Stress Analysis of Multilayer Thin Walled Pipes with Circular Cut-Outs

Rishicca Kamalarajah, John W. Bull, Mahmoud Chizari

***Abstract*— a finite element analysis of a double layered shell with a circular hole is carried out with the computer aided engineering software Abaqus (Dassault Systèmes, FR). The model proposed has been used to perform a stress analysis on three pipes with different sized hole. Moreover, thermal expansion has been implemented in the testing. For the purpose of the research, the elastic properties of the materials have been considered and the results compared with the ones previously published in literature. The outcome of the investigation will benefit towards the design of optimal and sustainable pipes with circular cut outs.**

***Index Terms*— Thermal effects, stress concentration, finite element analysis, shell, circular holes**

I. Introduction

THE introduction of thin shelled pipes as structural element has contributed to the development of several sectors of engineering industries featuring thermal and nuclear power plant, fluid supply systems or the aerospace field [1]. In recent years, the need of an opening in pipes is more and more required, reflecting the high demand for inspections and control operations. This hole, often circular, can be of different sizes or shapes, depending on its purpose, as it also allows for insertion of instrumentations, facilitates the introduction of mounting equipment or enables the extraction of materials within the element [2]. However, as the geometry of the pipe is altered, the circular hole attracts higher stresses when subjected to external loading [3]. These stresses rise until they reach a certain amount of localized stresses concentrated in a limited area.

The importance of understanding and quantifying the stresses around the perforation in pipes is vital during the design process as these types of structures can undergo to deformations that lead to cracking and eventually to failure. The failure of the structure not only has a great impact on the property in which it resides, but it can also compromise the health and safety of its occupants. To reduce the risk of failure, different systems of protection can be integrated, as for instance the use of cladded pipes. Many studies have been published regarding the different parameters involving the computation of the stresses at the cut-out, including the curvature effect on the stress concentration, the material's properties, the approach of the analysis or the modelling procedure.

In this paper, the model proposed in [4] has been used to perform a stress analysis on a thin double layered pipe subjected to a surface heat flux and to applied external loading, with the aid of the engineering software Abaqus CAE (Dassault Systèmes, FR v. 6.14). As it is not widely available in the literature, considerations on the thermal expansion due to the application of heat along with deformation due to the applied load are presented. The top surface is resting at atmosphere temperature while the internal surface is experiencing a higher thermal discharge which can be caused by any flow movement (e.g. water).

A three dimensional finite element analysis is carried out with the respct to elastic properties of the materials used. The impact of results obtained, hence, will be assessed and compared with the ones previously achieved in [4] and [5] and it will benefit the design methodology of optimal pipes with circular holes.

II. Methods

A. Pipe Design

An extensive amount of analytical work has been done over the years on the stress in a cylindrical shell having a circular hole [6]. However, it has been established that the use of finite element methods is preferable to achieve reasonably accurate prediction of the stress fields.

Traditional methods of modelling cylindrical shells with circular hole are usually expressed with the intersection of two cylinders. The innovative approach adopted in this research regards the description of curvature of the circular cut-out. Adopting the notation of x-axis in the direction of the pipe length and y-axis in the direction of the cut depth and placing the origin of the hole on the pipes edge over the centre of the cut; the cut-off equation was used as described in our previous publication [4].

The analysis assumes shallow, thin shells for which the coexistence of two sets of curvature in the same structure [7] has a small effect over the circumferential coordinate of the hole [6]. As it can be seen in Figures 1, 2, 3, three perforated uniform circular cylindrical shell accommodates large circular cut-out of radius of 62.86 mm, 126.49 mm and 196.01 mm located at the center of the pipe. In accordance with the Saint's Venants principles, the length of the pipe is sufficiently long in order to omit the stresses produced by the hole at the end of the shell. Therefore a steel pipe is

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created as a three-dimension deformable shell structure of 5.983 mm thickness in which a second inner layer of 1mm thickness of aluminum, is assembled in order to provide reinforcement and support to the pipe when subjected to heat flow and external load.

