive effect of increasing the collapse load for lower bend radii and the assumed cross sections produces minimal effect and hence circular cross section may be assumed. For the highest bend radius, actual cross section is preferable as the percent difference is higher than other cross sections for low pressures. In all the pipe bend models and loading, when the pressure is high, the effect of ovality is very less and hence circular cross section may be assumed.

Keywords: limit analysis, ovality, thinning, collapse load, in-plane, out-of-plane moment.

INTRODUCTION

Pressurized piping system is widely used in many industries particularly in power plants. Pipe bends are used to change the direction of the flow and it is considered as one of the critical components in the piping systems due to its flexibility. Pipe bends are made by bending process. As the pipe is being bent, external wall of pipe is stretched and the thickness is decreased and this phenomenon is called as thinning. Simultaneously, interior surface of wall is compressed and wall thickness increases and it is known as thickening. Because of the bending process the circular cross section is deviating from circularity and it is termed as ovality.

The finite element limit analysis is popular to determine the collapse load (the moment at which the pipe bend fails) of the pipe bends. The loading cases causing the bend structure to collapse are in-plane closing and opening bending and out-of-plane bending moments with or without internal pressure. From the literature, it is found that, almost all analytical and numerical studies on pipe bends to determine plastic loads 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. Therefore, it is more relevant to include ovality and thinning in the analysis of pipe bends. The existing works in the literature assumes elliptic [1-3] and semi-oval [4] cross-sections to include ovality in the analysis of pipe bends.

The effect of shape imperfections, particularly, ovality on collapse load is significant [5-8]. Therefore it is important to include shape imperfections in the limit analysis of pipe bend and also reduce the assumptions in the geometry to bring in reality to the analysis.

The purpose of the project is to reduce the assumptions in the finite element limit analysis of shape-imperfect pipe bends. A new methodology is introduced to reduce the assumptions. The collapse loads of the pipe bends modelled with assumed and actual cross sections will be compared.

FINITE ELEMENT LIMIT ANALYSIS

Modelling procedure

Proposed new methodology with actual cross section

Four pipe bends with same thickness, pipe radius and bend angle and different bend radii which passed the First-off-Trial (FOT) test has been chosen for the present work. Table 1 shows the different dimensions of pipe bend chosen for the present work.

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Table-1. Dimensions of different pipe bends (Courtesy, GB Engineering).

Model number	**Diameter** (mm)	**Thickness** (mm)	**Bend radius** (mm)	**Angle of bend**	**Ovality** (%)	**Thinning** (%)
1	51	5	31.75	180°	1.9	14.7
2	51	5	38	180°	6.7	9.28
3	51	5	95.25	180	8.5	9.5
4	51	5	121	180°	4.7	8

The pipe bend is cut at the mid-section. The mid-section impression of the pipe bend is taken on graph sheet to calculate the ovality and thinning during FOT test is shown in Figure-1. The JPEG file of graph sheet (impression of the cross section) is imported into SOLIDWORKS software [9] using 'Sketch Tool' option and change the aspect ratio of graph sheet to original size of graph to get the original size of the mid-section impression of pipe bend. The 'Spline' command is used to trace the inside and outside diameter of pipe bend. The IGES file of the traced profile is imported into CATIA V5 software [10] for 3D modelling. The traced actual cross section is placed at the mid plane and the circular cross sections are placed in their respective end planes to obtain the real pipe bend geometry as shown in Figure-2. The length of straight pipe is kept 5 times of pipe diameter [5].

Figure-1. Cross section impression of FOT test.

