IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 15, Issue 2 Ver. II (Mar. - Apr. 2018), PP 23-37
www.iosrjournals.org

Elastoplastic Behavioranalysis of Clamped Circular Perforated Thin Plates

E. Azelmad[1],A. Salmi[2], E. El Kennassi[3], L. Bousshine[4]
[1,2,3,4](National High School of Electricity and Mechanics /Hassan II University, BP8118, Oasis, Casablanca, Morocco)
Corresponding Author: E. Azelmad

Abstract:*Elastoplastic dimensioning is an important step in the design of Tubesheets. Indeed, they must be as thin as possible in order to reduce the internal temperature gradients and the risks related to thermal fatigue, and at the same time, to reduce the industrialization costs related to the material and perforations. Several studies have been developed with the aim of finding an elastoplastic model of calculation which is the most appropriate in analytical theor[1,2] or using finite element method. The aim of this work is, then to propose a 2D Typical model for the numerical simulation of the circular clamped perforated thin plates behavior in the elastic and elastoplastic domains. Unlike the majority of the literature calculations that are based on the equivalent solid plate model,this Model is based on the real geometry of plates and takes into account different perforation distribution patterns and ligament factors and it is then validated by experiments[1].*

Date of Submission: 10-03-2018 Date of acceptance: 28-03-2018

I. Introduction

Heat exchanger Tubesheet presents an important problem of dimensioning and resistance verification, due to its complicated geometry and complexity of behavior laws of its constitutive material under different mechanical and thermal loadings[3]. This work aims to describe the behavior of such perforated plates by the finite element method in order to make a contribution to their design.

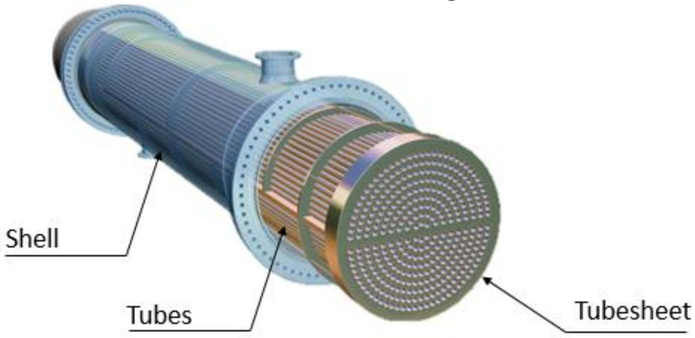


Figure 1: Tubesheet position in a shell and tubes heat exchanger

The tubular plates are perforated according to periodic perforations forming a network of equilateral square or triangular meshes[3,4]. This network is characterized by the ligament factor μ defined by:

$$\mu = \frac{h}{p} \quad (1)$$

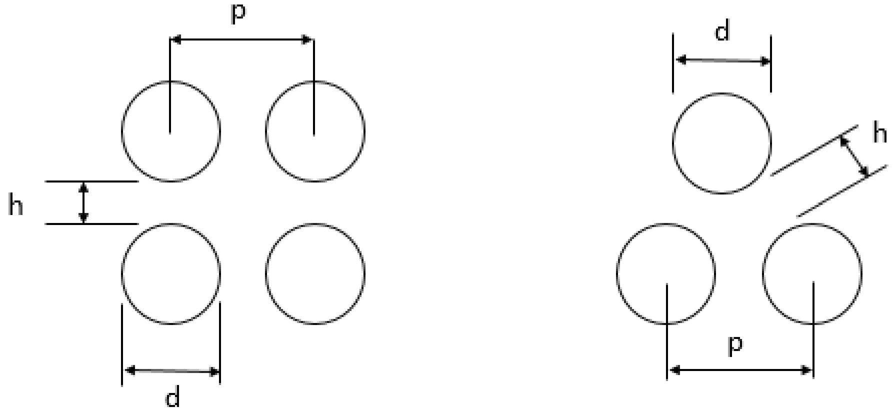
where h is the ligament and p the distance between two successive holes (figure 2).
The ligament values μ vary between 0.15 and 1.0 for a solid plate, but values between 0.2 and 0.5 are of greater technical interest[1].

II. Material AndMethods

The validation of the numerical model established in this work is based on the comparison of its results with the tests carried out as part of the thesis[1]. The section below gives an overview of the reference experiments.

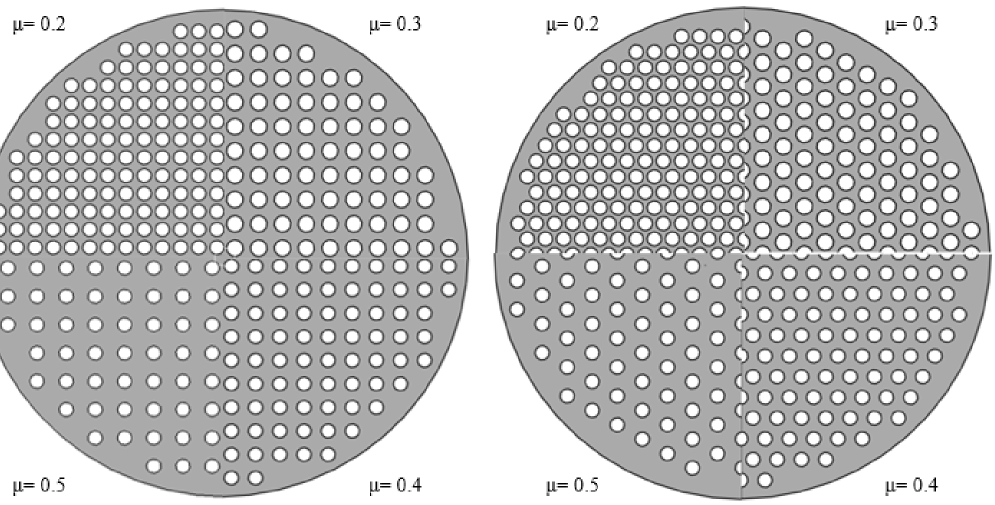
1. Experimental Analysis

The bending tests of the perforated circular plates were conducted in two categories; one simply supported (Figure 4 (a)) and the other clamped (Figure 4 (b)). Each of these two categories is divided into two subcategories in itself; one with square hole distribution (figure 2. (a)) and the other with triangular hole distribution (figure 2. (b)). This gives a total of 16 perforated circular plates.



(a) **(b)**

Figure 2: (a) Square distribution, (b) Triangular distribution



(a) (b)

Figure 3:Considered ligament factors for (a) square distribution, (b) triangular distribution

Thickness of the plates being 8 mm, their diameter is 206 mm and the holes diameters as well as pitches for each ligament factor are given in the following table (Table 1)[1]:

Table1: Geometrical characteristics of Tubesheet for each ligament factor

Ligament Factor« μ »	**Hole diameter« d »**	**Pitch « p »**	**Thickness « e »**
0.2	6	7.5	8
0.3	7	10	8
0.4	6	10	8
0.5	6	12	8

A series of characterization tests of the constructive material were done on specimens, and gave the Young's modulus, the Poisson coefficient and the yield stress to consider[1] (Table 2):

Table2: Considered clamped platesmaterial properties

	Clamped Plates
Young Modulus (MPa)	218930
Poisson Coefficient	0.293
Yield Stress (MPa)	262

All the previously described plates were progressively loaded into pressure until the rupture, and the results were recorded for two points: one at the centre of the plate and another at its mid-radius.

III. Computational Method

Among theoretical and experimental behavior investigations of circular plate[2,5], the numerical simulation has lately shown an important efficiency[6,7,8,9]. And as previously explained, the simulation concerned in this paper was done using the commercial software NASTRAN for the elastic and elastoplastic calculations.

