IJE TRANSACTIONS A: Basics Vol. 26, No. 4, (April 2013) 411-420

International Journal of Engineering

Journal Homepage: www.ije.ir

Buckling Analysis of Composite Lattice Cylindrical Shells with Ribs Defects

R. Akbari Alashti*[a], S. A. Latifi Rostami[a], G. H. Rahimi [b]

[a] *Department of Mechanical Engineering, Babol University of Technology, Babol, Iran*
[b] *Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran*

PAPER INFO

Paper history:
Received 15 Agusut 2012
Received in revised form 8 October 2012
Accepted 18 October 2012

Keywords:
Composite
Cylindrical Shell
Buckling
Rib Defect
Finite Element

ABSTRACT

In this paper, the buckling behavior of a composite lattice cylindrical shell is studied and effects of rib defects on the distribution of stress field and buckling response of the shell is investigated. A three dimensional finite element buckling analysis of the lattice shell is carried out using ANSYS suit of program. Geometrical data and material properties of the shell are obtained from the specimens made by filament winding method. Effects of various parameters including the geometrical ratios and defects of ribs on buckling response of the shell are studied. Buckling loads of composite lattice cylindrical shells under axial and shear forces are obtained experimentally and the results are compared with finite element results.

doi: *10.5829/idosi.ije.2013.26.04a.10*

1. INTRODUCTION

Due to their light weights and high load carrying capacities, composite structures have found several applications in various engineering fields including the aerospace and pressure vessels industries. Grid-stiffened composite structures are also known for their very high strength to weight ratios. The filament winding method is found to be the most convenient manufacturing method of these structures. Since, the stiffening ribs are the main load carrying parts of lattice structures; it is of utmost importance to carry out behavioral analysis of these structures with and without ribs defects. Different types of defects may arise in composite lattice cylindrical structures which include defects in the shell and its stiffening ribs. Comparison of buckling behavior of a composite structure with a defective model is increasingly important because of the fundamental importance of buckling phenomenon in the stability analysis of these structures.

Vasiliev and Razin [1] studied the design, construction and operational phases of composite lattice structures and investigated their applications in the aerospace industry. Totaro and Gurdal [2] performed the design optimization of composite lattice shells subjected to axial compressive load using the continuum model. Vasiliev et al. [3] studied design, construction and testing processes of carbon-epoxy composite lattice structures that were made by continuous filament winding method and were used in aircraft and other aerospace-related equipments. They also studied various types of construction methods and discussed their effects on rib strengthening.

Wodesenbet et al. [4] obtained numerical results of failure loads and modes of buckling by creating a three-dimensional finite-element model based on the distribution of the unit cell and verified answers with those reported in the literature. Morozov et al. [5] carried out the finite-element modeling and buckling analysis of composite lattice shells and studied effects of skin openings on their buckling loads and corresponding modes under different geometric and loading conditions. Kim [6] studied fabrication and testing of iso-grid composite reinforced cylinders and investigated various failure modes which could happen on the structures. They showed that buckling of stiffening ribs played a critical role on stability of iso-grid arrangement. However, it was shown that after

---

*Corresponding Author Email: raalashti@nit.ac.ir (R. Akbari Alashti)

failure of few ribs, the structure continued to bear the applied load.

Tafreshi [7] investigated the effect of opening on the critical buckling load of a composite cylindrical shell without stiffening ribs under the action of axial compression and internal pressure loadings. Hillburger et al. [8] examined the buckling behavior of a composite cylindrical shell with reinforced cutout under the axial compressive load and investigated the effects of cutout reinforcement on the buckling load. Frulloni et al. [9] studied instability of reinforced hollow structures under external hydrostatic loading for aeronautic applications using finite element and experimental methods. Composite structures were made of carbon fibers in various sizes and arrangements and tested under hydrostatic loadings. All phases of testing were also simulated using the finite element method. The results of finite element model were found to be in accordance with the experimental results.

Craig et al. [10] studied optimization of buckling characteristics of lattice composite shells with geometric defect incorporating Karhunen-Love based geometrical imperfections. Hualin et al. [11] found the local buckling strength of periodic lattice composites using the analytical method based on the classical beam-column theory. They investigated the strength and latitude factors of different lattice structures under uniaxial pressure and tension loadings. Numerical simulations of buckling surfaces were presented under plane stress mode.

Vasiliev et al. [12] reviewed the development and applications of composite lattice structures with cylindrical and conical shapes in the aerospace industry. In their article, a review of recent experiences in the development and applications of composite lattice structures is presented. In their study, information about manufacturing processes, design, analysis and mechanical properties of lattice composites in the aerospace industry was presented.

