Journal of Simulation and Analysis of Novel Technologies in Mechanical Engineering
16 (2) (2024) 0033~0046

Research article

Design and structural analysis of buckling and prestressed modal of an isogrid conical shell under mechanical and thermal loads

Behrooz Shahriari[1]*, Mahdi Sharifi, Hassan Izanlo

[1]*Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran,* shahriari@mut-es.ac.ir
[2]*Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran,* mahdisharifi13780@gmail.com
[3] *Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran,* Hassanizanlo1998@gmail.com

*shahriari@mut-es.ac.ir

(Manuscript Received --- 24 March 2024; Revised --- 04 May 2024; Accepted --- 20 May 2024)

Abstract

Aerospace structures are very important, so it is necessary to design aerospace structures with low weight and high resistance. In this study, the isogrid conical shell has been studied. At first, an algorithm for the isogrid conical shell is developed in MATLAB software. This algorithm generates the pattern of stiffeners (isogrid) on the conical shell. According to the isogrid conical shell plot in MATLAB software, a shell design has been done in SolidWorks software. Then, the isogrid conical shell has been analyzed under mechanical loads (axial and bending load and internal pressure) and temperature gradient in the ANSYS Workbench software using the finite element method (FEM). Buckling, modal, prestressed–modal, deformation and equivalent stress analyzes have been performed on the isogrid conical shell. The total mass of the system is about 41 kg and it is modeled for an optimal internal pressure (0.6 MPa) with safety factor of about 2. It was concluded that the conical shell with isogrid stiffeners under temperature conditions and mechanical loads can reduce the weight and resist buckling and vibration. At the end, the conditions of fixed support and remote–displacement are compared. This shell can be used in aerospace structures.

Keywords: Isogrid conical shell, Prestressed modal analysis, Buckling analysis, Design, Finite Element Method (FEM).

1- Introduction

Engineers in the aerospace industry should design structures with high strength and low weight because the structure is of great importance in these industries. Isogrid stiffener are stiffeners that have a combination of rib and stringer in the form of a triangle, which by being placed on the shells can increase the strength of the shell tremendously while reducing the weight. Structures with isogrid stiffeners are structures that have many applications in various industries, including aerospace industries. The application of these structures is often in the shell of engines, fuel tanks of spaceships, etc. The isogrid conical shell is in a form that has a special type of stiffener inside the shell, outside or both. Morozov et al. [1] developed a specialized method of finite element model generation. This method is used to analyze the buckling of composite anisogrid conical shells. They showed that the buckling resistance can be significantly increased by increasing the stiffness of multiple annular ribs near the larger diameter section or by introducing additional annular ribs in the same part of the conical shell. Kanou et al. [2] analyzed the cylindrical structure of isogrid composite lattice with and without skins by numerical method in ANSYS software. This latticed cylindrical structure consists of helical ribs and circumferential ribs ±ϕ (with respect to the shell axis). Reinhold et al. [3] investigated the use of the isogrid structure as a suitable alternative to the primary composite structure in small-scale rocket airframes. Johnson and Paramasivam [4] investigated the effect of short carbon fiber reinforcement with polyamide three-dimensional printing material on the compressive response of isogrid lattice shell structures with experimental and numerical modeling. They compared the numerical findings with the structures obtained by experimental methods. They also investigated the effect of geometrical parameters of rib width (helical and hoop), shell thickness, helical angle of ribs on buckling strength. Sorrentino et al. [5] designed an isogrid cylinder made of composite materials suitable for axial load. Finally, the designed part was produced and tested to evaluate the quality of the manufacturing process and the correspondence to the design requirements. Hao et al. [6] investigated the compression behavior of an eco-friendly natural fiber-based isogrid lattice cylinder made of pineapple leaf fibers and phenol-formaldehyde resin matrix. They conducted an experiment to investigate the effects of structural parameters on the mechanical behavior of lattice cylinders. Sakata and Ben [7] proposed a method for fabrication CFRP isogrid cylindrical shells. They conducted compression tests to investigate the effect of the grids on CFRP isogrid cylindrical shells and compared the results of static compression tests with numerical results. Vasquez et al. [8] using fused deposition modeling (FDM) technology, fabricated and tested polymer isogrid lattice cylindrical shell (LCS) structures using 3D printing software and hardware. In order to determine the strength and stiffness of the structure, as well as to check the structural instability, they created a 3D model in SolidWorks software using Visual Basic (VBA) programming language. After manufacturing the structure, they tested it. Francisco et al. [9] 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. Belardi et al. [10] presented a method for structural analysis and optimal design of conical anisogrid composite lattice shell structures that are applied under different external loads simultaneously and multiple stiffness constraints. Totaro and Gurdal [11] proposed an optimization method for composite lattice shell structures under axially compressive loads with the aim of preliminary design. This method implements the minimum configuration mass through numerical minimization. Fadavian et al. [12] numerically and experimentally, the buckling behavior of three samples of composite lattice cylinders made of Carbon/Epoxy, Glass/Epoxy and Aramid/Epoxy materials manufactured by wet filament winding method and under axial compressive loading has been investigated. Alkan et al. [13] discussed the optimal design of a lids with isogrid structure for aircraft and spacecraft that is under substantial force. Also, this lid was tested for production and design evaluation. Eskandari Jam et al. [14] investigated the parameters affecting the design of anisogrid lattice conical shells and finally, considering the relations, they performed the buckling analysis of the lattice conical structure under axial loading. Totaro [15] 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. Yang et al. [16] developed an improved modal pushover procedure. also, a good agreement was obtained in obtaining the response between the improved procedure and the nonlinear response analysis method, which attesting the correctness of the improved procedure. Morozov et al. [17] investigated the buckling behavior of anisogrid composite lattice cylindrical shells under axial compression, transverse bending, pure bending and torsion. They also investigated the effects of changing the length of the shells, the number of helical ribs and the angles of their orientation on the buckling behavior of lattice structures using parametric analysis. Zarei et al. [18] presented a new method to investigate the buckling behavior of laminated sandwich conical shells with lattice cores. Finally, the effects of design parameters such as the stiffener orientation angle, lamination angle, the number of the stiffeners, etc., were investigated on the buckling load.

