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Effects of Offset Oblique Circular Cross Bores on Elastic Pressurized Thick-Walled Cylinders

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Abstract

The purpose of this study was to determine the effects of offset oblique circular bores on elastic hoop stress and stress concentration factor. The effects of radial and offset oblique circular cross bore was investigated on seven different thick walled closed cylinders with thickness ratios ranging from 1.4 to 3.0. The studied location ratios were 0, 0.24, 0.48 and 0.685, whereas the orientation of the oblique angles $\boldsymbol{\alpha}$ were of 0^0,15^0, 30^0, 45^0 and $60^{0.}$ A total of 140 different finite element analysis part models having both radial and offset oblique cross bores were created and analyzed using Abaqus software version 2020. In most of the studied cases, it was established that as the oblique angles increased from 0^0 to 60^0, the magnitude of the hoop stress increased progressively as the offset ratio increased. The furthest offset location ratio with highest magnitude of 0.685 gave the lowest hoop stress magnitude at the radial position. Generally, the lowest hoop stress magnitudes occurred in thickness ratios of 1.4 and 1.5 when the radial cross bores were inclined at 15^0 and 30^0, respectively. Besides, the overall lowest SCF magnitude of 1.814 occurred when the cross bore was positioned radially at an oblique angle of 15^0 in a thickness ratio, K = 1.5.

This optimal SCF magnitude indicated a reduction of pressure carrying capacity of 44.8% in comparison to a similar plain cylinder without a cross bore.

Keywords: Offset oblique cross bores, finite element analysis, hoop stress, stress concentration factor

INTRODUCTION

High pressure vessels are used to hold large amounts of energy at extreme temperatures and pressures (Kihiu and Masu, 1995). Most designs of high pressure vessels strive to improve the holding energy capacity. However, there are some inevitable design features such as holes, commonly referred to as cross bores which are drilled on the wall surface of the pressure vessel to provide the provision of fitting operational and maintenance accessories (Masu, 1989). These accessories include temperature and pressure gauges, lubrication, maintenance and routine inspection manholes etc.

Unfortunately drilling of these cross bores is associated with tremendous increase in hoop stress in the cylinder especially in the region with close proximity to the cross bore. This leads to reduction of the allowable safe holding pressure capacity by up to 60% (Cole *et al,* 1976). More so, high stresses are associated with common design problems such as premature yielding, fatigue and fracture failures (Ford and Alexander, 1977).

To optimise the holding capacity of cross bored pressure vessels, numerous researches have been carried out to investigate the effects of the cross bore geometry with the aim of establishing the optimum geometry that gives minimum hoop stresses (Nziu, 2018). These studies have been done mainly on the effects of the cross bore geometry features such as the size, location, shape and obliquity. These design terminologies used in cross bored cylinders are detailed in Kiplagat et al. (2020) study.

Studies on the effects of cross bore obliquity on hoop stresses and stress concentration have been done majorly on radial circular cross bore (Cheng, (1978); Nihious *et al.* (2008)). Nonetheless, there is very scanty information on the effects of offset oblique cross bores on stress concentration.

Therefore, this study seeks to establish the effects of offset oblique circular cross bores on hoop stress and stress concentration factors (SCF) on various cylinders with different thickness ratios.

METHODOLOGY

Cylinder and cross bore sizes

Seven different thick walled closed cylinders with thickness ratio of 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0 were investigated. Throughout the investigation, both the sizes of the main bore and the circular cross bore were kept constant to provide effective comparison between different designs. The actual size of the main bore was 0.05 m, whereas, the cross bore size ratio (cross bore to main bore size) was 0.1.

Location of the cross bore

The cross bore was positioned at both radial and offset locations along the X axis plane of the cylinder, as illustrated in Figure 1. In order to compare the results directly with the existing literature, the actual offset positions were converted to offset location ratios by dividing the actual offset distance $\bar{x}$ and the main bore radius R_i, i.e., $\bar{x}/R_i$. The studied offset location ratios were 0, 0.24, 0.48 and 0.685.

