Shape Deformation Induced Stress Variation in Throughwall Critical Cracked Pipe Bends Loaded by Internal Pressure

Sumesh S, AR. Veerappan, and S Shanmugam

***Abstract*—This paper analyses the variation of Von Mises stresses determined across the bends of throughwall critically cracked pipe bends with shape imperfections when subjected to internal pressure. Two critically cracked 90 degree pipe bend models of pipe ratios of 5 and 10, each with bend ratios of 2 and 3 were considered for the 3D finite element analysis. Limit analyses using elastic–perfectly plastic materials with the small geometry change option was performed. The finite element results indicates the variation in stress in the inner surface of intrados, extrados, crown and crack tip due to effects of bend radius and also due to ovality and thinning underlining the need for inclusion of shape distortions in the analysis of cracked pipe bends.**

***Index Terms*—critical crack, finite element analysis, ovality, pipe bends, thinning**

I. INTRODUCTION

Shape deformations namely ovality and thinning are commonly observed in pipe bends during manufacturing stage. The stress analysis of curved pipes plays an important role in the design and integrity assessment of this type of structural component in piping engineering. The determination of stress distribution is a complex task as it is not possible to achieve a solution defined with elementary mathematical functions. During operation, pipe bends with ovality and thinning are subjected to higher stresses than pipe bends with perfectly circular cross-sections [1]. The authors discussed the types of geometric irregularities arising from the production of pipe bends and presented formulae which facilitate the calculation of stresses caused by each individual irregularity, when the pipe is subjected to internal pressure**.** Experimental stress analysis on a smooth pipe bends with flanged end constraints loaded under in plane bending has also been reported [2]. Stress analysis for out of round pipe bends considering pressurised pipe bends with semi oval/semi round cross section have been done by many researchers [3],[4],[5]. In reference [6] the effect of pressure on strain and stress analysis of pipe elbows subjected to in-plane bending moments was investigated. The behavior of pipe bends subjected to out-of-plane bending and internal pressure, have been studied taking geometric and material non linearity into account, using the finite element code ABAQUS [7]. Material behavior was taken as elastic perfectly plastic. The distribution of stress and strain along the axial direction and across the thickness of the bend was reported with and without internal pressure, at the onset of yielding and at instability. Reference [8] presented study on stresses introduced in pipe bends with different ovalities and thinning for a particular internal pressure calculated using finite element method. Crack-like defects develop on pipe bends not only during various stages during manufacturing and installation, but can also occur with cyclic loading and material deterioration as a result of continued operation [9]. Large throughwall circumferential crack could significantly reduce the load carrying capacity of elbows [10].There are many works in which stress analysis is done on pipe bends which are subjected to different loads. But in all these works the cross section of pipe is assumed to be circular, except very few works [11],[12],[13]. The aim of the present study is to perform limit analysis on 3D models of critical throughwall circumferentially cracked pipe bends subjected to internal pressure and determine the Von Mises stress variation at inside surfaces around the bend section of the pipe bend considering the ovality and thinning.

II. DEFINITIONS

During pipe bending, plastic flow of material occurs, causing distortion in cross-section. The cross-section of a pipe bend is assumed to become a perfect ellipse after bending as shown in Fig. 1.The wall thickness at the outside of the bend decreases and that at the inside increases. With reference to Fig. 1, pipe ratio, bend ratio, and the per cent ovality C_o, thinning C_t , are defined as follows
Pipe ratio=r/t, Bend ratio= R/r

Bend Characteristics,

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

% Ovality, $$C_o = \frac{(D_{\max} - D_{\min})}{D_o} \times 100 \tag{2}$$

Where $D_o = (D_{\max} + D_{\min}) \div 2$

Manuscript received March 24, 2015; revised April 08, 2015.

Sumesh S is Research Scholar at the Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India (e-mail: 411112006@nitt.edu).

AR. Veerappan is Associate Professor at the Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India (e-mail: aveer@nitt.edu).