In the reviewed studies, the analyzes were performed on the composite shell and the generative algorithm was not considered for the design of the isogrid conical shell. Thermal conditions were also disregarded. In this research, inconel 718 super alloy is used as the shell material, and the direction of the stiffeners in the shell is specified by developing the generating algorithm for the isogrid conical shell. Then, using the directions obtained for the stiffeners, the geometry of the isogrid conical shell was designed in SolidWorks software and analyzed in finite element software under thermal and mechanical loads (compressive and axial) in terms of buckling, deformation, natural frequency (prestressed modal analysis).

2- Algorithm development

In engineering, there are applications that allow us to control robots. The purpose of these applications is to allow engineers to interact with a computer to produce a structure or solve some kind of problem. Algorithm is defined as a specific method for solving and optimizing a computational problem. 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.

In this study, an algorithm is developed for the lattice conical shell that receives the radius of the large base (R_1) and the radius of the small base of the incomplete cone (R_2) and the cone length (L). In the beginning, mathematical models of stiffeners are developed to make their mathematical analysis easier. It is also investigated whether the mathematical model is capable of generating an isogrid pattern or not. For this developed generative algorithm, a flowchart is presented that shows the implementation of this algorithm step by step (Fig. 1).

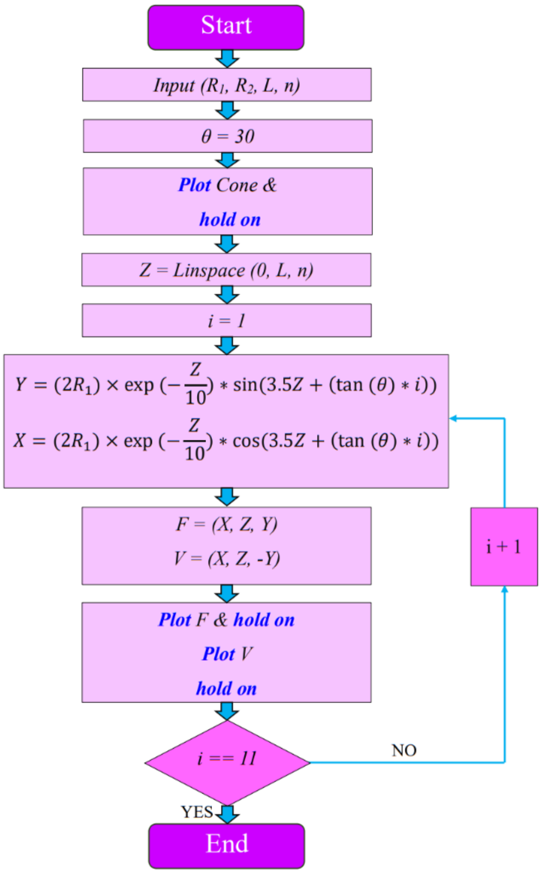

Fig. 1 Flowchart of the generative algorithm for isogrid conical shell

An explanation of the performance of the generative algorithm development flowchart is provided below, which is as follows:

Step 1-Algorithm At first, the large base radius (R_1), the small base radius (R_2) of the incomplete cone (a cone that is cut from one or both sides), the length of the isogrid conical shell (L) and the spiral resolution (n=10000) receives from the user. Because the conical shell has an isogrid structure, the angle of the stiffeners is 30 degrees (the angle of 30 degrees is the angle it makes with the flange). The input data values of the algorithm are listed in Table 1.

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 - X and Y values are calculated for a stiffener on a conical shell. The for loop is used for this equation and i is the counter of this loop.

Step 5- According to the values of X, Y and Z, the stiffeners are plotted in three dimensions. To form the isogrid structure, the value of Y is placed negative so that the stiffeners are plotted in the opposite direction of the previous stiffeners and collide with each other.

Step 6 - Since this algorithm uses a For loop, the code checks to see if i=11 show END and if not, i+1 and return to step 4. It should be $i \leq 11$ to avoid stiffeners overlapping each other.

This algorithm is written and plotted in MATLAB software (Fig. 2).

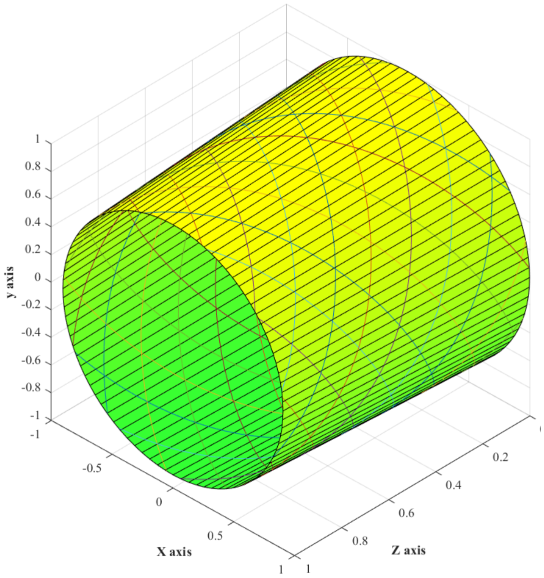

Fig. 2 Plot of the generative algorithm for the isogrid conical shell

3- Modeling

For finite element analysis, geometry should be designed. According to the plot of the conical shell with isogrid structure in

MATLAB software, this isogrid conical shell was designed in SolidWorks software.

3-1 Structure specifications

Isogrid cone shell an incomplete conical shell (a cone cut on one or both sides) that has a structure of isogrid stiffeners. This shell has the dimensions listed in Table 1.

Table 1: The dimensions of the isogrid conical shell

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

In this study, an isogrid conical shell made of inconel 718 material is designed. Inconel 718 is a nickel-chromium superalloy that has high strength and corrosion resistance. This superalloy is precipitation hardened to provide maximum strength and high creep rupture stress strength. Inconel 718, demonstrates outstanding weldability including resistance to post-weld cracking. The major applications are components for gas turbines, aircraft engines, fasteners and other high strength applications. The mechanical and thermal properties of inconel 718 are presented in Table 2.

