Numerical Investigation of the Grid Geometry Effect on the Modal Response and Buckling of Grid-Stiffened Composite Conical Structure

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Abstract: This study aims to the investigation of the effect of grid geometry on the modal response and buckling strength of a composite conical lattice structure under static axial loading by Finite Element Method (FEM). For this purpose, four structures with similar geometry have been designed through four grid structures. Abaqus finite element software has been used for modeling and analyzing the structures. The experimental results of Zamani and Ahmadifar study [1] have been used to validate the results of FEM. Given the results of numerical and experimental analysis, there is an accordance between the results and the FEM efficiency. The results show the contiguous natural frequency of the structures so that their negligible difference is due to the variations of structures' weight and stiffness. Changing the grid does not affect the shape of the modes. The isogrid bears a higher buckling loading than the anisogrid. Reducing the rib angle is an effective parameter, which increases the buckling loading on the structure. Although peripheral ribs play a role in load bearing, adding their numbers increases the total weight of the structure, therefore, it has no significant effect on increasing the stability of the structure.

Keywords: Buckling, FEM, Grid-Stiffened Composite Conical Structure, Modal Analysis

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1 INTRODUCTION

Composite lattice structures have been widely used in the aerospace, missile, and marine industries due to their high specific strength, lightness, and corrosion-resistant properties. These structures are constructed as conical lattice structures subjected to axial compressive loadings in some industries such as missile, projectiles, satellite carriers, and aircraft. Thus, the stability of conical structures under external forces is an important point. In this paper, the modal response and buckling of a composite conical lattice structure are investigated.
Vasiliev and Razin, in 2006, studied an adaptive construction project with a composite lattice structure. Composite lattice structures have been successfully utilized in rocket technology so that their operational lifespan is more than 10 years [2]. In 2016, Totaro presented an analytical study entitled "the properties of torsional and axial stiffness and flexibility of composite anisogrid lattice conical shells [3]. Mangas et al. (2016) presented the anisogrid adaptive construction project for the VEGA transport projectile. Lattice structure technology is a solution for weight reduction in some construction projects, whether satellite or projectile, compared to traditional sandwich panels or integrated structures [4]. In 2017, Khadem and Nezam-al-Islami conducted a study on free vibration of composite anisogrid lattice conical shells consisting of helical and circular geodesic ribs [5]. In 2018, Davar et al. experimentally and numerically examined incomplete composite lattice conical structures reinforced with and without carbon nanotubes under axial compressive force [6].

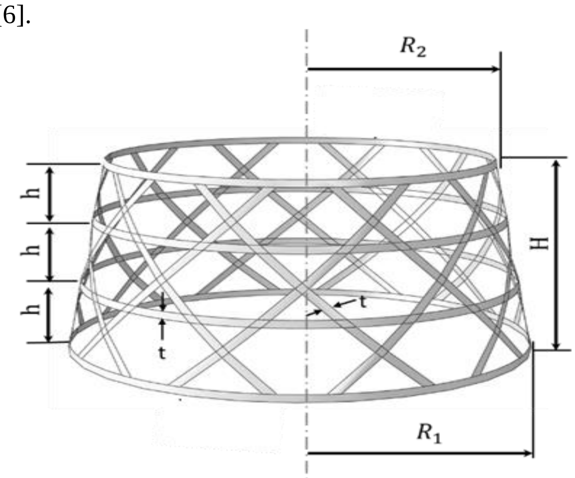

Fig. 1 Structure geometry.

Ahmadifar and Zamani in 2019 addressed the numerical and experimental analysis of buckling strength of composite lattice cones with external shell, before and after applying lateral impact. In this study, a composite conical lattice structure with a shell was analyzed by both numerical and experimental methods through the approach of determining the buckling strength of the structure before and after applying lateral impact [1].
In this study, four conical lattice structures with different grid structures, as shown in "Fig. 1", have been designed and investigated by FEM analysis to achieve the optimal model in specific dimensions. "Table 1" shows the geometric specifications of the structures.