S. Shanmugham is Professor at the Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India (e-mail: shunt@nitt.edu).

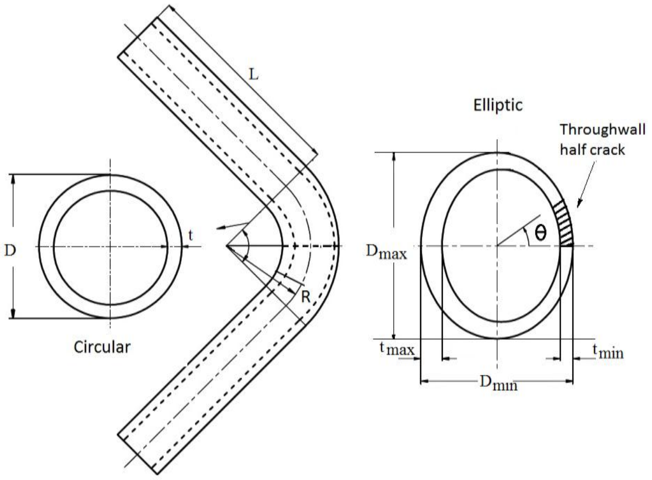

Fig. 1. Pipe bend geometry with ovality, thinning, circumferential throughwall crack and attached straight pipe.

$$\text{\% Thinning, } C_t = \frac{(t - t_{\min})}{t} \times 100 \qquad (3)$$

III. Finite Element Analysis

Abaqus [16] was used to perform finite element modelling of pipe bend with distorted cross sections and with critical circumferential throughwall cracks and for subsequent limit analysis.

Assumptions

The following assumptions are made in the stress analysis: linear behaviour, 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 owing 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 major axis of the elliptical shape of the pipe bend is assumed to be perpendicular to the plane of bending of the pipe bend. The minor axis of the elliptical shape of the pipe bend is assumed to be in the plane of the pipe bend. The pipe bend is assumed to be smooth, without ripples and flattening.

IV. Modelling and Meshing

The parameters of geometry and properties of material used for the present study are presented in Table 1. The mean radius and thickness of the pipe are denoted by r and t, respectively, and the bend radius by R. The length of the attached straight pipe, L, has been chosen to be 10 times the radius, L = 10r [15]. Throughwall circumferential crack has a higher detrimental effect on the collapse moment of elbows compared to surface and axial cracks.

The present study therefore considers only throughwall circumferential crack. The crack is assumed to be located in the centre of the elbow at the extrados. The circumferential throughwall crack is characterized by its relative crack length, θ/π, where θ denotes the half crack angle. Relative crack lengths corresponding to threshold crack angles have been considered. The threshold crack angles beyond which the weakening effect on collapse load starts is taken as the critical crack angle. The finite element model for the crack-tip was designed with collapsed elements, and a loop of wedge-shaped elements was used in the crack-tip region. Mapped meshing was utilized to mesh the bend models in order to control the number of elements. The element type chosen was C3D20R, 20-node iso-parametric quadratic brick, reduced integration element. Mesh refinement for the models were done by varying the number of elements across the thickness and the optimum minimum number of elements were chosen as 14400.

TABLE I

Parameters	Specification
Mean radius of pipe, r	50 mm
Pipe ratios, r/t	5.0 and 10.0
Bend characteristic, λ	0.6, 0.4, 0.3, 0.2
Crack angle at extrados,2θ	45° for r/t=5 60° for r/t= 10.
Ovality	0% to 20% in steps of 5%
Thinning	0% to 20% in steps of 5%
Normalized pressure, p	0.2
Material	Stainless Steel Type 304
Young's modulus	200GPa
Poisson's ratio	0.26
Yield stress	200MPa

