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Original Article

Elastic Working Stresses in High-pressure Vessels with an Offset Oblique Cross Bore

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Abstract *- The purpose of this study was to investigate the effects of oblique offset cross bore on elastic working stress in high-pressure vessels. A total of 140 different axisymmetric models were created and analysed in this work using finite element analysis commercial software Abaqus. Results from most of the cylinders studied revealed that the lowest working stresses predicted by both Tresca's and Von Mises's elastic failure theories occurred at an oblique angle of* 0^0*, with the exception of thickness ratios of 1.4, 1.5 and 2.0, which had their minima at* 15^0*. Moreover, the highest magnitudes of working stresses were noted at an inclination angle of* 60^0 *for all thickness ratios studied, apart from K = 2.0, which occurred at* 45^0*. Finally, it was established that a pressure carrying capacity ranging from 173.7% to 559.8% and 161.9% to 531.5% for Tresca's and Von Mises working stresses, respectively, can be reclaimed whenever the cross bore is positioned appropriately at the region of lowest working stresses.*

Keywords *- High-pressure vessels, Oblique angle, Offset location ratio, Working stresses.*

1. Introduction

High-pressure vessels store large amounts of energy at high pressures and temperatures. The design of pressure vessels is done using various scientific theories such as elastic, elastic-plastic and plastic [1], with the former being commonly used in many industrial applications [2]. Elastic failure theories, namely Tresca's and Von Mises's, are used to determine the safe working pressures despite their respective solutions having a difference of 15.5% in the analysis of plain cylinders [3].

Cross bores are openings drilled in the cylinder's surface to provide fitting essential accessories such as pressure gauges, manholes, hand holes, and lubrication holes, among others. However, drilling these cross bores creates regions of high-stress concentration, leading to the reduction of pressure holding capacity by up to 60% [4] and the use of high safety factors ranging from 2 to 20. The severity of this stress concentration depends on the configuration parameters of the cross bore. The main cross-bore configuration parameters are the size, shape, location and obliquity (also known as inclination). The following is a brief description of these parameters [1].

The size of the cross bore is categorised as either small or large. A small cross bore has the diametrical ratio of the cross bore and that of the main bore ≤ 0.5. Meanwhile, the same corresponding ratio is >0.5 for a large cross bore. The common shapes used for the cross bore are circular and elliptical. However, some studies have also analysed the effects of using notches as openings in the design of pressure vessels [2].

Additionally, the cross bore's location can be categorised as radial or an offset. A cross bore is termed to be radial whenever the main bore axis intersects with that of the cross bore. Some studies refer to the position of radial cross bores as zero offset. Alternatively, if the axis between the cross bore and the main bore is not intersecting, then the cross bore is referred to as being offset [5]. Actual offset positions are sometimes converted to offset location ratios by dividing the actual offset distance $\bar{x}$ and the main bore radius R_i, i.e., $\bar{x}/R_i$ (see Figure 1). This approach allows for easier comparison with other existing literature. Lastly, the cross bore is referred to as oblique whenever it is drilled in the axis of the RZ plane of the cylinder (see Figure 2).

Numerous studies have investigated the effects of these cross-bore configuration parameters on both stress concentration and elastic strength in high-pressure vessels [1], [5-9]. However, most of these studies focused on the effects of cross-bore size, shape and location on stress concentration in thick cylinders. Very little research has been done on the effects of cross-bore obliquity.

