CROSS BORE SIZE AND THICKNESS RATIO EFFECTS ON STRESS DISTRIBUTION ALONG THE TRANSVERSE PLANE OF A RADIAL CIRCULAR CROSS BORE IN ELASTIC PRESSURIZED PRESSURE VESSELS

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ABSTRACT

The effects of the size of the cross bore and the ratio of vessel thickness on hoop stresses and stress concentration factors were studied across the transverse edge of radial circular cross bore. The analysis was done on seven vessels with a radial cross bore having the ratio of thickness ranging between 1.4 and 3.0 using finite element method. The investigation was done in five radial plain circular cross bores with bore ratio of 0.1, 0.3, 0.5, 0.7 and 1.0. In general, the hoop stress magnitudes of the plain cylinder were lower than those given by the cross bored cylinder. It was further noted that vessels with thickness ratio of 1.4 and 3.0 gave the highest and the lowest magnitude of hoop stresses, respectively. The hoop stress increased with increasing cross bore size, irrespective of the ratio of vessel thickness. At the intersection of the cross bore, the bore ratio of 0.1 and 1.0 gave the lowest and the highest hoop stress magnitudes, respectively. Overall, the magnitude of stress concentration factor (SCF) in cross bored vessels was greater than that of plain cylinder across the cylinder thickness. Similar to the hoop stress, as the cross bore size increased, the corresponding SCF magnitude also increased; particularly in the areas in close proximity to the cross bore. For the whole range of thickness, the SCF at the intersection for the smallest cross bore size ratio of 0.1 were found to be $2.5 < SCF < 3.04$, whereas, the SCFs magnitude of the other sizes of the cross bore exceeded to 3.04 at the bore intersection.

KEYWORDS: Pressure vessels, Cross bores, Hoop stresses & Stress concentration Factor

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1. INTRODUCTION

Pressure vessels store large amount of energy at extreme pressures and temperatures. Typical applications of pressure vessels are in thermal power plants, process and chemical industries (Kihui, 2002).

Openings or holes commonly referred to as cross bores that are constructed in the walls of pressure vessels for provision of fitting operation and maintenance accessories. Cross bores are forms of geometric discontinuity that give rise to local stress disturbances of an otherwise uniform stress distribution across the vessel thickness (Nziu and Masu 2019a). This disturbance of stress distribution creates regions of high stress concentration. Unfortunately, high magnitude of hoop stress concentration in cylinders is one of the causes of fatigue failures, fractures and premature yielding (Nziu and Masu 2019b).

The configuration of the cross bore geometry depends majorly on its size, shape, location and obliquity. Various terminologies used in cross bore configuration geometry have been discussed in a recent study by Nziu and Masu (2019c). For instance, whenever the cross bore is located at the centroidal axis of the vessel, it is referred to as radial. Alternatively, in any other chord the cross bore is termed as being offset or oblique.

Stresses resulting from drilling of radial circular cross bore in pressure vessels have been reported to have

high magnitudes across the edge AA of the cross bore as indicated in Figure 1.

Figure 1: Configuration Showing Transverse Plane AA of a Circular Radial Cross Bore.

However, the hoop stress effects across the transverse plane of the cross bore as the size of the radial circular cross bore increases is not well established. Therefore, this study seeks to determine the effects of the size of the cross bore together with vessel thickness ratio on hoop stresses and stress concentration factors (SCF), across the cross bore transverse edge AA.

2. METHODOLOGY

The following closed end pressure vessels with ratio of thickness of $K = 1.4, 1.5, 1.75, 2.0, 2.25, 2.5$ and 3.0 , having a radial circular cross bore were analysed. The ratio of thickness was calculated by dividing outer and bore diameters of the vessel. For uniformity, the main bore diameter of 0.05 m was kept constant throughout the analyses. The study was done on five radial circular cross bores with bore ratios of $0.1, 0.3, 0.5, 0.7$ and 1.0 . The bore ratio was calculated by dividing respective cross bore and main bore diameters.

2.1 Finite Element Method

Three-dimensional Finite Element Analyses (FEA) was done using Abaqus commercial engineering software on the aforementioned cylinders. Owing to the configuration of the structure of the cross bored pressure vessel, only $1/8$ of the vessel structure was analysed. Figure 2 illustrates a sample of the model profile created.

Figure 2: A Sample of Model Profile.