The calculation modules used are:
- The linear static calculation modulusNASTRAN, SOL101.
- The non-linear static and dynamic modulus NASTRAN, SOL400.

For nonlinear computation under NASTRAN, the SOL400 is conceived just to deal withwith the different forms of geometric and material nonlinearity as its the case for our circular plates. This modulus uses displacement's method by finite element, having as objective to compute nodal displacements of the structure starting from system equations resolution[10].

1.1. Elastic Behavior Analysis

Mesh generation is the first step of the finite element method. It is a fundamental step which impacts all the rest of the calculation: calculation time and necessary resources (RAM, virtual memory, processor time), results precision and numerical model stability (possibility of divergence for the case of nonlinear calculations).

A "Good" mesh is therefore a mesh that:
- Allows results to be close to reality.
- Allows the calculation to run with the available resources (computer system capabilities), and at the same time respects the project deadlines

To have a result close to reality, we are often tempted to use a fine mesh. In fact, the finite element method consists of interpolating the values of the functions inside the meshes, so the larger the mesh is, the greater is the difference between the "real" value of the function and its interpolated values.

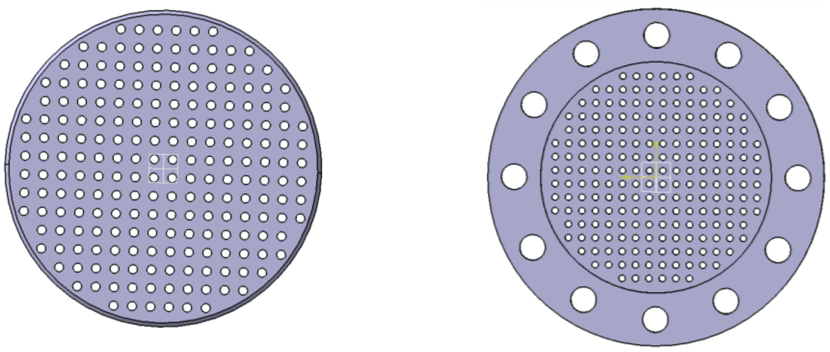
However, a fine mesh involves a large number of meshes and nodes, so requires a great power and a long computing time. Moreover, this does not necessarily improve the quality of the result, or may in some cases degrade it.

For this reason, we proceeded to determine, by a campaign of numerical simulations, the Typical meshingfor the analysis of the perforated circular thin plates behavior.

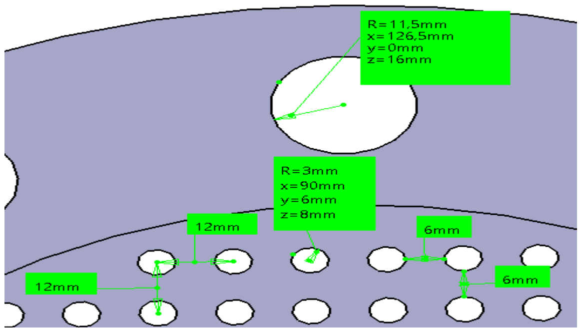
- **<u>Models Geometry</u>**:

According to the geometry presented in the context of the experiments above[1], CAD software was used for 3D design for simply supported and clamped circular plates and for both types of distribution (square and triangular) as well as ligament factors ranging from 0.2 to 0.5.

Hereafter is presented an example of a perforated plate (simply supported and clamped) conception (figure 4):



(a) **(b)**



(c)

Figure 4: Example of perforated circular plate with ligament factor equal to 0.5 (a) simply supported plate, (b) clamped plateand (c) geometricalmeasurements

- **Finite Element and Meshing**:

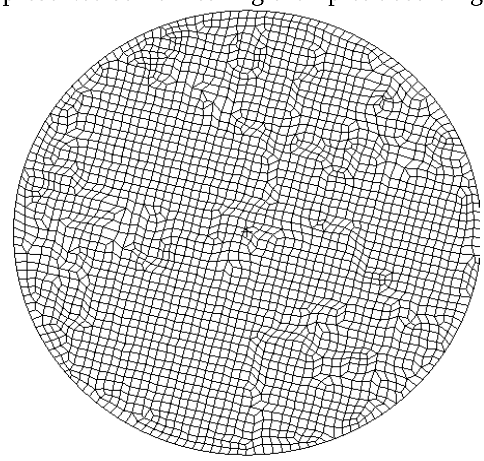
The set of the numerical tests that has been carried out concerns different mesh sizes depending on the thickness of the plate, starting with a coarse mesh to the finest one (the last one for which the calculation does not crash). The strategy adopted follows table 3below:

Table3: Element size analyzed for each plate ligament factor

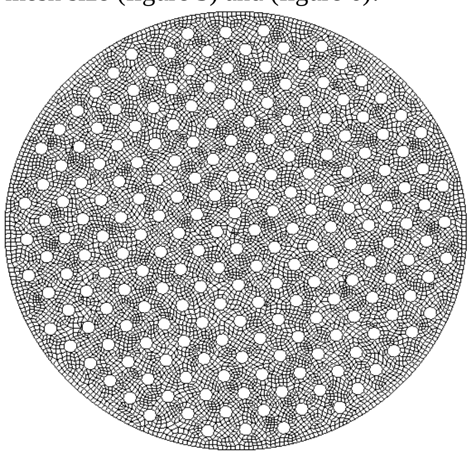
Kind of holes Distribution	Square / Triangular			
Ligament Factor	0.2 (less frequent in industry)	0.3(less frequent in industry)	0.4	0.5
Quadrilateral Meshing	e/6 and e/8	e/6 and e/8	From e/2 to e/8	From e/2 to e/8
Triangle Meshing	e/6 and e/8	e/6 and e/8	From e/2 to e/8	From e/2 to e/8

with « e » is the plate thickness in mm.

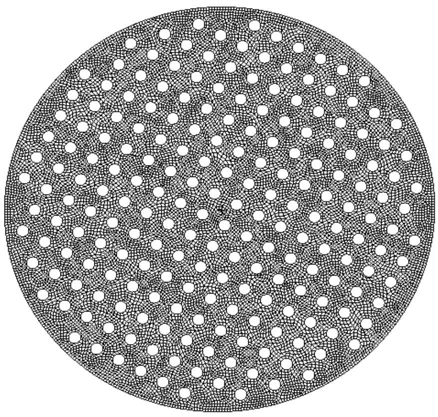
Here are presented some meshing examples according to each mesh size (figure 5) and (figure 6):



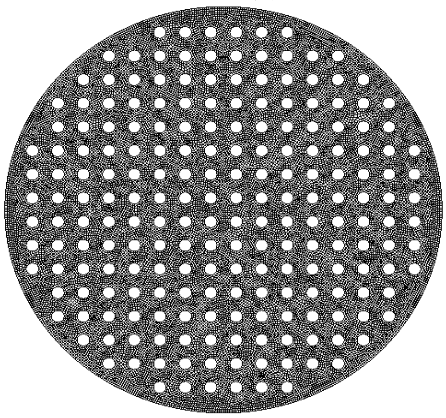
(a)



(b)