Table 1. Cylinder thickness ratio and cross-bore configuration

Cylinder thickness ratio K	1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0
Cross bore shape	Circular
Cross-bore size ratio	0.1
Cross-bore offset ratio $\bar{x}/R_i$	0, 0.24, 0.48 and 0.685
Cross oblique angle α	0^0, 15^0, 30^0, 45^0 and 60^0

Little and Bagci [10] study reported that small inclined cross bores in the transverse plane generate positions of major and minor axes on the main bore of the cylinder. Whenever the major axis is perpendicular to the Z direction, the maximum stresses occur at both ends of the major and minor axes. The same study also reported that small, inclined cross bores in the longitudinal plane have their major axis parallel to the Z direction. Therefore, maximum SCF occurs only at the ends of the major axis and was given by;

$$\mathrm{SCF} = \frac{4\mathrm{C}\mathrm{R}_2^2+\mathrm{R}_1^2}{\mathrm{R}_2^2+\mathrm{R}_1^2} \quad (1)$$

Where C is the ratio of the major and minor axes of the ellipse (Ellipticity), R1 is the cylinder's inside radius, and R2 is the cylinder's outside radius.

Cole [11] reported that an optimum oblique cross bore at a radial position gave lower working stresses by nearly 48% than a similar circular radial cross bore at the same position. However, the study did not investigate the effects of an oblique cross bore on working stresses whenever the cross bore is placed in an offset position. Cheng [12] gave the analytical solution of SCF for closed-end cylinders at the ends of the major axis as;

$$\mathrm{SCF} = \frac{2(\mathrm{C}-1)\mathrm{R}_2^2+\mathrm{R}_1^2}{\mathrm{R}_2^2+\mathrm{R}_1^2} \quad (2)$$

While at the end of the minor axis,

$$\mathrm{SCF} = \frac{\left(4\mathrm{R}_2^2/\mathrm{C}\right)+\mathrm{R}_1^2}{\mathrm{R}_2^2+\mathrm{R}_1^2} \quad (3)$$

Nihous et al. [13] studied radial oblique cross-bores oriented at five different angles using a finite element analysis for various cross-bore sizes. The oblique angles studied were 30°, 45°, 60°, 75°, and 90°. These oblique angles were measured counterclockwise from the cylinder's longitudinal axis. The authors reported increased mesh element distortion whenever the obliquity angle was below 30°. In addition, it was observed that, as the oblique angle reduced from 90° to 30°, the SCF magnitude increased significantly. These reviewed studies only investigated the effects of cross-bore obliquity at the radial position. Information on the effects of an oblique cross bore when placed in an offset position is scanty.

Therefore, this study aimed to investigate the effects of oblique offset cross bores on elastic working stresses in high-pressure vessels to establish the optimal configuration.

2. Materials and Methods

The cross-bore configuration parameters were chosen, as shown in Table 1 and studied on seven different thick-walled cylinders with thickness ratios varying from 1.4 to 3.0. The choice of these parameters was made in line with previous literature by Cheng [12] and Nihous [13] (2008) studies.

The configuration design parameters of the cross-bore offset ratio and obliquity are illustrated in Figures 1 and 2, respectively.

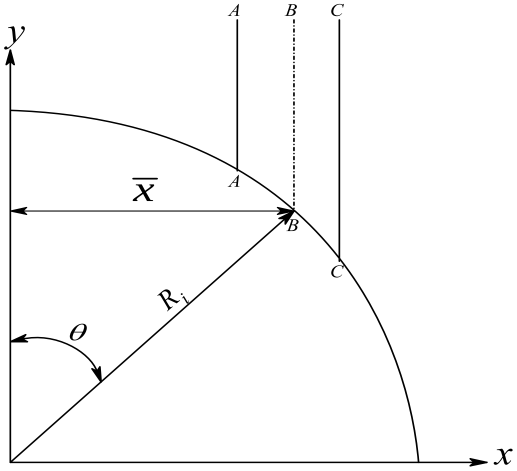

Fig. 1 Configuration of an offset cross bore

Where:

R_i is the internal radius of the main bore

$\bar{x}$ is the offset distance

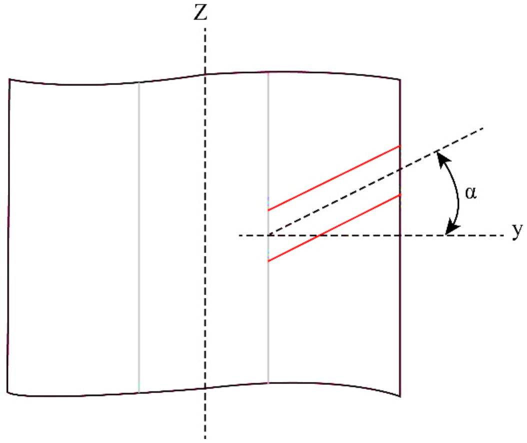

Fig. 2 Configuration of an oblique cross bore

Where α is the oblique angle

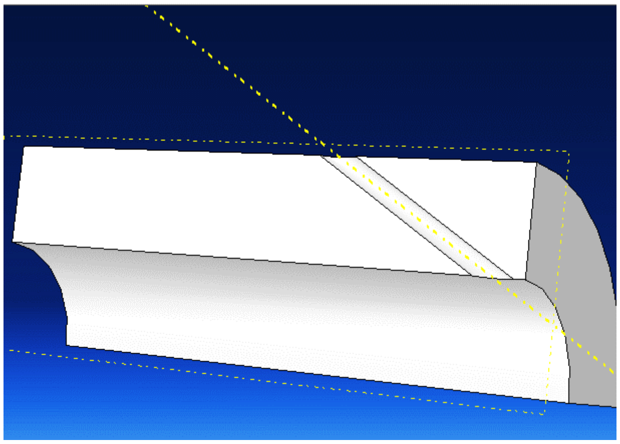

Fig. 3 Radial cross bored part profile

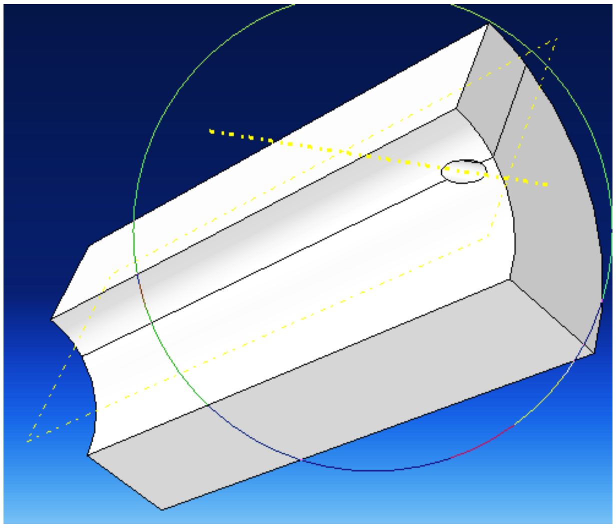

Fig. 4 Offset cross bored part profile

2.1. Finite Element Analysis

A total of 140 different axisymmetric part models were created and analysed using finite element analysis commercial software Abaqus. The cut-revolve technique tool embedded in the software created oblique circular cross bores. After this, full constraints were applied at each oblique angle, thus restricting any undesirable movement that could result in simulation errors. A sample of radial (zero offsets) and offset cross bored part profiles created is shown in Figures 3 and 4.The symmetrical boundary conditions were applied at each symmetrical axis to restrict any rotation or movement of the model. The model was then loaded with internal pressure at both the main bore and the cross bore. Further, restriction constraints were applied at the far end of the cylinder in the Z-axis direction. These restriction constraints simulate the end effects due to the end enclosures of the cylinder.

Second-order tetrahedral elements with 10-sided nodes were used to mesh the model due to the complexity of the geometry, thus eliminating the distortion of elements. In addition, the mesh density around the cross bore was biased to capture the localised elastic stresses.