Figure 3: A Sample of Mesh Profile.

To restrict any rotation or displacement of the model, respective boundary conditions were placed at the axes of the cut sections of the model. After which, internal pressure was applied at both the main bore and the cross bore. In addition, displacement in the Z axis direction at the far end of the cylinder was constrained from moving, thus simulating the end effects generated by the end closed enclosures.

Two mesh refinement techniques, h and p were used to mesh the model. For h refinement, the meshing of the model was achieved by partitioning the model into smaller parts. Besides, the mesh density close to the cross bore region was increased so as to capture localised hoop stresses, whereas, for p refinement second order, 20-noded brick elements were chosen for all the analyses as recommended in the guidelines of Abaqus software. The convergency of the mesh was found to occur when the element size ranged between 0.003 m and 0.004 m. A sample of meshed profile is exemplified in Figure 3.

2.2 Validation of the FEA Model

The validation of the results as well as the mesh convergency was done in accordance with St Venant principle (Masu, 1989). It is worth noting that the cross bore effects are limited to a linear distance not exceeding three times the cross bore diameter. The FEA results of the areas far away from the cross bore were compared with corresponding analytical results from the same areas. Further validation of the created model was also done by comparing the FEA model results with similar ones presented in the literature, particularly the experimental data.

3. RESULTS AND DISCUSSIONS

The results presented in this section were analysed across the cross bore transverse edge A-A as indicated in Figure 1, under the following subheadings:

3.1 Cross Bore Size and Thickness Ratio Effects on Hoop Stresses

Hoop stresses across the transverse plane of the cross bore for the five studied cross bore sizes and that of plain cylinder, are presented in Figures 4 to 10 for $K = 1.4, 1.5, 1.75, 2.0, 2.25, 2.5$ and 3.0 .

Figure 4: Thickness Ratio of 1.4.

Figure 5: Thickness Ratio of 1.5.

Figure 6: Thickness Ratio of 1.75

Figure 7: Thickness Ratio of 2.0.

Figure 8: Thickness Ratio of 2.25.

Figure 9: Thickness Ratio of 2.5.

Figure 10: Thickness Ratio of 3.0.

In general, the hoop stress magnitudes of the plain cylinder were lower than those given by the cross bored cylinder. The high and low magnitudes of hoop stresses were observed in vessels having thickness ratio of 1.4 and 3.0, respectively. This occurrence was attributed to the structural stiffness of the vessel. Notably, the stiffness of the structure reduces with reduction in ratio of thickness leading to higher magnitudes of hoop stresses and vice versa.

Further, as indicated in Figures 4 to 10, when compared with plain cylinder, the hoop stress was noted to increase due to the presence of the cross bore. The magnitude of the hoop stresses was seen to increase with increasing size of the cross bore, particularly at the cross bore intersection. Generally, whenever large cross bores are constructed, they leave very little material to carry the applied load. This results to tremendous increase of hoop stresses which can cause failure.

With exception of $K = 1.4$, the hoop stress magnitudes reduced gradually towards the vessel outside surface, though their magnitudes were higher than those of a plain cylinder. In contrast, for $K = 1.4$, the magnitude of hoop stress was found to be compressive at radius 0.0345 m with a magnitude of -0.0738 . Suggesting an existence of stress peak where the stress state changes.

For the ratios of vessel thickness of 1.4, 1.5 and 1.75 having bore ratio of 0.1, the hoop stress peaks occurred away from the cross bore intersection at an approximate distance of 1.25 mm from intersection. Respectively, the magnitude of these peak stresses were higher by 2.13%, 1.63% and 3.96%, when compared with corresponding stresses at the cross bore intersection. This observation was as a result of stress redistribution as the change in state of stress occurs. Probably, a change from plane stress to plane strain. This observation was similar to that presented in Masu (1989) work.

An analysis showing the maximum percentage increase of the hoop stresses in the cross bored cylinder in reference to that of a similar plain cylinder is presented in Table 1.

