Experimental and FEM Analysis of Ribs Defects on Composite Lattice Cylindrical Shells

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Abstract
In this study, the behavior of a composite lattice cylindrical shell is investigated in the buckling deforming. Also, the distribution of shell buckling response and the stress field is studied after making some defects on the ribs.Therefore using ANSYS software, a 3D finite element model of the shell has been created for the analysis. Material properties and geometrical data of the shell are obtained from the some experimental tests. In fact, these parameters have been extracted from the prototypesthat made with filament winding method. The parameters studied in this study include of the kind of ribs defects on buckling response and the geometrical ratios. Composite shells have been tested under axial force and obtained results are compared with the results of FEM. Based on the parametric study, the structural strength-to-weight ratio is increased around %50 by increasing the thickness of the outer shell. It is observed that in each consecutive buckling test, the buckling load is reduced; however the failed sample had reasonably good resistance to the applied load.

Keywords
Composite Lattice Cylindrical Shell, Buckling Deformation, Rib Defect, Finite Element Analysis (FEA), Experimental Test

1. Introduction

The composite structures (CS) have been used in many industries including the pressure vessels and aerospace industries due to the fact that they can withstand a lot of loads and at the same time have a low weight.One of these composites that are known for their very high strength to weight ratios is Grid-Stiffened Composite Structures (GSCS) and the most convenient manufacturing method for these composites is Filament Winding Method (FWM). It is so important to understand that the behavioral of deforming in these Composite Lattice (CL) structures especially when there are some defects on the ribs. It is because ofthe stiffening ribs are the most important partofthe structure to carry the external loads. Different types of defects may occur in these structures. Therefore it is important to investigate of the buckling behavior these composite models under the condition of with or without ribs defects.

Vasiliev, et al. [1] studied the construction, design and operational phases of these structures. They also presented a brief of the applications of this type of composite in the aerospace industry. Totaro and Gürdal [2] have done optimization of these kinds of composites under axial compression. The continuous models are selected by these researchers. Vasiliev and Rasin [3] on the next work investigated the processes of design, production, testing and analysis of carbon-epoxy composite lattice structures. They made these composites by the method of continuous filament winding. The prototypes made by this method are used in aircraft and other aerospace-related equipment. They also considered different types of construction methods and explored their effects on rib strengthening. Wodesenbet et al. [4] created a 3D-FE model according to the distribution of unit cells. They used analytical method to determine buckling loads and failure modes, and finally verified their r with those reported in the literature. FE modeling and buckling analysis of CL shells were considered by Morozov et al. [5]. They studied different loading and geometric conditions. Also they compared effects of corresponding modes and skin openings on the buckling loads under these conditions. Buragohain and Velmurugan [6] researched about filament wound cylindrical GSCS. They considered three different types of circular cylindrical structures named un stiffened shell (with outer shell only), lattice cylinder (with ribs only) and grid-stiffened shell (with outer shell and ribs) for experimental study. Disparate aspects of manufacturing that include tooling and other processing aspects were investigated in their work. Axial compression tests have been carried out and the results are compared with FEA. Vasiliev et al. [7] studied the applications and developments of CL structures in the aerospace industry. Their article reviews the recent experience of Russia in the expansion and usage of composite grid structures. Composite lattice structures are considered as cylindrical and conical. The results of this study suggest that the use of epoxy unidirectional carbon composite stiffeners in comparison with aluminum 35-45 percent decreased the weight of structures. RahbarRanji et al. [8] applied a new technique that named semi-analytical to study bending behavior of cylindrical panels. Different boundary conditions were used under general distributed loading. Mirdamadi et al. [9] investigated the free vibration of multi-directional functionally graded circular and annular plates. Additionally, a semi-analytical/numerical method was used which was called as a state space-based differential quadrature method. Mingfa et al. [10] in their study, the predicted failure of these structures was examined. In their article, a simple axially symmetric finite element model with different failure criteria to perform rapid analysis was presented. Axial compression test was carried out on the Kagome lattice cylindrical with the help of LVDT sensors and strain sensors failure progress was recorded. Lopatin et al. [11] studied the bending of a cantilever composite aniso-grid lattice cylindrical shell that a rigid disk was attached to its free end. Based on the membrane theory of orthotropic cylindrical shells, an analytical model was developed. Finally, by derivation of analytical formula, displacements of the disk and the bending stiffness of the structure under the transverse inertia load were attained. In addition, free vibrations of a cantilever CL cylindrical shell with the rigid disk attaching to its free end was probed by Lopatin et al. [12]. By using the semi-membrane theory of orthotropic cylindrical shells, the governing equations of motion are derived. Free vibration problem, according to this equation was reduced to a transcendental equation. The solution to this equation yields the fundamental frequency of the composite lattice cylinder. Zheng et al. [13] analyzed the stiffness and the critical axial load of the lattice cylinder theoretically. As a result, due to small strut thickness of the cylinder, failure of the large-scale lattice cylinder is dominated by global buckling. Additionally, strut thickness and number of oblique strut rows are considered as vital factors which have great effects on the stiffness and critical buckling force. Yazdi et al. [14] researched about the optimum values of geometric parameters in lattice composite shells. Experimental and the FEA were used to obtain best answers. Based on the verification of FEM data with experimental results, the modeling was developed and the required data essential for optimization process was gained.