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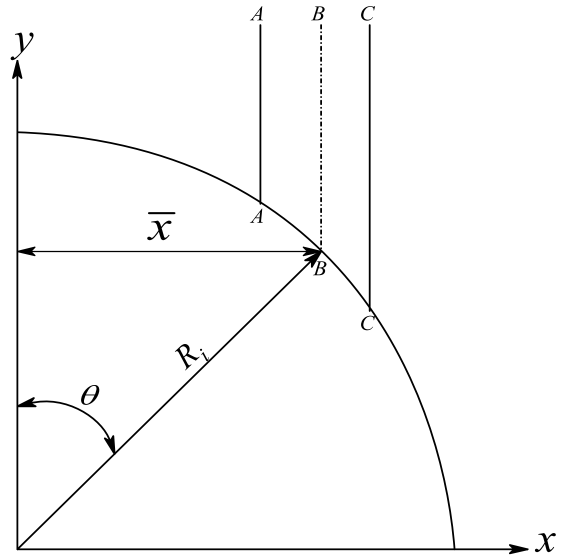

Figure 1: Configuration of an offset cross bore

R_i is internal radius of the main bore

$\bar{x}$ is the offset distance

Cross bore obliquity

Five different oblique angles α with orientation of 0^0,15^0, 30^0, 45^0 and 60^0 as shown in Figure 2 were studied on the aforementioned thickness and offset ratios.

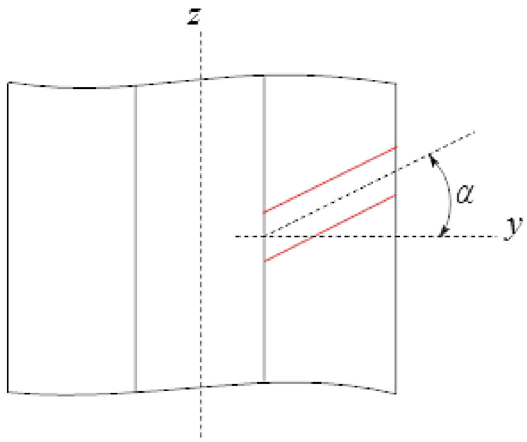

Figure 2: Oblique cross bore

Where α is the oblique angle

The first four inclination angles, were chosen to coincide with those investigated by Cheng (1978) and Nihous *et al.* (2008) on radially positioned cross bores for comparison with the current study. Oblique angles exceeding 60^0 were found to cause severe mesh element distortion. Usually, distortion of elements occurs when the software tolerances are exceeded leading to premature termination of the job analysis. Similar findings had also been reported by Nihous *et al.* (2008) study. It is worthwhile to note that, only sizeable oblique angles, which allow the considerable penetration of the cross bore to the main bore, are applicable.

Finite Element Analysis

A total of 140 different part models having both radial and offset oblique cross bores were created and analysed. The oblique circular cross bores were created using the cut revolve tool technique. The axis of the cross bore geometry was fully constrained at each angle of inclination to avoid any modelling errors. A sample of radial and offset cross bored part profiles created is shown in Figures 3 and 4.

