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Algorithm Development and Design of Lattice Conical Shell Under Mechanical and Thermal Loads

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Abstract: In this study, the development of a generative algorithm related to the lattice conical shell (Isogrid pattern) and the modeling of the stiffened shell under mechanical and thermal loads are discussed. An algorithm has been developed for the lattice conical shell (MATLAB software), which generates the pattern of stiffeners on the conical shell. Modeling of the lattice conical shell is done in SolidWorks software. The structure of stiffened shell is analyzed under loading using the Finite Element Method (FEM) in the ANSYS Workbench. The modeling of the lattice conical shell is investigated under mechanical (axial and bending load and internal pressure) and thermal loads. It is concluded that the stiffeners can resist buckling and mechanical failure under mechanical and thermal loading conditions, while the mass is significantly reduced. This shell can be used in various industries due to its lightweight and high resistance. Whereas the safety factor of the final model is about 2 and the model is acceptable for desirable internal pressure (0.6 MPa), the total system mass is about 41 kg.

Keywords: Design, Finite Element Method (FEM), Generative Algorithm, Lattice conical Shell

Biographical notes: Behrooz Shahriari was born in Isfahan, Iran in 1975. He received his BSc in Mechanical Engineering and MSc and PhD degrees in Aerospace Engineering from Malek Ashtar University of Technology in 2002, 2012, and 2016, respectively. His current research interests are structural optimization and artificial intelligence. **Mahdi Sharifi** received his MSc in Aerospace Engineering from the University of MUT, Isfahan, Iran, in 2024. His current research field is lattice conical shells. **Hassan Izanlo** is a researcher and his current research interests are optimization, robotic nonlinear dynamics, and nonlinear vibration.

Research paper

1 INTRODUCTION

In the aerospace industry, the efficiency of the structure is very important, which has made experts design these structures with high resistance and lightweight. Cone-shaped structures are structures that have many applications in various industries, including aerospace industries. The use of these shells in the aerospace industry is in the shells of engines, spaceship fuel tanks, etc. The lattice conical shell and Isogrid pattern are shells that have a special type of stiffener inside, outside or both. The mass of the thick shell structure is significantly decreased by redesigning it into a stiffened thin shell, while the reduction in strength is negligible. The stiffeners can have a rib and stringer combination in a simple form or a more complex form such as triangular, hexagonal, or square.

Kim [1] In his study, developed and tested stiffeners isogrid composite cylinder. He performed the axial compression test to extract the different failure modes in the structures such as the criticality of the ribs, shell buckling, and general instability. He proved that the isogrid cylinder can resist structural damage due to the large number of load paths; In this way, the cylinder continues to resist the compressive load even after breaking one or more ribs. In the experiment, it was determined that rib buckling is the critical failure mode for isogrid cylinders. Rahimi et al. [2] analyzed the buckling behavior of thin-walled GFRP cylindrical shells with triangular lattice stiffeners formed by helical and circumferential ribs under axial loading. They investigated different models of composite isogrid stiffener cylindrical shells with external diameter, shell thickness, height, and stiffeners that have the same properties, and constant cross-sectional area but different shapes and cross-sections. Their goal was to observe the effects of these differences on the buckling resistance of structures under axial load. They concluded that strengthening the shells increases the buckling load while decreasing the ratio of the buckling load to the weight of the unreinforced shell.

Totaro [3] analyzed the local buckling failure modes of triangular Latticed cylindrical shells in his study. He used accurate modeling to improve failure mode prediction. He verified the interaction of cross ribs and spiral ribs and investigated the effect of the number of shell sections, and the effect of pre-buckling tensile force on the ribs of the proposed model using finite element analysis. Eskandari Jam et al. [4] investigated the parameters affecting the design of anisogrid lattice conical shells and finally, they performed the buckling analysis of the lattice conical structure under axial loading, considering the relationships. Kim [5] made and tested the axial compression of reinforced composite isogrid panels. He performed this test to identify different failure modes in structures such as the critical condition of ribs, shell buckling, and general instability. He proved that the isogrid plate can resist structural damage due to a large number of load paths. Therefore, the plate resists the compressive load even after breaking one or more ribs. In the experiment, it was found that rib buckling is the critical failure mode for the isogrid plate. Sorrentino et al. [6] used coil robotics technology to fabricate an isogrid cylinder, made of composite materials. They performed geometric and structural tests on these structures and compared their results with the results obtained from hand-made structures. Their comparison determined the better quality of the robotic coil structures because these structures compiled with the geometrical changes and showed greater resistance to the axial compressive load.

Belardi et al. [7] presented a method for structural analysis and optimal design of composite anisogrid conical lattice structures subjected to various external loads. In this method, a finite element parametric modeling technique is used, which can manage all the geometrical parameters of the composite anisogrid lattice structure. Hao et al. [8] investigated the compression behavior of a natural fiber-based isogrid lattice cylinder made from pineapple leaf as fiber and phenol-formaldehyde resin as matrix, which is eco-friendly natural. They concluded that the lattice cylinder combined with the shell can be used to make a sandwich structure for use in parts of the building. Akl et al. [9] selected the best angle for the orientation of the stiffeners by presenting a logical design approach to optimize the static and dynamic characteristics of reinforced plates in the form of an isogrid.