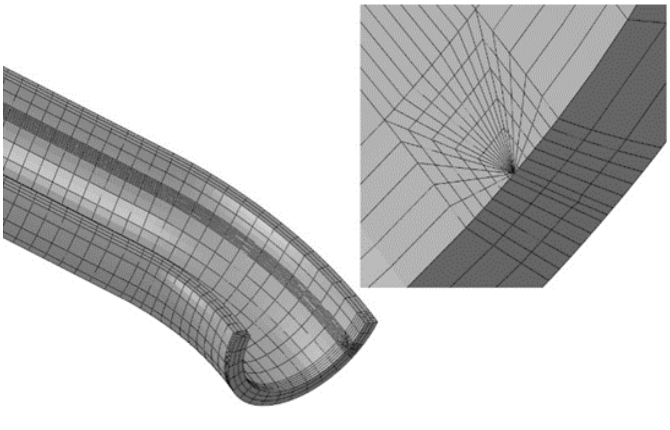

Fig. 2. Typical finite element meshes for the circumferential throughwall cracked pipe bend.

V. Loading and Boundary Conditions

Symmetry boundary conditions were applied as only one half of the pipe bend geometry is considered. Internal pressure was applied as a distributed load to the inner surface of the FE model, together with an axial tension equivalent to the internal pressure applied at the end of the pipe to simulate closed-ends. To avoid problems associated with convergence in elastic–perfectly plastic calculations, the RIKS option within ABAQUS was invoked.

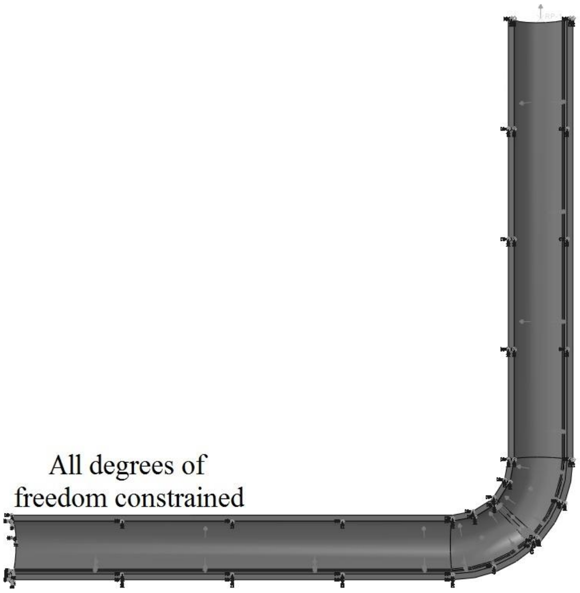

Fig. 3. Half symmetric model with boundary and loading conditions.

Limit analyses using elastic–perfectly plastic materials with the small geometry change option give clear limiting pressures.

VI. Validation of Finite Element Method

The finite element limit procedure was verified with published solution [14] given in (4) which has been developed for the cracked pipe bends with circular cross (corresponding to zero percentage ovality and thinning) section subjected to internal pressure. The finite element limit pressures were calculated from the pressure displacement plot wherein the radial displacement of an outer surface node at the centre along the length of the crack was measured.

$$\frac{P_L}{P_o} = \min\left[\begin{array}{l} 1.0, \\ 1.0 + \left\{1.3 - 0.06\left(\frac{r}{t}\right)\right\}\left(\frac{\theta}{\pi}\right) + \left\{-5.1 + 0.12\left(\frac{r}{t}\right)\right\}\left(\frac{\theta}{\pi}\right)^2 \end{array}\right] \tag{4}$$

where $P_o = P_o^s\left[\frac{1}{1 + A\exp(-B\lambda)}\right]$ (5)

Eq. (5) gives the limit pressure of uncracked 90 degree elbow.

and $A = 1.19\left(\frac{r}{t} + 1\right)^{0.09} - 1$

$$B = 0.0013\frac{r}{t} + 0.307$$

$$P_o^s = \frac{2}{\sqrt{3}}\sigma_o\frac{t}{r} \tag{6}$$

Eq. (6) denotes limit pressure for a straight pipe based on Von Mises yield criterion.

The variation between the finite element results and Eq.(4) is reasonably low which proves the reliability of the present finite element limit analyses.