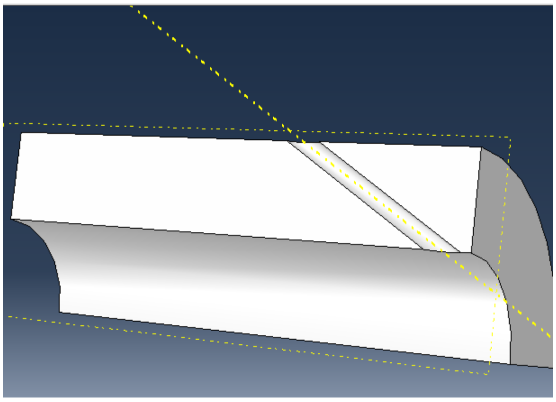

Figure 3: Radial cross bored part profile

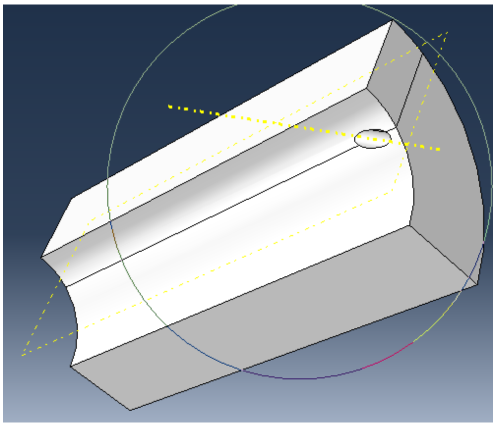

Figure 4: Offset cross bored part profile

The symmetrical boundary conditions were applied at each symmetry axis to restrict any model rotation or movement. The model was then loaded with internal pressure at both the main bore and the cross bore. Besides, the displacement in the Z axis direction (see Figure 2) at the far end of the cylinder was constrained to simulate the end effects of the closed end enclosures.

The density of mesh around the cross bore was increased to capture the localised hoop stresses. Due to the complexity of the geometry only second order tetrahedral elements having 10 sided nodes were used for meshing to avoid excessive element distortion. A sample of radial and offset cross bored meshed profiles created is shown in Figures 5 and 6.

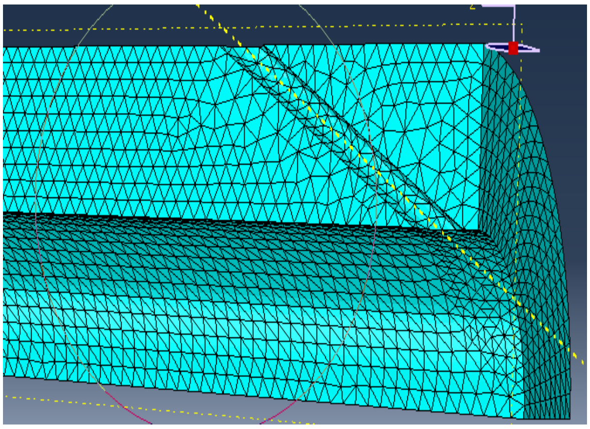

Figure 5: Radial cross bored meshed profile

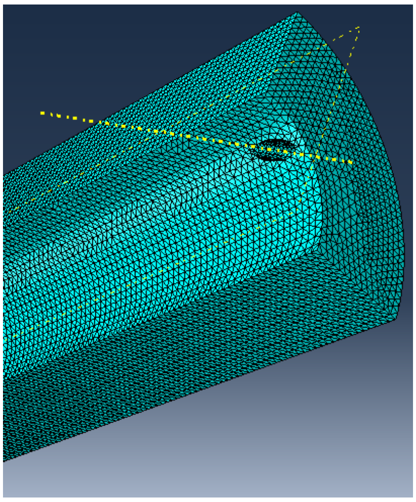

Figure 6: Offset cross bored meshed profile

The complete Abaqus modelling procedure adopted in this work is detailed in Nziu (2018) doctoral thesis.

Validation of FEA

The validation of the FEA results was done by comparing FEA results obtained from areas far away from the cross bore to their corresponding analytical results calculated based on Lame's theory. Further validation of the created model was also done by comparing the FEA model results with similar ones presented in the reviewed literature.

RESULTS AND DISCUSSION

The effects of offset oblique cross bore on hoop stresses in different sizes of cylinders are shown in Figures 8 to 14.