In this paper, according to this fact that the understanding of deforming behavioral is important for CL structures, the effects of defects on the rib is investigated by comparing of simulation method and experimental tests. Some prototypes were made by FWM and then tested under shear force and compression loading and the buckling behavior and distribution of stress field is studied. At the end of this paper, the results were compared with those obtained by the FE method.

2. Materials

2.1 Manufacturing Process

A CL structure is builtby a collection of ribs that are conjunct to each other and therefore shaped a continuous structure. These ribs are usually produced by some rigid, tough and continuous fibers. The main ingredients of a these CL structuresincludes of ribs, nodes and the unit cells. Generally, the CL structuresare made by revolving several unit cells. In fact, the stability, rigidity and strength of a CL structure is directlydepend on these cells. Actually for designing of CS,some parameters such as width, thickness, number of ribs and also the angles and distances relative to the shell axis are so important. These structures often require operations such as cutting or openings on their outer shells.In this case, some damages may occur on the reinforcing strips and ribs.The investigation of buckling behaviors of these structures with or without a defective model is so critical because these defects directly effects on the stability of these structures. The aim of this research is to study the effects of ribs that have some defects. Epoxy resin as the matrix and E-glass fibers are used to make CL composites in this research. Two types of resins, CY219 as the base and HY5160 as the hardener, merged together for producing the epoxy resin. The ratio of the combination of these two resins was 2 for the base and 1 for the hardener. Test samples were fabricated by FWM. In this method, a cylindrical mold (Figure 1) was designed and the frames were conjunct to it. After that Paths of ribs were manufactured in the mold. The mold installed on the machine and the process started to fabricate the ribs and the CL shell. The outer shell was fabricated after completing this part of process. At the end, the mold was set on the spinning machine and spin at a low rotational speed in order to obtain uniform resin thickness. The mold and a sample of lattice cylinder are shown in figure1. The CL shell produced for this research has helical ribs with an angle of $\pm\Phi$. This angle is based on the cylinder longitudinal axis. The geometric parameters used in the modeling of this composite include the length of 300 mm, diameter of 162 mm, the rib thickness of 6 mm, the shell thickness of 0.8 mm and the rib angle of 30^o.

Figure1. (a) Mold (b) CL Shell

This is just a model on a laboratory scale that because of the lack of space and facilities, it was built in this scale in order to simulate the behavior of a real model. Construction and FEA was performed with the aim of information of reference [6]. It should be noted that length to diameter ratio in reference [6] is less than our research. Thus dimensions considering in this study comparing to the reference [6] are tried to be changed. As a result, better behavior in buckling was observed. Mechanical and geometric parameters of the shell used in FEA are based on the values extracted from the prototype model. The prototypes are fabricated with the condition of six ribs that have ±30º angles. Also, the fiber angle of external shell with respect to the radiant direction is equal ±14º (perpendicular to linear direction).

2.2 Finite Element Model

Modeling and FEA of the structures was done in ANSYS 10 software [15]. Two sorts of elements in Finite element analysis were used. One of them is linear element using for linear analysis. Shell99 and Solid 191was used in this study for this purpose. Shell 99 element which had 8 nodes and 6 degrees of freedom for each node was used to mesh the shell. Solid191 element which had 20 nodes and 3 degrees of freedom for each node was used to mesh the ribs. Other types of elements using in this paper are nonlinear. These elements consist of Shell 91 and Solid 46 that were used for nonlinear analysis and obtained the critical buckling loads. Solid 46 is structure element with eight nodes and their application is similar to SOLID 191. SHELL 91 is layer element that was used for modeling of layered shell and thick sandwich structures. The loads and boundary conditions of the structure were considered as followed: lower end of the cylinder was clamped, and in the upper end the load was applied. The structure can move only in shell axial direction. The FE model was used here is illustrated in Figure 2. A CL shell is composed of an external shell and some stiffening ribs. Linear buckling analysis under axial pressure loading is employed to attain the stress distribution and buckling modes in the shell. In order to proceed with the linear buckling analysis, an initial small axial deformation equivalent to an axial force in the elastic range is applied. Actually the buckling phenomenon occurs when this deformation is in the axial direction. Then by stimulating the shell, buckling modes and their corresponding loads are obtained. On the other hand, a nonlinear buckling analysis of the shell is performed for both complete and defective samples. This analysis is used for obtaining ultimate buckling load and observing the structural changes during the process to reach the point of failure.