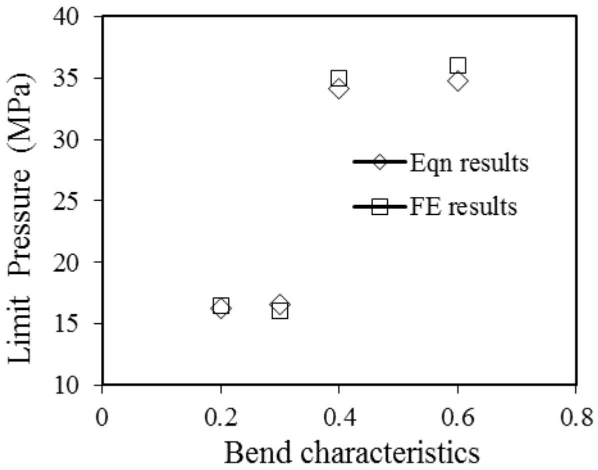

Fig. 4. Comparison between FE results and Equation (4).

VII. Results and Discussion

Fig. 5 shows the stress contours for the 90° pipe bend with extrados circumferential throughwall crack under pressure loading, as obtained from the FE limit analyses. Fig.6 shows the variation of Von Mises stress with ovality for the pipe bend with 45 degree critical crack at bend ratios of 3 and 2. With increase in ovality, the stress increases at the inner surfaces of extrados and crown. The stress at the crown reaches value higher than yield stress at 20% ovality, but the stress at the extrados is below the yield stress even for maximum ovality. As ovality increases the minor axis of the elliptic cross section decreases providing a toughening effect. Hence stress at the inner surface of intrados decreases upto 10 percent ovality. The induced stress predominates after 10 percent ovality hence the stress behavior changes.

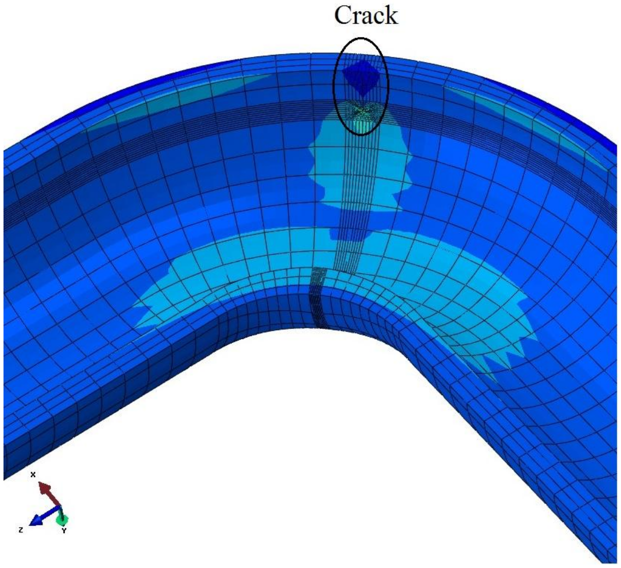

Fig. 5. Stress contours along the inner surface of the cracked pipe bend model under internal pressure.