Table 1 Geometric specifications and mechanical properties of the structure

Value	Symbol (unit)	Specification	Specification type
6	(mm) t	Helical rib thickness	Geometric Specification
6	(mm) t	Peripheral rib thickness	
140	(mm) R1	Short radius	
170	(mm) R2	Long radius	
162	(mm) H	Structure height	
6	(mm)	Structure thickness	
18	Gpa	Module (E11)	Mechanical properties of epoxy-glass composite
3.5	Gpa	Module (E22)	
0.3	-	Poisson's ratio (v12)	
1.4	Gpa	Shear module (G12)	
1.4	Gpa	Shear module (G13)	
1	Gpa	Shear module (G23)	

2 GEOMETRIC AND FINITE ELEMENT MODELING

CATIA software was used for geometric modeling. This software is a practical, powerful tool in the field of CAD and CAM while in the field of CAE, it needs the help of its complementary software Abaqus to be effective. Since the amplifiers behave like beams, the shell element type was considered. Amplifiers are composite that was made of E-type glass fibers and epoxy base. "Table 1" shows the mechanical properties of epoxy glass composite. Hashin failure criteria have been used to estimate fiber and base damages.
The natural frequency and shape of modes are calculated under free-free boundary conditions. Explicit dynamic analysis was used to obtain the critical buckling load, moreover, two parallel solid plates were used to simulate the boundary conditions in the buckling mode. Each of these plates was assembled at the top and bottom of the structure. Degrees of freedom were also considered in such a way that all displacements were limited at the

lower plate while the upper plane could not have any displacement except in the axial direction. The type of axial compressive loading was used for the simulation. A comparative diagram of kinetic energy and internal energy of the structure during loading (“Fig. 2”) can be considered to ensure the quasi-static process of simulation and numerical analysis of buckling.

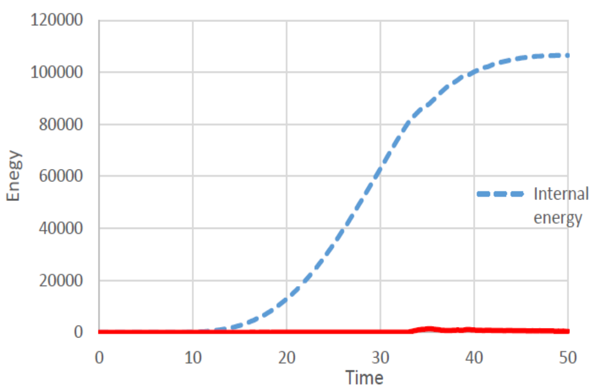

Fig. 2 Comparison diagram of kinetic and internal energies in compressive axial loading.

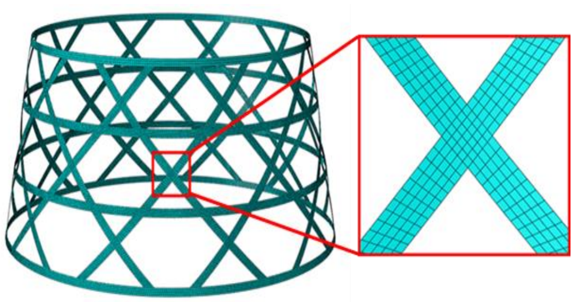

Fig. 3 Meshing of the lattice composite structure.

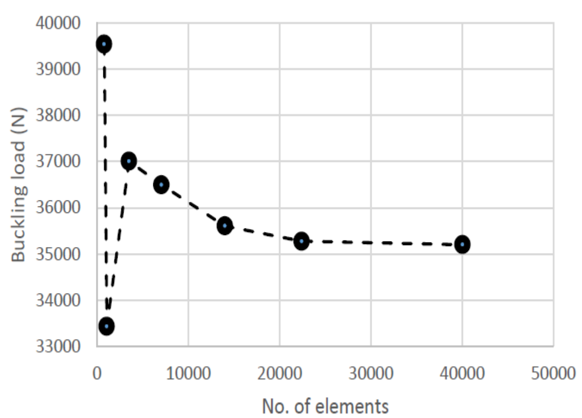

Fig. 4 Mesh convergence diagram of the numerical model.

As shown in “Fig. 3” , the S4R element (quadrilateral shell elements) was used for meshing. This analysis was performed via a different number of elements to achieve the optimal results of numerical problem solving. Finally, the resulted values had a proper convergence by increasing the number of elements (“Fig. 4”). At the end, approximately 23,000 elements were utilized to simulate structures.

Figure 5 shows four conical structures. Figure 5A demonstrates an anisogrid conical structure while “Fig. 5B” shows a isogrid conical structure in which the ends of the left and right-hand helical ribs, respectively, intersect in the long and short diagonal of the cone. Figures 5C and 5D are, respectively, similar to “Figs. 5B and 5A” except that, in the former, there is a larger space between helical ribs in long diagonal, and in the later, the position and numbers of the peripheral differ because one rib has been added.