The steel, having a Young's Modulus E of 212.414 kN/mm^2, is a uniform, homogenous, isotropic and perfectly elastic material which is used to form the outer part of the pipe. Being modelled as a shell element, the distribution of the thickness occurs at the mid-surface. As previously mentioned pipe with an opening attires higher stresses and deformation compared to the one intact one, therefore an additional thin-walled pipe, made out of aluminum, is inserted within the steel pipe. Aluminum is a common material for internal cladding of pipes as it considered a good insulating material. For the purpose of this research, no geometrical imperfection, due to fabrication process, is taken in account.

Fig. 1. Finite Element model of shell A with r_1= 62.87 mm.

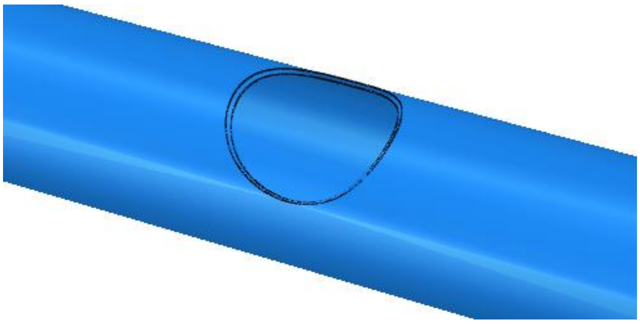

Fig. 2. Finite Element model of shell B with r_1= 126.49 mm.

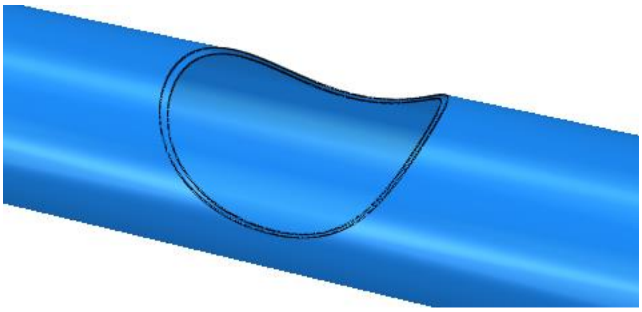

Fig. 3. Finite Element model of shell C with r_1= 196.01 mm.

B. *Finite Element Procedure*

This section deals with the modelling process of three pipes of 2000mm length having a circular perforation. As previously described, the properties of the materials have been implemented in the analysis with the respect of the elastic behaviour of the shell under applied loading. The properties notations are shown in Table I, followed by Table II describing the materials properties and Table III for the pipes specification.

TABLE I
PROPERTIES NOTATION

Symbol	Quantity
ν	Poisson's ratio
E	Young's modulus
R_1	Radius of the outer pipe
R_2	Radius of the inner pipe
t_1	Thickness of the outer pipe
t_2	Thickness of the inner pipe
r_1	Radius of the outer hole
r_2	Radius of the inner hole
ρ	Density
λ	Thermal conductivity
α	Thermal expansion
c	Specific heat capacity

TABLE II
MATERIALS PROPERTIES

	Steel	**Aluminum**
E [kN/mm^2]	212.414	70.000
ν	0.3	0.33
ρ [ton/mm^3]	7.8×10^{-9}	2.7×10^{-9}
λ [W/(m.K)]	50	160
α	1.2×10^{-5}	2.3×10^{-5}
c [J/(kg.K)]	450	900

TABLE III
THE PIPES SPECIFICATIONS

	Pipe A	**Pipe B**	**Pipe C**
R1 [mm]	133.5	133.5	133.5
t1 [mm]	5.983	5.983	5.983
r1 [mm]	62.87	126.49	196.01
R2 [mm]	126.82	126.82	126.82
t2 [mm]	1	1	1
r2 [mm]	59.72	120.16	186.21
R/t	22.65	22.65	22.65
t1 [mm]	5.983	5.983	5.983

The procedure of testing coupled temperature-displacement with a steady-state response of the three pipes is specified in the step module where the geometry is considered linear. The solution technique is fully Newtonian and matrix storage is unsymmetrical in order to improve computational efficiency. The load variation over time is linearly over each step, as prescribed by default; the extrapolation of previous state at start of each increment is also linear. Since the two pipes are fitted in one another, the interaction between them is defined as a surface-to-surface contact with finite sliding. The interaction property, on the other hand, it is appointed for the tangential behavior with a friction formula frictionless, and for the normal behavior with a pressure-overclosure of hard contact. Moreover, a rigid body constraint ties each pipe edges together to a common reference point located at the center of the outer pipe ends. In this way, the loads and boundary conditions are applied to the two references points described in the step module. The end conditions are, hence, enforced for which

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one end is fully fixed, and the other one is flexible for adjustments based on the type of loading that is being applied. As thermal expansion is implemented in the procedure, change in temperature is added having the external pipe resting at environmental temperature of 273.15 K while the internal pipe is experiencing an increment in temperature of 26.85 K. This discharge is activated at the edge of the pipe and propagated along its length.