Li et al. [10] designed an isogrid-shaped structure with T-shaped ribs to increase buckling resistance and plastic performance, manufactured it by 3D printing, and verified their model using finite element analysis. Totaro [11] formulated the constraint design Equations for longitudinally compressed lattice panels in buckling failure mode. His approach focuses on minimizing mass using analytic minimization. His approach was confirmed by the finite element results. Li and Fan [12] designed and manufactured a composite reinforced cylinder with carbon fiber in the form of an isogrid by applying the coiling and co-curing technique. They deduced the failure modes from the design of this optimized model in terms of minimum weight. Francisco et al. [13] optimized an isogrid structure considering six different responses using the sunflower algorithm to find the best shape. They optimized their model using multi-objective optimization. Pereira et al. [14] employed the multi-objective optimization of the isogrid pipe considering six objectives using the Lichtenberg algorithm to find the best design. In this regard, they used the finite element method to develop a numerical model for the complex structure.

The mentioned Studies did not consider the generative algorithm for modeling the lattice conical shell. They also did not consider the thermal conditions. In the current study, using the development of the generative algorithm for the lattice conical shell, generating and obtaining the angles and direction of the stiffeners on the conical shell will be developed. Then, using the angles and directions obtained for the stiffeners, the geometry of the lattice conical shell has been modeled in the SolidWorks software and analyzed for loading in the finite element software ANSYS Workbench under thermal and mechanical loads (compressive and axial). In order to validate the developed method, the Equations applied to the simple conical pressure vessel are derived. Finally, the results obtained from the finite element analysis are compared and validated with the numerical solution.

2 DEVELOPED ALGORITHMS

Generative algorithm development is a process that uses computational methods to achieve an optimizing algorithm that can optimize a set of data. In a generative algorithm development process, the required data and initial constraints are defined by the user, and the required outputs are requested from the algorithm. The algorithm developer must still use insight, knowledge, and intuition to develop the algorithm.

In this study, an algorithm is developed for the lattice conical shell that receives the large radius (R_1) and the small radius (R_2) of the incomplete cone. The inputs also contain the cone length (L) and initial stiffener angle. For this developed generative algorithm, a flowchart is presented that shows the implementation of this algorithm step by step (“Fig. 1”).

The mentioned flowchart includes the steps that will display the required output. In order to specify the algorithm, the steps are explained:

Step 1- The large radius (R_1), the small radius (R_2) of the incomplete cone (a cone that has been cut on one or both sides), the length of the lattice conical shell (L), angle of the stiffeners (angle of stiffeners with flange) (β) and the spiral resolution (n=10000) are received from the user.

Step 2- Based on the received information, the conical shell is plotted as a three-dimensional diagram.

Step 3- The value of Z is specified using the linspace function, which creates a linearly spaced vector (equally spaced).

Step 4- The values of X and Y are determined according to the Equation governing the cone as well as the values of i and Z that have been selected in advance.

Step 5- The direction and angle of the first stiffener are determined and plotted in three dimensions by determining the values of X, Y, and Z.

Step 6 - The algorithm checks that if i=11, show the End, and if it is not, add one unit to it and return to step 4. The values of i must be less than or equal to 11. Choice 11 is to prevent stiffeners from overlapping each other.

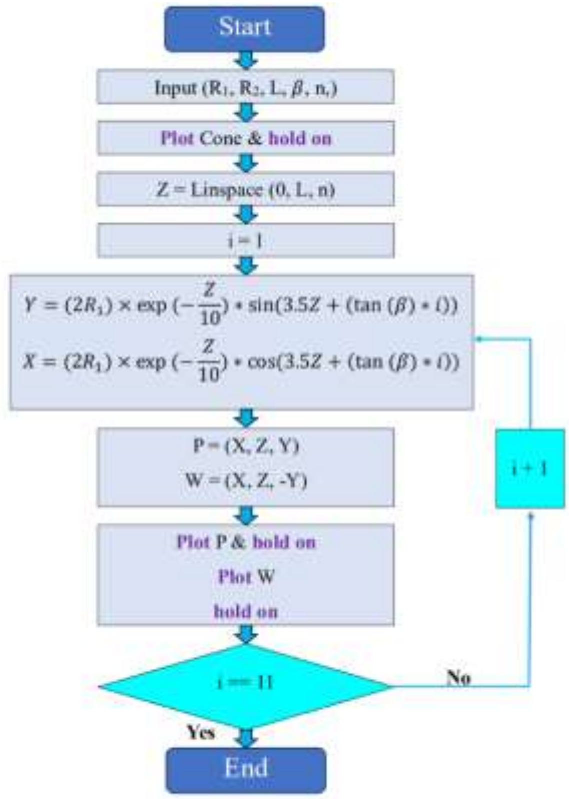

Fig. 1 Flowchart of the developed generative algorithm for lattice conical shell.