Table 2: Mechanical, physical, and thermal characteristics of inconel 718 [19]

Properties	Value
Density	$8170\ ({}^{kg}/_{m^3})$
Yield tensile strength	1158 MPa
Ultimate tensile strength	1246 MPa
Thermal conductivity	11.4 W/m-K
Elongation at the breaking point	%20
Modulus of elasticity	200 GPa

3-2 Modeling method

Isogrid conical shell is modeled based on the dimensions mentioned in Table 1 in the SolidWorks software. The modeling steps of the isogrid conical shell are specified in the form of a flowchart (Fig. 3).

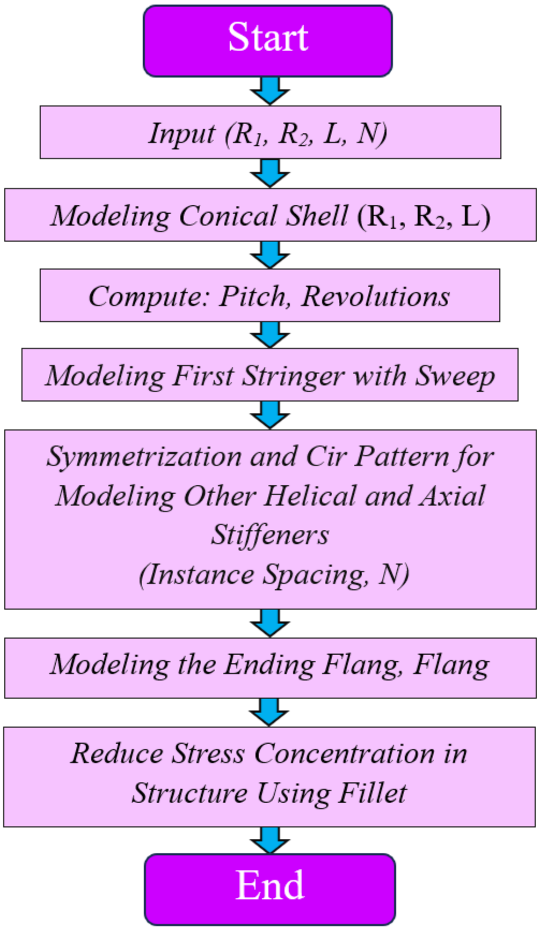

Fig. 3 Isogrid conical shell modeling flowchart

The explanation of the steps of the isogrid conical shell modeling flowchart is as follows:

The data in Table 1 is used for modeling.

Step 1- The large radius of the conical shell is (R_1), the small radius is (R_2) and the length of the cone is (L).

Step 2- Stiffeners should be modeled according to the results of the algorithm. In this step, Revolution and Pitch are calculated. Next, the first stiffener is modeled with the Sweep command.

Step 3- Symmetrization and Cir Pattern commands are used to model other helical and axial stiffeners (number of stiffeners N= 24).

Step 4- Two flanges at the beginning and end of the shell are modeled so that applied loading can be done on it. To prevent buckling near the flanges, two ribs are modeled which have the same height as the other stiffeners.

Step 5- In order to reduce stress concentration, the sharp edges are filleted in the isogrid conical shell.

The final geometry is shown in Fig. 4.

Fig. 4 Isogrid conical shell

4- Finite element analysis

The isogrid conical shell has been analyzed by the finite element method in ANSYS software. The final model of the isogrid conical shell should be subjected to buckling, modal and prestressed-modal analyses. 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.

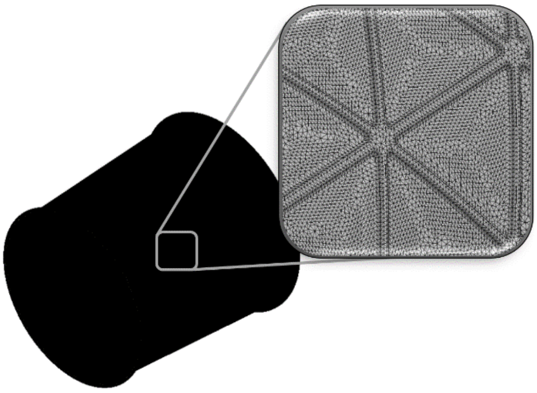

Fig. 5 Isogrid conical shell meshing

Isogrid conical shell is under mechanical and thermal loading conditions and its values are given in Table 3.

Table 3: Mechanical loading and thermal conditions

Load	Value
Internal Pressure	0.57 MPa
Axial Compressive Force	29000 N
Vertical Compressive Force	1450 N
Temperature Gradient	125-145 ℃

The value of the internal pressure of the shell is considered with a safety factor of 2 (the value of the internal pressure is 0.28 MPa, which in this study considering the safety factor of 2, the value of the internal pressure is 0.57 MPa). Axial compressive force and vertical force are applied on the primary flange. The remote–displacement condition is imposed on the end flange and all degrees of freedom are zero (Fig. 6). The temperature gradient has been applied on the isogrid conical shell, and its value is 125 to 145 ℃ (Fig. 7).