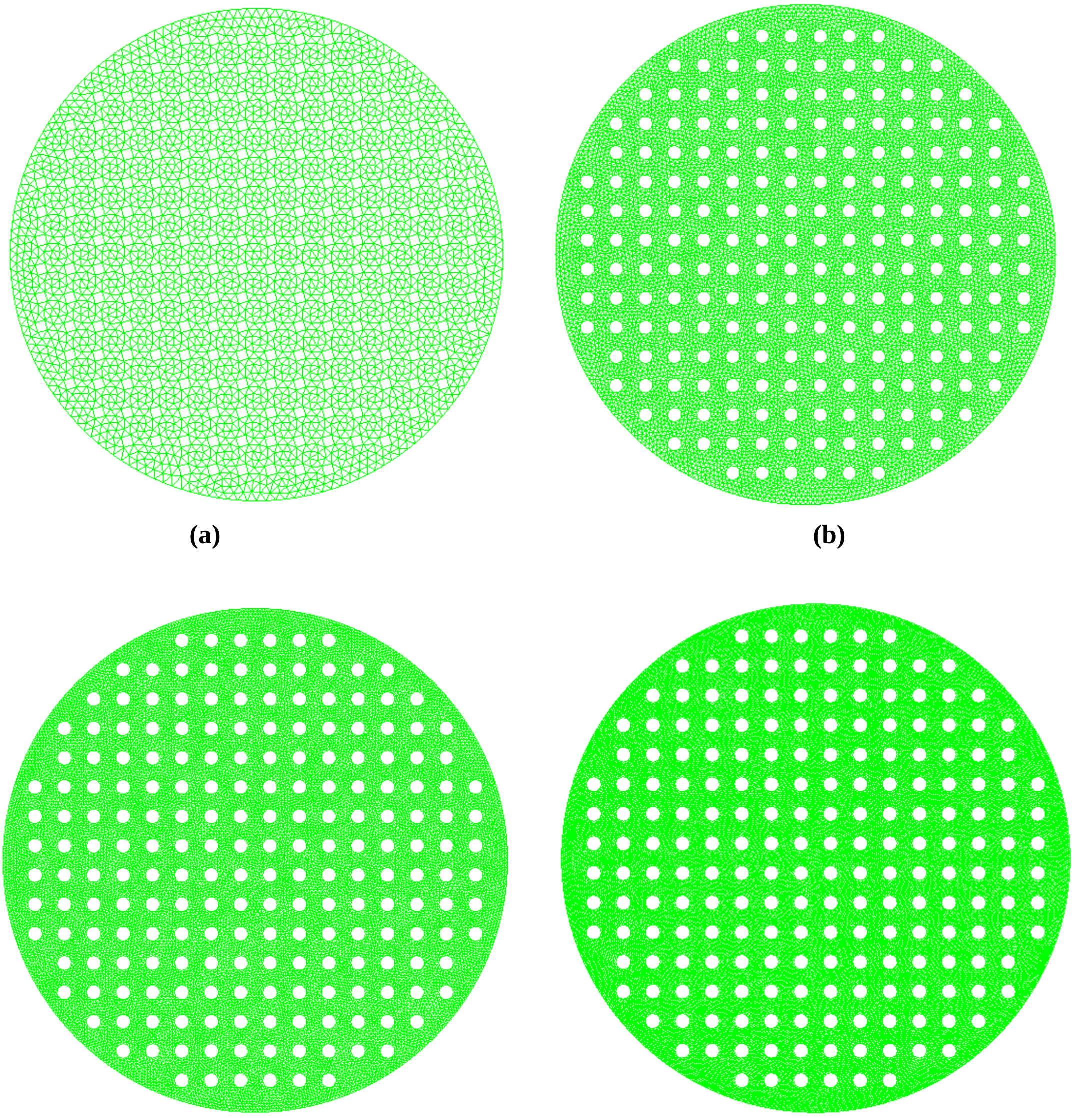


(c)



(d)

Figure 5: Quadrilateral meshing example of a circular perforated plate with ligament factor equal to 0.5 (a) e/2, (b) e/4, (c) e/6 and (d) e/8



(c) (d)

Figure 6: Trianglemeshing example of a circular perforated plate with ligament factor equal to à 0.5 (a) e/2, (b) e/4, (c) e/6 and (d) e/8

1.2. Elasto-plastic Analysis

As explained before, the objective of the elastic calculationsis to find the numerical model that is more representative to the plates behavior. In the elastoplastic calculations, this model will be used and modified (see paragraph 2 of the Result section), since calculations in the nonlinear mode takes too much time and memory space.

IV. Result

1. **Elastic Analysis Results** :

In this section, we aim to compare the computed maximum elastic strain in the elastic domain from NASTRAN numerical simulations with experiments[1] and simulations under ALGOR[1]in order to deduce the typical mesh for the perforated circular plates.

All calculations were made under a loading of 10 Bars to remain in the elastic domain, except for plates with ligament factor of 0.2 which had a loading of only 5 Bars (while 10 Bars gives a Von Mises stress higher than the plate material yield stress).

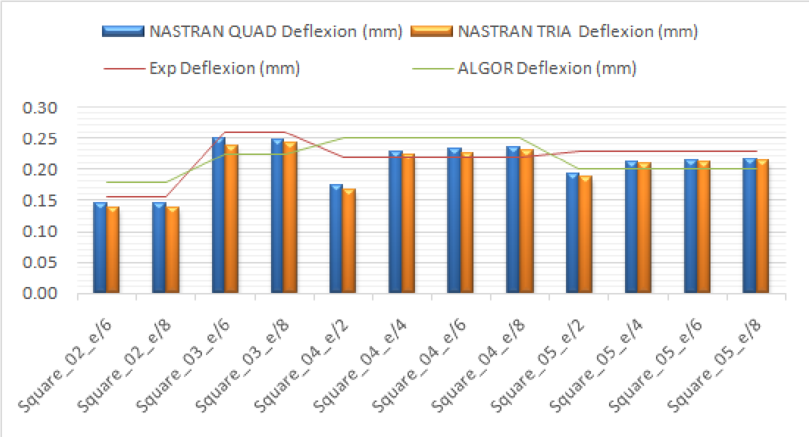


Figure 7: Results of the elastic calculations for each ligament factor and each size of Mesh for Square Pattern

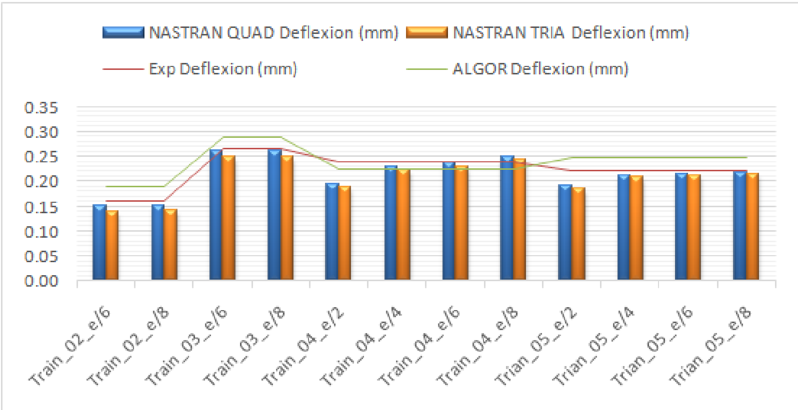


Figure 8:Results of the elastic calculations for each ligament factor and each size of Mesh for TriangularPattern

For all bars, NASTRAN results are more efficient than ALGOR ones.
For 80% of these results, quadrilateral elements give results closer to the experiments than the triangular ones.
38% of results of quadrilateral e/6 and e/8 are the same; 38% where e/6 results are better than e/8 and 25% where e/8 are better than e/6.

