OPTIMIZATION OF NOZZLE HOLE REINFORCEMENT PARAMETERS AND WALL THICKNESS IN CYLINDRICAL PRESSURE VESSEL USING FEM

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ABSTRACT

Nozzle openings in pressure vessels are indispensable, and all the pressure vessels must have nozzle openings to facilitate transfer of fluid from and to the vessel. These holes are responsible for geometric discontinuities. Stresses around the vicinity of the nozzle openings are comparatively higher and this leads to the failure of the vessel. Additional materials should be provided near the openings to strengthen the vessel and also to reduce the stress concentration factor. Three dimensional finite element models were developed for three different internal diameters namely 200, 250, 300mm with circular and elliptical openings and analyzed with appropriate boundary conditions using finite element method (FEM). Results indicate that introducing elliptical hole with appropriate major and minor axis orientation rather than circular hole significantly reduces the stress concentration factor. As a further step, reinforcement parameters and nozzle wall thickness were optimized.
Keywords: Pressure vessels, Stress Concentration Factor (SCF), Finite Element Method (FEM) and elliptical hole.

1.Introduction

Pressure vessels find wide applications in nuclear and thermal power plants, chemical and process industries, in space and ocean depths, and fluid supply industries. The failure of pressure vessels may result in loss of life, health hazards and damage of property. A number of numerical analysis are available for nozzle hole reinforcement in spherical pressure vessel head [1,2]. The main purpose of this research work is to perform a stress analysis on a thick-walled pressure vessel cylinder and optimize the reinforcement parameters and nozzle wall thickness using finite element method. FEM offers a great deal of promise over other methods mainly experimental, in terms of low cost, high speed, complete information, and the ability to simulate realistic and ideal conditions. Strength is an inherent property of a mechanical element and it is an important characteristic feature of the material. It is present even if there is no external load applied on the mechanical element. To avoid the pressure vessel failure, the designer must have the positive assurance that the stresses generated will never exceed the material strength [3]. In the present work, the main consideration in the design of pressure vessels is, the effect of concentration of stresses due to geometric discontinuities resulting from openings for manholes, gauges and to facilitate transfer of fluid from and to the pressure vessel. These geometric discontinuities alter the stress concentration factor in the vicinity of discontinuity so that elementary stress equations no longer prevail. Such discontinuities are called “stress raisers” and the regions in which they occur are called the areas of stress concentration. Reinforcement of an opening cannot be indisputably obtained by adding huge amount of material because this has a reverse effect. But the end result of under reinforcing creates hard spot in the vessel [4]. Analytical solution is not available to determine the optimal size of the reinforcement and nozzle wall thickness. Therefore, numerical simulation is carried out using FEM to determine the optimal reinforcement parameters and nozzle wall thickness. The numerical approach adopted here is the analysis using finite element analysis software, Ansys, which is a very powerful and versatile tool for structural, thermal, fluid, electric, magnetic and electro-magnetic analysis.

2.Validation

The cylinder dimensions were considered such that the ratio of the thickness to radius of the cylinder is greater than 0.05 to satisfy the requirement of thick-walled cylinder. The cylinder is subjected to internal pressure, p_i= 5 MPa and external pressure, p_o=0.1MPa,

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having a constant height 300mm and wall thickness 20mm. Three internal diameters namely 200, 250 and 300mm were considered for the analysis. Flanges (upper and lower) at the end of the cylinder were attached with 20mm height and 40mm thick in radial direction. The following equations were used to calculate the theoretical stress values [5].

$$\sigma_t = [p_i a^2 - p_o b^2 - a^2 b^2 (p_o - p_i)/r^2]/b^2 - a^2$$

$$\sigma_r = [p_i a^2 - p_o b^2 + a^2 b^2 (p_o - p_i)/r^2]/b^2 - a^2$$

$$\sigma_l = p_i a^2 / b^2 - a^2$$

$$\sigma_{eqv} = [(\sigma_l - \sigma_t)^2 + (\sigma_t - \sigma_r)^2 + (\sigma_r - \sigma_l)^2 /2]^{1/2}$$

The model of the cylinder without hole as shown in Fig.1 was considered for the validation. Finite element models of pressure vessel cylinders were developed and analyzed with appropriate boundary conditions. The following Boundary conditions were used for the analysis: Two extreme flange ends were constrained in all DOF. Internal pressure of 5MPa was applied at the inner area and external pressure of 0.1MPa was applied at the outer area of the cylinder. Three-dimensional element, SOLID185 was selected for the analysis. It is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The element has plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilities.