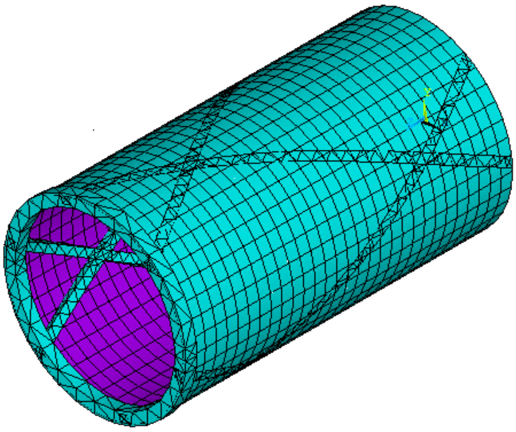


Figure2. FE model of the CL shell

For investigation of the process behavior, the structure should be entered to the plastic range. Therefore, the nonlinear analysis is required and the nonlinear elements must be used to demonstrate this behavior. In experimental tests, the compression test loading is increased incrementally until the fail of composite structure.

3. Result and Discussions

The aim of this research is studying the buckling behavior of CL structures with or without broken stiffening ribs using the experimental data and FE model. According to experimental results, the mechanical properties of the prototypes were gained. Table 1 depicts some of these parameters such as modulus of elasticity, Poisson'sratio and modulus of rigidity.

Table 1. Mechanical properties that was used for FE model

E_x (GPa)	E_z ,E_y (GPa)	ν_{xy},ν_{xz}	ν_{yz}	G_{xy},G_{xz}(GPa)	G_{yz}(GPa)
6	1.9	0.25	0.15	1	0.3

Mechanical and geometry properties, manufacturing process and the shape of defects are created the same for all prototypes. For FEA, boundary conditions are assumed to be free at one side and the clamped at the ones. The axial pressure loading is performed at the free end. In order to have the correct conditions for simulation, the convergence of force by changing the number of elements is studied. Figure 3 shows the effect of number of elements on buckling load calculation. When the number of elements increases, the buckling load is improved too. However the rate of changes reduces and the load converges to a fixed value. The best number of elements was chosen around 3340 elements according to the rate of convergence and calculation timing. Now, the effect of the size of defect on the rib is studied.

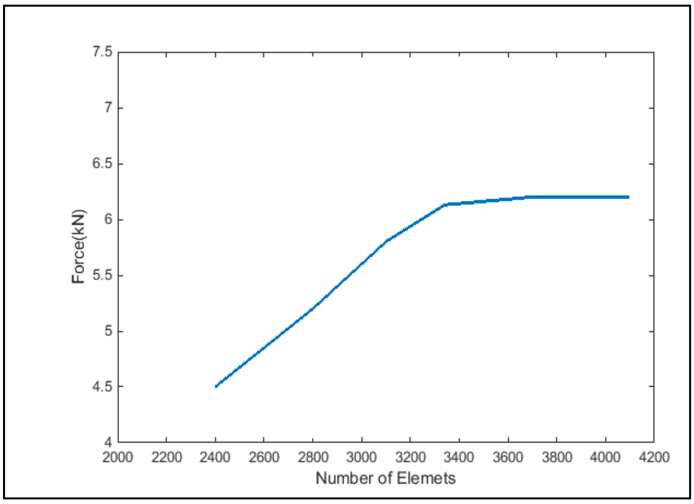
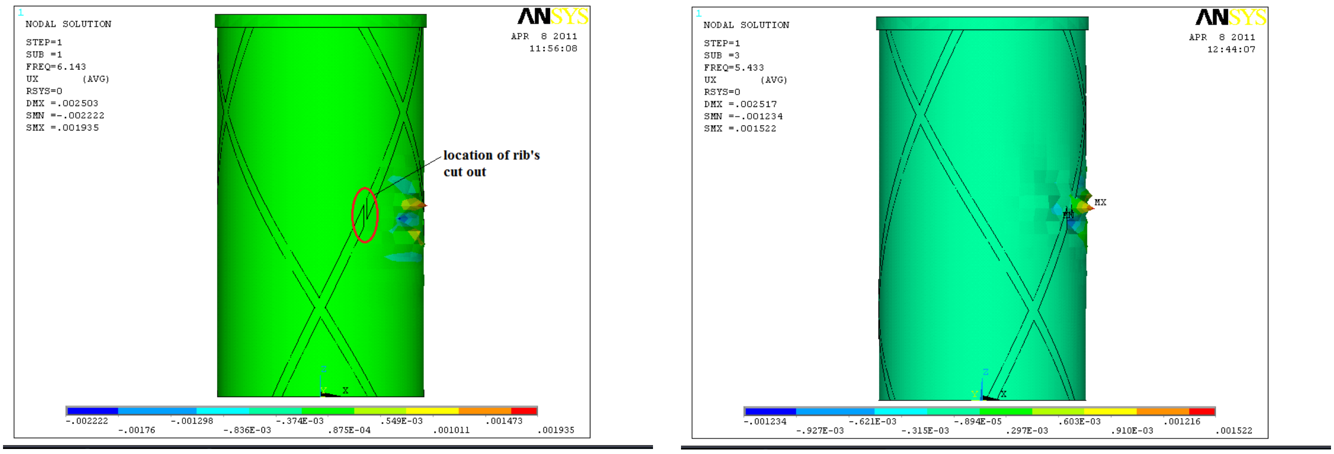


