Stress Concentration Factors of Various Adjacent Holes Configurations in a Spherical Pressure Vessel

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Abstract: The analysis of stress concentration factor (SCF) of adjacent holes in a spherical pressure vessel can be approached by considering a thin plate undergoing hydrostatic stresses. This work adopts the approach to investigate the SCF of various adjacent holes configurations in a spherical pressure vessel using finite element analysis. The von Mises stress is considered to determine the SCF. Various arrangements of adjacent holes are investigated i.e., two, three, four, and five adjacent holes are taken into account. The SCF curves with respect to the ratio of the distance between adjacent holes to the diameter of hole, L/d, and for a certain ratio of the diameter of hole to the plate thickness, d/t, are then plotted. The results show that the decreasing of L/d will affect the increasing of SCF, while for the case of five adjacent holes configuration, the increasing of d/t doesn’t make any significant effect to the increasing of SCF.

Keywords: adjacent holes, circular thin plate, finite element analysis, spherical pressure vessel, stress concentration factor (SCF).

1 Introduction

The higher local stress around the nozzle-vessel connection due to internal pressure, temperature, and other external loads has postulated the occurrence of the crack initiation and attracted much attention of researchers and pressure vessel designers. Though the tremendous advances in numerical simulation, all reported papers were in the case of a single nozzle-vessel connection.

Previous work on the use of von Mises equivalent stresses to compute the stress concentration factors (SCF) based on finite element calculation have been reported [1-5]. The case of an opening in a spherical shell under internal pressure without and with pressure acting at the bore was reported by Schindler [1]. The results obtained by the usage of thin shell theory was reported elsewhere [2], three-dimensional volume FEM elements was discussed [3], and axisymmetric ring-elements [4]. In the latter parametric investigation, nozzle to shell weld seams were included in the model.

The information on the SCF of various adjacent nozzles-vessel connections, either spherical or cylindrical vessel, has not been reported yet. To overcome the complexities of investigating various adjacent nozzles-vessel connections, it is important to introduce another method instead. This paper reports the study on SCF of various adjacent holes configurations in a spherical pressure vessel. The study uses a thin plate subjected to a constant bending moment which creates hydrostatic stresses within the plate element. The finite element method is used for solving the stress analysis to find the values of SCF.

In the earlier report [6], the study has been done by using an infinite thin element subjected to hydrostatic stresses in the periphery of the element. However, this method is effective for analyzing a single hole but it will produce a greater deviation of stress distribution in the region between holes due to the disturbances of stress induced flow.

In this study, the von Mises stress is also considered to determine the SCF of the adjacent holes. Various arrangements of adjacent holes are investigated i.e., two, three, four, and five adjacent holes are taken into account. The SCF results for each case are plotted with respect to the ratio of the distance between adjacent holes to the diameter of hole, and the ratio of the diameter of hole to the plate thickness are also taken into account. A formula for employing the results to calculate the allowable stress, \( \sigma_{\text{all}} \), in designing a spherical pressure vessel is also given.
2 Stress and Finite Element Analysis in a Circular Thin Plate.

The analysis of stress distribution in a spherical pressure vessel can be approximated by considering a thin plate undergoing hydrostatic stresses. This work adopts the approximation to investigate the SCF of various adjacent holes configurations in a spherical pressure vessel using finite element analysis. A circular thin plate is circumferentially and symmetrically overhanging supported, and in the periphery of the plate is subjected to a uniform circumferential distributed load as shown in Figure 1(a). The segment of the plate which is constrained by the circumferential balls supports will undergo a constant bending moment, as shown in Figure 1(b), and therefore, the hydrostatic stresses will be produced within the segment.

Various adjacent holes configurations are then positioned in the inner segment of the thin circular plate, and the stress distribution over the segment is analyzed using ANSYS finite element software. The SCF, $K_t$, is defined as the ratio of the maximum von Mises stress that occurs around the holes to the von Mises stress without hole, or it is expressed in the following formula:

$$K_t = \frac{\text{Maximum von Mises stress around holes}}{\text{von Mises stress without hole}}$$

(1)
Note that the von Mises stress that occurs over the surface of the segment without hole is constant at any point and it is similar with the hydrostatic stress which is taken as a reference stress. A number of 3-dimensional finite element computations were performed on various adjacent holes by considering the ratio of the diameter of the holes to the thickness of the plate and the ratio of the distance between two holes centre to the diameter of the holes. The arrangement of various adjacent holes configurations taken into account for the current analysis is depicted in Figure 2.