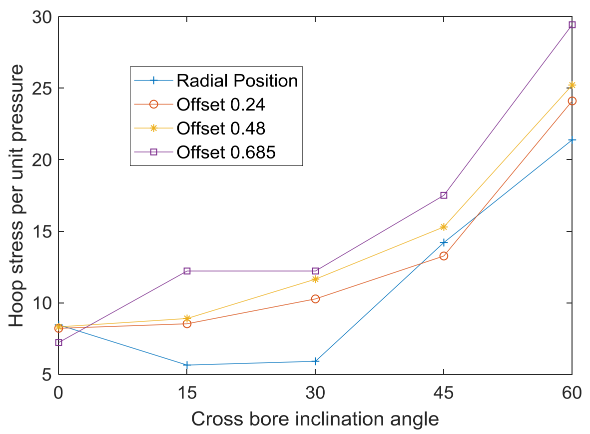

Figure 8: Hoop stress vs oblique cross bores for K = 1.4

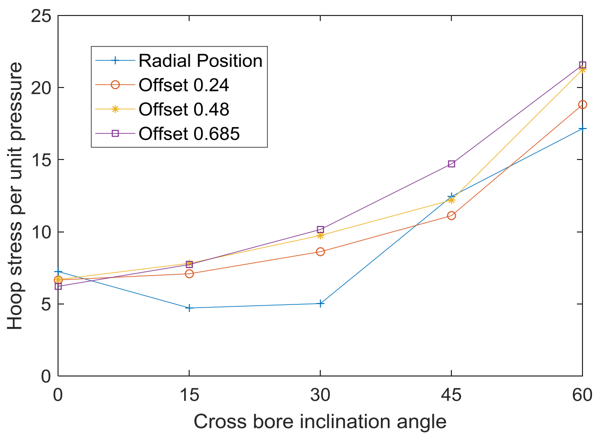

Figure 9: Hoop stress vs oblique cross bores for K = 1.5

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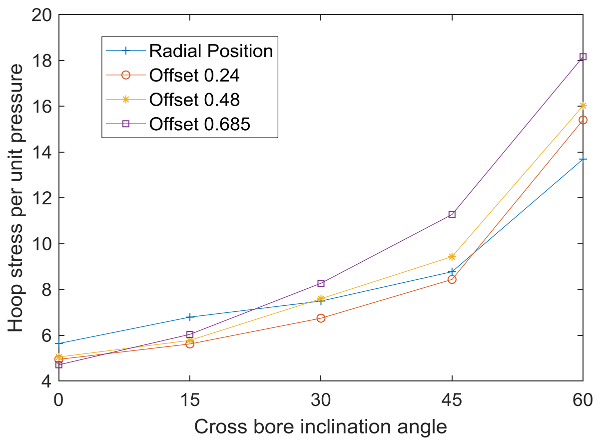