Table 1: Increase in the Hoop Stress as a Result of Cross Bore Introduction

K	Percentage Increase of the Hoop Stress for each Bore Ratio				
	0.1	0.3	0.5	0.7	1.0
1.4	188.83	266.88	398.92	535.7	669.48
1.5	198.43	248.84	357.69	480.76	638.26
1.75	208.7	224.87	301.0	394.92	534.52
2.0	192.14	216.14	266.52	338.5	456.69
2.25	183.5	210.32	248.53	303.49	402.01
2.5	186.75	207.75	236.71	280.16	361.84
3.0	204.8	206.4	221.6	248.0	304.72

The trend of hoop stress magnitude noted in table 1, further confirms that the stiffness of the vessel structure depends on the size of the cross bore and its ratio of thickness.

3.2 Cross Bore Size and Thickness Ratio Effects on Hoop Stress Concentration Factor

The SCF was calculated by dividing localised hoop stresses in a vessel having a cross bore with the corresponding hoop stresses in plain vessel (Ford and Alexander, 1977). It is worth noting that in cylindrical pressure vessels having a cross bore, the magnitude of the largest hoop stress does not always occur at the intersection with the main bore (the nominal area), hence necessitating this form of SCF definition. Therefore, for a plain cylinder the SCF at any particular radius is unity. Further, the SCF definition shows the intensity of stress concentration at each particular point, across the transverse edge of the cross bore.

Graphs illustrating the SCF across the transverse edge of the cross bore for each thickness ratio are presented in figures 11-17 for K = 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0.

Figure 11: Thickness Ratio of 1.4.

Figure 12: Thickness Ratio of 1.5.

Figure 13: Thickness Ratio of 1.75.

Figure 14: Thickness Ratio of 2.0.

Figure 15: Thickness Ratio of 2.25.

Figure 16: Thickness Ratio of 2.5.

Figure 17: Thickness Ratio of 3.0.

From Figures 11 to 17, it can be seen that the magnitude of the SCF is greater than unity, that of plain cylinder across the thickness of the cylinder. Similar to the preceding section, the SCF magnitude increased with cross bore size

increase, particularly in the close proximity regions of the cross bore.

Further, two distinct SCF stress patterns were realized, for $K = 1.4, 1.5$ and 1.75 , the SCF magnitudes reduced towards the outside surface of the cylinder. In contrast, in most of the other thickness ratios, the SCF magnitudes increased away from the intersection until it reached a peak value, and then they started to reduce gradually. Though, the SCF magnitude was depended on the size of the cross bore, the observed trend of SCF was attributed to the increase of cylinder thickness ratio enabling variation in state of stress from plane stress to plane strain.

Normally, fatigue and other related failures initiate at points with magnitudes of high hoop stresses and SCF. Nonetheless, these two conditions are satisfied mainly at the cross bore intersection. This observation explains the reason why most studies in the literature focused more on the SCF research at the cross bore intersection. In this study, the magnitude of the SCF at the cross bore intersection for the smallest bore ratio of 0.1 was $2.5 < SCF < 3.04$. This SCF range was in favorable agreement with other previous studies (Ford and Alexander, 1977; Faupel and Harris, 1957; Masu, 1989). For instance, the analytical solution for small circular cross bores predicted by Ford and Alexander (1977) study gave a SCF magnitude range for all the thickness ratios studied in this work from 2.9 to 3.7 . Faupel and Harris (1957) gave SCF magnitude of 2.5 for a plain circular cross bore regardless of its size. Whereas, Masu (1989) gave a SCF of 3.03 for a small radial plain circular cross bore. Unfortunately, strict comparison could not be done since parameters such as the cross bore size were not the same. Nevertheless, the SCF magnitude of the other studied cross bore sizes exceeded 3.04 .

4. CONCLUSIONS

- The magnitude of hoop stress of the plain cylinder was lower than those given by the cross bored cylinders.
- The high and low magnitudes of hoop stresses were observed in vessels with $K = 1.4$ and 3.0 , respectively.
- The largest hoop stress increased with increasing size of the cross bore. At the cross bore intersection, the highest bore ratio of 1.0 , gave the highest hoop stresses. Whereas, the lowest stresses occurred in bore ratio of 0.1 .
- The magnitudes of the SCFs given by the cross bored cylinders are greater than that of plain cylinders. In addition, the magnitude of the SCF increased with increase in the size of the cross bore; particularly in the regions in close proximity to the cross bore.
- In all the thickness ratios, the SCFs for the smallest bore ratio 0.1 at the intersection were found to be $2.5 < SCF < 3.04$. For other cross bore sizes ratios studied the SCF magnitude was found to be > 3.04 at the intersection of the cross bore.

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