The pipes present identical characteristics and same mesh refinement. The presence of the perforation highly affects the mesh orientation and shape: this can also be reflected in the stress field orientation and hence in the results. The disruption of the meshing is caused by the elaborated geometry of the three dimensional model, for which, as a result of the mesh convergence study, it is proposed the use of free triangular element shapes to best fit the topography of the curvature of the pipe and of the hole. The mesh density is another important aspect to take in account during the finite element modelling as it is directly depended on the degree of accuracy desired. However, it should be noted that high level of accuracy and density also require a high level of computational capacity and greater time of analysis. Eventually, as the model is subjected to heat flow, the family of the mesh elements is coupled temperature-displacement and the type is S3T: a three mode thermally coupled triangular general purpose shell, finite membrane strains for linear geometric order.

Figure 4 shows the details of the meshing of the pipe and the discontinuance of the meshes orientation around the circular cut out.

C. *Model Specifications*

Torsional loading has been chosen as the external force applied to the member. For the torque model, the rotation is prescribed at the end of the edge, conversely to the fully fixed edge. Twisting, therefore, is given at UR3 with the respect to the yield stress of the steel plate.

III. Results and Discussion

A. *Von Mises Stress*

The stresses are recorded for Von Mises values for all the pipes. The results are presented in Figure 4 and Table IV. As it can be seen, in all the pipes, the inner member made out of aluminum is trying to pull out of the steel pipe. This is due to the thermal expansion and its relation to the thickness of the cladding. Although the highest deformation occurs in the inner pipe, this phenomenon prevents the formation of higher stresses at the hole on the external shell.

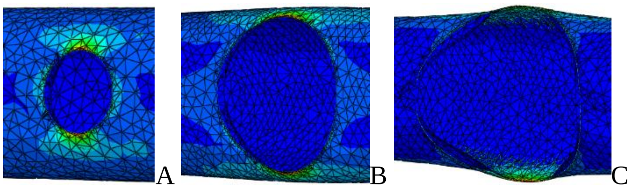

Fig. 4. Von Mises stress results for pipe A, B, C.

TABLE IV
MISES STRESS RESULTS ON PIPES

Stress at	Inner pipe	Outer pipe
A	$9.95x10^3$	$9.95x10^3$
B	$3.433x10^3$	$3.433x10^3$
C	$2.641x10^3$	$2.641x10^3$

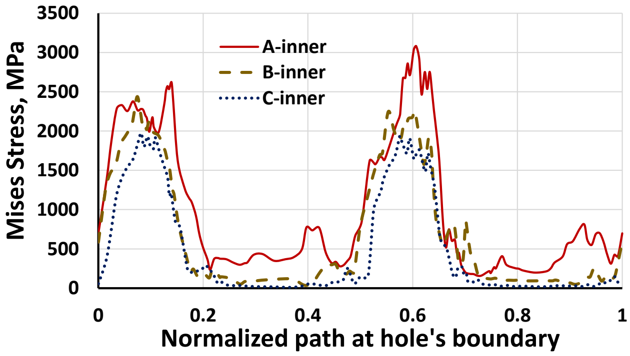

Fig. 5. Comparison of Von Mises stress results for inner pipe A, B, C.