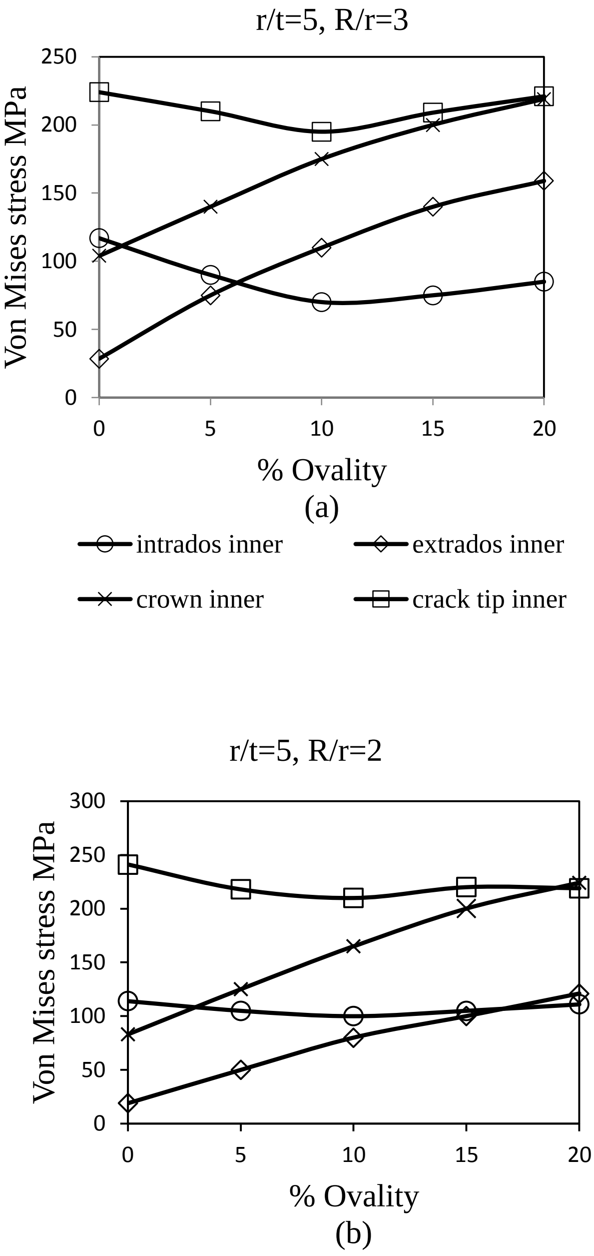

Fig. 6. Variation in Von Mises stresses with ovality for 45 degree through wall circumferential crack pipe bend at (a)bend ratio 3 (b) bend ratio 2.

Fig.7 illustrates the variation of Von Mises stress with ovality for the pipe bend with 60 degree critical crack at bend ratio of 3 and 2. At the intrados and crack tip, the variation in stress is similar in trend as observed for the 45 degree cracked pipe bend. In both cracked pipe bend models, it is evident from the figures that ovality has a considerable effect on the stress induced. For the same bend ratio, the pipe bend model with longer through wall crack has a higher value of stress for all cases of ovality.