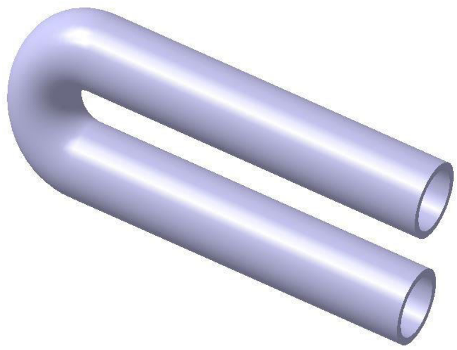
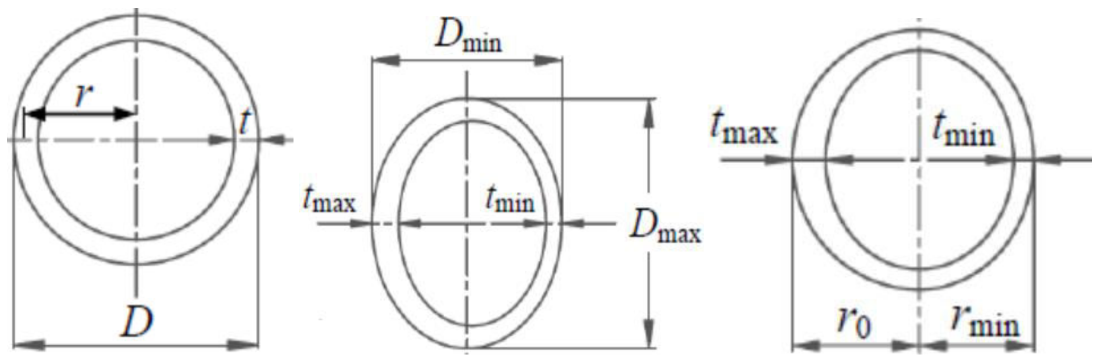


Figure-2. Isometric view of 180° pipe bend.



(a) Circular (b) Elliptic (c) Semi-oval

Figure-3. Assumed cross sections.

Existing methodology with assumed cross sections

The finite element limit analyses assumes the cross sections to be circular with uniform thickness, elliptic and semi-oval with variation in thickness as shown in Figure-3. The circular cross section was modelled with the radius and thickness given in Table-1. The elliptic and semi-oval cross sections were modelled with the required ovality and thinning given Table-2 based on the definition of ovality and thinning [5]. The t_{max} and t_{min} are same for the elliptical and semi-oval cross-section of pipe bend.

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Table-2. Dimensions for elliptic and semi-oval cross section.

Bend radius (mm)	**Shape**	$\mathbf{D_{max}}$(mm)	$\mathbf{D_{min}}$(mm)	**t** (mm)	$\mathbf{t_{max}}$(mm)	$\mathbf{t_{min}}$(mm)
31.75	Elliptical	51.48	50.52	5	5.74	4.27
	Semi-oval	51	50.03	5		
38	Elliptical	52.17	49.29	5	5.46	4.54
	Semi-oval	51	47.58	5		
95.25	Elliptical	53.17	48.83	5	5.48	4.53
	Semi-oval	51	46.67	5		
121	Elliptical	52.20	49.80	5	5.4	4.6
	Semi-oval	51	48.60	5		

FINITE ELEMENT MODELLING

The finite element modeling is same for both actual and assumed cross-sections.

The material used for the finite element analysis of pipe bend is Type 304 Stainless Steel [5]. The material properties of stainless steel as given below:

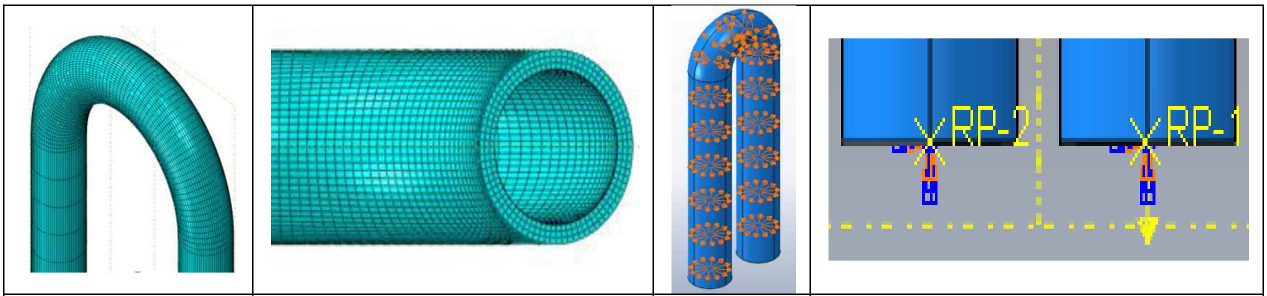
Table-3. Material properties.