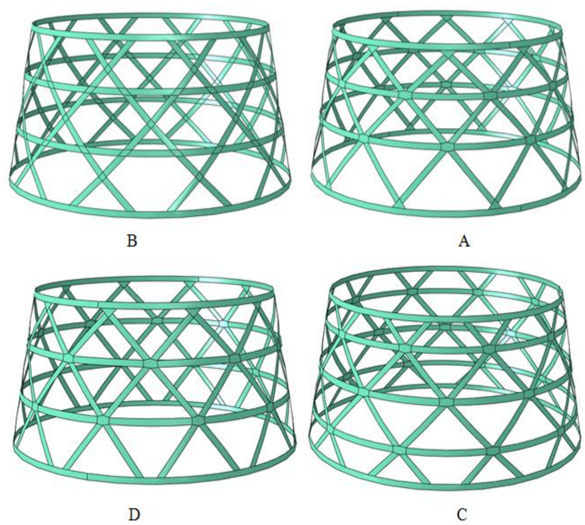

Fig. 5 Conical structure.

3 RESULTS AND DISCUSSION

The results of the modal analysis are presented considering free-free boundary conditions. The first six mode shapes of modal analysis and the natural frequency of the samples are shown in “Fig. 6” and “Table 2” , respectively. The shape of the modes does not differ in different structures, but the natural frequency of the structures is different due to a slight difference in the weight and stiffness of structures.

3.1. Numerical Analysis Results of Axial Buckling of Structures

Figure 7 shows a simulated model of structures in finite element software. According to these figures, the critical points throughout the structure body are specified at the maximum bearable load to the structure where failure occurs. According to structures A and B, failure and buckling, respectively, occurs at the intersection of the left and right-hand ribs and the helical ribs near the long diagonal of the structure.

Buckling in structure C and structure D, respectively, occurs at the intersection of the helical and peripheral ribs of the long diagonal and the intersection of the helical and peripheral ribs in the long and short diagonal of the cone.

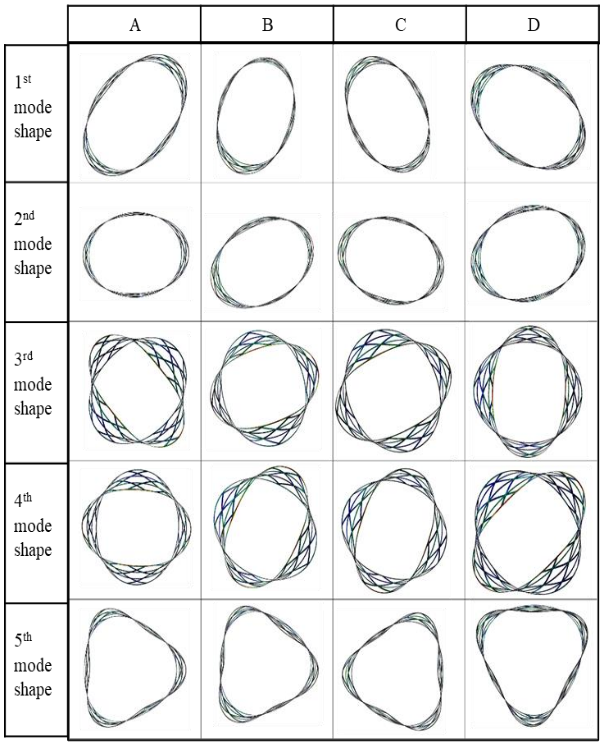

Fig. 6 Modal analysis of modes' shape.

Table 2 Natural frequency values

Natural Frequency	Experimental results [1]	Model A	Model B	Model C	Model D
First	72.67	73.256	73.586	78.02	82.372
Second	74.72	73.302	73.586	78.02	82.373
Third	107.79	115.29	112.89	119.12	123.83
Fourth	109.54	115.47	112.89	119.12	123.83
Fifth	204.49	204.91	204.73	217.40	228.98

Figure 8 shows the force-displacement diagram for structures. According to the diagram, structures C and A withstand, respectively, the most and the least buckling force, also, since structure B has a grid similar to structure C and differs only in the angle of helical ribs, it withstands a maximum amount of buckling load close to structure C.

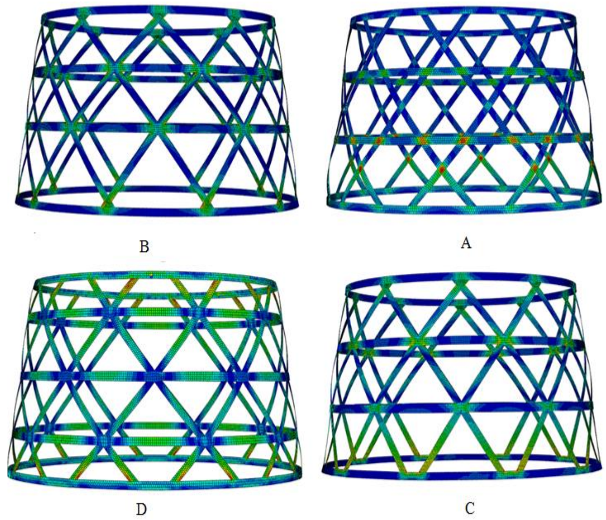

Fig. 7 Numerical simulation of buckling.