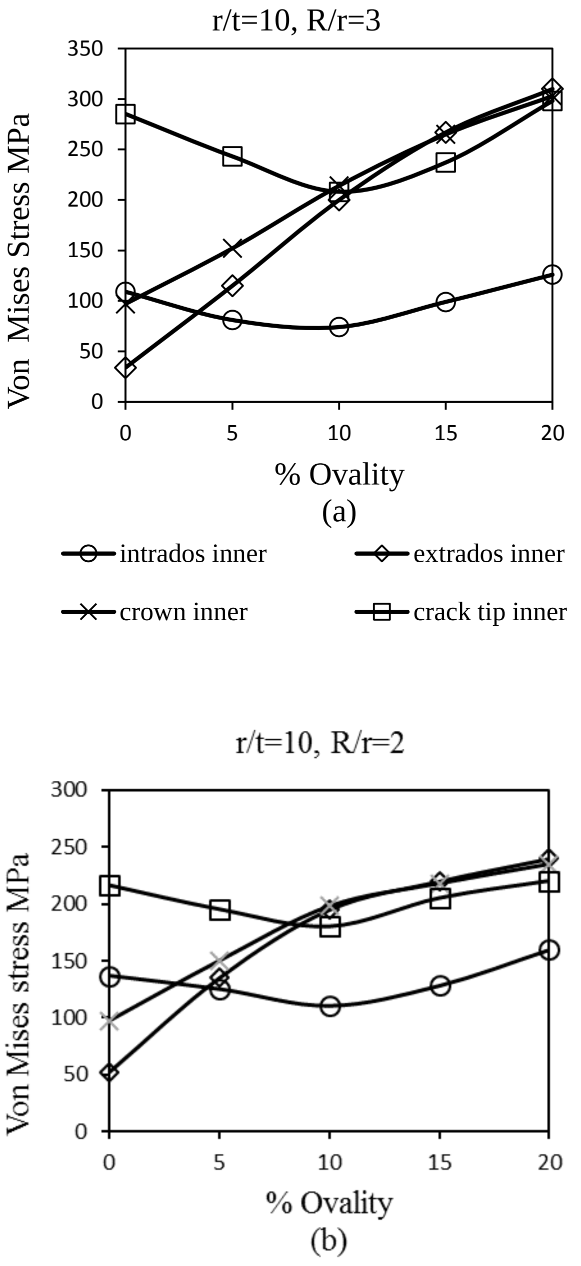

Fig. 7. Variation in Von Mises stresses with ovality for 60 degree through wall circumferential crack pipe bend with (a)bend ratio 3 (b) bend ratio 2.

With decrease in bend ratio, there is notable variation in the stress for the same cracked pipe bend model. The effects of thinning on the variation of Von Mises stress is shown in Fig. 8. At bend ratio of 3, for both pipe bend models with critical circumferential through wall cracks of 45 and 60 degrees, an increases in percent thinning do not produce considerable effect on the stress induced.

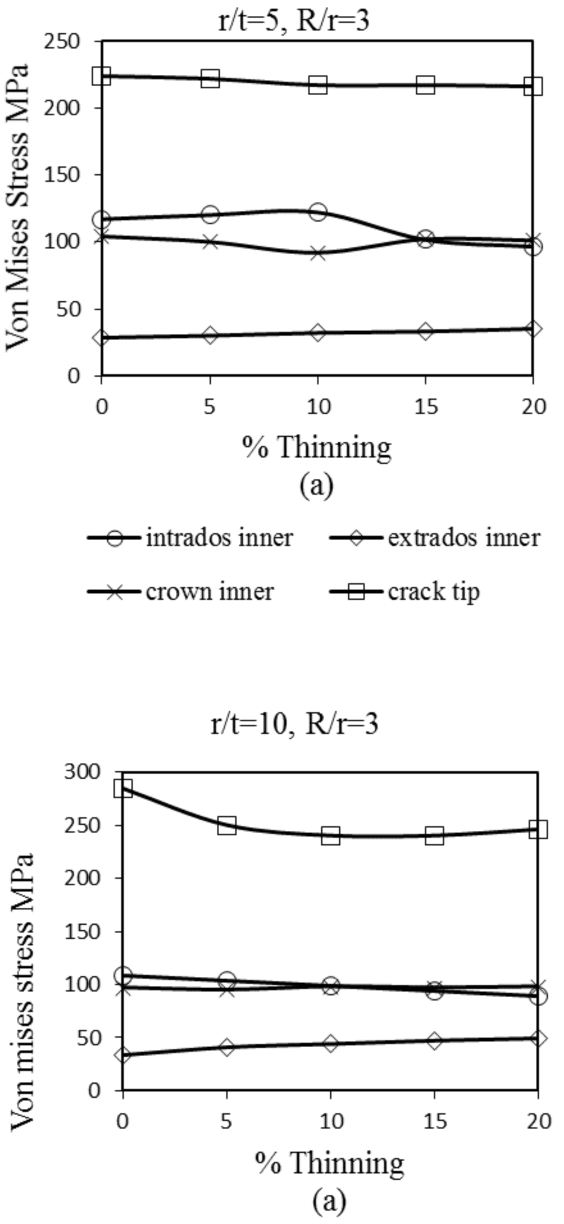

Fig. 8. Variation in Von Mises stresses with thinning for cracked pipe bend with bend ratio 3 for (a) 45 degree and (b) 60 degree through wall circumferential cracked pipe bend.

VIII. CONCLUSION

The influence of ovality on variation of Von Mises stresses evaluated at the inner surfaces across the critical cracked pipe bend models loaded with internal pressure is dominant compared to the effects of thinning. Hence inclusion of these ovality in the analysis of cracked pipe bends is imperative for an accurate assessment of the integrity of the piping system having pipe bends with the geometry considered.

