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Determination of safe stress limit of High-Pressure pipe bends used in chemical industries

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ABSTRACT

Piping system in industries like petroleum rigs and power plants is used to carry chemically reactive substances with high pressure and temperature from one place to another, which could cause a negative effect on health and environment. This is the reason why we need correctness and precision in design code. A piping system with high pressure causes stresses in pipes, especially in elbows. The reason being elbows are more flexible than straight pipes. Whenever a pipe has bent the cross-section of the pipe is no longer circular, it slightly changes from circular to ovular. Bend can cause thickening of the inner surface and thinning of the outer surface. This causes uneven distribution of stresses in elbow which makes it the weakest link in the piping system. Due to this change in cross-section, stresses developed in the elbow leads to the phenomenon called "ratcheting". Ratcheting or fatigue ratcheting is nothing but cycle by cycle accumulation of strain on the application of cyclic load characterised by constant stress amplitude along with non-zero mean stress. Severe ratcheting may result in premature failure due to either accumulation of deformation or fatigue cracks. This work presents the effect of ovality on ratcheting.

KEY WORDS: Petroleum rigs, chemically reactive substances, High pressure, Ratcheting, Ovality.

1. INTRODUCTION

The failure of pipe bends in a pipeline used in the chemical industries results in damage to the environment. Hence, proper design of the bends is very important to transmit the chemically reacting hazardous fluids safely. Also during seismic loads, the pipeline should not be damaged. The corrosion and erosion also play a major role in the wall thickness of the pipes which in turn reduces the life of the bends. Loads acting on pipes and components are mainly subjected to internal pressure and cyclic bending load. Whenever the piping system is subjected to high internal pressure and cyclic bending a phenomenon called ratcheting is observed, also known as fatigue ratcheting. Fatigue ratcheting is referred to as accumulation of plastic strain. It occurs when the pipe is subjected to a cyclic load at constant stress amplitude along with non-zero mean stress. The reason causing the ratcheting to happen is the inelastic behaviour of the material. Ratcheting largely affects the estimated fatigue life of the system. It is clear from the studies and experiments were done by Raghava (2013), that when subjected to quasi-cyclic loading, pipes and pipe bends may fail in less number of cycles even if the load amplitude is much below the collapse load. The specimens in the experiment showed up to 31% in life reduction. Shi (2013), worked on ratcheting behaviour of pressurised elbow pipe with local wall thinning at extrados and crown. They found out that largest strain occurs at extrados where wall thinning is located during initial three cycles, later it occurs at intrados with increasing cycle. Also ratcheting strain of elbow with local wall thinning at the crown, axial ratcheting strains are low. Largest wall thinning shows highest hoop ratcheting strain. Vishnuvardhan (2013), studied failure for both straight pipe as well as elbow pipe and discovered that during ratcheting specimens underwent significant ratchet swelling (swelling), ovalization and thinning of the cross section. Also, there was a significant amount of wall thinning. 8-16% in straight pipes and 12-15% in elbow pipes.

Studies have shown that ratcheting strain and tensile mean stresses tend to cause the drastic reduction in fatigue life of the material. A study was made by Zeinoddini (2011), for steel tubular having rectangular defects under the effect of axial cyclic loading. The experimental and analytical results revealed that the non-linear isotropic hardening rule is able to predict ratcheting more accurately than the kinematic hardening rule. It was observed from the work by Mishra (2015) that as the cycle time increases, strain experienced in the pipe also increases. Also, ratcheting occurs mainly in the circumferential direction. Ratcheting in the axial direction is very low and can be neglected. The main concern is always of circumferential ratcheting.

Veerappan (2008), conducted an analysis regarding the limit of ovality and thinning so as to determine the flexibility in both the parameters. They concluded that there can be more than one value for thinning and ovality based on the dependence of pressure ratio on bend ratio. Also, they suggested that if the values of ovality and thinning in pipe bend are known then it can be measured that, whether the given pipe bends will withstand the inner pressure it is designed for. Michael (2011) in their work clearly suggested that the effect of ovality in pipe bend is much more than that of the thinning at extrados and hence can be reconsidered. Determination of ratcheting boundary plays very important role in pipe designing. The reason to find the ratcheting boundary is that to ensure the limit within which the pipe is safe and after what limit the ratcheting will start to occur. This is the reason why in 2001 ASME Boiler and Pressure vessel code, Section III (2010) included specifications regarding reversed dynamic loading and ratcheting.