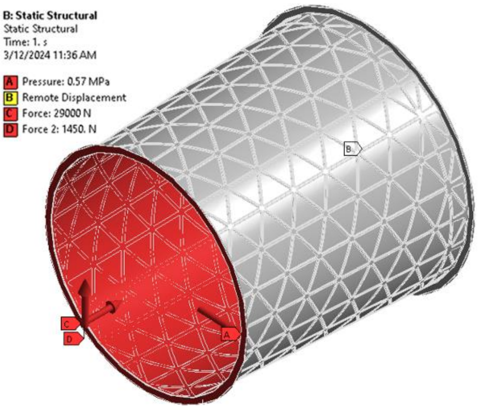

Fig. 6 Isogrid conical shell under Mechanical loading

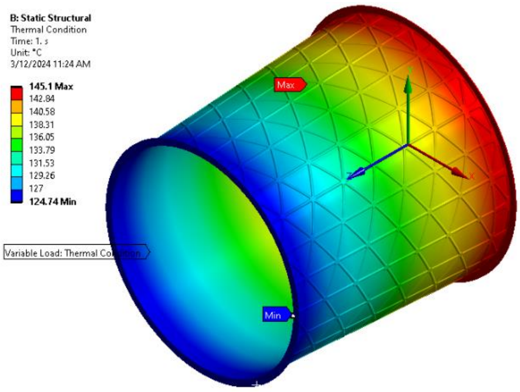

Fig. 7 Isogrid conical shell under thermal conditions

5- Results

The isogrid conical shell has been analyzed by finite element method after applying mechanical loading and thermal conditions in ANSYS software. The isogrid conical shell has been investigated in terms of equivalent stress and deformation. The results of finite element analysis are shown in Figs. 8-12.

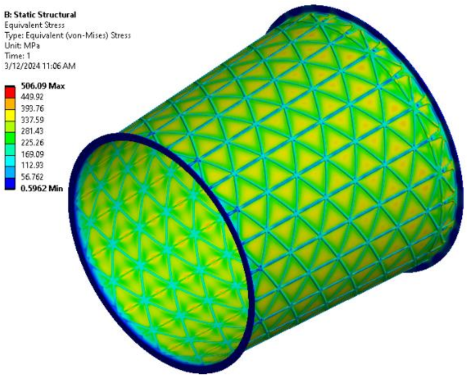

Fig. 8 Contour of the equivalent stress

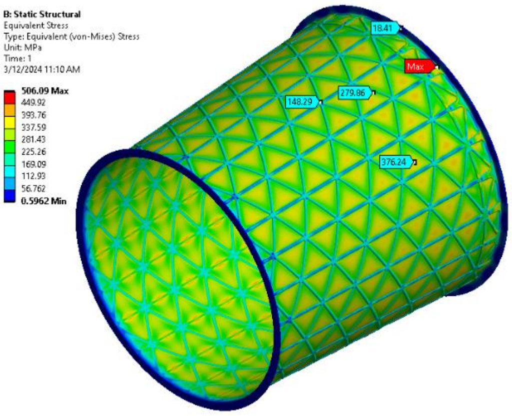

Fig. 9 Different values of stress on the isogrid conical shell

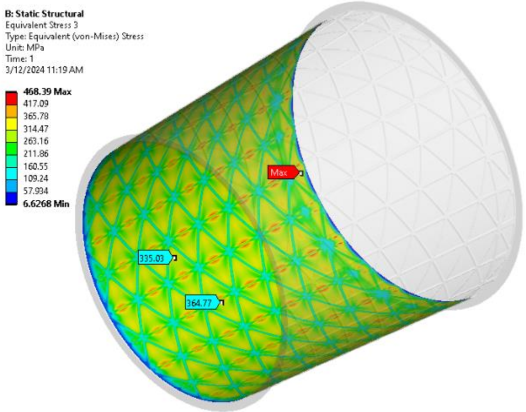

Fig. 10 Different values of stress inside the isogrid conical shell

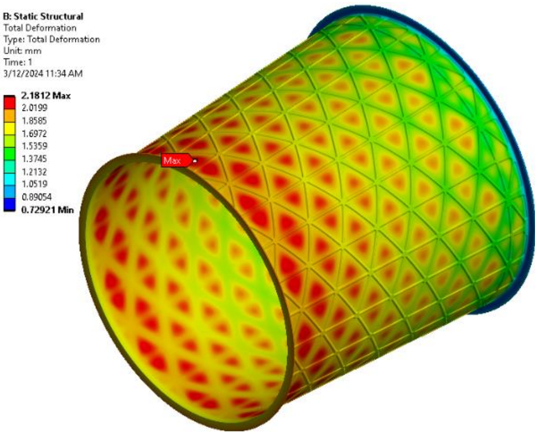

Fig. 11 Deformation in the isogrid conical shell

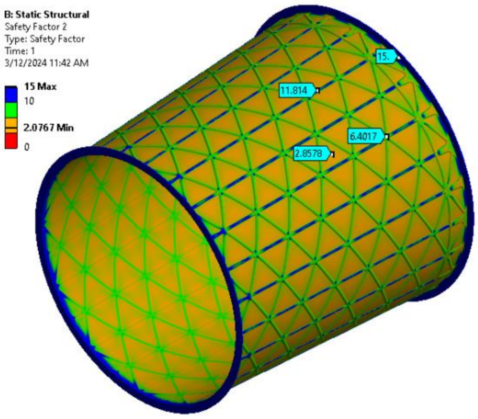

Fig. 12 Safety factor contour for isogrid conical shell

Mesh independence study has been done for isogrid conical shell. Fig. 13 shows that the results related to stress have converged. The horizontal axis corresponds to the number of elements and the vertical axis corresponds to the maximum stresses on the isogrid conical shell.

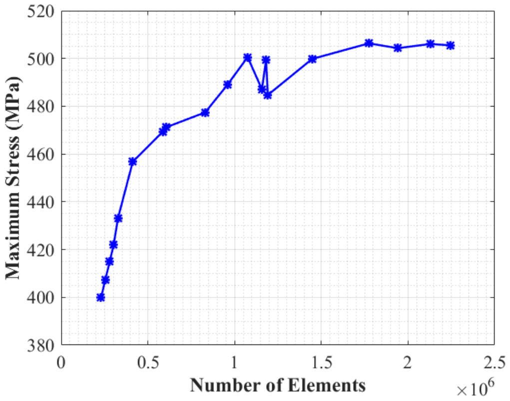

Fig. 13 Mesh study of the stress on the isogrid conical shell

Also, buckling, modal and prestressed-modal (natural frequency) analyses have been performed on the isogrid conical shell. In this analysis, the support conditions are taken into account once as fixed and once as remote–displacement. The aim is to study the behavior of the support in fix and displacement conditions. In the condition of fixed support and remote–displacement support, all degrees of freedom of the shell are zero. The difference is that in the fixed support condition the shell in end flange has a rigid behavior, but in the remote–displacement support condition the shell in end flange has a deformable behavior (similar to reality).