Figure 10: Hoop stress vs oblique cross bores for K = 1.75

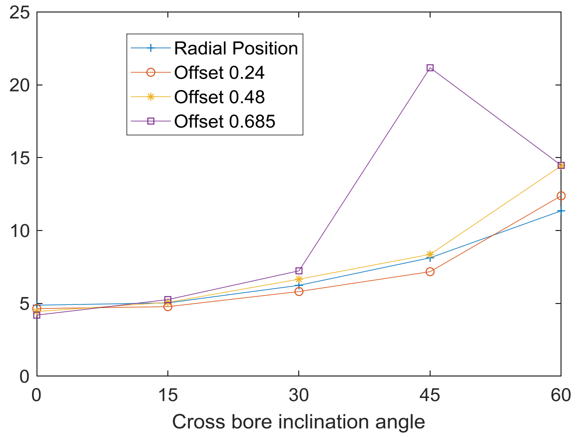

Figure 11: Hoop stress vs oblique cross bores for K = 2.0

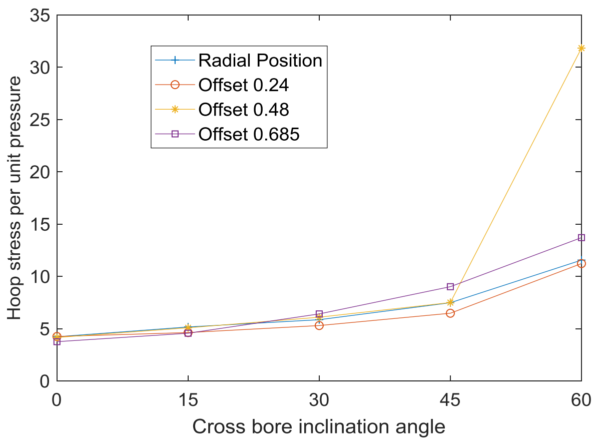

Figure 12: Hoop stress vs oblique cross bores for K = 2.25

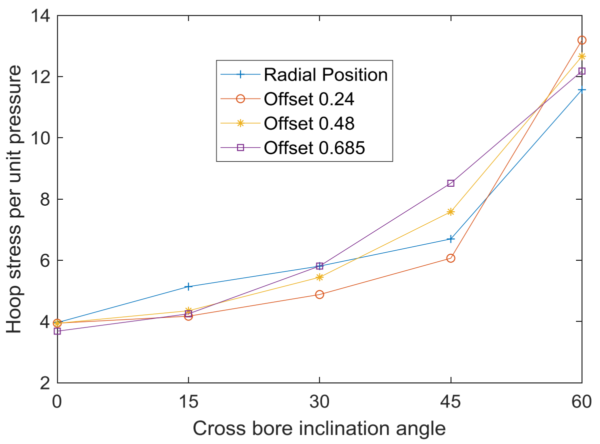

Figure 13: Hoop stress vs oblique cross bores for K = 2.5

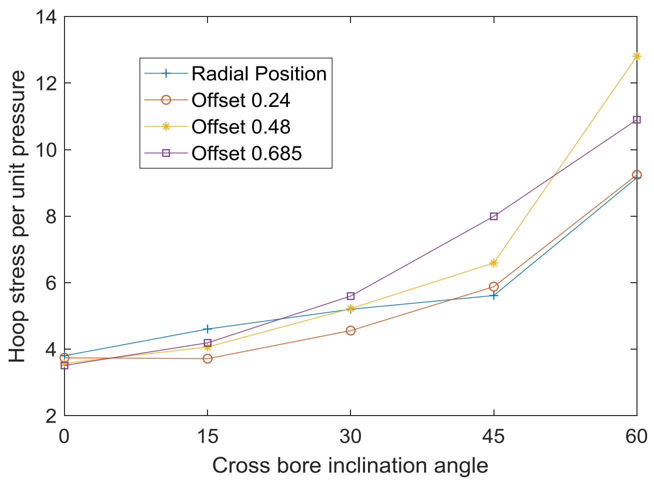

Figure 14: Hoop stress vs oblique cross bores for K = 3.0

It was observed in Figures 8 to 14 that as the oblique angles increased from 0^0 to 60^0, the magnitude of the hoop stress increased progressively as the offset ratio increased, in most of the studied cases.

The furthest offset location ratio with highest magnitude of 0.685 gave the lowest hoop stress magnitude at the radial position, similar to an earlier finding by Cole et al (1979) study. Conversely, this 0.685 offset ratio also gave the highest hoop stress magnitudes at oblique angle of 60^0 between thickness ratios of 1.4 and 2.0. On the other hand, beyond cylinder thickness ratio of 2.0, the offset ratio of 0.48 gave the highest stress magnitudes as seen in figures 12 to 14. Noticeably, the overall lowest hoop stress magnitudes occurred in thickness ratios of 1.4 and 1.5 when the radial cross bores where inclined at 15^0 and 30^0.

Effects of offset oblique cross bore on stress concentration factor

The Stress Concentration Factor (SCF) was calculated by dividing localised hoop stresses in a cross bored pressure vessel with the corresponding hoop stresses in a similar plain pressure vessel without a cross bore (Ford and Alexander, 1977). Since 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, usually referred to as the nominal area. Hence necessitating this type of SCF definition.

The effects of offset oblique cross bore on hoop SCF in different sizes of cylinders are shown in Figures 15 to 21.