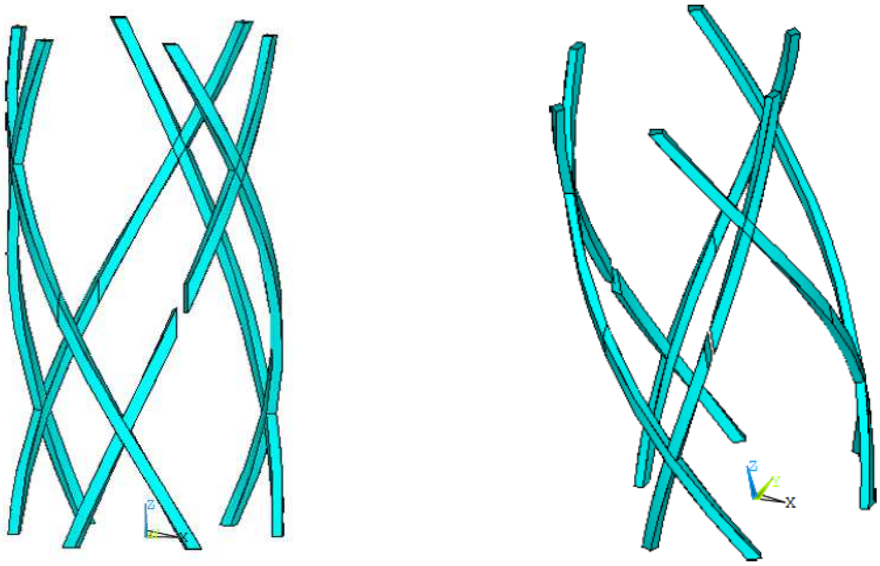
Figure3. Variation of buckling load with number of elements

Buckling of the cylindrical shell under axial loading for two different sizes of defects are shown in Figure 4.The defect is considered in the middle of the rib. (The location is specified in Figure 4a). As shown in Figure 4a, buckling occurs far from the rib defect. Therefore, the cut out does not make impression on the buckling mode shape. However, buckling mode was seen around the area of cut out in Figure 4b. According to these results, the model that was shown in Figure 4b can be used for basic model to the analysis. In Figure 5, the FE model of ribs and the position of the defect in prototypes are shown.



(a) (b)

Figure4. Buckling of the cylindrical shell; (a) Cut out size: 2.5 mm and (b) Cut out size: 5 mm



(a) (b)

Figure5. FE model of defective ribs, (a) cut out in the center, (b) model with two cut outs in rib

According to the experimental tests, it was determined that the buckling occurs at the initial stages. Also the results show that with increasing of load, local buckling happens at different situations. The results of a perfect shell (without any defect) showed that local buckling usually occurs at the middle region of the shell. With increasing the load, this local buckling shifts towards the ribs. On the other hand with investigation of the behavior of defective prototypes, it is obvious that local buckling occurs near the defect area and then stretches to the whole prototype. Also the results show that after elimination of the load, the shell comes back to its original state. The strength and stiffness of ribs are found to be the main reasons for the return of the shell to its primary position. Figure 6 shows different prototypes modes in different loading modes.