The algorithm used in this study is coded in MATLAB software (“Fig. 2”).

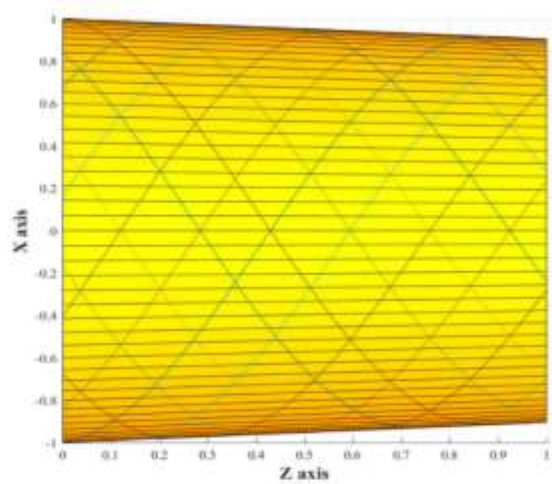

Fig. 2 Generating stiffeners by the developed generative algorithm for lattice conical shell.

3 MODELING

Whereas the modeling of the lattice conical shell is difficult due to its complex structure, the developed algorithm verified the mathematical model of the stiffener. Therefore, this pattern is designed in SolidWorks software as a three-dimensional model.

3.1. Introduction of The Structure

The lattice conical shell is an incomplete cone (a cone that has been cut on one or both sides). This shell has dimensional specifications and these values are presented in "Table 1" for the mentioned structure.

Table 1 Dimensional characteristics of lattice conical shell

Parameter	Value
Large radius (R_1)	0.5 m
Small radius (R_2)	0.446 m
Slope of the cone (θ)	3 deg
Length of the cone (L)	1 m

In this study, a lattice conical shell made of Inconel 718 material is designed. Inconel 718 is a nickel-chromium superalloy that has high strength and corrosion resistance and is used in the temperature range of -253 to 704 degrees Celsius. The hardness of the alloy increases through the aging process, and its production and shaping capabilities are also reachable. This alloy has good weldability and its resistance to cracking caused by stress is also very desirable. The presence of features such as ease and economy in manufacturing along with high tensile strength, desirable fatigue, creep behavior, and acceptable rupture strength have made Inconel 718 widely used in the industry. The mechanical and thermal properties of Inconel 718 are presented in "Table 2".

Table 2 Mechanical and thermal characteristics of Inconel 718 [15]

Properties	Value
Density	8170 ($^{kg}/_{m^3}$)
Ultimate tensile strength	1243 MPa
Yield tensile strength	1154 MPa
Modulus of elasticity	200 GPa
Elongation at the breaking	%18
thermal conductivity	11.4 w/m-k

3.2. Modeling Method

The modeling of the lattice conical shell with the mentioned dimensions has been done in the SolidWorks software. For the modeling method, a flowchart is developed that shows step-by-step modelling of the lattice conical shell ("Fig. 3").

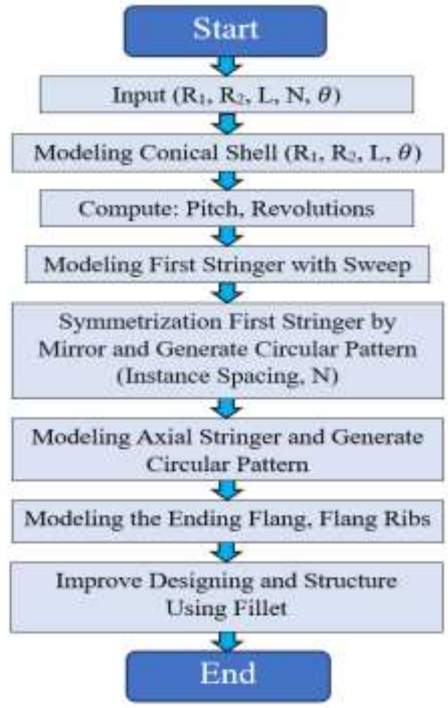

Fig. 3 Conical shell modeling flowchart.

The above flowchart contains steps that show how to model. The step-by-step explanation to clarify the details:

Step 1- To model the lattice conical shell, the geometry of the cone is generated with the large radius (R_1), the small radius (R_2), the slope of the cone (θ), and the length of the cone (L).

Step 2- To model stiffener, the results of the algorithm are used, and Revolution and Pitch are calculated. Then, the first stiffener is modeled by drawing the geometry of the cross-section and using the Sweep command.

Step 3- Another stiffener is modeled, by Symmetrization the first stiffener is in the opposite direction. The CirPattern command is used to generate stringers (N=24) on the lattice conical shell.

Step 4- To increase the strength and resistance to buckling, stiffeners are created horizontally (in line with the cone) and more are generated with the CirPattern command.

Step 5- Two flanges are modeled at the beginning and end of the shell so that it can be loaded. To prevent buckling near the flanges, two ribs are modeled which have the same height as the other stiffeners.

Step 6 - Fillets are used to reduce the stress concentration and distribute the stress more evenly between the lattice conical shell and the stiffeners.