Young's Modulus	**193 GPa**
Yield stress	271.93 MPa
Poisson's Ratio	0.2642

The material is assumed to be isotropic and elastic-perfectly-plastic.

The element type used for the non-linear finite element analysis of pipe bend is C3D20R, three dimensional 20 nodes, reduced integration with hourglass effect quadratic element. A detailed mesh study was performed on all the four models and optimum number of elements for *R*=31.75 mm and *R*=38 mm is 6000 and for other two cases the number of elements is 21600.

One end of the straight pipe is fixed and the bending moment is applied as rotation at the other end using a multi-point constraint node where end surface nodes are connected. When internal pressure is included in the analysis, it is defined at the inner surface of the pipe bends as distributed load as shown in Figure-4(c). An axial tension equivalent to internal pressure is also applied at the end of the pipe where rotation is applied as shown in Figure-4(d).



(a) (b) (c) (d)

Figure-4. Mesh density of pipe bend and boundary conditions.

VALIDATION

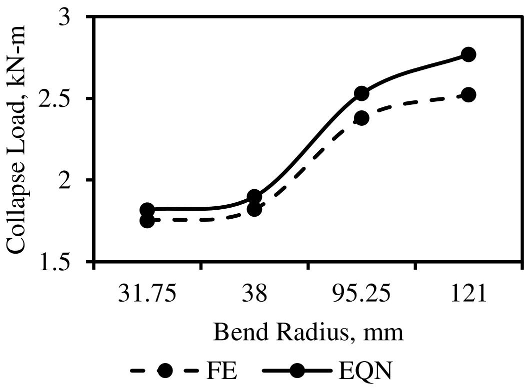


Figure-5. Validation of collapse loads.

The validation is carried out using circular cross section by applying in-plane closing moment on 90˚ pipe bend to find the collapse load. The FE and mathematical equation results are compared for validation purpose. The maximum difference of collapse load is found to be 8% as shown in Figure-5. The Eq. (1) [11] used to find the collapse load is given below:

$$\frac{M_0}{M_0^S} = A_c(\lambda + k_c)^{n_c} \quad (1)$$

with, $A_c = 0.800\left(\frac{r}{t}\right)^{-0.017}$; $k_c = 1.460\left(\frac{r}{t}\right)^{-0.911}$; $n_c = 0.423\left(\frac{r}{t}\right)^{0.127}$

RESULTS AND DISCUSSIONS

Four pipe bends models of different bend radius are analyzed using actual, circular, semi-oval and elliptical cross-sections (c/s). For each pipe bend, in plane (closing and opening) moment and out-of-plane moment are applied to obtain the collapse load of pipe bends. For all bending moment cases, pressure is varied from 0 MPa to 10 MPa with the increment of 2 MPa and an axial force equivalent to pressure is also applied. Therefore, a total of 288 cases are analyzed. For these cases the moment-rotation curves are generated through finite element ABAQUAS software [12]. From the moment-rotation curves, the collapse load is obtained using twice-elastic-slope method [11] which is preferred by ASME code [13]. The percent difference for all bend radii with different cross sections is calculated. The circular cross section is chosen as the standard/reference cross section for calculation of percent difference of collapse load.