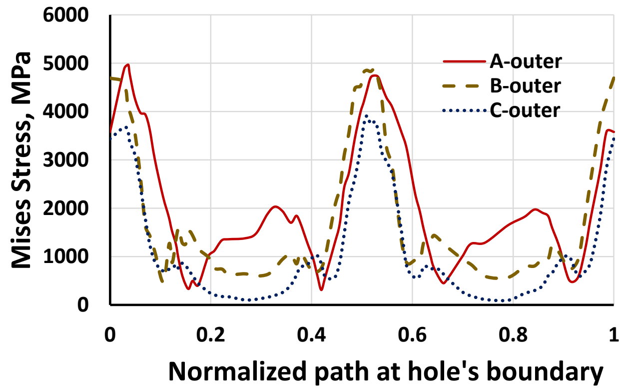

Fig. 6. Comparison of Von Mises stress results for outer pipe A, B, C.

It can also be seen that the hole with the smaller radius attires higher stresses whereas pipe C release low stresses around the stress raiser. This is due to the ovalization of the hole and the flattening of the pipe caused by both the thermal expansion and applied torque. From a visual estimation, pipe B appear to propagate the stresses in a uniform way, and the deformation of the pipe do not cause major change in shape which implies that cracking do not occur.

B. *Tensile Stress*

The tensile stresses are here discussed. As the members undergo to applied torque, both compressive and tensile stresses are formed within the pipe, Figure 5 and Table V shows the symmetry of the stresses that has been maintained even if temperature discharge has been applied.

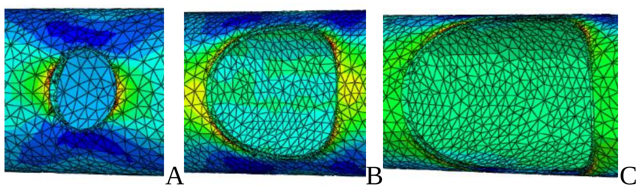

Fig. 5. Tensile stress results for pipes A, B, C.

TABLE V
TENSILE STRESS RESULTS ON PIPES

Stress at	Inner pipe	Outer pipe
A	$9.969x10^2$	$9.969x10^2$

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B	3.730×10^3	3.730×10^3
C	9.294×10^2	9.294×10^2

As the pipe is subjected to thermal expansion, the distribution of the stresses appears to be equally distributed. It should be noted that the color gradation used, shows some discrepancy in the symmetry of the stress circulation as result of the 26.85 K temperature difference that it has been applied to the shell.

In order to illustrate the stress diffusion, the scaling factor of the visualization has been taken as zero.

C. *Compressive Stress*

As for the tensile stresses, the compressive nature of the stresses is herein considered. Figure 6 and Table VI are a clear representation of the way of the stress diffusion along the pipes. Torsion is one of the load combinations that a uniform cylindrical shell with circular perforation can be subjected to when dealing with application such as hollow circular shaft. The compressive stresses have as well, great role in determining the areas of major weakness.

Contrary to the tensile stress, the compressive stresses show a more uniform spreading pattern which can be the result of the fact that applied torque on one of the edges, while the other one is fixed, produces higher tensile stresses compared to the compressive one.

The general oval shape that the hole obtains in each of the pipe is due to the boundary conditions previously described.

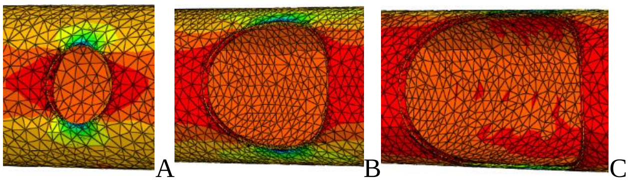

Fig. 6. Compressive stress results for pipes A, B, C.

TABLE VI
COMPRESSIVE STRESS RESULTS ON PIPES

Stress at	Inner pipe	Outer pipe
A	3.078×10^2	3.078×10^2
B	4.947×10^2	4.947×10^2
C	5.109×10^2	5.109×10^2

Similarly to the tension results, in order to illustrate the stress diffusion, the scaling factor of the visualization has been taken as zero.

In general terms, when comparing to preceding results, the stresses around the circular hole are reduced as part of the additional support given to the pipe. The inner layer, therefore, has not only diminished the peak stress around the stress raiser, but has also contributed in reducing the effects of thermal expansion in the pipes.

D. *Thermal analysis*

As it can be seen from Figure 7, the heat discharge applied causes the thermal expansion within the pipes, causing the change in the shape of the perforation. The higher stresses are seen to be distributed perpendicularly to the pipe length which results in an ovalization of the hole. The flattening of the pipes is also markedly enhanced. The effects of the heat diffusion deform the aluminium layer in each pipe, which is expected to be damaged, if considered the damage for ductile metals.