Grid independence study was carried out by altering the number of elements. Coarse meshes were first used to study the behavior of stresses. Finally, 46675 elements were used for the analysis. The von misses stress plot for the 200mm diameter cylinder is shown in Fig. 2. The FEM solutions have been compared with the analytical solution in Fig. 3 & 4. The comparison shows that FEM solution is in accordance with the analytical solution.

Fig. 1. Pressure vessel cylinder without hole

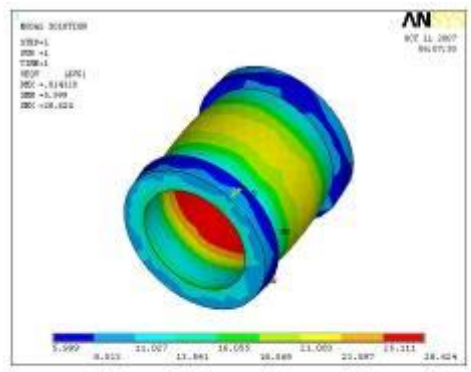

Fig. 2. Von Misses stress plot for 200mm diameter cylinder

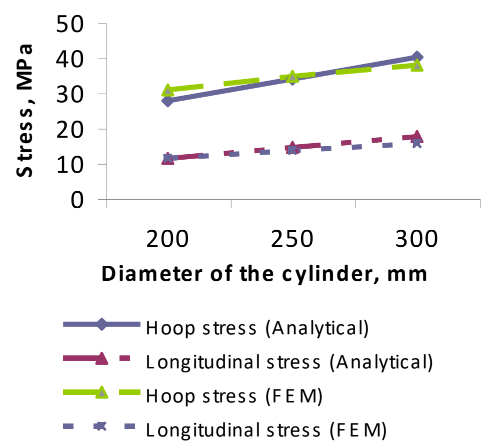

Fig. 3. Comparison of analytical and FEM result of Hoop & Longitudinal stresses in cylinders without hole

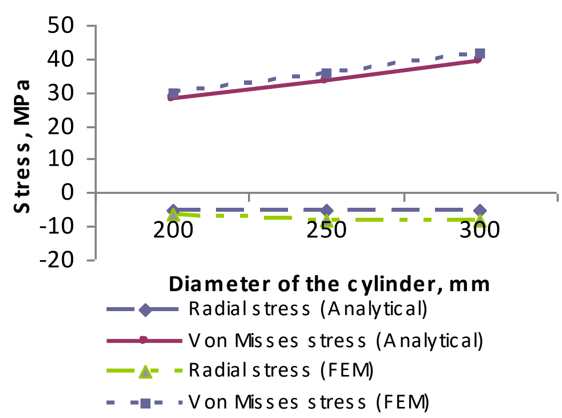

Fig. 4. Comparison of analytical and FEM result of Radial &Von Misses stresses in cylinders without hole

3. Analysis Of Pressure Vessel Cylinder With Circular Hole

The analysis was performed on the pressure vessel cylinder with circular hole at the middle (Fig.5), and it is subjected to internal and external pressures. The analysis was performed on the pressure vessel cylinder with three different internal diameters by keeping the hole diameter as 20mm.

Fig. 5. Pressure vessel cylinder with circular hole

The various stress values have been compared in Fig. 6. It was found that, the maximum stress value available in the vicinity of the hole. The stress values increases with the increase in cylinder diameter.