In-Plane closing moment

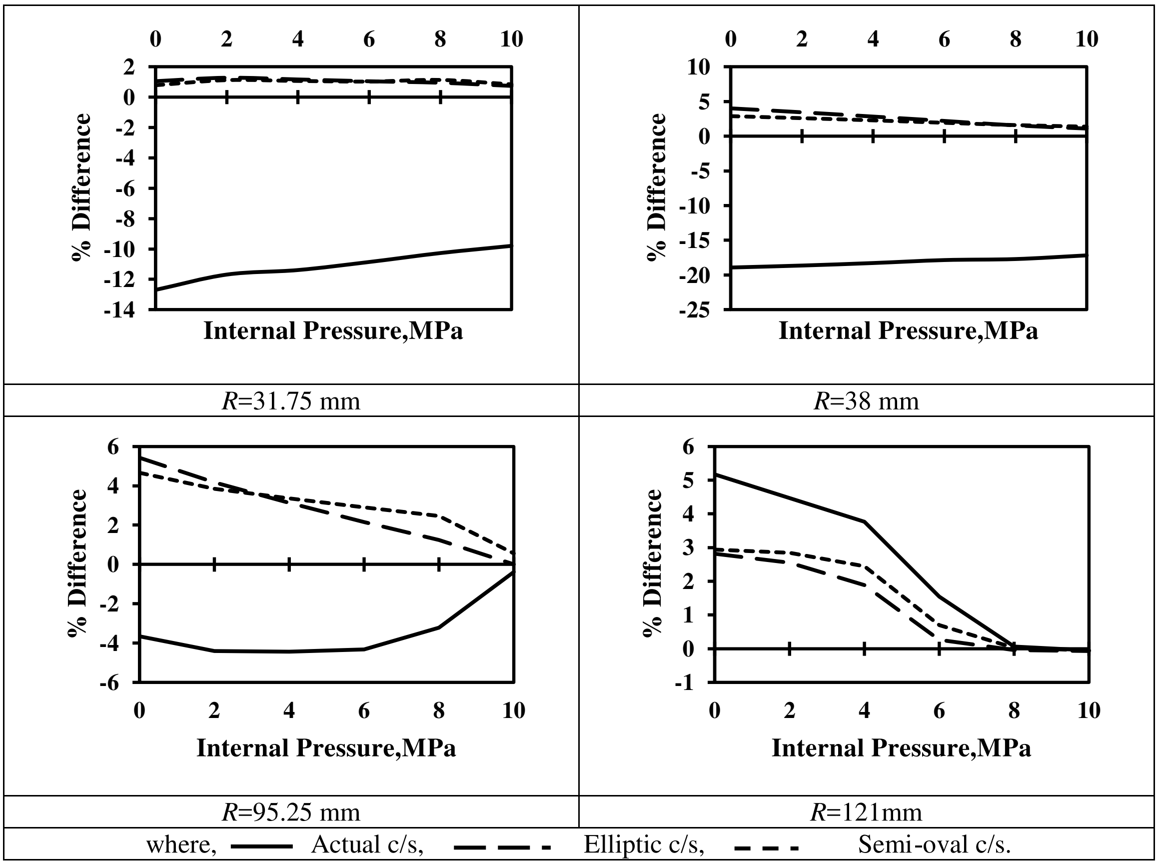


Figure-6. Percent difference of collapse load for in-plane closing moment.

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From Figure-6(a) to (c), for up to *R*= 95.25 mm, it is observed that the collapse load of actual cross section is higher than the circular cross section and it is advantageous to the pipe bend. For *R*=121 mm, as shown in Figure-6(d) the percent difference of actual cross section is higher than the other cross sections and hence the design of pipe bend for higher bend radii must consider the actual cross section to determine the collapse load, particularly for low pressures. Elliptic and semi-oval cross sections do not influence much on the bends with *R*=31.75 and 38 mm and therefore, circular cross section may be assumed for the analysis. When the bend radius *R*=95.25 mm, for low pressures, elliptic cross section is preferable as the maximum percent difference 5.4 %. It is also observed from Figure-6 that for high pressures, the effect of shape imperfections are very minimal and hence circular cross section can be assumed. Similar trend is observed for in-plane opening bending moment loading.

Out of plane moment

The similar trend of in-plane closing and opening bending moment is realized for the out-of-plane bending loading as well for the bend radii *R*=31.75 and 38 mm as shown in Figure-7(a) and (b). Hence, circular cross section may be assumed for the finite element analyses as the effect of ovality and thinning is minimal and the actual cross section produces positive effect by increasing the collapse load. For *R*=95.25 mm, the semi-oval cross section produces more effect and the percent difference is within 1.6 % and hence the effect of ovality and thinning need not be considered. For lower pressures, the percent difference of actual cross section is higher and hence the finite element analysis must include actual cross section for the highest bend radius considered as shown in Figure-7(d).