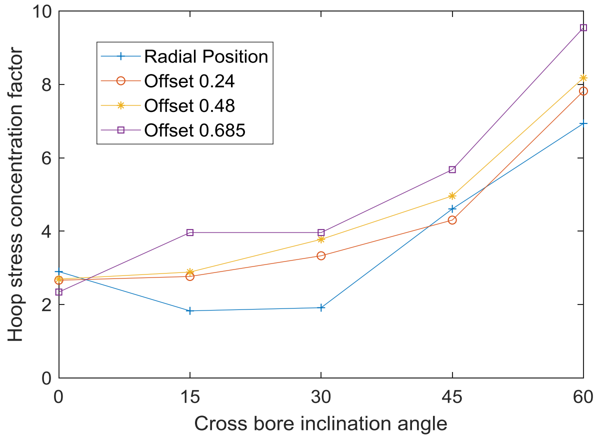

Figure 15: Hoop SCF vs oblique cross bores for K =1.4

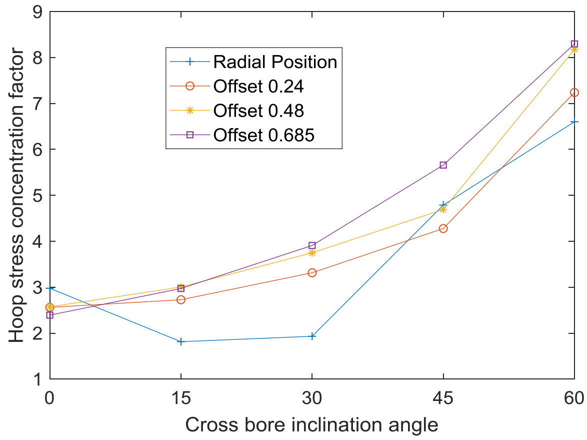

Figure 16: Hoop SCF vs oblique cross bores for K =1.5

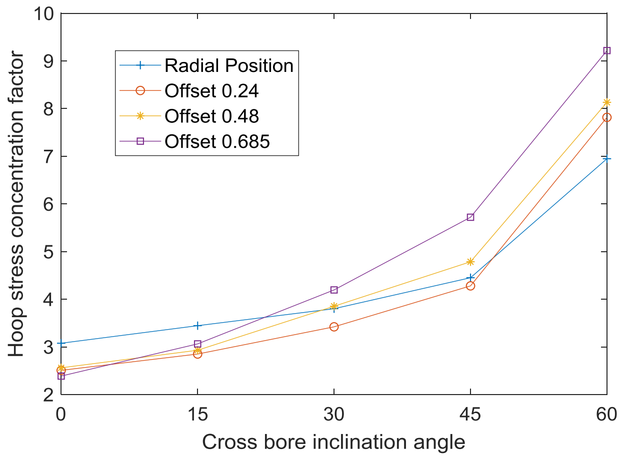

Figure 17: Hoop SCF vs oblique cross bores for K = 1.75

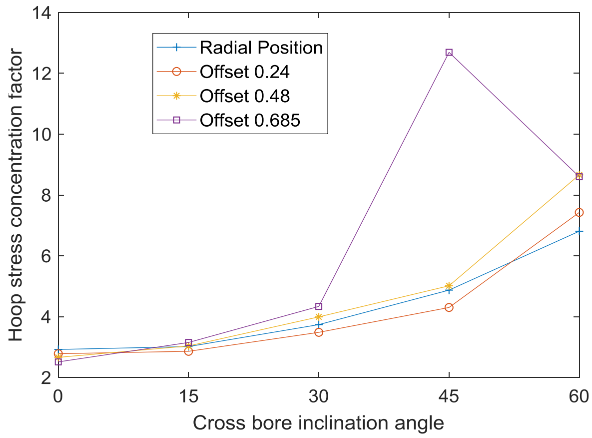

Figure 18: Hoop SCF vs oblique cross bores for K = 2.0

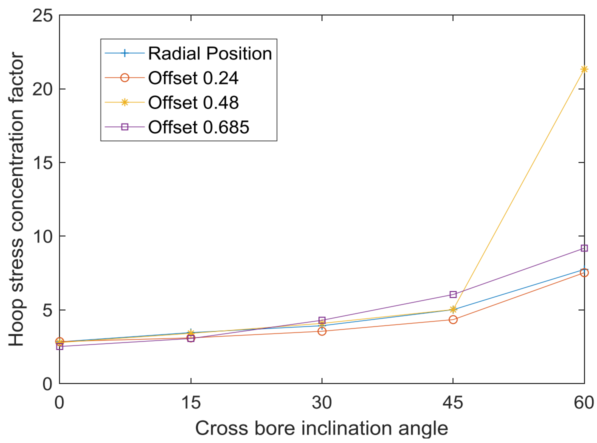

Figure 19: Hoop SCF vs oblique cross bores for K = 2.25

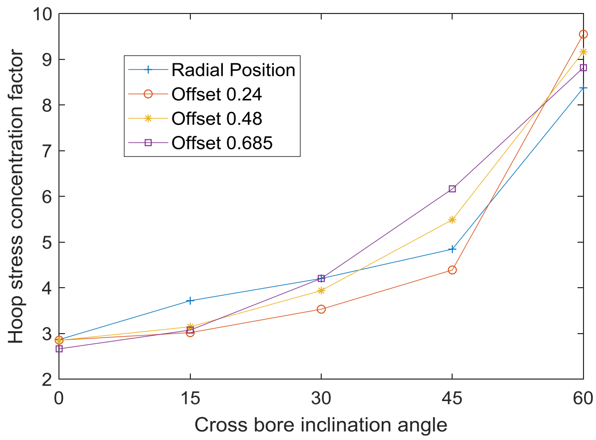

Figure 20: Hoop SCF vs oblique cross bores for K = 2.5

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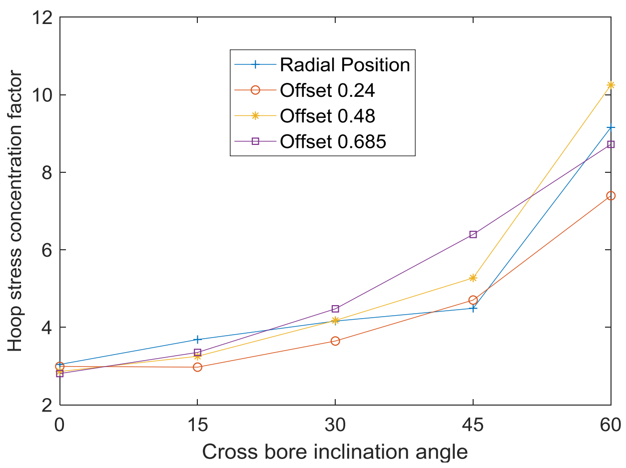

Figure 21: Hoop SCF vs oblique cross bores

for K = 3.0

Similar to the preceding sections, the offsetting of radial cross bore was seen to predict lower SCF magnitudes as illustrated in Figures 15 and 21. The overall lowest SCF magnitude of 1.814 occurred when the cross bore was positioned radially at oblique angle of 15^0 in K = 1.5. This optimal SCF magnitude indicates a reduction in pressure carrying capacity of 44.8% in comparison to a similar plain cylinder without a cross bore. Other SCFs with lower magnitudes of 1.83 and 1.916 were recorded at oblique angles of 15^0 and 30^0, respectively for K = 1.4. However, with increase in the oblique angle, the offset cross bores