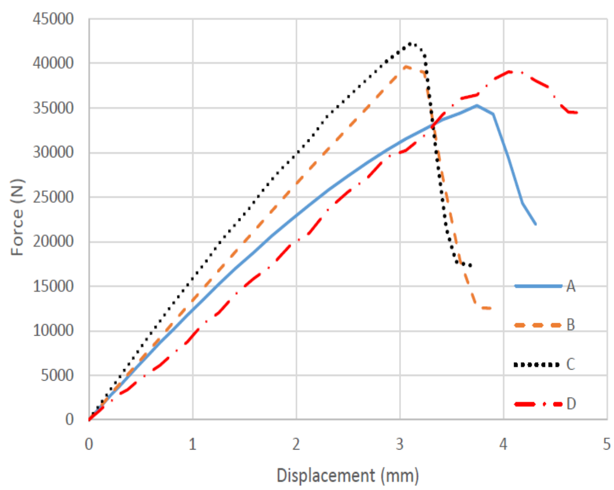

Fig. 8 Force-displacement diagram of structures.

3.2. The Ratio of Strength to Weight in Structures

Considering the weight of the structures presented in "Table 3" and the results obtained from the axial buckling simulation of the structures, the ratio of buckling strength to weight can be obtained in the structures. According to the weight and bearing strength of the structures, structure C has the highest efficiency compared to other structures while structure D does not show desire results due to the addition of a peripheral rib which increases the total structure weight.

3.3. Validation

According to "Fig. 9", the result of this analysis is compared with the study [1], which experimentally analyzed structure A of "Fig. 7", to validate the accuracy of FEM, as it is clear that the numerical and experimental results overlap properly. However, there is a negligible difference between the experimental and the numerical analysis because of the defects that occur during the construction process as well as the assumptions applied in the numerical analysis.

Table 3 The ratio of buckling strength to weight of structures

N/kg	Weight (kg)	
60500	0.55	Experimental analysis of structure A
71261.41	0.498	Numerical analysis of structure A
80246.96	0.494	Numerical analysis of structure B
84212.72	0.503	Numerical analysis of structure C
69600.71	0.561	Numerical analysis of structure D

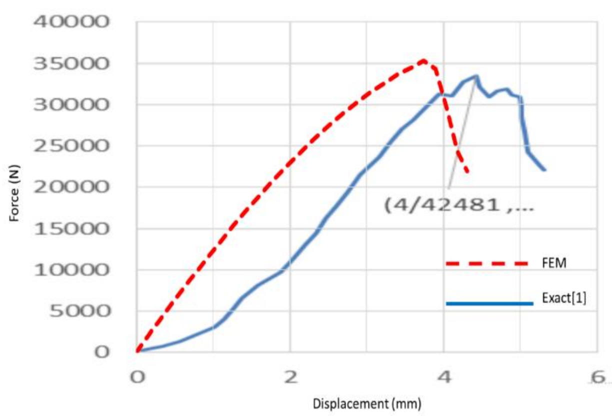

Fig. 9 Comparison of experimental analysis and numerical analysis of structure A.

4 CONCLUSION

In this paper, the effect of grid geometry on the modal response and buckling strength of a composite conical lattice structure under static axial loading is investigated by FEM. Variation in grid type and the number of peripheral ribs were selected as the parameters. Modal analysis results indicated that according to the higher stiffness and weight of the isogrid structure compared to the anisogrid, the values of the natural frequency of the isogrid structure are higher than the values of the anisogrid structure while the grid geometry does not affect the shape of the buckling modes of the structures. The results of buckling analysis of the structure highlighted that the buckling load in the isogrid structure has increased by 17% compared to the anisogrid structure, which indicates a growth in the strength of the isogrid structure. The mechanical behavior of the structure has changed because adding a rib to the anisogrid structure resulted in higher load bearing of the structure, however, the weight increase caused by adding the peripheral rib and comparison of the parameter of the strength-weight ratio showed the negative effect, so that the strength-weight ratio of this structure has the lowest value compared to other structures. Besides, the value of buckling load in the isogrid structure has increased by decreasing the angle of helical ribs.

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