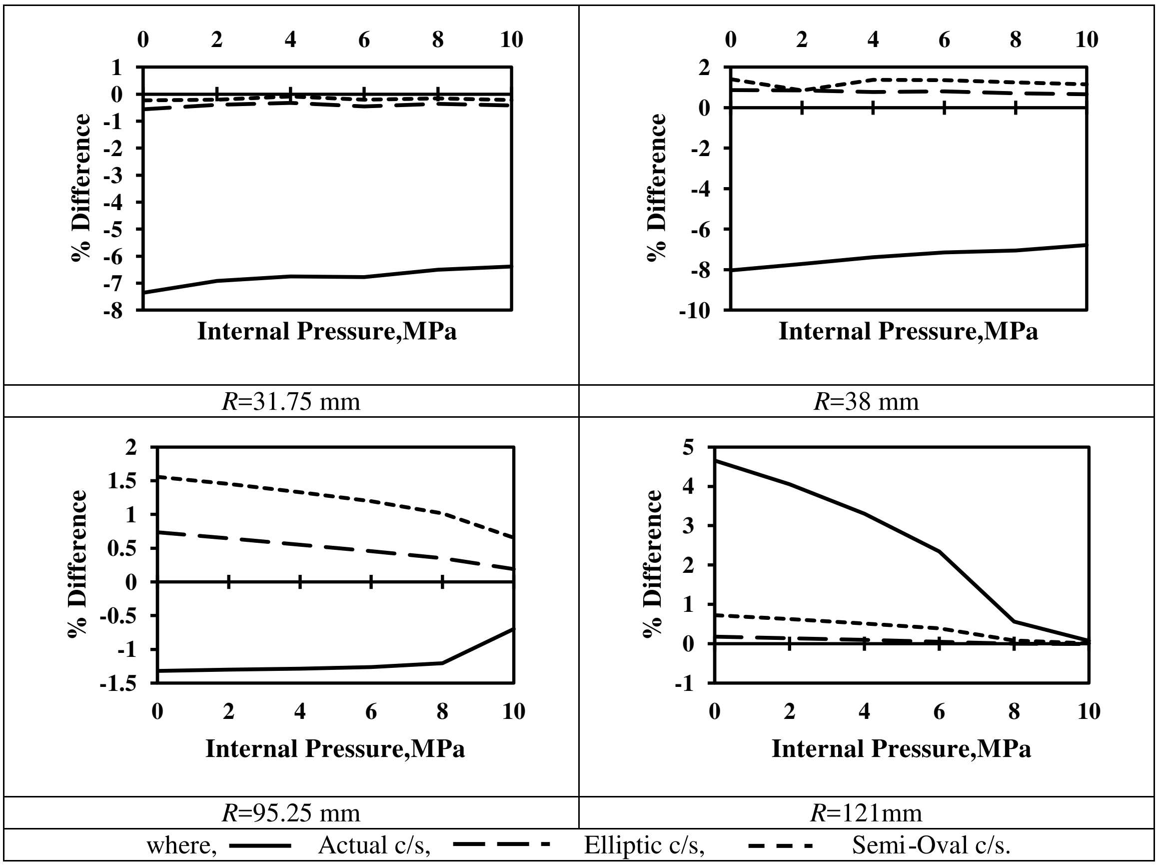

Figure-7. Percent difference of collapse load for out-of-plane bending.

CONCLUSIONS

The new methodology of finite element analysis of pipe bend includes the actual cross section and compares the collapse load with the assumed cross sections.

- The collapse load is higher when internal pressure is included in the analysis.
- The increase of internal pressure increases the stiffness of pipe bend initially for up to a particular pressure and then start decreasing as the internal pressure is increased further.
- In the absence of internal pressure, collapse load for elliptical and semi-oval cross section is found to be almost identical.
- For both in-plane closing and opening loading, elliptic and semi-oval cross sections do not influence much on lower bend radii and therefore, circular cross section may be assumed for the analysis. For medium

bend radius for low pressures, elliptic cross section is preferable as the maximum percent.

- For both in-plane closing and opening loading, at high pressures, the effect of shape imperfections are very minimal and hence circular cross section can be assumed. Similar trend is observed for in-plane opening bending moment loading.
- For out-of-plane loading, circular cross section may be assumed for the finite element analyses as the effect of ovality and thinning is minimal for lower bend radii.
- For lower pressures, the percent difference of actual cross section is higher and hence the finite element analysis must include actual cross section when the bend radius is high.

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