The final geometry is prepared for finite element analysis ("Fig. 4").

Fig. 4 Final model of lattice conical shell.

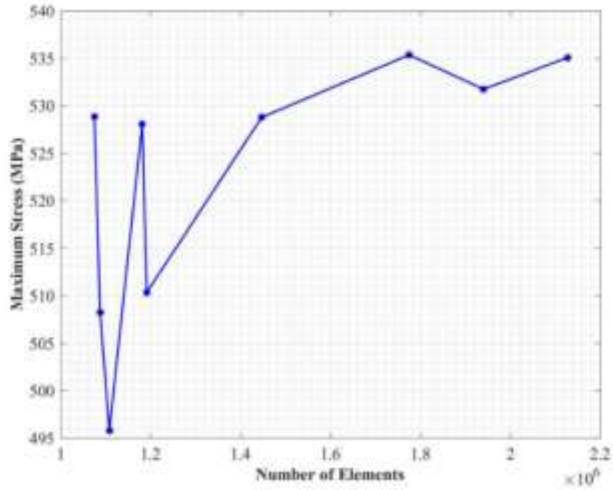

Fig. 6 Mesh independency study diagram for lattice conical shell.

4 FINITE ELEMENT ANALYSIS

The lattice conical shell should be subjected to loading after modeling. The analysis of this shell has been done in the ANSYS finite element software of the Static Structural part. In this analysis, very fine shell meshing is considered to get the best result ("Fig. 5"). A tetrahedral element has been used for finite element analysis.

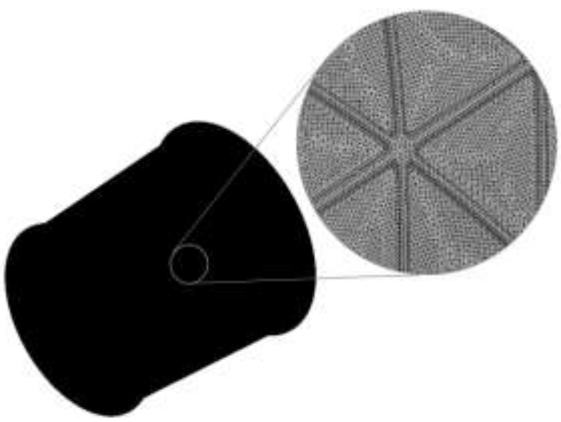

Fig. 5 Meshed lattice conical shell.

In order to converge the results of the analysis related to the lattice conical shell, the mesh independency study was performed for this shell ("Fig. 6"). In "Fig. 7", the horizontal axis corresponds to the number of elements and the vertical axis corresponds to the maximum stresses on the lattice conical shell. The results show that the convergence of the analysis is acceptable. In the loading conditions section, the internal pressure force, the axial pressure force on the primary flange, and the vertical pressure force on the primary flange are applied ("Fig. 8").

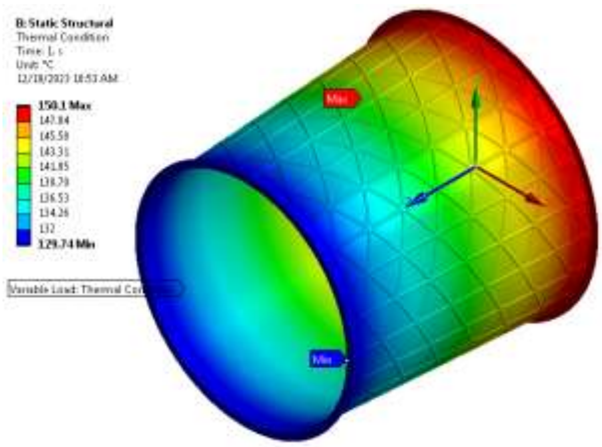

Fig. 7 The temperature gradient applied to the shell.

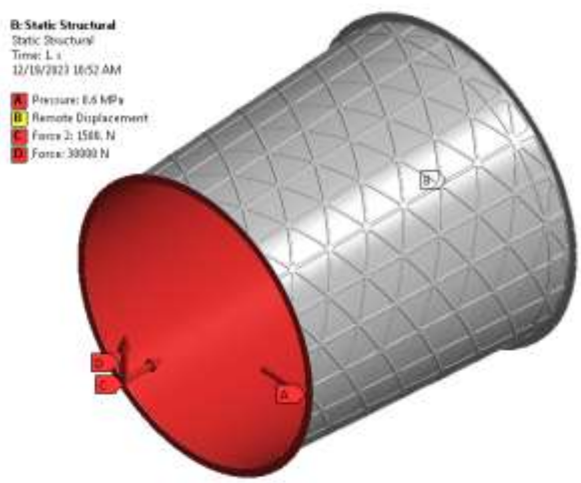

Fig. 8 Lattice conical shell under loading conditions.