In this paper, the effects of rib defects on the buckling behavior and distribution of stress field of a composite lattice cylindrical shell is presented. Test specimens were made by filament winding and tested under compression and shear force loading. The results were compared with those obtained by the finite element method. Effects of various parameters including the geometrical ratios and defects of ribs have been studied.

2. MANUFACTURING PROCESS

A composite lattice structure is made of a set of composite ribs that are connected to each other and form a two or three-dimensional continuous structure. These sets of ribs are made of tough, rigid and continuous fibers. The main components of a lattice structure consist of nodes, ribs and the unit cell, as shown in Figure 1.

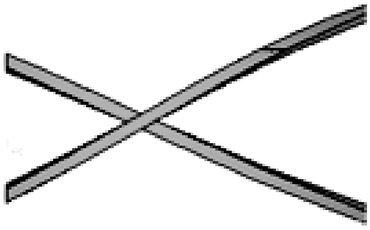


Figure 1. A unit cell

Generally, each structure is made by repeating several unit cells. The strength of a composite lattice structure is directly related to these cells. In lattice composite shells that are often made with curved ribs, the dimensions including width, thickness, number of ribs, their distance from each other and placement angles relative to the shell axis are design outputs. These structures are often required to have cutouts and openings on the outer shell due to operational requirements and might be subjected to defects during manufacturing or service life such as breakage of reinforcing strips and ribs. Due to the fundamental importance of buckling phenomenon in analyzing the stability of these structures, comparison of buckling behaviors of perfect composite structures with a defective model is important. The purpose of this study is to investigate effects of defective ribs on the distribution of stress field and buckling behavior of composite cylindrical lattice structures.

The manufacturing process is briefly described here. Composites which were used in this project constitute of epoxy resin as the matrix and E-glass fibers. The resin was made by combining two types of resins namely CY219 as the base and HY5160 as the hardener with the ratio of 2 to 1, respectively. Test samples were made using the filament winding method. To perform this process, a cylindrical mold was designed and the frames were connected to it. Paths of ribs were then created in the mold. After preparing the mold, it was installed on the machine in order to fabricate the ribs and the lattice composite shell. After completion of the rib construction process, the outer shell was fabricated. Finally, in order to obtain uniform resin thickness in the total shell, the mold was put on the spinning machine and rotated at a low rotational speed. The mold and a sample of lattice cylinder are shown in Figure 2.

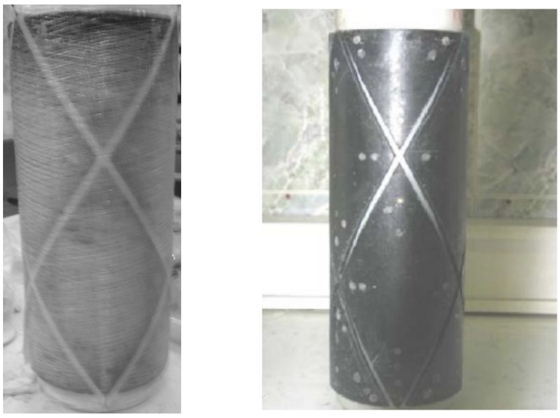


Figure 2. Mold and composite shell

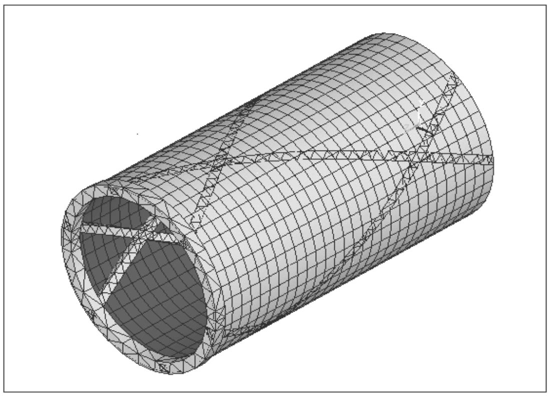


Figure 3. Finite element model of the lattice composite shell

TABLE 1. Geometrical parameters of the shell and rib, dimensions are in mm

No.	L	Φ	Inner radius	Outer radius	Shell diameter	Shell thickness
1	300	60°	75	81	162	0.8

TABLE 2. Mechanical properties of finite element 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

3. MODELING

As mentioned in the previous section, ribs are the major components of composite lattice shells. The lattice shell under study is composed of helical ribs with an angle of ±*Φ* with respect to the cylinder longitudinal axis. The geometric parameters which are used in modeling of the shell include the sample length, *L*, diameter, *D*, rib thickness, shell thickness and rib angle, *Φ*. Geometric and mechanical parameters of the shell used in finite element analysis are based on values associated with the real model as made by the authors. The sample is made of six ribs with angles of ±60º to the cylinder axis. The fiber angle is equal to ±14º with respect to the radial direction (perpendicular to longitudinal direction). Geometrical parameters used in the analysis are shown in Table 1.