REFERENCES

[1] AR. Veerappan and S.Shanmugam, “Analysis for Flexibility in the Ovality and Thinning Limits of Pipe Bends,” *Journal of Engineering Applied Science*, vol.3, no.1, pp.31–41, 2008.

[2] P. Hilsenkopf, B.Boneh and P. Sollogoub, “Experimental Study of Behaviour and Functional Capability of Ferric Steel Elbows and Austenitic Stainless Steel Thin Walled Elbows,” *International Journal of Pressure Vessel Piping*, vol.33, pp.111–28, 1998.

[3] J. W. Kim, M. G. Na and C.Y. Park, “Effect of Local Wall Thinningon the Collapse Behaviour of Pipe Elbows Subjected to a Combined Internal Pressure and In-Plane Bending Load,” *Nuclear Engineering Design*, vol. 238, pp. 1275–1285, 2008.

[4] T. Christo Michael, AR. Veerappan and S. Shanmugham, “Effect of Internal Pressure and Shape Imperfections on Plastic Loads of Pipe Bends under In-plane Closing Moment,” *Engineering Fracture Mechanics*, vol. 105, pp.1-15, 2013.

[5] M.A. Shalaby and M.Y.A. Younan, “Limit Loads for Pipe Elbows with Internal Pressure under in-Plane Closing Moments,” *Journal of Pressure Vessel Technology*, vol. 120, pp.35-42, 1998.

[6] J. Chattopadhyay, D.K. Natahani, B.K. Dutta and H.S. Kushwaha, “Closed-form Collapse Moment Equations of Elbows under Internal Pressure and In-plane Bending Moment,” *Journal of Pressure Vessel Technology*, vol.122, pp.431–6, 2000.

[7] A. Austin and Swannell J H, "Stresses in a pipe bend of oval cross-section and varying wall thickness loaded by internal pressure,” *International Journal of Pressure Vessels Piping*, vol.**7**, pp.167–182, 1979.

[8] R Natarajan and S Mirza "Effect of thickness variation on the stress analysis of piping elbows under internal pressure,” *Computer Structures*, vol.18, no.5, pp.767-778, 1984.

[9] A.G. Miller, “Review of Limit Loads of Structures Containing Defects,” *International Journal of Pressure Vessel Piping*, vol.32, pp.191–327, 1998.

[10] J.E. Griffiths, “The Effect of Cracks on the Limit Load of Pipe Bends under In-Plane Bending: Experimental Study,” *International Journal of Mechanical Science*, pp.119-30, 1979.

[11] K. Yahiaoui, J. Chattopadhyay, B.K. Dutta and H.S. Kushwaha, “Experimental and Analytical Study of Three Point Bend Specimen and Throughwall Circumferentially Cracked Straight Pipe,” *International Journal of Pressure Vessels and Piping*, vol.77, pp. 455-471, 2000.

[12] J.Chattopadyay and B.K.Dutta, “Closed-Form Moment Equations of Throughwall Circumferentially Cracked Elbows Subjected to In-Plane Bending Moment,” *Journal of Pressure Vessel Technology*, vol. 126, pp.307-17, 2004.

[13] J. Chattopadhyay and A.K.S.Tomar, “New Plastic Collapse Moment Equations of Defect Free and Throughwall Circumferentially Cracked Elbows Subjected to Combined Internal Pressure and In-plane Bending Moment,”*Engineering Fracture Mechanics*, vol.73, pp.829–854, 2006.

[14] Y.J. Kim, Young Kim and Tae-Kwong Song, “Finite Element Plastic Loads for Circumferential Cracked Pipe Bends Under In-plane Bending,” *Engineering Fracture Mechanics*, vol.74,pp.643-68, 2007.

[15] Y.J. Kim and C.S. Oh, “Effect of Attached Straight Pipes on Finite Element Limit Analysis of Elbows,” *International Journal of Pressure Vessel Piping*, vol.84, pp.177–84, 2007.

[16] ABAQUS version 6.10. User’s manual. USA: Simulia 2010.