Prefect Sample

Defective Sample

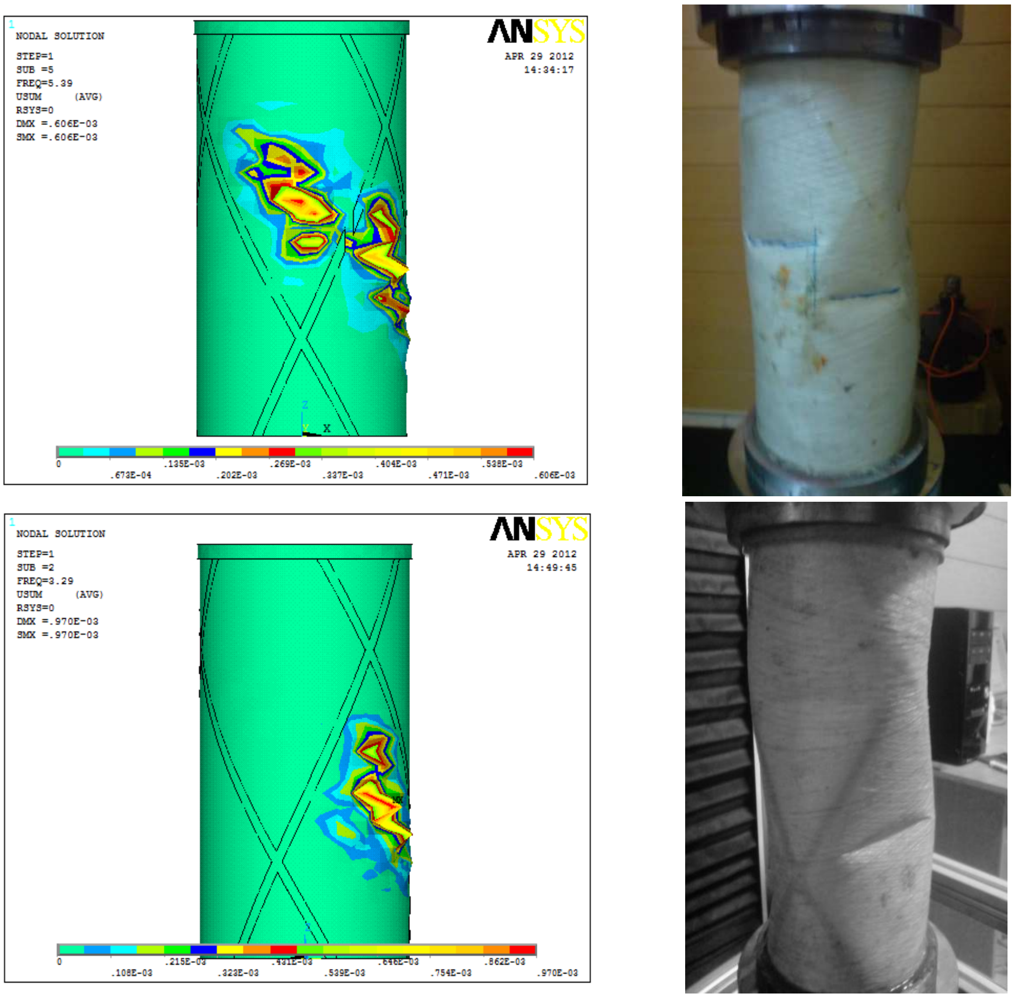
Figure6. The result of experimental tests

The results attained from the FE simulation demonstrated that the deformation usually happened around the slicing area on the prototypes that have the defect. The experimental results also confirmed this issue. These deformations were produced in the middle areas at first and then shifted towards the ribs in the perfect prototypes but in about defective ones, buckling modes were created around the slicing area and then expanded in other parts of the shell. Figure 7 shows the Buckling modes of the perfect and defective shells. Figures 7 and 8 show the correct fit between the simulation results and the experimental ones. Based on these results, this analysis can be extended and a parametric study by using of finite element was considered.

Figure 9 shows a comparison among all the scenarios in this research. The curves of the perfect samples and defective ones in FE model were verified by experimental tests. Also it can be seen that by increasing the number of the cut ribs, the strength of the CL structure will be reduced.Shell thickness is a parameter that plays a pivotal role in the strength of CL structures. It can be derived that by increasing the thickness of shell, the ultimate load (critical buckling load) increases noticeably. Anyway, the critical loads obtaining by the FE simulations and the experimental tests are in a suitable agreement.

Defective Sample

Perfect Sample



Simulation result   Experimental result

Figure7. Comparison of simulation and experimental of buckling test

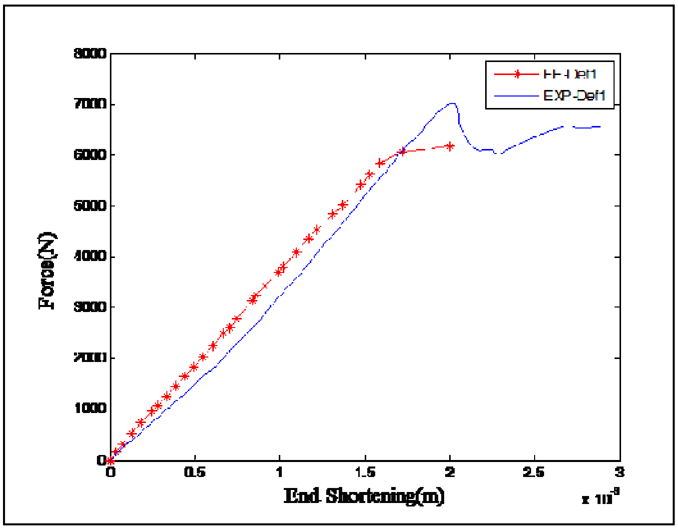


Figure8. Comparison between FE and Experimental results: Force-Displacement Graph