Considering safety requirements, manufacturability, uncertainty in material strength, operating conditions, and possible defects in lattice shells, the value of internal pressure is considered with a safety factor of 2 (The value of internal pressure is 0.3 MPa, which becomes 0.6 MPa by considering the safety factor of 2). Also, the temperature gradient has been applied to the lattice conical shell ("Table 3"). The lattice conical shell is modeled in such a way that the heat source is adjoined to the large flange. As a result, the temperature in the large flange is higher and the temperature decreases as it moves away from the heat source ("Fig. 7"). In applying the boundary conditions, the outer surface of the conical end flange is under the remote displacement support condition, and all its degrees of freedom are set to zero.

Table 3 Mechanical loading and thermal conditions applied to the lattice conical shell

Applied Load	Value
Internal Pressure	0.6 MPa
Axial Compressive Force	30000 N
vertical compressive force	1500 N
Temperature Gradient	130-150 ℃

The final model of the lattice conical shell is finite element analysis after applying the loading conditions. The shell has been analyzed in terms of the equivalent stress value, maximum stress value, deformation, and necessary safety factor.

5 RESULTS

The finite element method is used to study the lattice conical shell under axis compressive, internal compressive, vertical compressive, and thermal gradient loads. In general, the aim of the finite element method of lattice conical shell is to provide a practical method to study the behavior of this structure.

The lattice conical shell has been analyzed under the mentioned loads. The lattice conical shell has been investigated in terms of equivalent stress and deformation. The results of finite element analysis are shown in "Figs. 9-15".

According to the figures and diagrams, the following results are deduced:

1. It can be seen that the maximum stress occurred at the intersection of the horizontal stiffeners and end flange and the minimum stress occurred at the flanges.
2. Considering that the internal pressure is applied to the lattice conical shell, the inside of the shell is uniform, but the outside of the shell has stiffeners and fillets, so the maximum stress outside the shell is more than the maximum stress inside the shell.
3. The maximum deformation was near the initial flange because the axial and vertical compressive loads were applied to this area. The minimum deformation is in the end flange because this part is under the remote displacement support condition.
4. The deformation in the radial direction is less than the deformation in the axial direction ("Fig. 13").
5. An increase in vertical force on the lattice conical shell causes an increase in the stress (Figure 15).
6. The maximum safety factor is on horizontal stiffeners and flanges.
7. The total mass of the system is about 41 kg.
8. The final minimum safety factor is about 2 and the model is acceptable for the desirable industrial conditions.

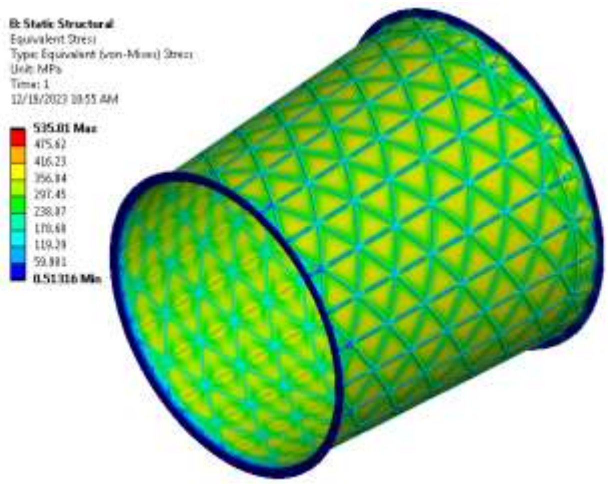

Fig. 9 The contour of the maximum stress on the lattice conical shell.

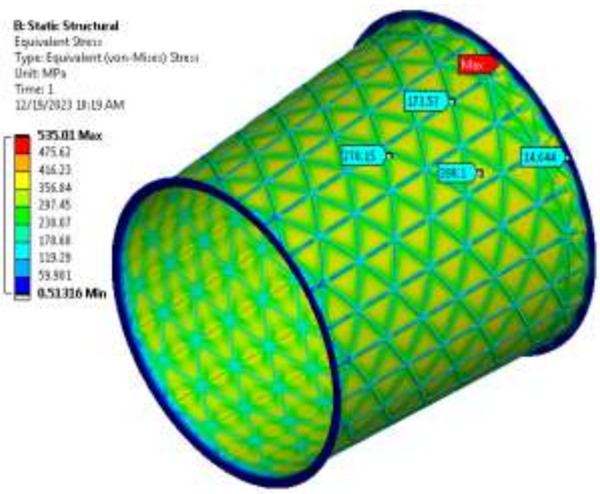

Fig. 10 Different values of stress on the lattice conical shell.

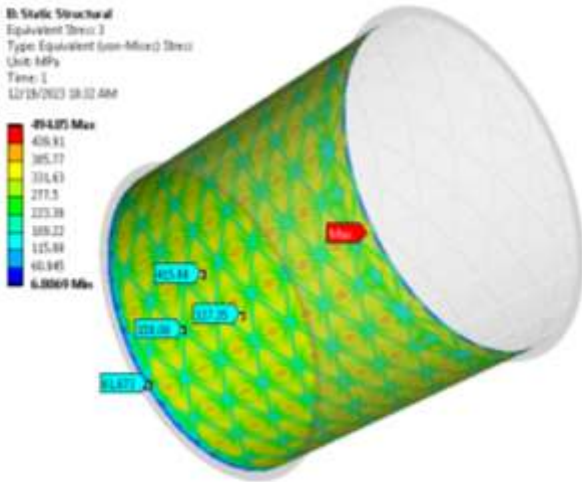

Fig. 11 The maximum stress contour on the inner surface of the lattice conical shell.