The objective of the present work is to analyse the behaviour of high-pressure pipe bends with and without shape imperfection so as to determine the safe limits to protect the environment.

Finite Element Analysis: For modelling the pipe bends Solid works software (2013) is used and ANSYS (2014) is utilised for analysis.

Geometry: One main goal of this study is to investigate the effect of internal pressure with varying percentage of ovality. As shown below in Fig.1 an elbow (horizontal section) with uniform cross-section throughout its length. The bend radius is 95 mm and the straight pipe is of 240 mm at both the ends. The nominal diameter of the pipe is 73.03 mm and thickness is of 5.03 mm. The data for the pipe is taken from the pipe standards given in the piping catalogue of SS 304.

The geometry of pipe with uniform cross-section was prepared by using Solid Works and with simple commands like a sweep. In Fig. 1, the horizontal cross-section of the pipe is shown, it can be seen that the thickness of the pipe is maintained throughout the length. Other models include 5%, 8%, 10%, 15% and 20% ovality and thinning.

2. MATERIALS AND METHOD

Material: The material used throughout the study is type 304 stainless steel. The reason behind selecting this particular material is that ASME in its section 3 of boiler and pressure vessels has suggested using this material. Following table.1 gives information about the properties of SS 304 taken at room temperature from ASME technical data sheet.

Table.1. Material properties

Properties	SS304
Density	7900 kg/m^3
Young's modulus	209 GPa
Ultimate tensile strength	597 MPa
Yield strength	210 MPa
Poisson's ratio	0.26

Ovality and Other Dimensions: As the study is based on changing percentage of ovality, there are other dimensions which are to be taken care of in order to get the perfect geometry. Perfect dimensions lead to perfect geometry and hence perfect results. We know that the ovality of the bend section is such that at intrados the wall is thicker than the wall present at extrados. Hence in order to obtain the dimensions, formulae derived by Michael (2011) are used. The typical cross section of the bend with ovality and thinning is given in Fig.2 with 8% percentage of ovality.

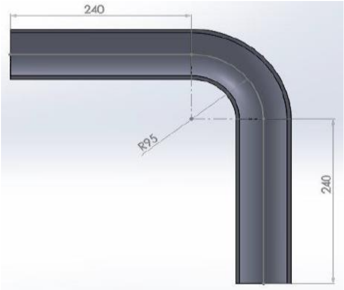

Fig.1. Symmetric pipe bend

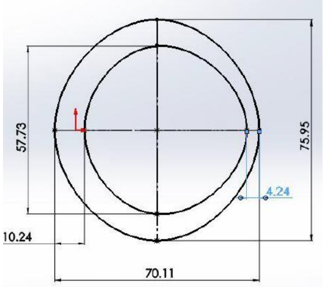

Fig.2. Cross-section of the bend with 8% ovality and thinning

Meshing: Meshing is one of the most important features for analysis. The meshing decides the approximation of final results and runtime of analysis. The finer the mesh more accurate is the approximation. But the thing to remember is the run time of analysis. Meshing should be in the order such that the run time is low and the result is close to the desired result. For the pipe bends mapped meshing was used as the profile is circular and to avoid the unwanted elements, because of the simple reason that the mapped meshing gives equal sized elements and the mesh quality also retains. As it is known that the mapped meshing is difficult to obtain for complex geometry but for simple geometry as shown in Fig.3, it holds good control over the elements. Another reason to select mapped meshing was to reduce the number of elements and mapped meshing has this quality.