Axis symmetric analysis is used to achieve the best results. The results of the analyses are shown in Figs. 14-19.

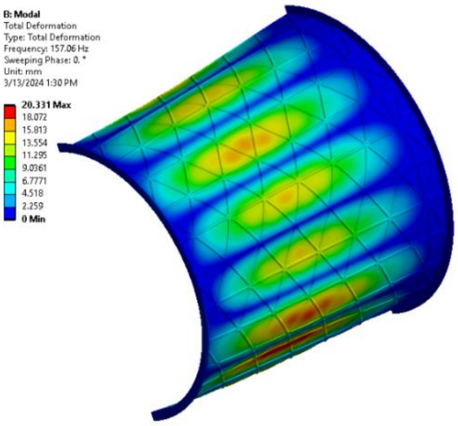

Fig. 14 Modal analysis under fixed support condition

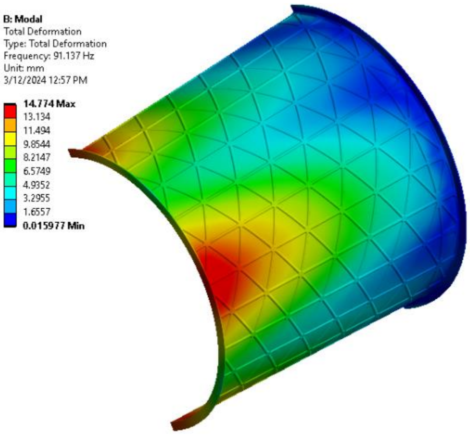

Fig. 15 Modal analysis under remote–displacement support condition

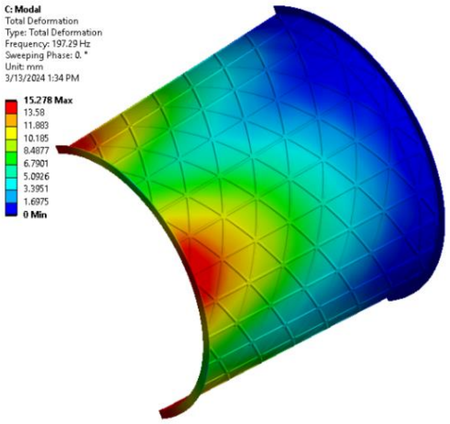

Fig. 16 Prestressed-modal analysis under fixed support condition

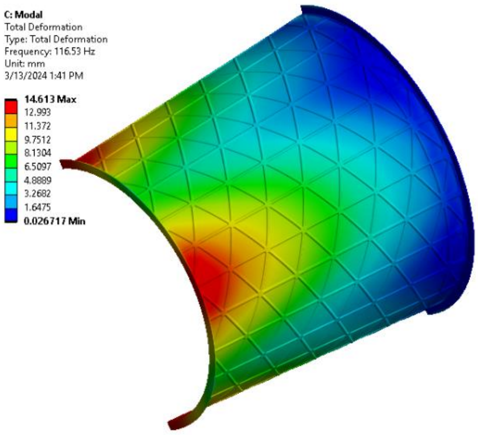

Fig. 17 Prestressed-modal analysis under remote– displacement support condition

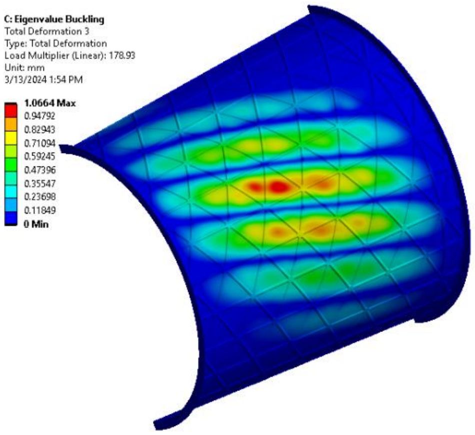

Fig. 18 Buckling analysis under fixed support condition

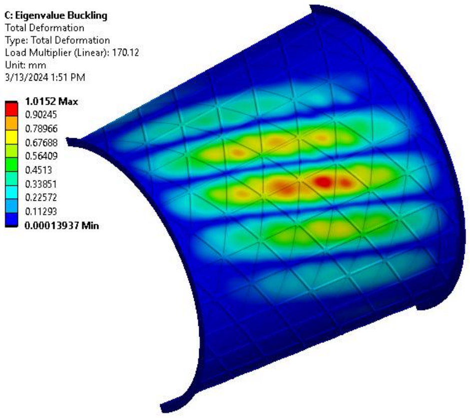

Fig. 19 Buckling analysis under remote– displacement support condition

The mesh independence study of buckling, modal and prestress-modal analyses have been done for the isogrid conical shell. The results show convergence (Figs. 20-25).

Because the analysis was done in axis symmetric, the number of elements in the graphs has been doubled.