2. **Axisymmetric Model**:

As stated before, finite element calculation in the plastic area takes a long time and a large memory space and risks sometimes with luck of memory capacity to stop running. Hence the interest of defining an axisymmetric model whose behavior is equivalent to that of the entire plate.
To do this, a complete plate model 3D and its 1/8 for the circular plate with square perforation network were studied in the elastic domain and under the same loading and boundary conditions.

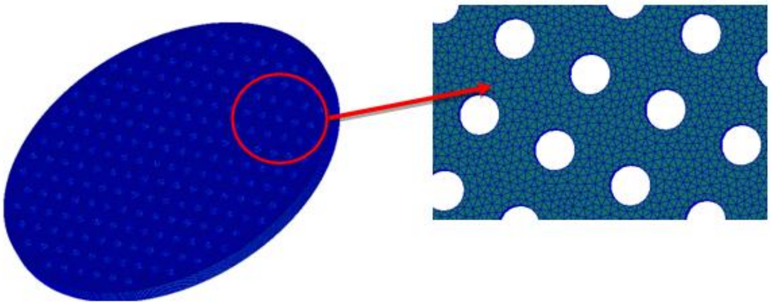


Figure 9:Whole Plate 3D modeling (CAD Software)

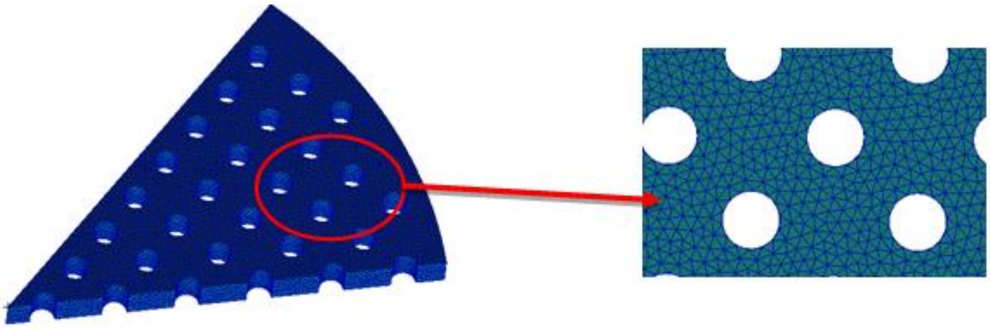


Figure 10: 3D modeling of 1/8 Plate for Square penetration Pattern(CAD Software)

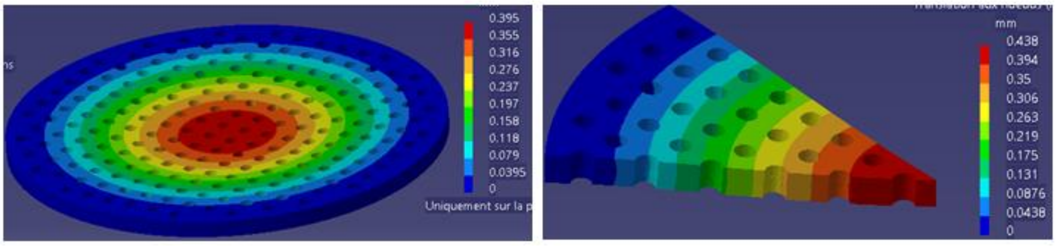


Figure 11: Max deflection of both whole plate and 1/8 3D modeling for a Square penetration Pattern (CAD Software)

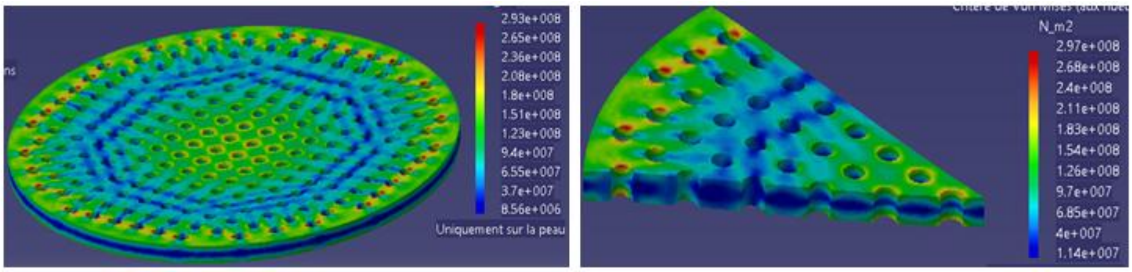


Figure 12: Max Vom Mises Stress of both whole plate and 1/8 3D modeling for a Square penetration Pattern (CAD Software)

NASTRAN Analysis Results:

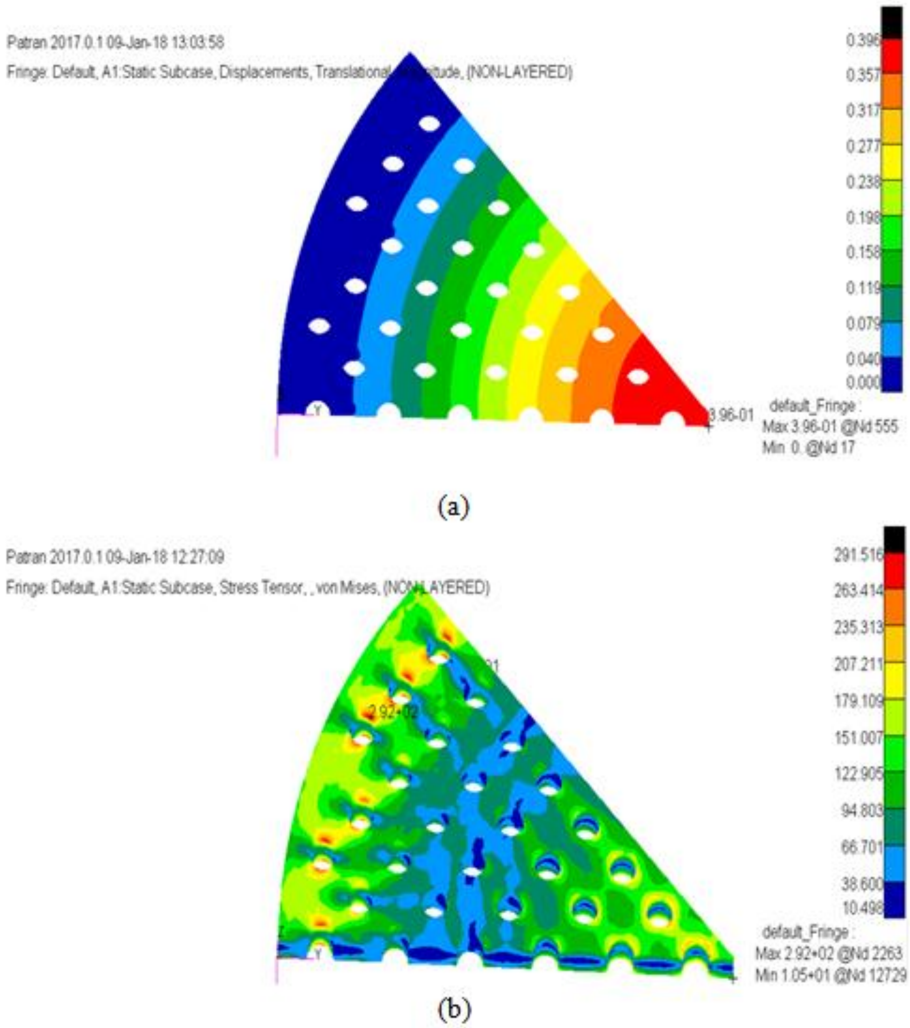


Figure 13: (a) Deflection and(b) Von Mises stresses for axisymmetric plate portion (NASTRAN)

From these results, it is clear that it is sufficient to model the behavior of the entire plate to pass through its axisymmetric model (1/8 for square distribution plates for holes).
In the same way, the axisymmetric model has been validated in the case of plates with triangular hole distribution (in this case the behavior of the entire plate is equivalent to that of its 1/4).