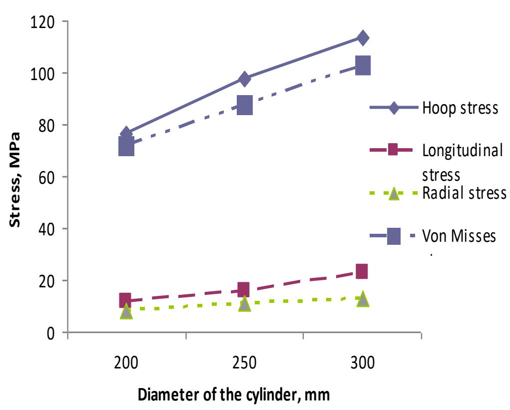

Fig. 6. Stress vs Diameter of the cylinder with circular hole.

4. Analysis Of Pressure Vessel Cylinder With Elliptical Hole

The analysis was performed on the pressure vessel cylinder with elliptical hole. There is no provision in ANSYS to create the elliptical hole. Hence, the model was created in Pro/E and then exported to ANSYS through IGES. The analysis was performed on the pressure vessel cylinder with three different internal diameters with the elliptical hole major axis was perpendicular to the cylinder axis. The major and minor axis dimensions were 20 and 10mm.

The von misses stress values have been compared in Fig. 7. It was found that, the maximum value of the stresses is available in the vicinity of the hole. The stress values increases with the increase in cylinder diameter.

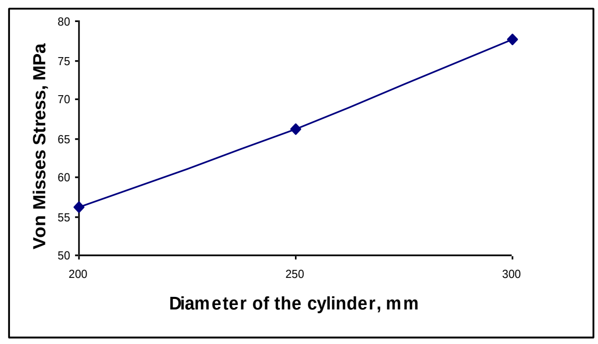

Fig. 7. Stress vs Diameter of the cylinder with elliptical hole major axis perpendicular to the cylinder axis

4.1. Elliptical hole major axis parallel to the pressure vessel cylinder axis

The analysis was performed on the pressure vessel cylinder of diameter 250mm with the elliptical hole major axis parallel to the cylinder axis as shown in Fig. 8. Five a_e/b_e ratios were considered for the analysis and its corresponding stress values have been compared in Fig. 9. It shows that, the Von Misses stress value increases with the increase in a_e/b_e ratio.

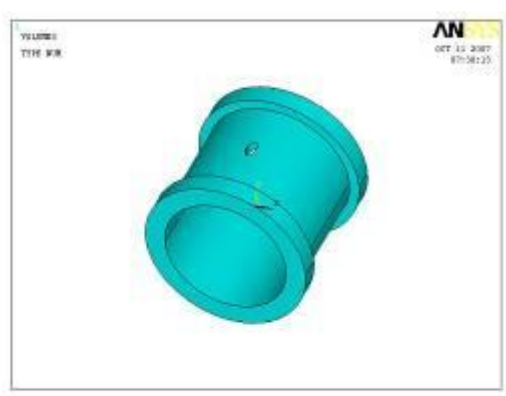

Fig. 8. Pressure vessel cylinder with elliptical hole major axis parallel to the cylinder axis.

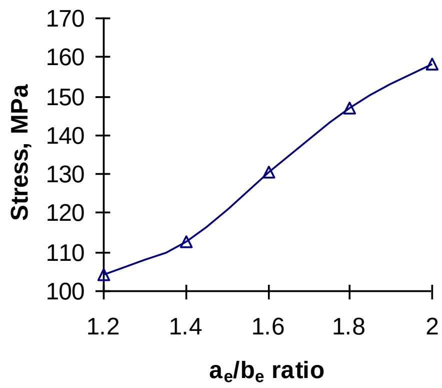

Fig. 9. Stress Vs a_e/b_e ratio for the major axis of an ellipse parallel to cylinder axis.