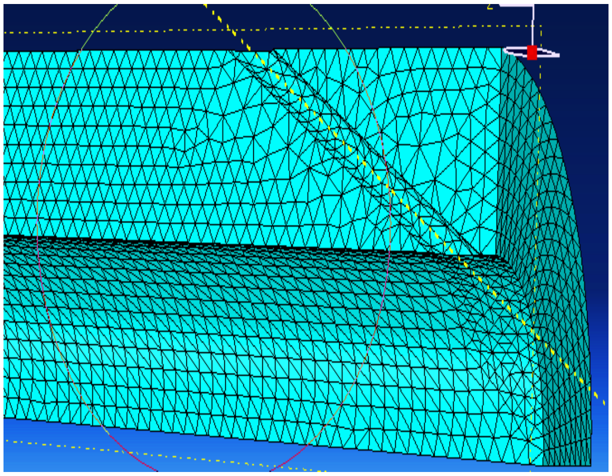

Fig. 5 Radial cross bored meshed profile

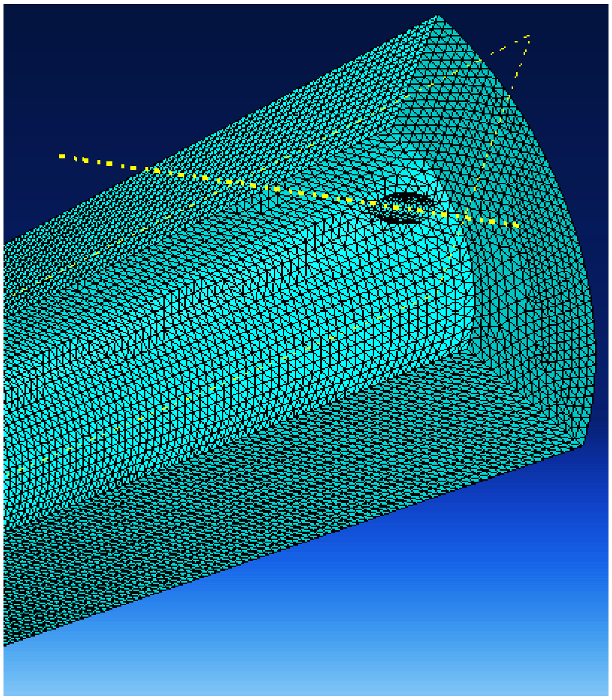

Fig. 6 Offset cross bored meshed profile

A sample of radial and offset cross bored meshed profiles created is shown in Figures 5 and 6.

This high mesh refinement with no element distortion ensured that the generated results had a high degree of accuracy. Moreover, the generated results were validated using two different methods. First, the FEA results obtained from areas far away from the cross bore were compared to their corresponding analytical results calculated based on Lame’s theory. Because the effect of a discontinuity such as a cross bore is presumed to be limited to the region around it; usually a distance of about 2.5 cross bore diameters. Secondly, the validation of the created model was also done by comparing the FEA model results with similar ones presented in the reviewed literature.

The complete Abaqus modelling procedure adopted in this work is presented elsewhere in doctoral thesis of author.

3. Results and Discussion

The effects of offset oblique cross bore on elastic working stresses per unit pressure for different sizes of cylinders are shown in Figures 7 to 20.

As indicated in Figures 7 to 20, similar stress profiles of Tresca and Von Mises's working stresses were exhibited in all thickness ratios despite the two methods predicting different magnitudes of working stresses. A sharp increase in working stresses was noted in K = 2.0 in an offset location ratio of 0.685 at an oblique angle of 45^0, implying a change of state of stress from plane stress to plain strain. This observation was attributed to the change of the cross bore shape from circular to an ellipse whenever the cross bore is viewed at the intersection of the cross bore and main bore. As reported by Nihous *et al.* [13], an ellipse-shaped cross bore with a major diameter less than the minor diameter leads to increased magnitudes of working stress and vice versa.