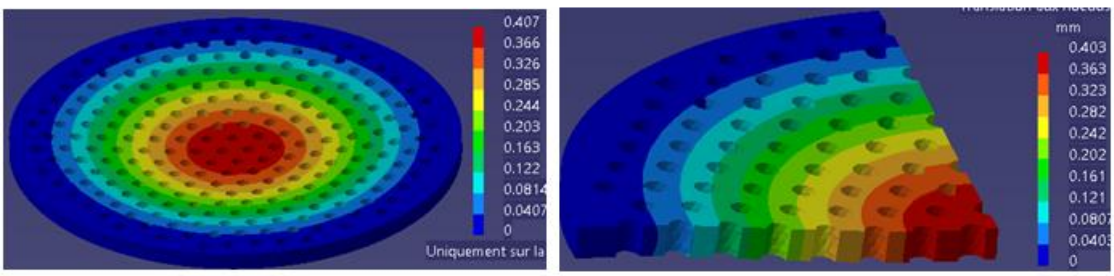


Figure 14: Max deflection of both whole plate and 1/4 3D modeling for a Triangular penetration Pattern (CAD Software)

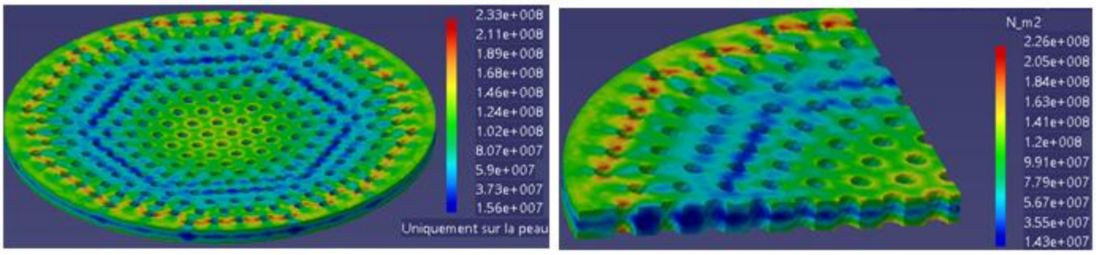
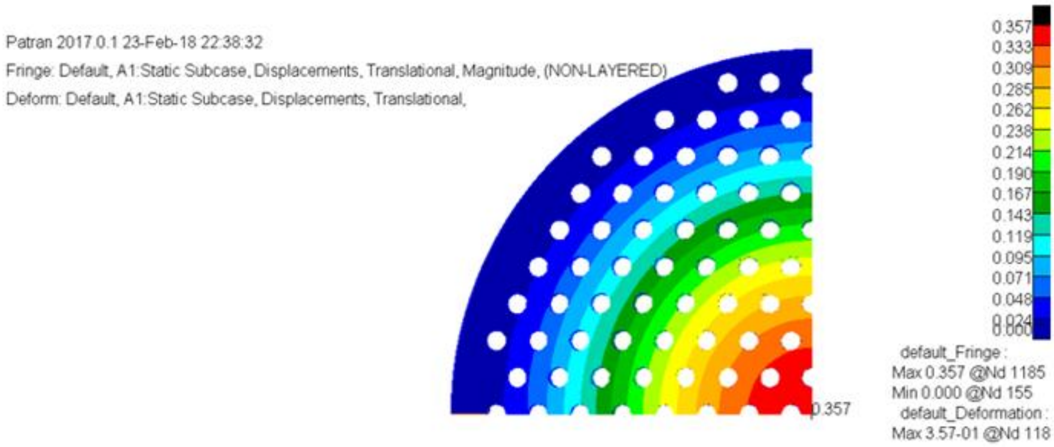
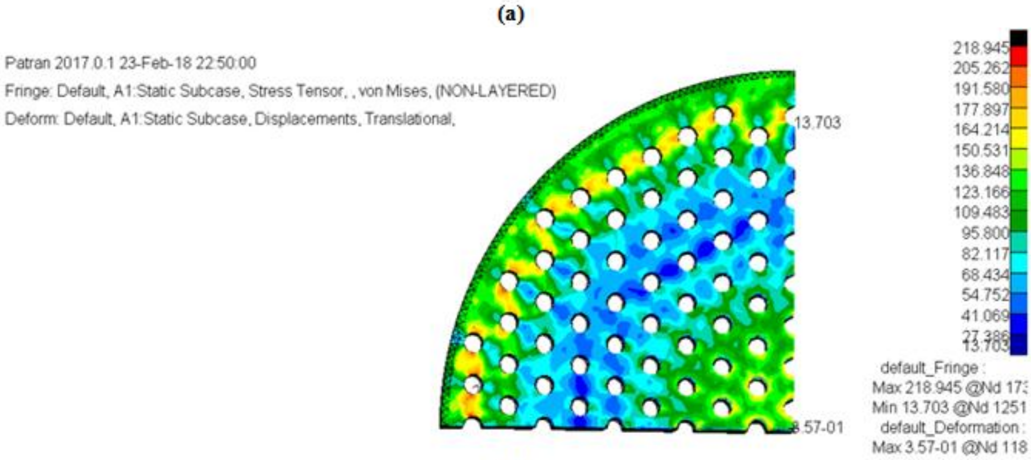


Figure 15: Max Vom Mises Stress of both whole plate and 1/4 3D modeling for a Triangular penetration Pattern (CAD Software)

NASTRAN Analysis Results:



(a)



(b)

Figure 16: (a) Deflection and (b) Von Mises stresses for axisymmetric plate portion (NASTRAN)

Due to lack of hardware resource (memory) we could not run the calculation of the entire plate under NASTRAN.

More results discussionsare given in Discussion section.

V. Elasto-Plastic Analysis Results :

In this section we presentall the elastoplastic results for clamped plates with square and triangular perforation patterns.

We, first did a test with a solid plate without perforation in order to verify all previously described simulation hypothesis (meshing, loading, axisymmetric model…etc.).

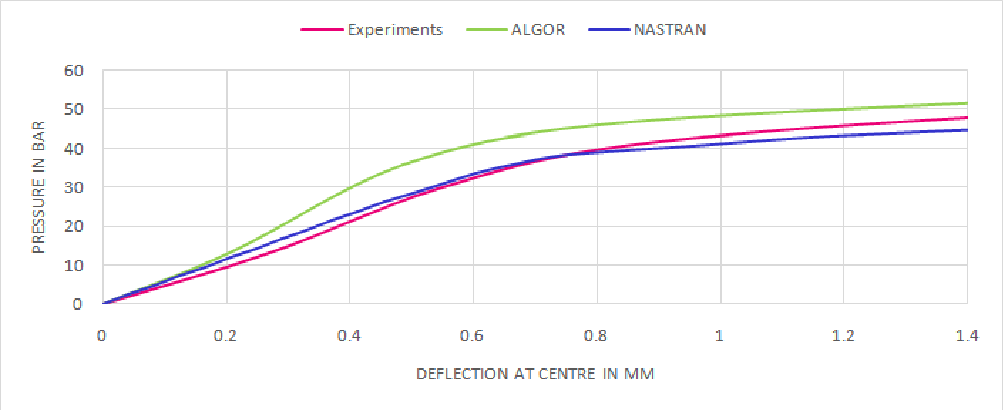


Figure 17: A comparative graph of elastoplastic behavior of a solid clamped circular plate according to experimental and numerical results

It is clear from this graphical illustration (figure 17) the efficiency of our numerical simulation, that NASTRAN results follow the experimental one for both elastic and elastoplastic behaviors, and it is more effective than ALGOR results, with for example, under a loading of 30 Bars (Transition phase), NASTRAN's results are 90% closer to experimental tests, whereas ALGOR gives an accuracy of only 70%.