4.2. Elliptical hole major axis perpendicular to the pressure vessel cylinder axis

The analysis was performed on the pressure vessel cylinder of diameter 250mm with the elliptical hole major axis perpendicular to the cylinder axis as shown in Fig. 10. The Von Misses stress values for the different b_e/a_e ratios have been plotted in Fig. 11. The Von Misses stress value increases with the increase in b_e/a_e ratio.

When the major axis of an elliptical hole was parallel to the cylinder axis, the Von Misses stress value was 158.3MPa. The above stress value was reduced to 58.5% and its value was equal to 66.2Mpa when the major axis of an elliptical hole made perpendicular to the cylinder axis. The Von Misses stress value was 88MPa for the cylinder with circular hole. This stress value was reduced to 66.2MPa by replacing circular hole with elliptical one with the major axis of an elliptical hole was perpendicular to the cylinder axis. The reduction in stress value is 25%. The stress around the vicinity of elliptical hole with the major axis perpendicular to the cylinder axis was found to be less severe.

Fig. 10. Pressure vessel cylinder with elliptical hole major axis perpendicular to the cylinder axis.

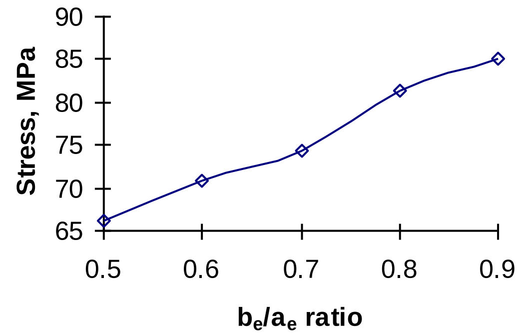

Fig. 11. Stress Vs b_e/a_e ratio for the major axis of an ellipse perpendicular to cylinder axis.

For the further investigation, the elliptical hole in the pressure vessel cylinder was made inclined to the cylinder axis. Fig. 12 shows the von misses stress plot for 250mm internal diameter cylinder with the elliptical hole minor axis was inclined at 45^0 to the cylinder axis. The von misses values for the different minor axis orientation have been compared in Fig. 13. It was found that, the stress value increases with the minor axis inclination until 45^0. There was some reduction in the stress value between the angle of inclinations 45^0 and 60^0. The stress value is 87.67MPa at 60^0. This value is 32.4% higher than the value of the stress (66.2Mpa) when the minor axis parallel to the cylinder axis. Hence, changing the orientation of the minor axis will not have any considerable impact on the stress reduction around the vicinity of the hole.

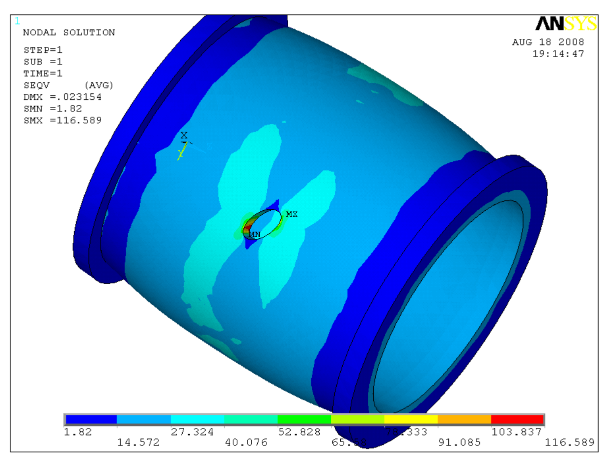

Fig. 12. Von misses stress plot for 250mm diameter cylinder with elliptical hole minor axis inclined at 45^0 to the cylinder axis