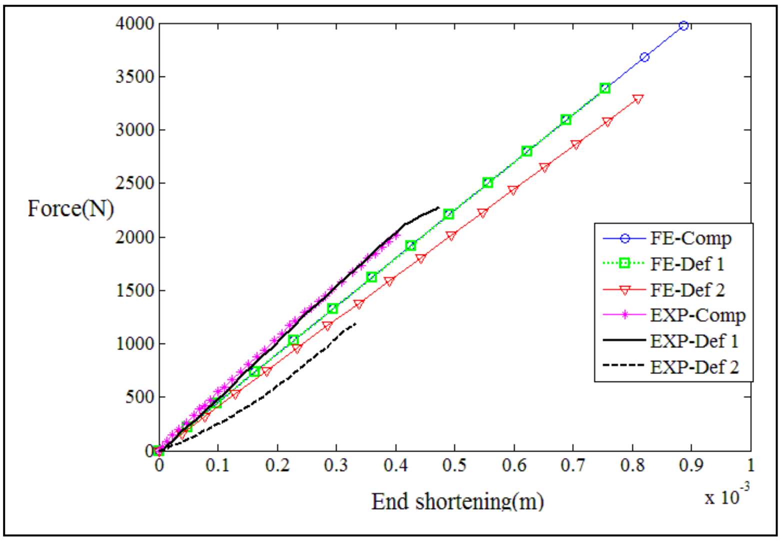


Figure9. Comparison between FE and Experimental results: Force-Displacement Graph for complete, one slicing and two slicing shell

Table 2 shows a comparison of the critical loads between FE and experimental test according to different thickness. In another study, the shell thickness in different models was decided to be tested, i.e. perfect and defective model. The specific loads (the ratio of buckling load to the weight) for specimens with disparate thicknesses are presented in Table 3. According to Table 3, the importance of thickness of the outer shell is clear. Increasing the thickness of the outer shell has caused ignoring the impact of cut outs in rib. Also, this table shows that by increasing of this thickness from 0.7 to 0.9 mm, the specific load is increased around %13 for the prototype with one slicing in the middle of part and %34 for the prototype with two slicing in versus of the perfect prototype. However, the weight of the structure has increased by 9%. As one of the most important features of these structures is their low weights, so to achieve the best design in CL, structures should be evaluated both of the buckling and weight at the same time. Thus the specific load is considered as one of the most fundamental design parameters of CL structures. Increasing the thickness will have an optimized value, because the weight of the structure also increases. According to the results of increasing in the thickness, it was cleared that at every step in increasing, the amount of variation of buckling load decreases, while the percentage of the gained weight increases. In Figure 10 variation of specific load versus shell thickness is demonstrated.

Table2. Variation of critical buckling load (N)

Thickness (mm)	Numerical results	Experimental Results	Relative Error(%)
0.8	6180	6542	5.53
0.9	8080	8163	1.02
1.2	11343	11420	0.67

Table3. The specific load according to different shell thickness

No.	Shell Thickness (mm)	Weight (kg)	Perfect prototype	Prototype with one slicing	Prototype with two slicing
1	0.7	0.1617	35884.97	31505.88	22468.77
2	0.8	0.1763	39679.52	35053.89	28115.14
3	0.9	0.1984	40725.81	36312	30141.13

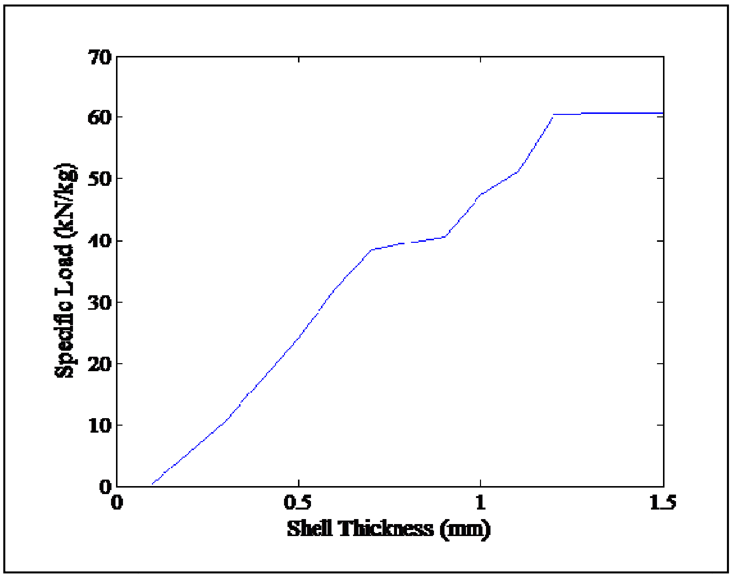


Figure10. Load-Thickness Graph

The mechanical behavior of the cylindrical shell changes as the thickness of the shell increases. Also, in this case, theshell can withstand greater load.Figure 11 is shown the effect of buckling test repeating on the final load of the shell. The Figure shows that in each buckling test, the load is decreased. However, the defective prototype had reasonably good strength and can resist to the applied load in the second stage. It is so important to note that some critical portions of the composite start to over weary by increasing the applied load. In fact, because of that the elasticity modulus is reduced, the strength of the shell is decreasedtoo.