Here is a first presented the elastoplastic results for plates with Square penetration pattern (figure 18):

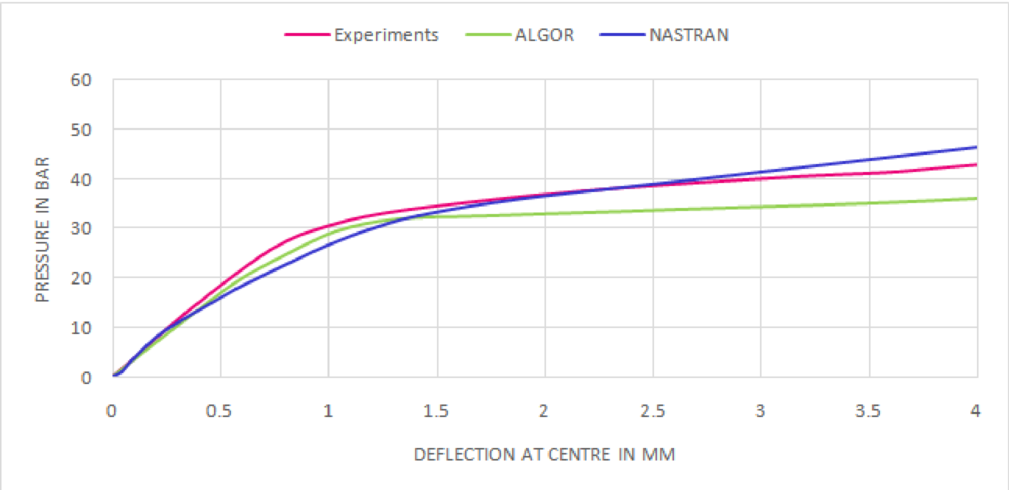


Figure 18: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with square pattern distribution according to experimental and numerical results for 0.5 ligament factor

As for the solid plate, elastoplastic results of plate with square distribution and 0.5 is more efficient than the one with equivalent plate simulation. This efficiency is clearly seen for both elastic and plastic fields.

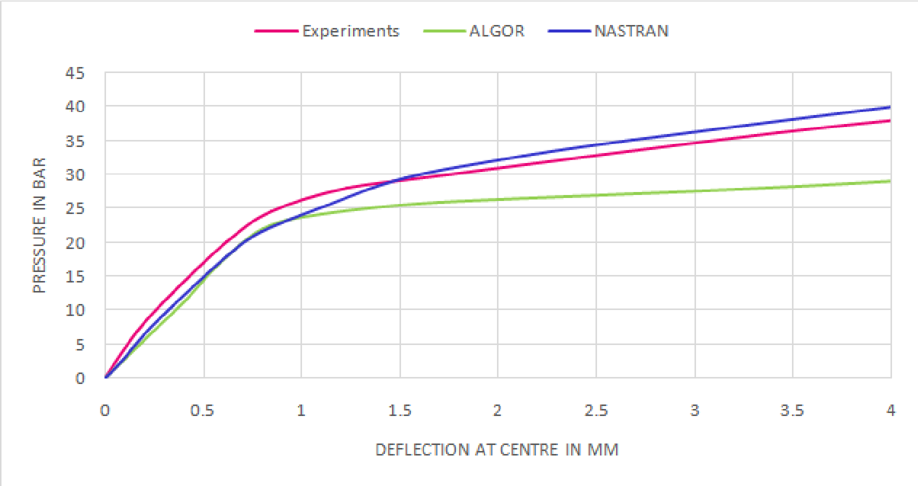


Figure 19: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with square pattern distribution according to experimental and numerical results for 0.4 ligament factor

For the case of square perforation pattern and 0.4 ligament factor, we have a good concordance with experimental results (better than ALGOR one), and also for both elastic (under 15 bars loadings) and plastic field (up to 24 bars loading).

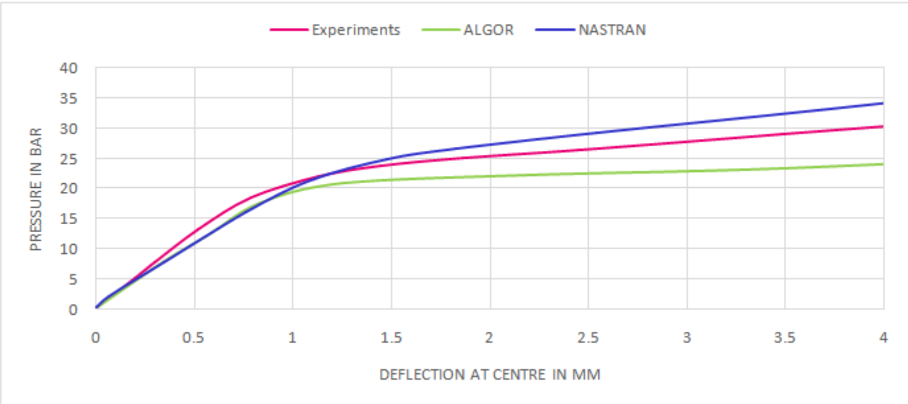


Figure 20: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with square pattern distribution according to experimental and numerical results for 0.3 ligament factor

For this case, both ALGOR and NASTRAN give the same results in the elastic domain, except that we have a better concordance between NASTRAN and experiments results in the plastic domain (up to 23 bars loading).

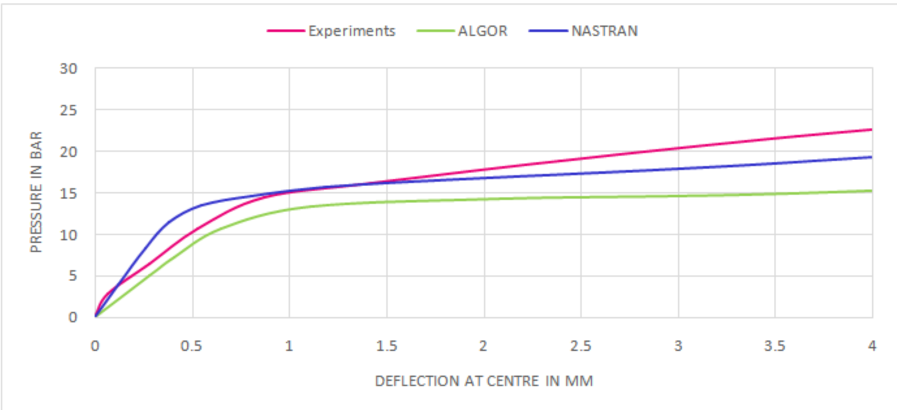


Figure 21: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with square pattern distribution according to experimental and numerical results for 0.2 ligament factor

Plate with 0.2 ligament factor presents a special case; in the elastic domain and under a loading less than 5bars, NASTRAN results are better than ALGOR one, and between 5 and 10 bars we have a slight better concordance of ALGOR ones. However, in the plastic domain, NASTRAN results are still having better concordance.
In the next graphics, we present the elastoplastic results for clamped plates with triangular penetration pattern:

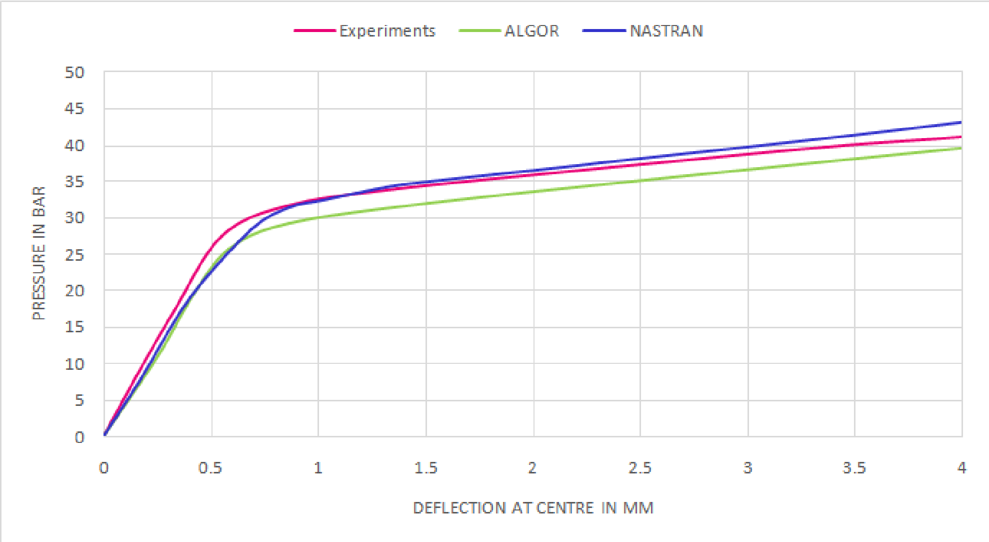


Figure 22: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with triangular pattern distribution according to experimental and numerical results for 0.5 ligament factor

As for plate with square penetration pattern, triangular one with 0.5 ligament factor show a very good concordance between Experiments and numerical simulation under NASTRAN.

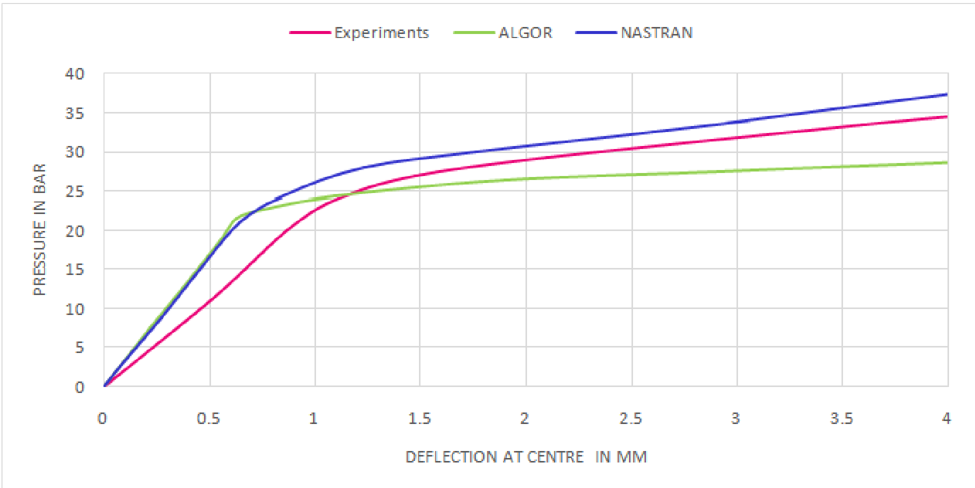


Figure 23: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with triangular pattern distribution according to experimental and numerical results for 0.4 ligament factor

For this case both NASTRAN and ALGOR give the same results in the elastic domain, except that we have a better concordance between NASTRAN and Experimental results for the elastoplastic one.

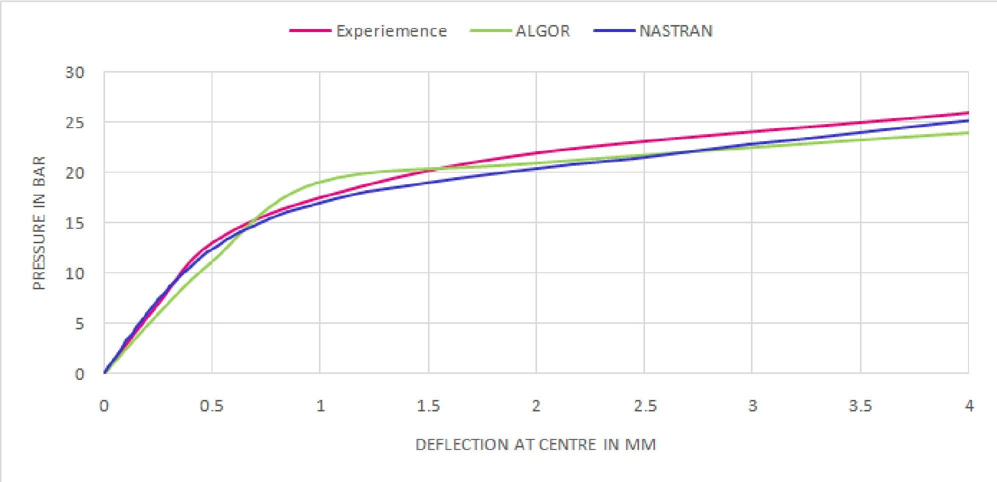


Figure 24: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with triangular pattern distribution according to experimental and numerical results for 0.3 ligament factor

For both elastic and elastoplastic phases, NASTRAN results are better than ALGOR ones.

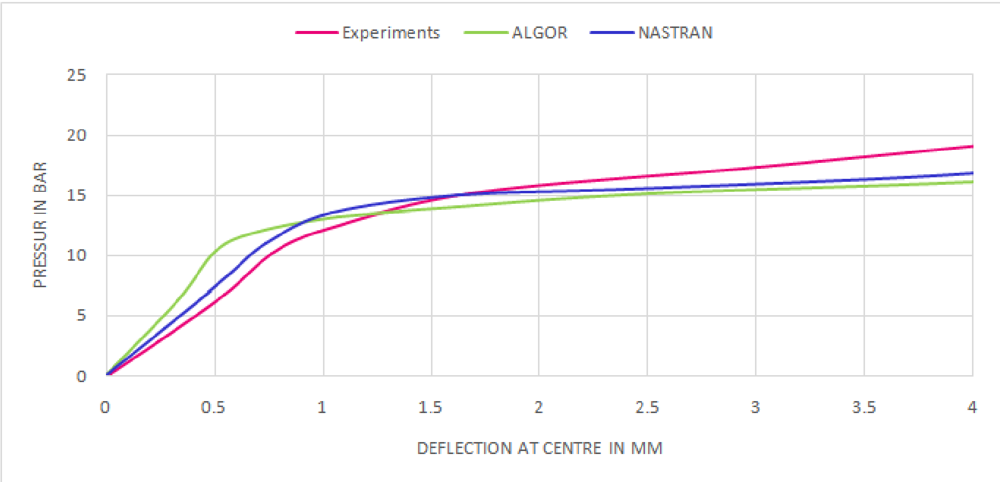


Figure 25: A comparative graph of elastoplastic behavior of a perforated clamped circular plates with triangular pattern distribution according to experimental and numerical results for 0.2 ligament factor

In the elastic domain, NASTRAN results are better than ALGOR ones. The slight gap in the plastic one is not significant as max deflection ratio on plate diameter does not exceed 2%.