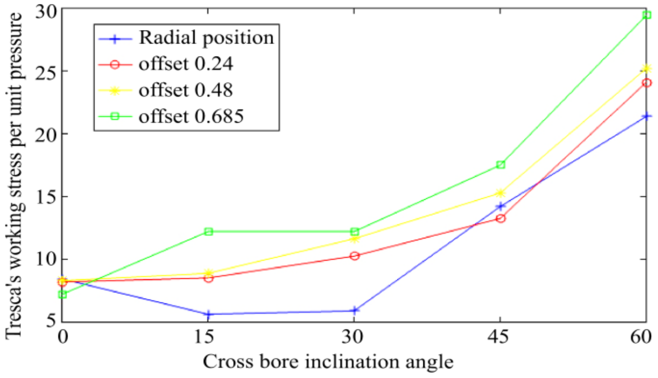

Fig. 7 Tresca's stress for K = 1.4

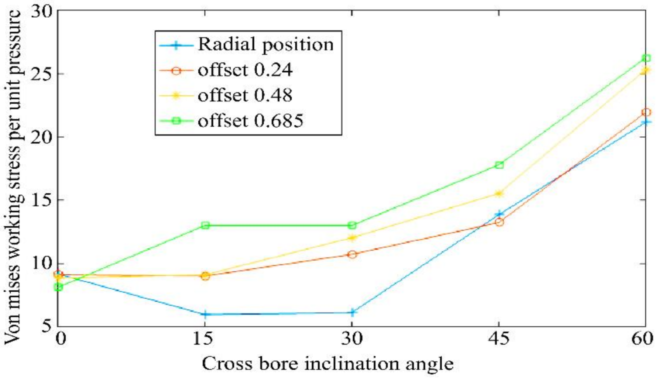

Fig. 8 Von Mises stress for K = 1.4

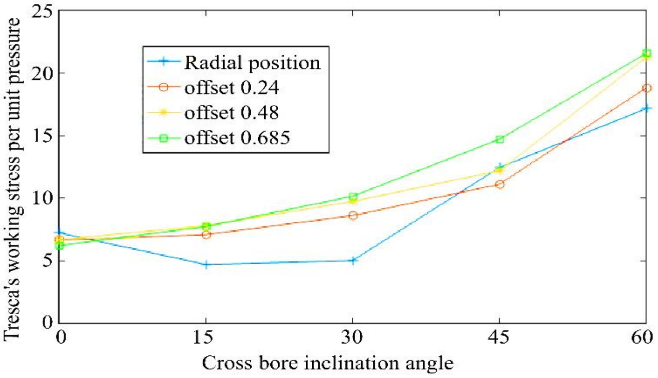

Fig. 9 Tresca's stress for K = 1.5

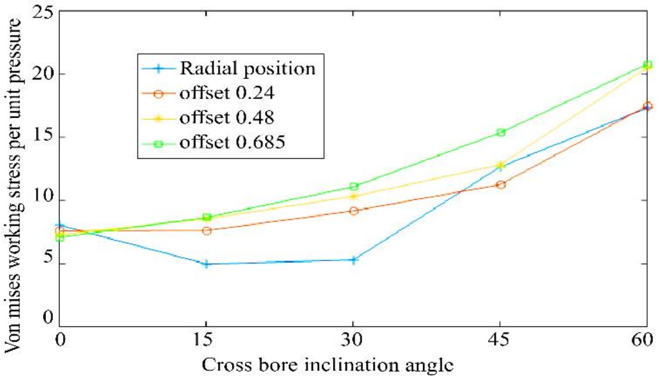

Fig. 10 Von Mises stress for K = 1.5

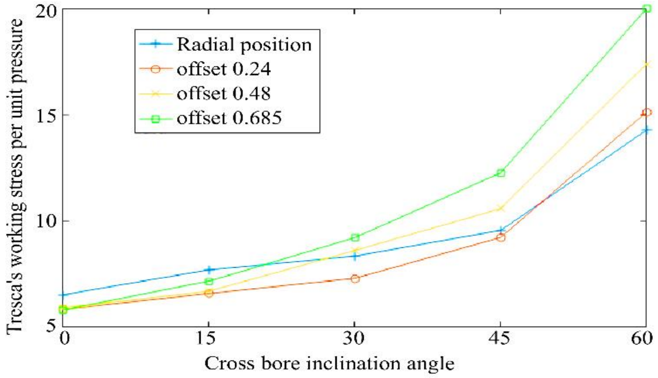

Fig. 11 Tresca's stress for K = 1.75

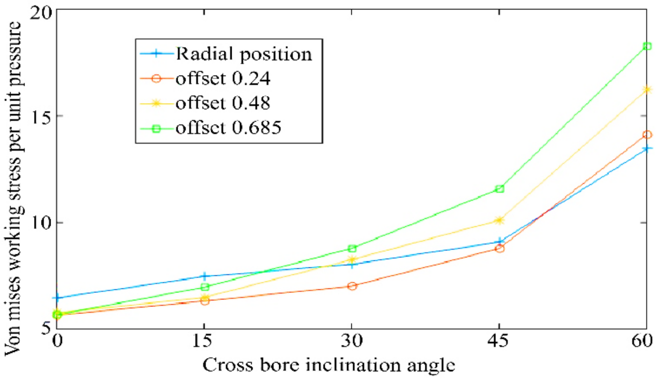

Fig. 12 Von Mises for K = 1.75

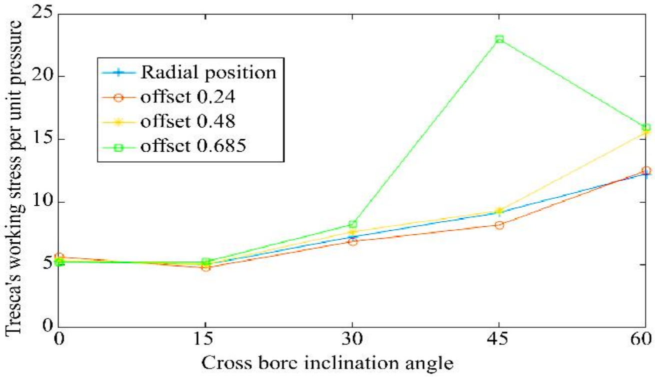

Fig. 13 Tresca's stress for K = 2.0

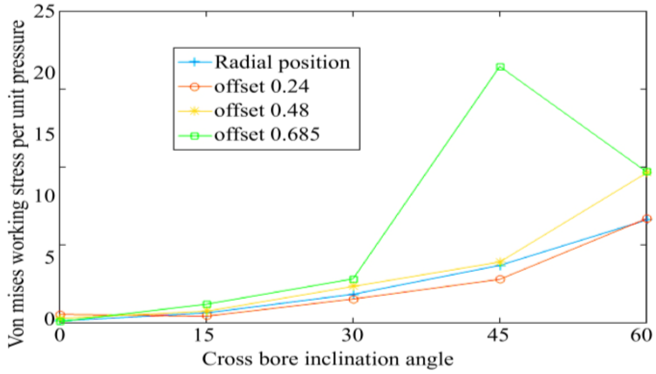

Fig. 14 Von Mises stress for K = 2.0

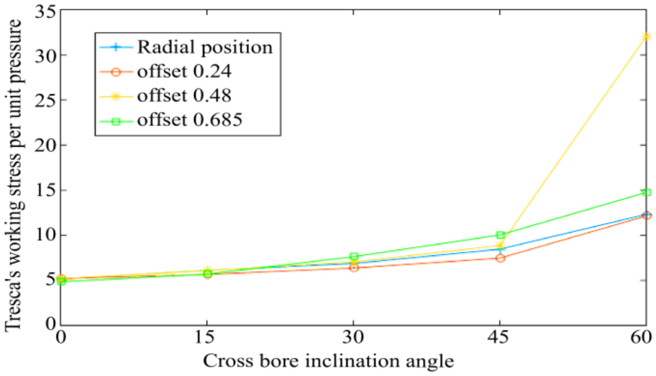

Fig. 15 Tresca's stress for K = 2.25

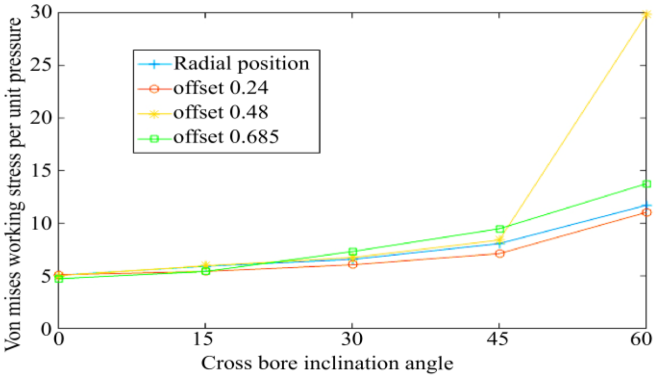

Fig. 16 Von Mises stress for K = 2.25

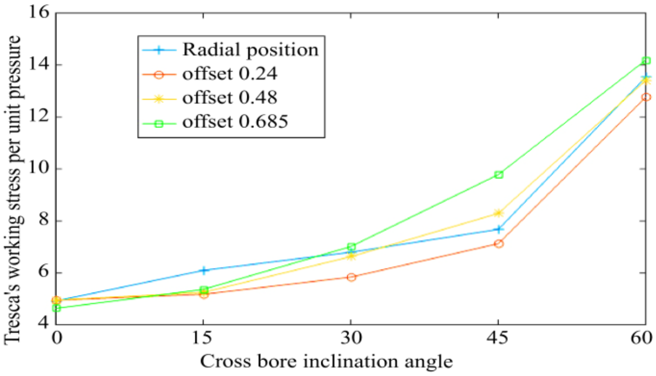

Fig. 17 Tresca's stress for K = 2.5

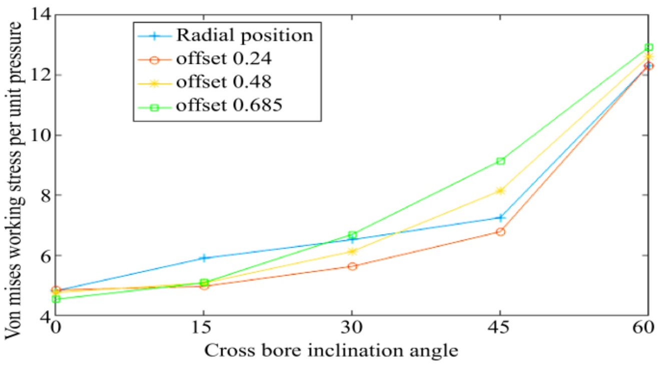

Fig. 18 Von Mises stress for K = 2.5

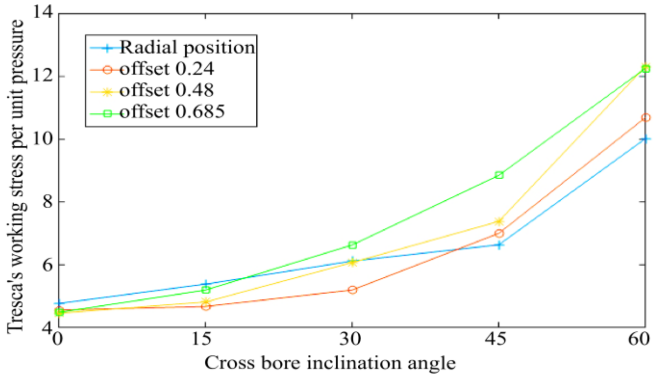

Fig. 19 Tresca's stress for K = 3.0

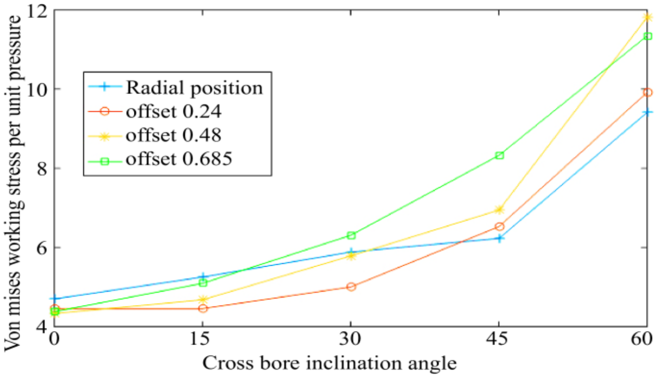

Fig. 20 Von Mises for K = 3.0

Table 2. Position of the lowest working stresses

Thickness	Location Ratio	Oblique Angle
1.4	Radial	15^0
1.5	Radial	15^0