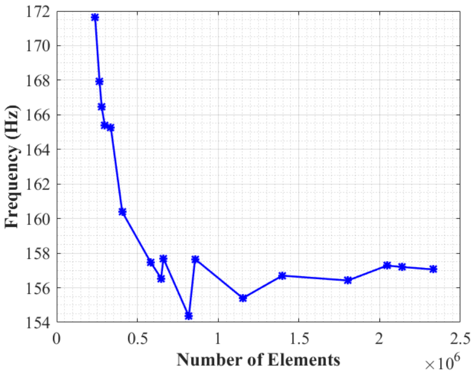

Fig. 20 Mesh study for modal analysis under fixed support conditions

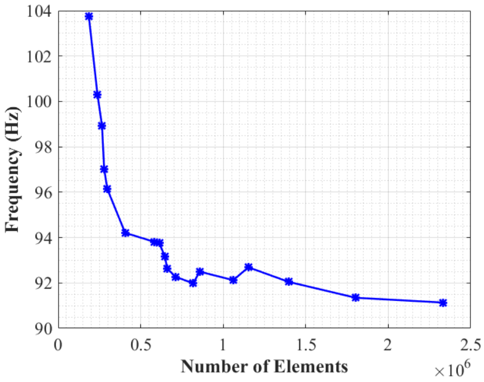

Fig. 21 Mesh study for modal analysis under remote– displacement support conditions

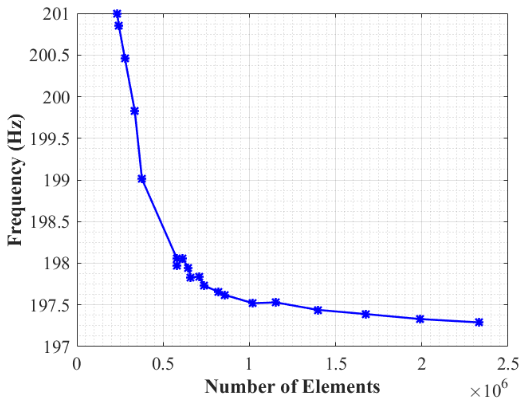

Fig. 22 Mesh study for prestressed-modal analysis under fixed support conditions

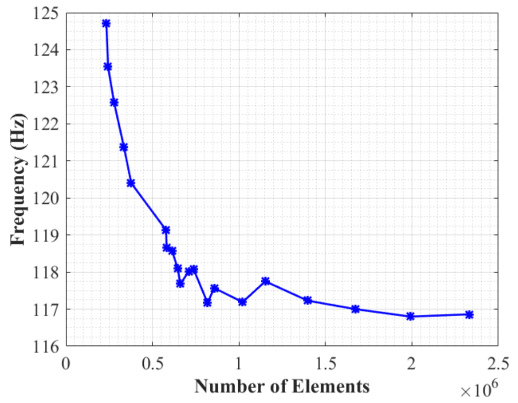

Fig. 23 Mesh study for prestressed-modal analysis under remote– displacement support conditions

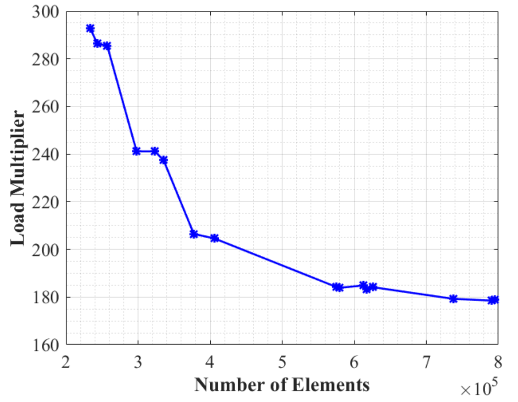

Fig. 24 Mesh study for buckling analysis under fixed support conditions

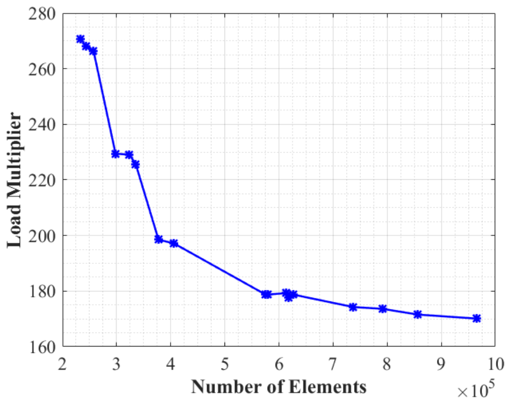

Fig. 25 Mesh study for buckling analysis under remote– displacement support conditions

According to the contours and diagram, the following results are deduced:

1. The maximum stress in the isogrid conical shell is 506 MPa, which has a safety factor of 2.1.
2. The maximum stress is where the stiffeners connect to the end flange and the minimum stress is at the flanges.
3. The maximum deformation was near the primary flange because the axial and vertical compressive force were applied to this zone. The minimum deformation is in the end flange because this zone is under the condition of remote–displacement supported.
4. In the modal and prestressed-modal analysis, a lower frequency for remote–displacement support conditions compared to fixed support conditions has been reported in the isogrid conical shell.
5. In buckling analysis, a lower load multiplier for remote-displacement support conditions compared to fixed support conditions has been reported in the isogrid conical shell.
6. In prestressed-modal analysis, the frequency is higher than that of modal analysis in an isogrid conical shell

because internal pressure exists in prestressed-modal analysis.

6- Validation

To validate the finite element method in this study, the pressure vessel under internal pressure is investigated (Table 4). The pressure vessel is modeled in SolidWorks. Finite element analysis of this structure has been done in ANSYS software.

Table 4: Values of effective parameters in pressure vessel

Parameter	Value
Internal Pressure (P)	0.3 MPa
Middle radius (r)	473×10^{-3} m
Slope of the Cone (θ)	3 deg
Length (L)	1 m
Thickness (t)	1.05×10^{-3} m

After the numerical solution of the pressure vessel using the finite element method, the stress in different radius of this pressure vessel is shown (Fig. 26).