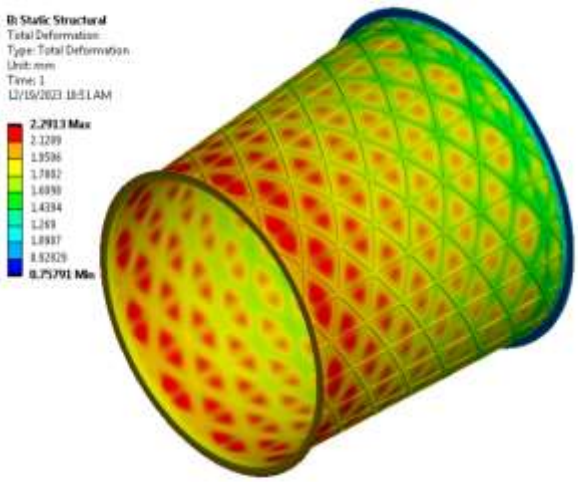

Fig. 12 Deformation contour of lattice conical shell under applied loads.

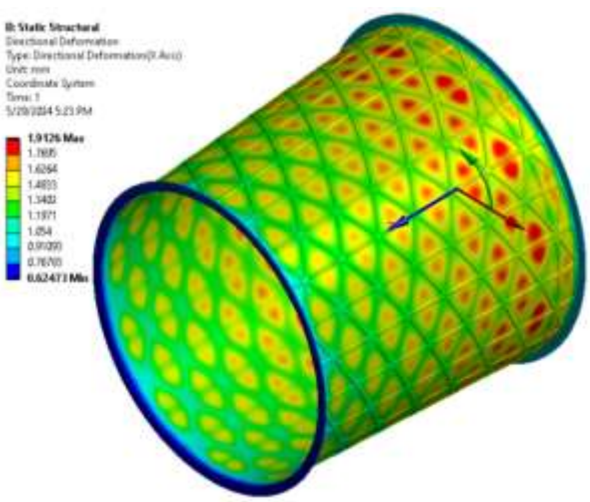

Fig. 13 Deformation contour of the radial direction of the lattice conical shell.

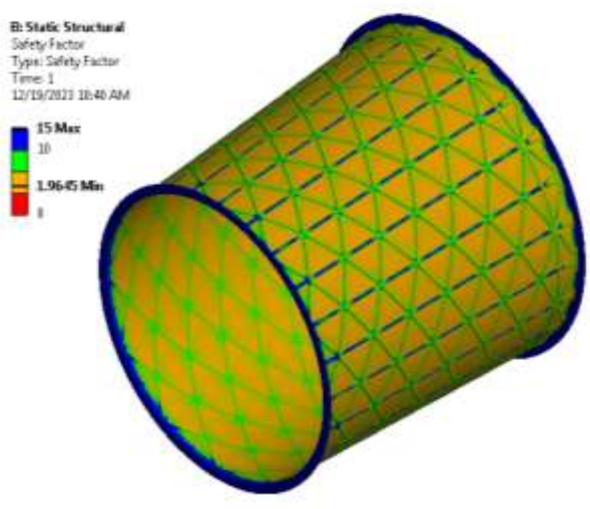

Fig. 14 Safety factor contour for lattice conical shell.

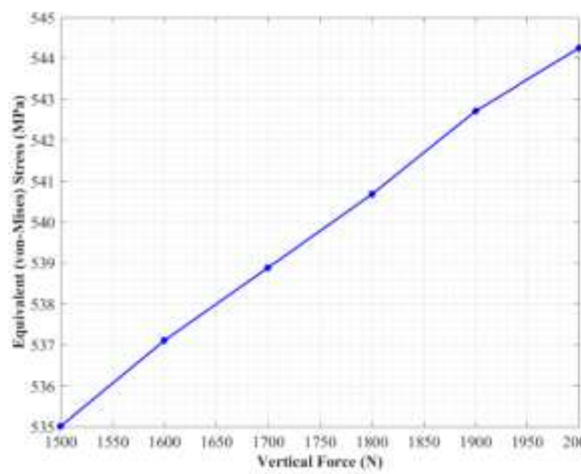

Fig. 15 The effect of changing the vertical force on the value of stress.

6 VALIDATIONS

To confirm the performed finite element method, the stress on the pressure vessel is investigated. The Pressure vessel is modeled in SolidWorks software (The dimensions of this Pressure vessel are equal to the dimensions of the lattice conical shell). The pressure vessel is subjected to internal pressure. The pressure vessel is implemented for finite element analysis in the ANSYS Workbench and its results are obtained (“Fig. 16”). Figure 17 shows that according to the linear Equation (1), the stress value (σ) increases with the increase of the radius (R).

$$\sigma(MPa) = (0.44 \times R) + 53.22 \tag{1}$$

Fig. 16 The value of stress in different radii of the cone.