Another parameter studied in this research is the influence of the radial rib on the model behavior. With the addition of these ribs expected that the sample to show more resistance under pressure. Figure 12 shows the FE model of a prototype with radial ribs. The results of nonlinear analysis in Table 4 are presented.

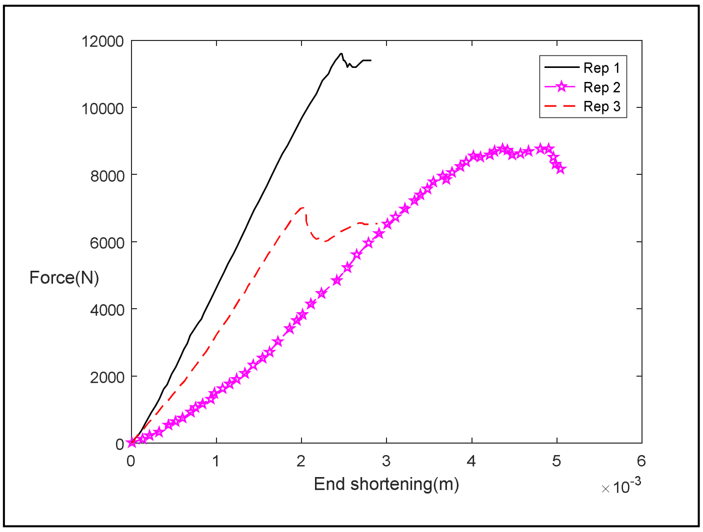
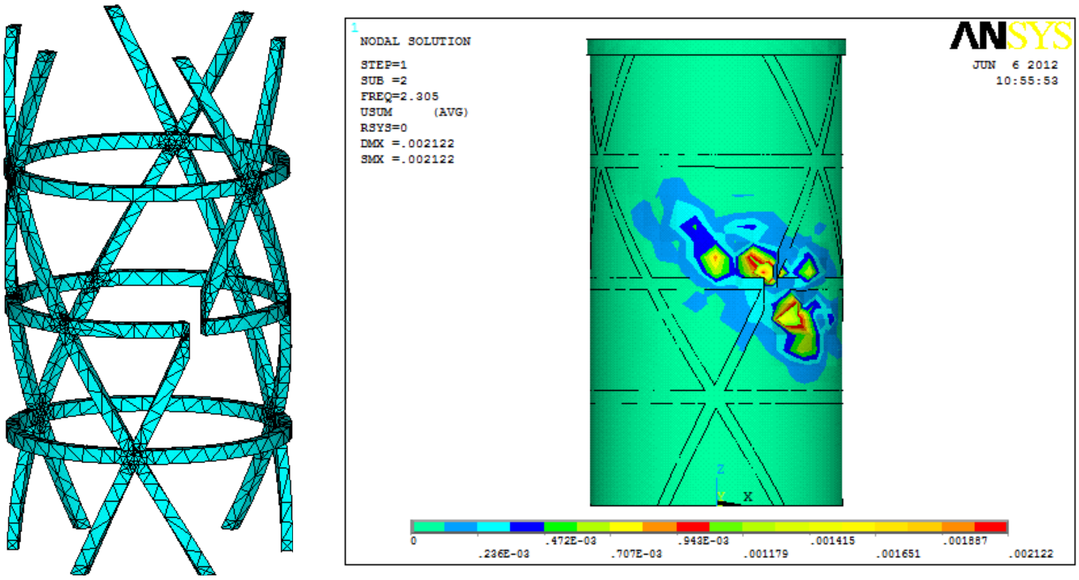


Figure11. Force-Displacement Graph: investigation of repeating tests



(a) (b)

Figure12. (a) FE model, (b) buckling mode

Table4. Critical buckling load (N) for different samples

No	Shell thickness (mm)	Prototype without radial ribs	Prototypewith radial ribs
1	0.7	5094.5	5998.7
2	0.8	6180	7292.6

Because of the stiffening nature of ribs, it can be seen that the buckling strength has increased considerably. But it should be noted that by increasing the number of ribs, a marked increase occurs in the weight of the structure.

Finally, the effect of the shear force on the buckling behavior of the CL shell is investigated. Figure 13 is shown this effect. It is clear that the most important parts of the shell are the areas close to fixed locations at the top and bottom of structure. So using the shear force at the free end, these regions beginto surrender at the beginning of the loading applied.