gave higher SCF magnitudes compared to those located at the radial position. The highest SCF increase by at least three times more than the other offset location ratios was observed at 60^0 in K = 2.25 for 0.48 offset ratio.

These findings were in line with other earlier studies done by Cheng (1978) and Nihous *et al.* (2008). Cheng (1978) had investigated experimentally a radial cross bore size ratio of 0.1 for K = 1.84 at oblique angles, α, of 30^0 and 50^0. The study also reported an increase in SCFs as the oblique angle, α, increased. Nihous *et al.* (2008) had studied various radial oblique cross bores oriented at five different angles. Fortunately, one of the studied cross bores had a size ratio of 0.1 and thickness ratio of 2.25, similar to the current study. Figure 22 shows a comparison graph between the two studies.

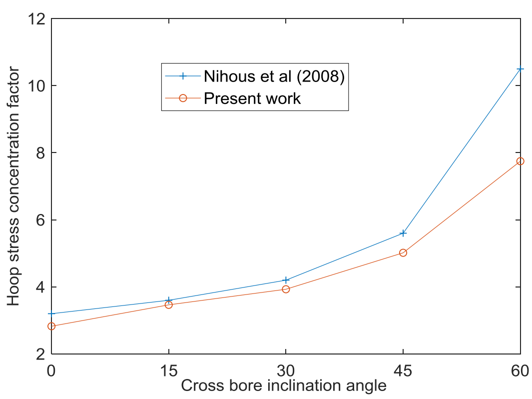

Figure 22: Comparison of hoop SCF magnitudes between oblique holes at radial position for K = 2.25 and cross bore size ratio of 0.1

Figure 22 shows a close correlation between the two results, further validating the modelling technique adopted in this work. The small discrepancies in the results between the two studies was associated with the use of different software's having varying modelling capability such as the degree of mesh refinement, element distortion tolerances etc.