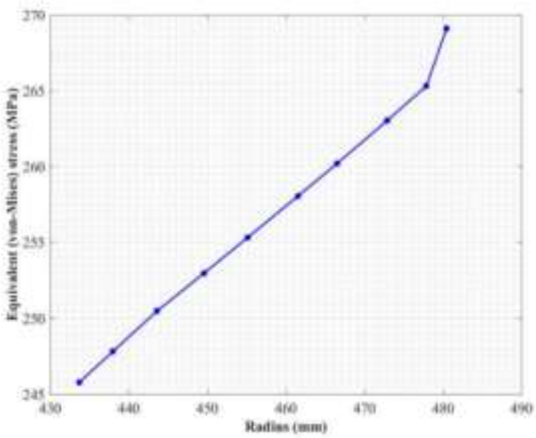

Fig. 17 Stress distribution diagram along the cone.

Therefore, the stress formula can also be used in pressure vessels. To prove the stress value obtained from the finite element analysis, The analytical solution of the pressure vessel is discussed. In the analytical method, the stress in each direction is according to "Fig. 18". Considering that the value of σ_3 is much smaller than the value of σ_2 and σ_1, then it is ignored.

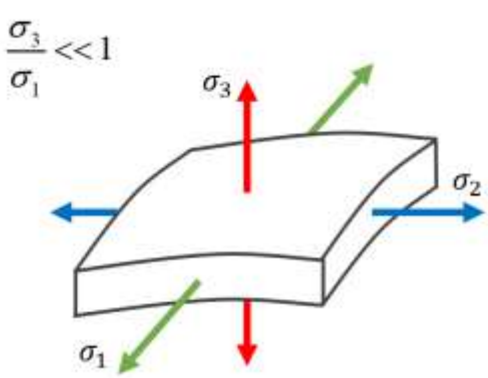

Fig. 18 Stress in coordinate Axis.

To obtain the stress value in the radial direction (σ_1), an element of the pressure vessel is considered ("Figs. 19 and 20).

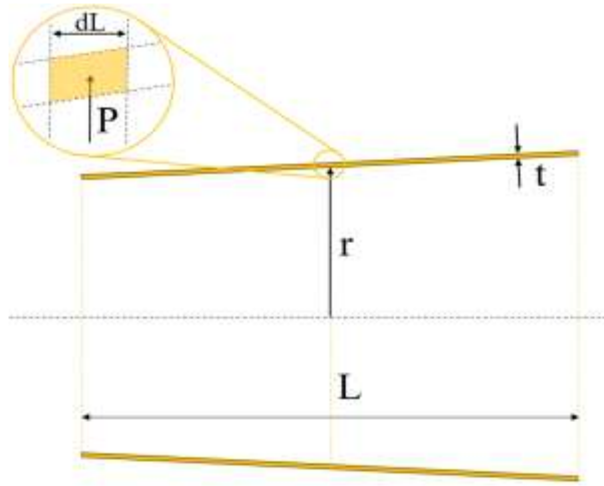

Fig. 19 Effective parameters in the pressure vessels (σ_1).

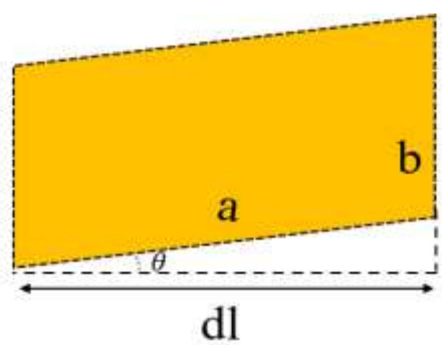

Fig. 20 Element of the pressure vessel.

The area of shell element is obtained from Equation (2):

$$A = ab\sin(\frac{\pi}{2} - \theta) = ab\cos\theta \quad (2)$$

The values of (a) and (b) in Equation (2) are equal to (Equation (3)):

$$a = \frac{dl}{\cos\theta}, b = t \quad (3)$$

By inserting the values of 3 in Equation (2), it is obtained:

$$A = t \times dl \quad (4)$$

The force of the element is obtained from Equation (5):

$$ElementForce = P \times (2t \times dl) \quad (5)$$

Because this shell has a thin thickness and this shell is under internal pressure and the strain vector is zero, the problem is solved in the form of plane stress. According to "Fig. 19", if an element of pressure vessels is considered, the equivalence Equation in the radial direction (σ_1) is equal to:

$$\sigma_1(2t \times dL) = P(2r \times dL) \quad (6)$$

The stress in the radial direction (σ_1) is obtained from Equation (7):

$$\sigma_1 = \frac{Pr}{t} \quad (7)$$

Table 4 Values of effective parameters in pressure vessel

Parameter	Value
Internal Pressure (P)	0.6 MPa
Middle radius (r)	473×10^{-3} m
Slope of the Cone (θ)	3 deg
Length (L)	1 m
Thickness (t)	1×10^{-3} m

The value of stress in the radial direction on an element of pressure vessel is obtained, by putting the values ("Table 4") in Equation 7:

$$\sigma_1 = \frac{0.6\times10^6 \times 473\times10^{-3}}{1\times10^{-3}} = 283.8\times10^6\, Pa \quad (8)$$

To obtain the stress value in the longitudinal direction (σ_2), the element of the pressure vessel is considered ("Fig. 21").