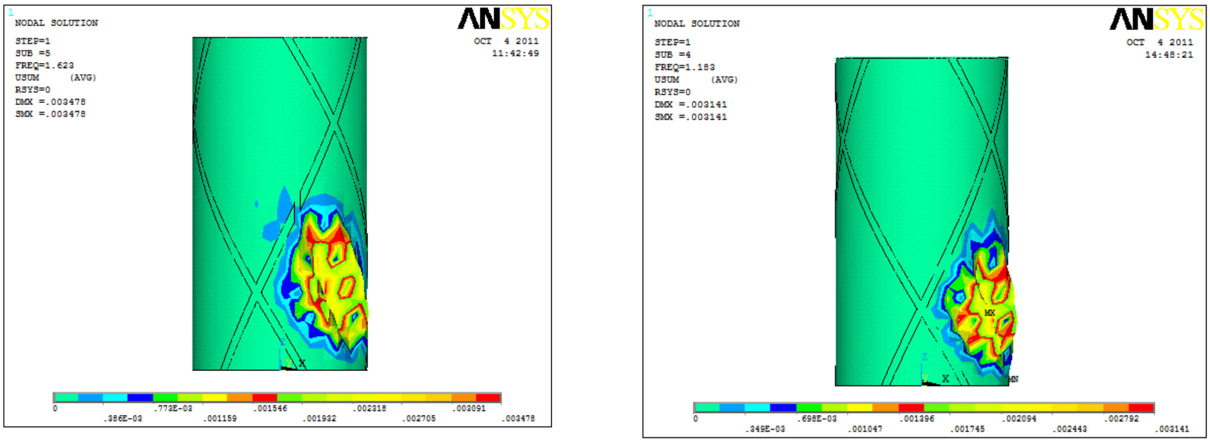


Figure13. Buckling deformation according to applied shear force

Table 5 is shown the numerical result of buckling loads for the perfect and defective shells under axial compressive and shear force loadings. These results obtained from FEA. It is shown that the critical shear force loading is less than that of the critical compressive load for both prototypes.

Table5. Buckling loads for the perfect and defective shells

Loading Condition	Shell Thickness (mm)	Defective sample	perfectsample
Compressive Force	0.8	6180	6995.5
Shear Force	0.8	1930	1840

4.Conclusions

In this paper, FEA using ANSYS software and some experimental tests was carried out for investigating the buckling behavior of CL structures. The results proof that FE and experimental have a suitable agreement. Two kind of CL structure are investigated here and it showed that the buckling modes happened around the cut out area in the defective shells with wider slicing ribs. Also shell thickness has a vague effect on the structure strength. The result proved that the load increase with arising the shell thickness and therefore the strength will improve. Some repetition tests have done. The result of these tests showed that the load decreased after each repetition. Also, the strength of the CL structure raised by increasing the radial ribs but it had a negative effect according to this fact that the weight of structure will raised too. The buckling modes were observed to be close to the ribs when the shear forces loading effect on the structure.

6. References

[1]Vasiliev V V et al (2001), Anisogrid lattice structures – survey of development and application,

Composite Structures, 54 (2-3): 361-371.

[2] Totaro, G. and Grdal, Z. 2009. Optimal design of composite lattice shell structures for aerospace applications. Aerospace Science and Technology. 13 (4-5): 157–164.

[3] Vasiliev, V. V. and Rasin, A. F. 2006. An isogrid composite lattice structures for spacecraft and aircraft applications.Composite Structures. 76 (1-2): 182-189.

[4] Wodesenbent, E. et al. 2003. Optimization for buckling load of grid stiffened composite panels.Composite Structure. 60 (2): 159-169.

[5] Mozorov E V et al (2011), Finite element and buckling analysis of anisogrid composite lattice cylindrical shells,*Composite Structures*, 93 (2): 308–323.

[6] Buragohain, M. and Velmurugan, R. 2011. Study of filament wound grid-stiffened composite cylindrical structures. Composite Structures. 93(2): 1031–1038.

[7] VasilievVV et al (2012), Anisogrid composite lattice structures – Development and aerospace applications, *Composite Structures*, 94 (3): 1117–112.

[8] RahbarRanjiA et al (2012), A semi-analytical technique for bending analysis of cylindrical panels with general loading and boundary conditions, *Journal of Mechanical Science and Technology*, 26 (6) : 1711-1718.

[9] DavoodiKermaniI et al (2012), Free vibration analysis of multi-directional functionally graded circular and annular plates, *Journal of Mechanical Science and Technology*, 26 (11): 3399-3410.

[10] Mingfa R et al (2014), Numerical investigation into the buckling behavior of advanced grid stiffened composite cylindrical shell, *Journal of Reinforced Plastics and Composites*, 33(16): 1508-1519.

[11] Lopatin A V et al (2015), Deformation of a cantilever composite anisogrid lattice cylindrical shell loaded by transverse inertia forces, *Composite Structures*, 129 (1): 27-35.

[12] Lopatin A V et al (2015), Fundamental frequency of a cantilever composite filament-wound anisogrid lattice cylindrical shell, *Composite Structures*, 133 (1): 564–575

[13] Zheng, Q. et al (2015), Analysis of failure loads and optimal design of composite lattice cylinder under axial compression, *Composite Structures*, 131(1): 885–894.

[14] SadeghYazdi, M. et al(2016), Optimization of geometrical parameters in a specific composite lattice structure using neural networks and ABC algorithm, *Journal of Mechanical Science and Technology*, 30 (4): 1763-1771.

[15] ANSYS Inc., Release 12. User Manual.