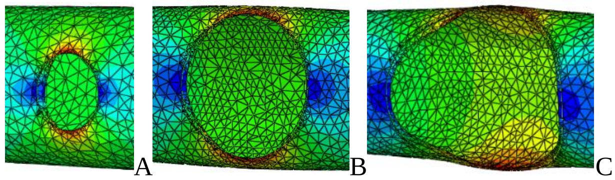

Fig. 7. Thermal analysis results for pipes A, B, C.

TABLE VII
THERMAL ANALYSIS RESULTS ON PIPES

Temperature at	Inner pipe	Outer pipe
A	4.543	4.543
B	4.610	4.160
C	4.763	4.763

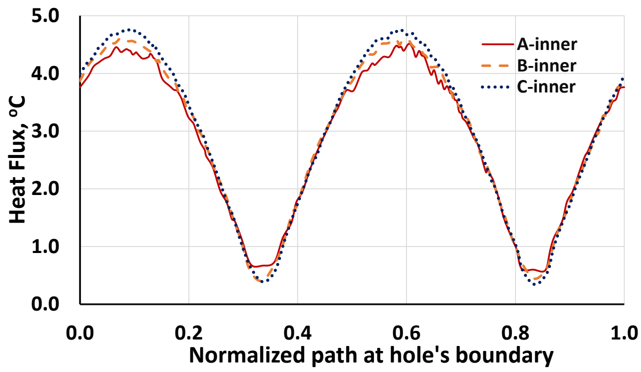

Fig. 8. Comparison of heat flux for inner pipe A, B, C.

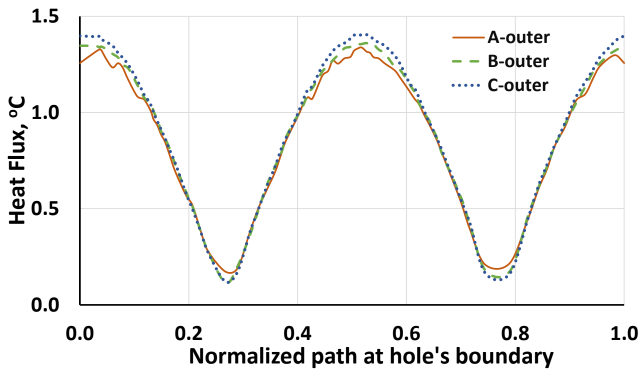

Fig. 9. Comparison of heat flux for inner/outer pipe A, B, C.

Subsequently to the high level of deformation presented in pipe with hole radius of 196.01 mm, the optimal hole size in this analysis appear to be the smaller one. This can be seen in Table VII where pipe A have the lowest value for the max heat flux per unit area. The positive sign of the recorded value, indicated the flowing of the heat within the element; heat dissipation caused by the presence of the hole is not taken in account.

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IV. CONCLUSION

An appreciation of the stresses around circular cut-out of 62.86 mm, 126.49 mm or 196.01 mm located at the center of a pipe has been examined with the finite element method on Abaqus CAE. As a supplementary support to the thin-walled steel pipe, an inner layer made out of aluminum has been implemented and properly adjusted to the outer part.

As part of the research, the pipes are subjected to thermal expansion due to the application of heat along with deformation due to torsional loading. The results show an improvement in the stress concentration in the vicinity of the cut-out of the outer layer, as the inner pipe attenuate the effect of external forces within the whole member.

Additional considerations should be given to the modelling approach. In first place, the level of accuracy can be improved by a more detailed re-meshing or by transforming the shape of the pipe from “shell” to “solid”. Furthermore, the choice for cladding system can be reviewed and as for the material used or for the type of contact that is being enforced. There is still lack in the literature of extended work on the reinforcement of pipes with optimal circular cut outs.

Therefore, as part of a series of testing which are still to be completed, the authors will further analyse circular holes in multilayer thin walled pipes and compare results for alternative thicknesses of the pipe to suggest the most appropriate hole size to shell diameter to eliminate localised peak stresses around the perforation.

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