3 Numerical Results and Discussion

The SCF for two, three, four, and five adjacent holes configurations have been analyzed numerically using the finite element analysis. The results are then plotted to identify the stress concentration factor, $K_t$, and the ratio of the distance between the holes centre to the diameter of the holes, $L/d$, for various thickness of the circumferential plate. The guideline in employing the results to calculate the allowable stress, $\sigma_{all}$, in designing a spherical pressure vessel is given by the following expression,

$$\sigma_{all} = K_t \left( \frac{p r}{2t} \right)$$

where $p$ is the fluid pressure within the spherical pressure vessel, $r$ is the mean radius of sphere, and $t$ is the wall thickness of the sphere.

All analyses are conducted with the variation of $L/d$ ranging from 1.5 to 2.4 with the value of $d/t$ equals to 3, 3.4, and 4. The ratio $L/d$ less than 1.5 tends to give rise of the SCF value higher exponentially, and, therefore, it is beyond our consideration. While the ratio $L/d$ greater than 2.4 tends to indicate constant SCF value. The SCF values are plotted with respect to $L/d$ for respective three values of the aforementioned $d/t$. The interpolation method can be applied to find the value of SCF which is not provided in this study. Numerical results indicate that for the same value of $L/d$, the greater the value of $d/t$ the greater the value of SCF, however, it does not show any significant increasing of SCF.
Table 1. The stress concentration factor for $L/d = 1.5$ and $2.4$, and for $d/t = 3$, $3.4$ and $4$.

<table>
<thead>
<tr>
<th>Number of holes</th>
<th>Holes Configuration</th>
<th>Stress Concentration Factor, $K_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L/d = 1.5$</td>
<td>$L/d = 2.4$</td>
</tr>
<tr>
<td></td>
<td>$d/t = 3$</td>
<td>$d/t = 3.4$</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2.52</td>
</tr>
<tr>
<td>3</td>
<td>Right angled triangle</td>
<td>2.48</td>
</tr>
<tr>
<td>3</td>
<td>Triangle</td>
<td>2.32</td>
</tr>
<tr>
<td>4</td>
<td>Square</td>
<td>2.36</td>
</tr>
<tr>
<td>5</td>
<td>Square</td>
<td>2.62</td>
</tr>
<tr>
<td>5</td>
<td>Pentagon</td>
<td>2.50</td>
</tr>
</tbody>
</table>

Our investigation has shown that the value of SCF for a single hole is 2.0. Figures 3 to 8 show the results of various adjacent holes configurations taken for analysis in this study. The SCF for each case for $L/d = 1.5$ to 2.4 are tabulated in Table 1. For three holes configurations, the SCF for right angled triangular configuration is greater than the triangular one. For the five holes configuration, it is found that the SCF for square configuration is slightly greater than the pentagonal one.

Again, the increasing of SCF with respect to the increasing of $d/t$ does not exhibit any significant effect. It can be observed that the more the number of holes, the more insignificant the effect of the increasing of $d/t$ to the value of SCF. In fact, for the case of five adjacent holes configurations, the increasing of SCF due to the increasing of $d/t$ is very small and, therefore, it can be neglected. The results for two and three adjacent holes configurations show a good agreement with the results reported by Nishida as referred in [6] using an infinite thin element subjected to hydrostatic stresses in the periphery of the element.

4 Conclusion

The SCF of various adjacent holes configurations have been studied using the finite element analysis. It is found that the decreasing of $L/d$ will affect the increasing of SCF significantly, while the more the number of holes, the more insignificant the effect of the increasing of $d/t$ to the value of SCF. In turn, for the case of five adjacent holes configurations, the effect of increasing $d/t$ to SCF can be neglected. Eq.(2) gives a guideline in employing the SCF results to calculate the allowable stress, $\sigma_{all}$, in designing a spherical pressure vessel.

References

Figure 3. Stress concentration factor for two adjacent holes.

Figure 4. Stress concentration factor for three adjacent holes with right angled triangular configuration.

Figure 5. Stress concentration factor for three adjacent holes with triangular configuration.
Figure 6. Stress concentration factor for four adjacent holes with square configuration.

Figure 7. Stress concentration factor for five adjacent holes with square configuration.

Figure 8. Stress concentration factor for five adjacent holes with pentagonal configuration.