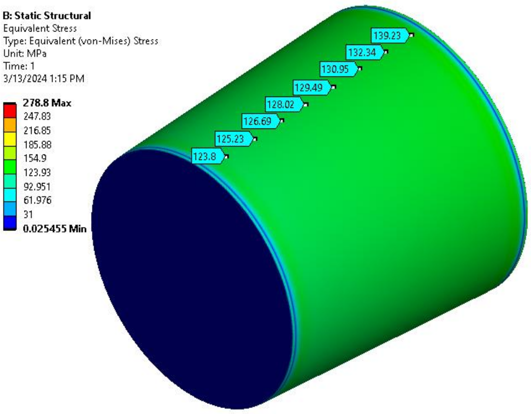

Fig. 26 Stress in different radius of pressure vessel

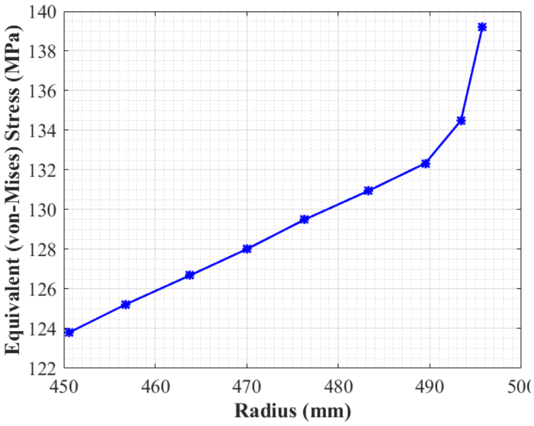

Fig. 27 Radius effects on stress changes

Fig. 27 shows that as the radius increases, the stress value increases and the relationship is linear. 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 vessels is discussed. In the analytical method, the stress along each direction is according to Fig. 28. Considering that the value of σ_3 is much smaller than the value of σ_2 and σ_1, then it is ignored.

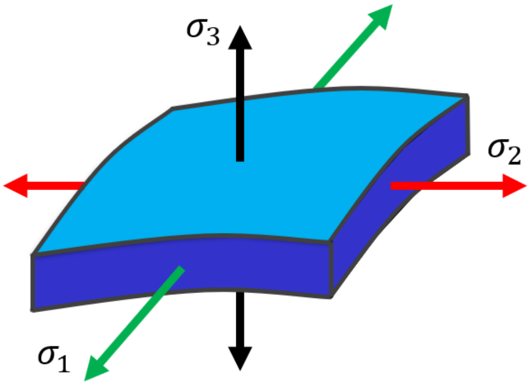

Fig. 28 Stress along coordinate axis

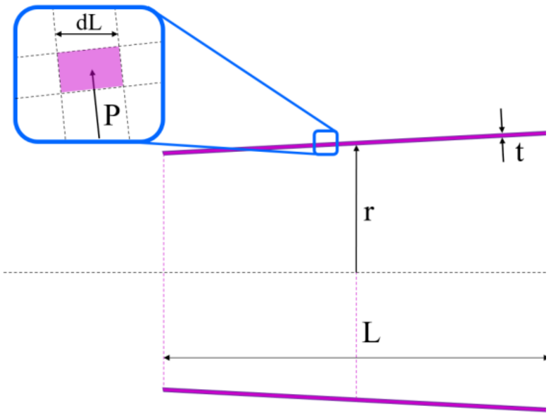

Fig. 29 Effective parameters in the pressure vessels (σ_1)

Fig. 29 shows the effective parameters for σ_1 in the pressure vessel. If an element of the pressure vessel is considered, the σ_1 in it is obtained from Eq. 1:

$$\sigma_1(2t\times dL)=P(2r\times dL)\rightarrow\sigma_1=\frac{Pr}{t}\qquad(1)$$

By putting the values of table 4 in Eq. 1, the value of σ_1 is obtained:

$$\sigma_1=\frac{0.3\times10^6\times473\times10^{-3}}{1.05\times10^{-3}}=135.14\times10^6\,Pa\qquad(2)$$

The effective values in σ_2 are the same as in σ_1, which is shown in Fig. 30.

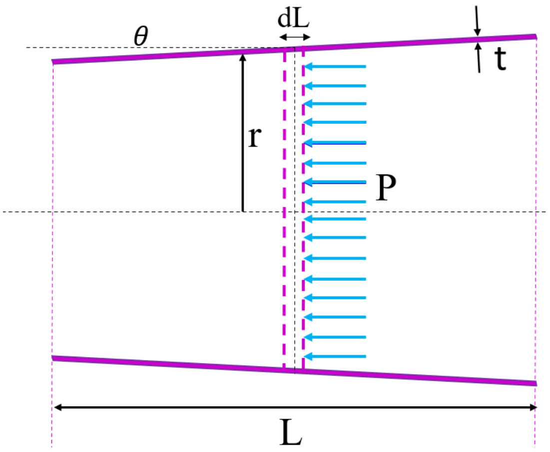

Fig. 30 Effective parameters in the pressure vessels (σ_2)

Fig. 30 shows the effective parameters for σ_2 in the pressure vessel. If an element of the pressure vessel is considered, the σ_2 in it is obtained from Eq. 3:

$$\sigma_2(2\pi rt)=\mathrm{P}(\pi\,\mathrm{r}^2)\times\cos\theta\rightarrow\sigma_2=\frac{\mathrm{Pr}}{2t\cos\theta}\qquad(3)$$

By putting the values of table 4 in Eq. 3, the value of σ_2 is obtained:

$$\sigma_2=\frac{0.3\times10^6\times473\times10^{-3}}{2\times(1.05\times10^{-3})\cos(3)}=67.66\times10^6\,Pa\qquad(4)$$

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. 31).

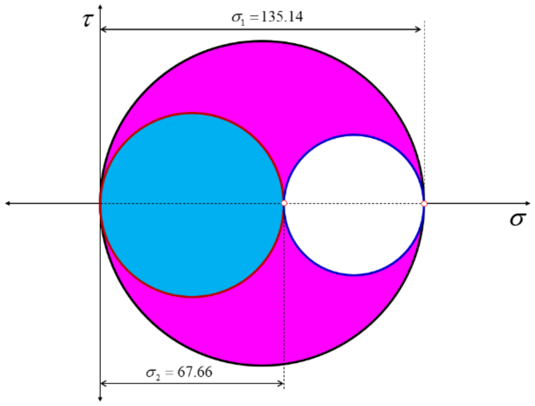

Fig. 31 Mohr's circle for (σ_1 , σ_2)

In the numerical solution of a finite element method, the stress value in the radius of 473×10^{-3} meter is equal to 128.02×10^6 Pa, which is close to the value obtained from the analytical solution. The value of the Relative Error (RE) is equal to:

$$RE=\frac{(135.14\times10^6)-(128.02\times10^6)}{135.14\times10^6}=5.2\%\qquad(5)$$

The results obtained from the numerical solution using the finite element method have a minor difference from the results obtained from the analytical solution; It is concluded that the numerical results of the isogrid conical shell are acceptable.