Boundary Conditions: After meshing, the required boundary conditions were applied to the model. Now it is very important to understand and apply the boundary conditions, failing to which will produce false results and deviated from the approximate solution. As discussed earlier, we assumed that one of the ends is fixed hence nodes on that end were given nodal displacement as X=0, Y=0 and Z=0. Face on the other end was kept free in X and Y direction, whereas in Z direction the displacement was kept 0. Inner surface was applied with a constant pressure of 20 Mpa and nodal force of 20 kN was applied in positive X and negative X direction. The pressure is 20 Mpa is applied to the inner surface which is also normal to the inner surface. The reason behind taking pressure up to 20 Mpa is that this much amount of pressure is generated in nuclear power plant and the fluid pressure is it water, steam or any other fluid varies from 15 Mpa to 20 Mpa. Fig.4 shows all the boundary conditions and how they are applied to the bend.

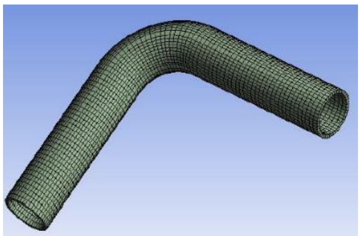

Fig.3. Mesh model of the pipe bend

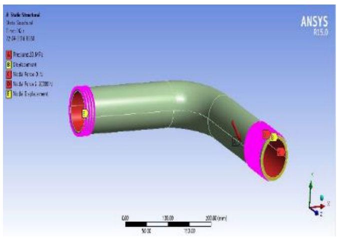

Fig.4. Boundary and loading conditions

3. RESULTS AND DISCUSSIONS

The cases were solved for the applied boundary conditions and the stress, strain and deformation was studied for all the 6 cases. The results obtained from the stress v/s angle plot are significant and matches with the reference journal. Though the values differ in this case because of the different material is used, but the behaviour of the material does not change. The plots are discussed below and the behaviour of the pipe bend is also interpreted one by one.

Sound Elbow (without ovality and thinning): Figure.5 shows in great detail about the variation of stress along the circumference of the cross-sectional area. Both outer and inner wall variation is plotted, which clearly shows that the inner wall experiences the highest amount of stress and again the stress grows after the crown i.e. 90 degrees attaining the stress of 222.26 Mpa. Meanwhile, the outer surface experiences a low range of stress at intrados and extrados. The maximum stress is developed at the 90 degrees (crown).

From the Fig.5 the stress plot is shown between stress and angle that is from intrados to extrados. Stress variation shows that the stress at the inner wall is highest at intrados and lowest at the crown. Again the stress value rises but does not reach or exceeds the value at intrados. On the other hand, the stress value on outer surface starts from the lower value and gives the maximum value at the crown and again tends to the lowest as it reaches the extrados. Hence it is clear that the stress value will be maximum at intrados at the inner surface, while it will be maximum at the crown on the outer surface as shown in Fig.6.

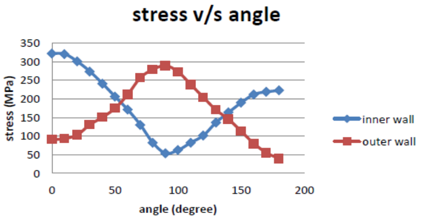

Fig.5. Stress for the sound pipe

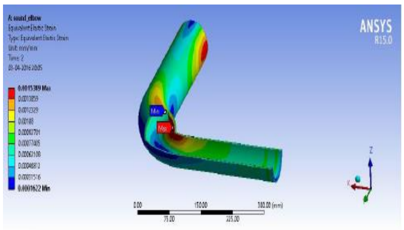

Fig.6. Stress at intrados and crown of the bend

For 5% Ovality: Figure.7 explains the behaviour of pipe bend with 5% ovality. The plot shows the similar behaviour but this time, the outer wall experiences low stress value at 90 degrees. The bump of the outer wall is not as steep as that of the uniform thickness. This goes to prove that the change in cross section surely affects the stress distribution along the circumferential area. Multiple peaks are seen in this case i.e. near 45 degrees from intrados and 135 degrees from intrados. If this case is compared to the pipe bend with uniform thickness we can interpret that outer wall experiences the highest value of stress at the crown but in this case, the value is extraordinarily low. Hence the 5% ovality change shows the tremendous effect on the stress generation.