1.75	0.685	0^0
2.0	0.24	15^0
2.25	0.685	0^0
2.5	0.685	0^0
3.0	0.48	0^0

With the exception of some instances at K = 1.4, 1.5 and 2.0 at an oblique angle of 15^0, the lowest working stresses predicted by the two theories generally occurred at the radial position at an oblique angle of 0^0. This observation further reaffirmed the finding of previous studies by Cole *et al.* [11] that the location of circular cross bores in an offset position gives lower working stresses by up to 170% than those at radial positions or inclined. On the other hand, the highest magnitudes of working stresses were noted at an inclination angle of 60^0 apart from K = 2.0, which occurred at 45^0. This assertion was similar to that cited in Cheng's [12] study.

Moreover, it was noted that the two elastic failure theories predicted the same location where the lowest working stresses occurred. However, the magnitudes of Tresca's stresses were lower than Von Mises. A summary showing the location and oblique angle having the lowest working stress magnitudes for each thickness ratio as predicted by the two theories of elastic failure is tabulated in Table 2.

Results presented in Table 2 imply that the cylinder's pressure-carrying capacity can be improved whenever the cross bore is located in a region with minimal working stress.

3.1. General Discussion of Results

In general, working stress in close regions where there is an abrupt change in shape, such as a cross bore, rises rapidly until the yield point is reached. This rise in stress causes yielding to occur, which in turn relieves a significant amount of stress in these regions. As long as the yielded region is confined within a continuous field of elastic stresses, the vessel will likely fail due to hydrostatic tensile stress rather than yielding. Therefore, as a remedy in the pressure vessel design, it is recommended that any inevitable discontinuities, like cross bores, should be positioned in regions where safe working stresses are as low as possible. This design approach leads to an increase in the pressure-carrying capacity of the cylinder.

Table 3. Reclaimed pressure whenever the cross bore is located at the lowest stress regions

Thickness	Type of Working Stress	Reclaimed Pressure
1.4	Tresca	354.2 %
	Von Mises	339.6%
1.5	Tresca	305.3%
	Von Mises	317.5%
1.75	Tresca	244.1%
	Von Mises	222.9%
2.0	Tresca	382.4%
	Von Mises	321.9%
2.25	Tresca	559.8%
	Von Mises	531.5%
2.5	Tresca	206.2%
	Von Mises	184.6%
3.0	Tresca	173.7%
	Von Mises	161.9%

Thus, the largest possible amount of pressure-carrying capacity that can be reclaimed by positioning the cross bore in the region of the lowest working stresses in place of other regions of high-stress magnitudes is presented in Table 3. From Table 3, it can be seen that pressure carrying capacity ranging from 173.7% to 559.8% and 161.9% to 531.5% for Tresca's and Von Mises working stresses, respectively, can be reclaimed whenever the cross bore is located at the region of the lowest working stresses.

4. Conclusion

- With the exception of instances at K = 1.4, 1.5 and 2.0 at an oblique angle of 15^0, the lowest working stresses predicted by the two theories generally occurred at the radial position at an oblique angle of 0^0.
- The highest magnitudes of working stresses were noted at an inclination angle of 60^0 for all thickness ratios studied, apart from K = 2.0, which occurred at 45^0.
- Pressure carrying capacity ranging from 173.7% to 559.8% and 161.9% to 531.5% for Tresca's and Von Mises's working stresses can be reclaimed whenever the cross bore is located at the region of the lowest working stresses.

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