7- Conclusion

In this study, the isogrid conical shell is investigated. First, an algorithm for isogrid conical shell is written in MATLAB software that plots the conical shell and its stiffeners. In the next step, this shell was modeled in SolidWorks software and analyzed under mechanical loads and temperature gradient by finite element method in ANSYS software. Equivalent stress, deformation, modal, prestressed–modal and Buckling analyzes have been performed on the isogrid conical shell. Also, the conditions of fixed support and remote–displacement for the isogrid conical shell have been studied. Finally, it was concluded that the isogrid conical shell shows high resistance to mechanical loads and thermal conditions.

The results obtained from this study are:

1. The maximum stress is where the stiffeners connect to the end flange and the minimum stress is at the flanges. In this zone, the safety factor is 2, so the isogrid conical shell design is acceptable.
2. The maximum deformation is in the zone where the force is applied.
3. By comparing the results of fixed support condition and remote–displacement in modal, prestressed-modal and buckling analyses, it is clear that remote–displacement has a lower frequency value and load multiplier than the fixed condition.
4. The weight of this structure is 41 kg and due to its low weight and high resistance, it can also be used in aerospace structures. This trait can have a significant effect on reducing fuel.
5. The real internal pressure of the system is about 0.3 MPa, the system is designed for 0.6 MPa. This subject increase total safety factor and reliability of the system.

References

[1] Morozov, E. V., Lopatin, A. V., & Nesterov, V. A. (2011). Buckling analysis and design of anisogrid composite lattice conical shells. *Composite Structures*, 93(12), 3150-3162.

[2] Kanou, H., Nabavi, S. M., & Jam, J. E. (2013). Numerical modeling of stresses and buckling loads of isogrid lattice composite structure cylinders. International Journal of Engineering, Science and Technology, *5*(1), 42-54.

[3] Reinhold, H., Zarfas, D., Eltzroth, M., McCloud, P., & Greenberg, A. (2024). Analysis, Optimization, and Destructive Testing of Machined Isogrid Cylinders for Small Scale Rocket Airframes. In *AIAA SCITECH 2024 Forum* (p. 0561).

[4] Johnson, A. J. T., & Paramasivam, S. (2022). Compression behavior of 3D printed isogrid cylindrical shell structures using experimental and finite element modeling. *Polymer Composites*, *43*(10), 7278-7289.

[5] Sorrentino, L., Marchetti, M., Bellini, C., Delfini, A., & Albano, M. (2016). Design and manufacturing of an isogrid structure in composite material: Numerical and experimental results. *Composite Structures*, 143, 189-201.

[6] Hao, M., Hu, Y., Wang, B., & Liu, S. (2017). Mechanical behavior of natural fiber-based isogrid lattice cylinder. *Composite Structures*, 176, 117-123.

[7] Sakata, K., & Ben, G. (2012). Fabrication method and compressive properties of CFRP isogrid cylindrical shells. *Advanced Composite Materials*, 21(5-6), 445-457.

[8] Vasques, C. M., Gonçalves, F. C., & Cavadas, A. M. (2021). Manufacturing and testing of 3D-printed polymer isogrid lattice cylindrical shell structures. *Engineering Proceedings*, 11(1), 47.

[9] Francisco, M. B., Pereira, J. L. J., Oliver, G. A., da Silva, F. H. S., da Cunha Jr, S. S., & Gomes, G. F. (2021). Multi objective design optimization of CFRP isogrid tubes using sunflower optimization based on metamodel. *Computers & Structures*, 249, 106508.

[10] Belardi, V. G., Fanelli, P., & Vivio, F. (2018). Design, analysis and optimization of anisogrid composite lattice conical shells. *Composites Part B: Engineering*, 150, 184-195.

[11] Totaro, G., & Gürdal, Z. (2009). Optimal design of composite lattice shell structures for aerospace applications. *Aerospace Science and Technology*, 13(4-5), 157-164.

[12] Fadavian, A., Fadavian, H., Davar, A., & Jamal-Omidi, M. (2022). A Comparative Experimental and Numerical Study on Buckling Behavior of Composite Lattice Cylinders. Iranian Journal of Science and Technology, *Transactions of Mechanical Engineering*, 46(4), 1175-1193.

[13] ALKAN, M., CELIK, E., SUNECLI, A. A., CAN, U., & KOCADAG, S. B. (2021). Isogrid Structure Design and Mass-Strength Optimization in Airplane Lids.

[14] Jam, J. E., Noorabadi, M., Taghavian, H., & Namdaran, N. (2012). Design of Anis Grid Composite Lattice Conical Shell Structures. *Researches and Applications in Mechanical Engineering*, 1(1), 5-12.

[15] Totaro, G. (2015). Optimal design concepts for flat isogrid and anisogrid lattice panels longitudinally compressed. *Composite Structures*, 129, 101-110.

[16] Qu, Y., Luo, Y., Huang, Q., & Zhu, Z. (2020). Seismic response evaluation of single-layer latticed shells based on equivalent modal stiffness and linearized iterative approach. *Engineering Structures*, 204, 110068.

[17] Morozov, E. V., Lopatin, A. V., & Nesterov, V. A. (2011). Finite-element modelling and buckling analysis of anisogrid composite lattice cylindrical shells. *Composite Structures*, 93(2), 308-323.

[18] Zarei, M., Rahimi, G. H., & Hemmatnezhad, M. (2020). Global buckling analysis of laminated sandwich conical shells with reinforced lattice cores based on the first-order shear deformation theory. *International Journal of Mechanical Sciences*, 187, 105872.

[19] Kutz, M. (Ed.) (2015). *Mechanical engineers' handbook, volume 1: Materials and engineering mechanics*. John Wiley & Sons.