For 8% Ovality: Figure.8 explains the variation of stress along the circumference of the pipe section. Though the behaviour of the curve for the 5% ovality is same but differs in values. The stress accumulated at 5% ovality intrados is much more than that of the 8% ovality. Similarly, the stress at the outer wall in 8% ovality is more than that of the 5% ovality. This only goes to show that as the ovality percentage increases the stress accumulation on outer wall increases.

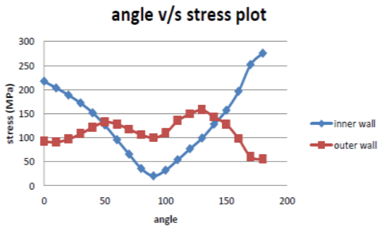

Fig.7. Stress for 5% ovality

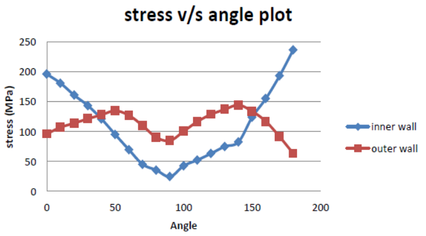

Fig.8. Stress for 8% ovality

For 10% Ovality: From the Figure.9, it is observed that the stress values have increased significantly at extrados. Also, strain at the inner wall is higher as compared to previous cases. The stress value at the inner surface at extrados has reached up to 250 Mpa which is more than the yield stress; hence the material fails in this case also. At a crown position at the outer surface, there is a drop in stress value from 84.4 Mpa to 75 Mpa. Though the difference in peak values at 45° and 135° has a quite bit of a difference. Also, a drop to 5 Mpa can be seen at intrados as compared to 8% ovality case. If we look at the change in strain it is observed that the value has increased with respect to 8% ovality case.

For 15% Ovality: In Figure.10 it is observed that the stress creation in the outer wall as well as in the inner wall follows the same path. It means that the stresses in the outer and inner wall at any particular instant are same. Hence the rate of decrease in fatigue life drops instantly.

For 20% Ovality: Similar behaviour as in 15% ovality is observed as shown in Fig.11, for angle ranging from 90 to 150 degree. Though the behaviour is same but the thinning in the later 90 degrees is more hence the behaviour of the tube is showing drastic fluctuations and sudden rises and valleys in stress values.

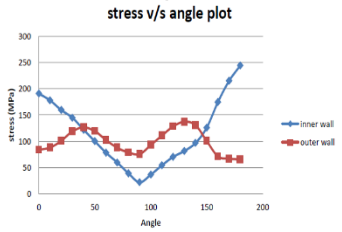

Fig.9 Stress for 10% ovality

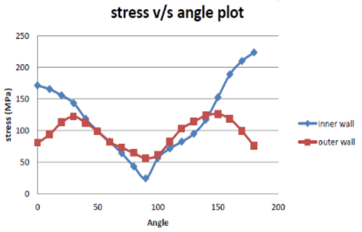

Fig.10 Stress for 15% ovality

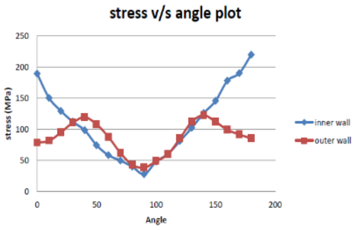

Fig.11 Stress for 20% ovality

4. CONCLUSIONS

From the results obtained for all the six cases, it is clearly observed the ovality surely affects the behaviour of pipe bends. And it will affect more in the long run because the behaviour of bend section cannot be predicted. Following conclusions can be drawn from the results and discussion in the previous section:

- The change in ovality affects the stress distribution in circumferential bend section and cannot be neglected.
- Till now the variation in ovality is not studied thoroughly and hence should be given priority, for the very simple reason that whenever the bending of pipe will take place the cross-section will change may be a little bit but it will change and will surely affect the stress distribution.
- As the ovality percentage increases the stress and strain on the outer wall increases at extrados.
- The stresses produced at mid-section of intrados and crown, and crown and extrados are higher than rest of the points. Hence the angle 45 degree and 135 degrees cannot be neglected.

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