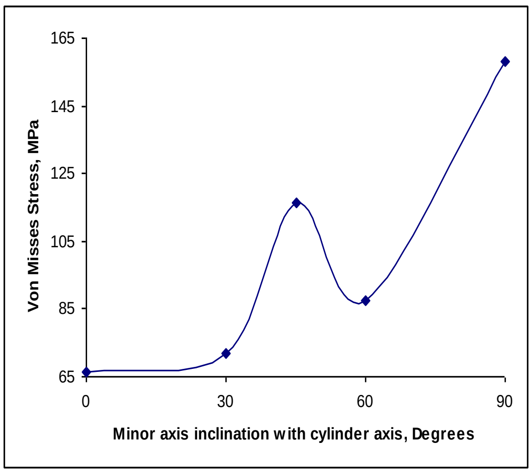

Fig. 13. Stress vs Inclination of the minor axis with cylinder axis.

5. Reinforcement Around A Circular Hole In Pressure Vessel Cylinder

The cylinder material near the opening needs to be increased to strengthen the cylinder. The two basic requirements of the reinforcement are [4]:

1. Sufficient material should be added to compensate the weakening effect of the opening.
2. The reinforcing material should be placed immediately adjacent to the opening, but suitably disposed in profile and contour so as not to introduce an over riding stress concentration itself.

6. Effect Of Location Of Reinforcement On The Stress Concentration At An Opening Of The Pressure Vessel

To find the effective reinforcement action, the pressure vessel cylinder was modeled with reinforcements in two ways: 1. Reinforcement is one sided and 2. Reinforcement is on both sides. The Von Misses stress values have been compared in Fig. 14. It is apparent from the Fig. 14 that, the reduction in stress concentration is obtained only by balanced reinforcement. This can be explained by the fact that, one side reinforcement will leads to eccentricity or an imbalance and creates local bending moments and stresses [4].

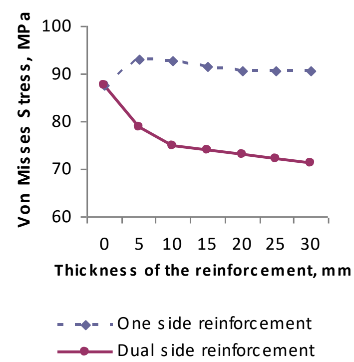

Fig. 14. Comparison of one sided reinforcement with both sided reinforcement.

7. Reinforcement Diameter For Circular Openings In A Pressure Vessel Cylinder

Maximum reinforcing action with minimum material is obtained when the material is kept within the effective boundary limits. To find the optimum diameter of the reinforcement, the following dimensions of the cylinder were considered for the analysis. Inner diameter 250mm, outer diameter 270mm, height 300mm, hole diameter 20mm and the flanges with same dimensions are attached at the ends. The optimum diameter of the reinforcement can be obtained by generating the stress distribution profile through the hole, as shown in Fig. 15.

The center of the hole is 150 mm and the edges of the hole are 140 and 160mm.Von Misses stress is maximum at the edges of the hole and its value precipitously decreases with the distance away from the edges of the hole. The same trend continues until the distance reaches 130 and 170mm. The distance between these two points are 40mm, which is twice the hole diameter.

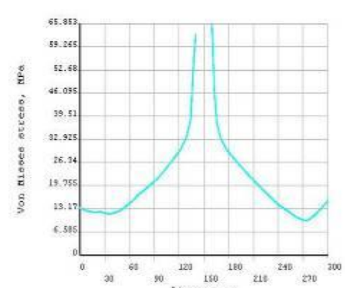

Fig. 15. Plot for Von misses stress Vs distance in 300mm height cylinder.

8. Reinforcement Thickness For Circular Openings In A Pressure Vessel Cylinder

The similar dimension of the cylinder utilized for finding the optimal reinforcement diameter was used for this analysis too. Thickness of the reinforcement was varied from 4 to 20mm at an interval of 4mm and the Von Misses stress values have been plotted in Fig. 16. It was found that, Von Misses stress precipitously decreases until the thickness of the reinforcement is 10 mm. There was no considerable change in the stress value beyond 10mm.