More Graphical results discussions are done in the next section.

VI. Discussion

In order to determine the Typical numerical model, the elastic analysis illustrated in Figure 7 and Figure 8 allows us to evaluate different values of maximum deflections at the center of the circular perforated plates.

For most of calculations, the quadrilateral element gives result closer to the experience than the triangular element. In addition, numerical calculations with the element sizes e/6 and e/8 are the closest to experimental results, except for a few exceptions where we have a slight precision for e/8 (with a maximum difference of 6 % in precision the case of triangular distribution plates with ligament factor of 0.5).For more numerical details, refer to paragraph 1 of Result's section.

The objective being to optimize the mesh of these plates we thus used the Typical model which will be the mesh with quadrilateral elements and size of mesh of 1.33 mm, which represents the sixth of the plate thickness.

The calculation that was done after in the elastic domain was done in 3D because, according to the simulations made in 2D, the calculation time and the capacity in memory allowed it for a CAD software. By consequence, it was not possible to run the entire plate in 3D under NASTRAN. The max displacements show an average similarity of more than 90% between the whole plate and its 1/8 for the square distribution and of more than 99% between the whole plate and its 1/4 for the triangular distribution. In terms of max equivalent constraints, we have an average agreement of 99% between the results of the whole plate and its 1/8 for the square distribution and of more than 97% between the results of the whole plate and its 1/4 for the triangular distribution.

From these results we can validate the symmetry model, a hypothesis that we have extended in the elastoplastic domain.

In the presented thesis1, the numerical simulation of perforated circular plates behavior was made using ALGOR Commercial Software by adopting the equivalent full plate model[11,12]. In our work, the objective being to study the same plates behavior in both elastic and elastoplastic domains, the model validated in the elastic domain in comparison with the experimental tests was used in the elastoplastic field but with some precisions. Mesh using quadrilateral elements of size equal to 1.33 mm (e/6) is considered on all the axisymmetric plate models, a refinement around the holes by using elements of size 1 mm (e/8) is also taken into account for all plates.

The combination of two mesh sizes has shown well and good efficiency on all analysis results, especially that even if we considered the plate real geometry (with holes), our results are the best in front of those developed with ALGOR in comparison with experimental results.

Result with best concordance is clamped circular square distribution plate with a ligament factor of 0.5; we have a maximum approximation of the pressure/deflection curve with that of the experiments even in the elastic-plastic transition area.

For ligament factors 0.4, 0.3 and 0.2 (square distribution), we have a good connection with experimental results especially on plastic deformations area (88% average accuracy for NASTRAN against 76% for ALGOR).

Concerning, triangular distribution plates, the closest result to experimental curve is the one with a ligament factor of 0.5. This may be justified by the fact that it is the ligament factor giving the least holes and therefore less heterogeneity. The other triangular distribution circular plates with ligament factors 0.4, 0.3 and 0.2 also show our simulation’s efficiency with an average accuracy respectively of 91% for NASTRAN against 86% for ALGOR, 92% for NASTRAN against 85% for ALGOR and 90% for NASTRAN against 80% for ALGOR.

From all this we have successfully validated the numerical model which we have established and demonstrated NASTRAN capacity to give more accurate results even by considering the real plates geometry compared to ALGOR one for what an equivalent solid plate was considered.

VII. Conclusion

This work is part of set of works that deal with the elastoplastic behavior of perforated circular plates[13,14,15] with Von Mises plasticity criterion[16] .

In search of finding a Typical Mesh, a 2D numerical simulation was chosen for its speed to turn especially in elastic domain, thing that allows us to analyze anappropriate number of simulations. From this campaign of simulations, we concluded on a model based on quadrilateral elements with 4 nodes and of a size equal to the thickness of the plate divided by 6.

Before moving on to the elastoplastic domain, we validated by a 3D elastic static comparison the behavior of an entire plate and its axisymmetric model since we have symmetrical geometry and loading. This comparison validated the 1/8 axisymmetric model for square hole distribution plates and 1/4 axisymmetric model for triangular distributions.

Taking into consideration the axisymmetric model and the Typical Mesh, we evaluated with NASTRAN numerical simulation commercial software, the elastoplastic behavior of these plates that we compared later with experiments and simulations under ALGOR1.

To conclude, it is clear that the consideration of the actual perforated plate instead of the equivalent solid one for this simulation was on one hand, more representative of the real response of these parts, however, some difficulties still must be masteredas for example the fact that we couldn’tdetermine the area in which the simulations stick the most with experimental results (elastic or plastic).

Finally, we have well noticed in all the obtained graphs, that there is in the elastic or plastic field a better concordance between our results and experimental ones, than between ALGOR simulations and experimental results.

References

[1]. A. LAYAD (Faculté Polythechnique de MONS). Simulation du comportement des plaques circulaires perforées. (Faculté Polythechnique de MONS, 1999).

[2]. WIERZBICKI T & FLORENCE AL. Theoretical and Experimental Investigation of Impulsively Loaded Clamped Circular Viscoplastic Plates. *Int. J. Solids Struct.*6, 553–568 (1970).

[3]. Indus-, Y. C., Alto, P. & City, A. Heat-Exchanger Tube-Sheet D e s i g n — 3 . U-Tube and Bayonef Tube Sheets. (2016).
[4]. W.J O'Donnell, F. L. Design of Perforated Plates. *ASME Ser. B, vol 84* (1962).
[5]. Lakce, R. H. & Onat, E. T. A comparison of experiments and theory in the plastic bending of circular plates. *J. Mech. Phys. Solids*10, 301–308 (1962).
[6]. Qian, C. F., Yu, H. J. & Yao, L. Finite Element Analysis and Experimental Investigation of Tubesheet Structure. *J. Press. Vessel Technol.*131, 11206 (2009).
[7]. Cantemir, D., Bertini, L., Beghini, M., Barbieri, L. & Spadaccini, F. A finite element procedure for prediction of tube hole distortion due to welding of large perforated plates. *Int. J. Press. Vessel. Pip.*84, 460–468 (2007).
[8]. Island, R. ELASTIC-PLASTIC UNDER BENDING OF A BUILT-IN CIRCULAR LOAD + UNIFORMLY. 5, (1935).
[9]. Atanasiu, C. & Sorohan, S. Displacements and stresses in bending of circular perforated plate. *IOP Conf. Ser. Mater. Sci. Eng.*147, (2016).
[10]. MSC. MSC Nastran 2013 Quick Reference Guide. (2013).
[11]. Meijers, P. Plates with a doubly-periodic Pattern of Circular Holes Loaded in Plane Stress or in Bending. *FIC PVT Delft* (1969).
[12]. Duncan, J. P and Upfold, R. . Equivalent Elastic Properties of Perforated Bars and Plates. *J. Mech. Eng. Sc*5, (1963).
[13]. Save, M. A., Massonnet, C. E. & De Saxce, G. *Plastic Limit Analysis of Plates, Shells and Disks*. (1997).
[14]. Timoshenko, S. & Woinosky-Krieger, S. Theory of Plates and Shells Classic. 580 (1959).
[15]. Chen, F. K. Analysis of plastic deformation for sheet metals with circular perforations. *J. Mater. Process. Tech.*37, 175–188 (1993).
[16]. G. Guerlement, D. . L. Analyse limite de plaques circulaires avec la condition de plasticité de Von Mises. (2017).

E. Azelmad."Elastoplastic Behavioranalysis of Clamped Circular Perforated Thin Plates." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 15, no. 2, 2018, pp. 23-37