In general, whenever the cross bore is viewed at the intersection between the inclined cross bore and main bore, its shape resembles that of an ellipse with major diameter parallel to the axial direction of the cylinder. This increase in the minor diameter is more pronounced whenever the obliquity angle reaches 60^0. The resulting configuration leads to high stress profiles as discussed in the previous section. This analogy is further reaffirmed by Figures 23 and 24 showing the cross bore views done at the inside surface of the main bore for both cases with minimum and maximum SCF magnitudes.

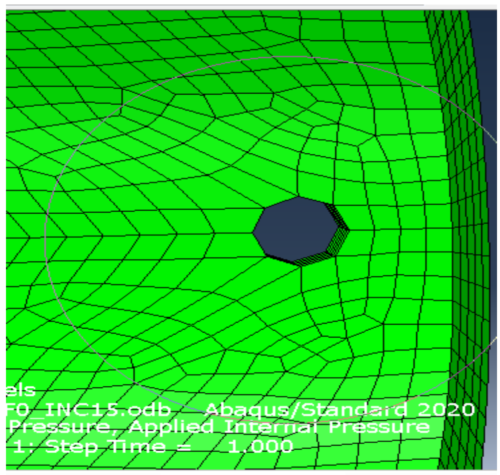

Figure 23: The shape of the radial cross bore when viewed along the main bore for the cylinder with overall minimum SCF from model K = 1.5 and oblique angle 15^0

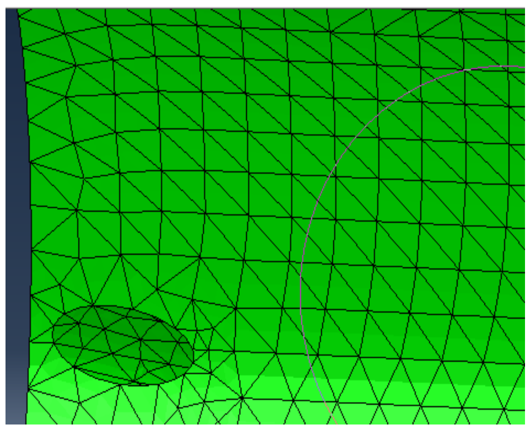

Figure 24: The shape of the offset cross bore when viewed along the main bore for the cylinder with overall maximum SCF from model K = 2.25, offset ratio 0.48 and oblique angle 15^0.

To this end, therefore, any offset cross bore obliquity in pressure vessel design that is located in the RZ plane should be avoided.

Table 1 shows comparison of SCF magnitudes among other optimal cross bore geometries from previous studies.

Table 1: Comparison of SCF magnitudes from different optimal cross bore geometries

	Radial circular cross bore Nziu & Masu (2019a)	Offset circular cross bore Nziu & Masu (2019b)	Radial elliptical cross bore Nziu & Masu (2019c)	Radial oblique circular cross bore Present study
SCF	2.836	2.312	1.733	1.814
Reduction in carrying capacity	64.7%	56.7%	42.3%	44.8%

As seen in table 1, the optimal radial elliptical cross bore geometry generally gave the overall minimum SCF magnitude. Besides, it was evident that the SCF magnitude for optimal radial oblique circular cross bore was lower than those of radial and offset circular cross bores by 36% and 21%, respectively.

CONCLUSION

1. In most of the studied cases, it was established that as the oblique angles increased from 0^0 to 60^0, the magnitude of the hoop stress increased progressively as the offset ratio increased.
2. The furthest offset location ratio with highest magnitude of 0.685 gave the lowest hoop stress magnitude at the radial position.
3. The overall lowest hoop stress magnitudes occurred in thickness ratios of 1.4 and 1.5 when the radial cross bores where inclined at 15^0 and 30^0, respectively.
4. The overall lowest SCF magnitude of 1.814 occurred when the cross bore was positioned radially at oblique angle of 15^0 in K = 1.5. This SCF magnitude indicated a reduction of pressure carrying capacity of 44.8% in comparison to a similar plain cylinder without a cross bore.

ACKNOWLEDGEMENTS

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