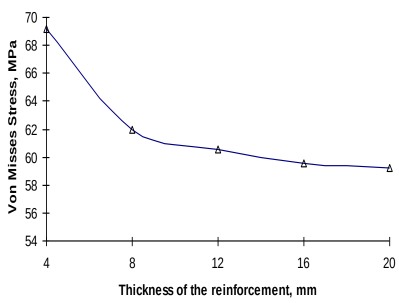

Fig. 16. Thickness of the reinforcement, mm Vs Von misses stress, MPa.

9. Nozzle Wall Thickness For Circular Openings In Pressure Vessel Cylinder

The similar dimension of the cylinder utilized for finding the optimal reinforcement diameter was used for this analysis also and nozzle wall thickness was varied from 1 to 5mm at an interval of 1mm. Fig. 17 shows that, the exact occurrence of the maximum Von Misses stress value for 3 mm nozzle wall thickness.

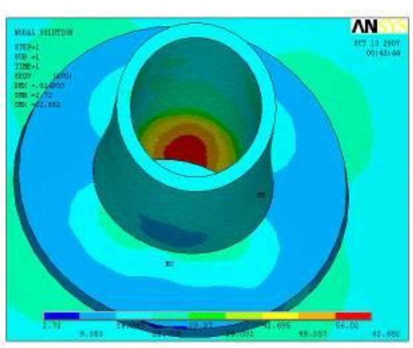

Fig. 17. Von Misses stresses plot for 250 mm diameter cylinder with 3 mm nozzle wall thickness.

The Von Misses stress values for different nozzle wall thickness have been plotted in Fig. 18. It was observed that the Von Misses stress decreases rapidly till the nozzle wall thickness of 2mm, and there was no considerable change in the stress values beyond this. Therefore, the optimal thickness of the nozzle wall thickness is 2mm for the pressure vessel cylinder considered for the analysis.

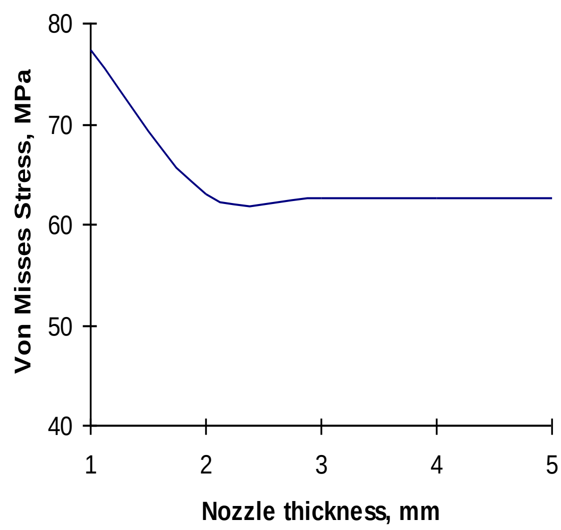

Fig. 18. Nozzle wall thickness, mm Vs Von misses stress, MPa.

10. Conclusions

Three-dimensional finite element analysis has been carried out to analyze the stress concentration around the openings in a pressure vessel cylinder.

The following observations were made in the analysis of thick-walled pressure vessel cylinder.

- Introducing elliptical hole with the major axis of an ellipse perpendicular to the vessel cylinder axis significantly reduces the stress concentration factor at the opening of the pressure vessel cylinder.
- It was observed that the optimal thickness of the reinforcement was half the thickness of the pressure vessel cylinder and the optimal diameter of the reinforcement was found to be twice the diameter of the hole.
- It was also observed that optimal nozzle wall thickness is 2mm for the pressure vessel cylinder considered for the analysis.

Nomenclature

σ_t - Tangential Stress, MPa
σ_r - Radial Stress, MPa
σ_l - Longitudinal Stress, MPa
σ_{eqv} - Equivalent (or) Von Misses Stress, MPa
p_o - External pressure, MPa
p_i - Internal pressure, MPa
a - Inner radius of the pressure vessel, mm
b - Outside radius of the pressure vessel, mm
a_e - Major axis of elliptical hole, mm
b_e - Minor axis of elliptical hole, mm

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