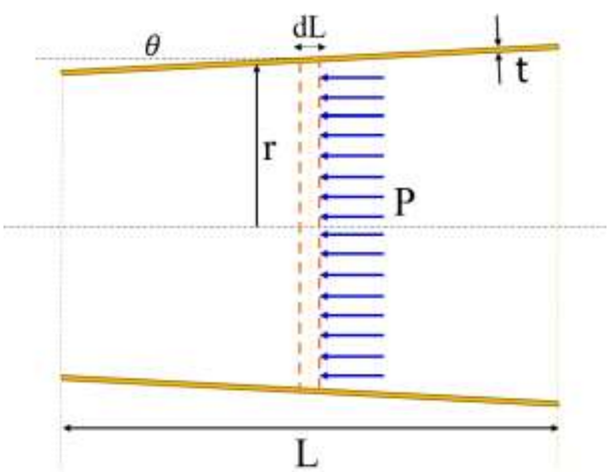

Fig. 21 Effective parameters in the pressure vessel (σ_2).

Static equilibrium is in the longitudinal direction (σ_2). The value of longitudinal (tensile) stress is equal to:

$$\sigma_2(2\pi \times rt) \times \cos\theta = \mathrm{P} \times (\pi\, \mathrm{r}^2) \quad (9)$$

The stress in the longitudinal direction (σ_2) is obtained from Equation (10):

$$\sigma_2 = \frac{\mathrm{Pr}}{2t \times \cos\theta} \quad (10)$$

The value σ_2 is obtained, by substituting the values ("Table 4") into "Eq. (10)":

$$\sigma_2 = \frac{0.6\times10^6 \times 473\times10^{-3}}{2\times(1\times10^{-3})\cos(3)} = 142.09\times10^6\, Pa \quad (11)$$

According to Mohr's circle, since $\sigma_2 < \sigma_1$, then the value of σ_1 is accepted as the final stress in the element ("Fig. 22").

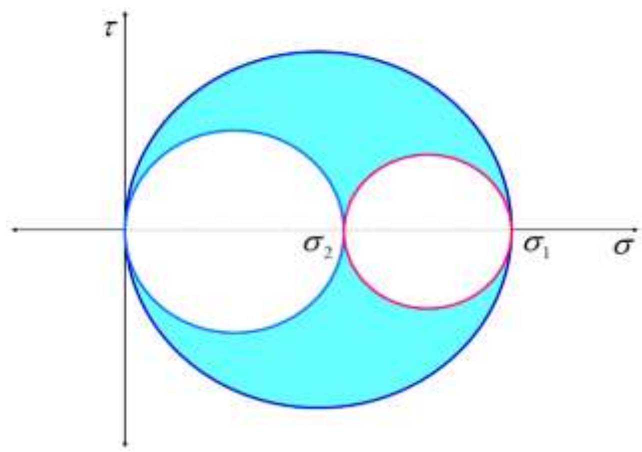

Fig. 22 Mohr's circle for (σ_1 ,σ_2).

In the finite element analysis, the stress value at the radius of 473×10^{-3} m is equal to 263.4×10^6 Pa, which is close to the value obtained from the analytical solution. The value of the Relative Error is equal to:

$$RE = \frac{(283.8\times10^6) - (263.4\times10^6)}{283.8\times10^6} = 7.18\% \quad (12)$$

The results obtained from the analytical solution using the finite element method have a minor difference from the results obtained from the numerical solution, so it can be concluded that the numerical results of the lattice conical shell are acceptable.

7 CONCLUSIONS

In this study, the development of a generative algorithm related to the lattice conical shell and the modeling of this lattice conical shell under mechanical and thermal loads were discussed. To this purpose, an algorithm for the lattice conical shell has been developed in MATLAB software, which generates the stiffener pattern on the conical shell. Using this model, the lattice conical shell was modeled in SolidWorks software and analyzed for loading in ANSYS Workbench. The lattice structure reduced the total mass significantly, while the structure has acceptable resistance to mechanical loading and the final safety factor is acceptable.

1. The combination of ribs and strings is very resistant to loads.
2. The maximum stress is at the intersection of the horizontal stiffeners with the end flange. Considering that the safety factor of this part is acceptable, the modeling is reliable.
3. This structure can also be used in aerospace systems due to its low mass and high resistance. The design with minimal mass can have a significant effect on fuel reduction.
4. Whereas the safety factor of the final model is about 2 and the model is acceptable for desirable industrial conditions, the total system mass is about 41 kg.
5. Whereas the real internal pressure of the system is about 0.3 MPa, the system is designed for 0.6 MPa. This subject increases the total safety factor and reliability of the system.

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