4. FINITE ELEMENT ANALYSIS

The finite element modeling of the shell is carried out using ANSYS suite of program. Since, composite lattice shells have layered configuration, elements with the same capabilities namely SOLID191 and SHELL99 are used in the finite element simulation .

SHLL99 with 8 nodes and 6 degrees of freedom per node is used to mesh the shell and SOLID191 with 20 nodes and 3 degrees of freedom per node is used to mesh the ribs. In finite element simulations, it is necessary to input orientation angle, geometrical data and mechanical properties of materials [13]. The finite element model used in the present analysis is shown in Figure 3.

As shown in Figure 3, a composite lattice cylindrical shell composed of an outer shell and stiffening ribs is considered. Linear buckling analysis is employed to obtain buckling modes and the stress distribution in the shell under axial pressure loading. In order to proceed with the linear buckling analysis, an initial small axial deformation in the elastic range is applied and 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. In this analysis, pressure loading is increased incrementally until the structure can no longer resist even the slightest addition in the external load.

5. RESULTS AND DISCUSSIONS

The purpose of the finite element analysis is to study the behavior of complete and defective samples with broken stiffening ribs. Mechanical properties of the shell used in the finite element analysis were obtained experimentally, as shown in Table 2.

For all samples, manufacturing process, mechanical properties, geometry and the shape of cuts has been the same, however the thickness of shells and locations of cuts are different.

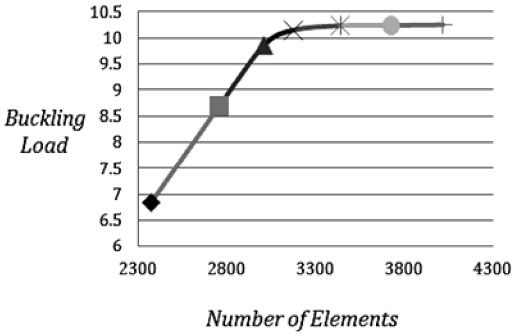


Figure 4. Variation of buckling load with number of elements

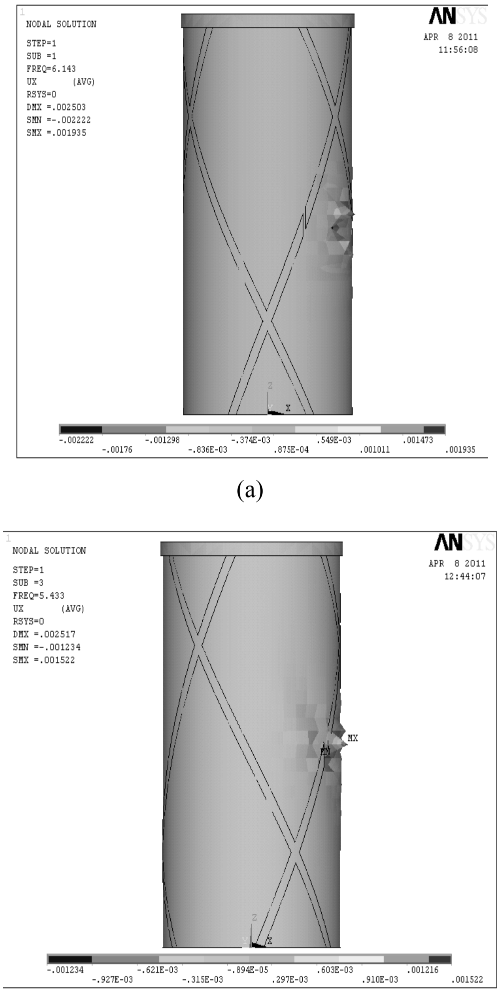


Figure 5. Buckling of the cylindrical shell; (a) Incision size, 2.5 mm and (b) Incision size, 5 mm

In this analysis, boundary conditions of the shell are assumed to be free at one end and clamped at the other. The axial pressure loading is applied at the free end of the shell. At first, the effect of number of elements on buckling load calculation is studied and the result is shown in Figure 4.

As it can be observed in Figure 4, as the number of elements increases, the buckling load is improved, however the rate of convergences reduces and the load converges to an asymptotic value. Considering the calculation timing and rate of convergence, the optimal number of elements for this analysis was chosen to be 3340 elements.

Then, the effect of the size of the rib cut on the distribution of stress field and buckling load of the shell is studied. Buckling of the cylindrical shell under axial pressure loading for various sizes of cuts are shown in Figures 5a and 5b.

Comparison of results presented in Figures 5a-5b reveals that most of the buckling modes occur around the cut area. The linear and nonlinear buckling of the defective cylinder was carried out with one or more 5 mm wide cuts of the stiffening ribs.

In Figure 6, the finite element model of ribs and the position of the incision in samples under test are shown.

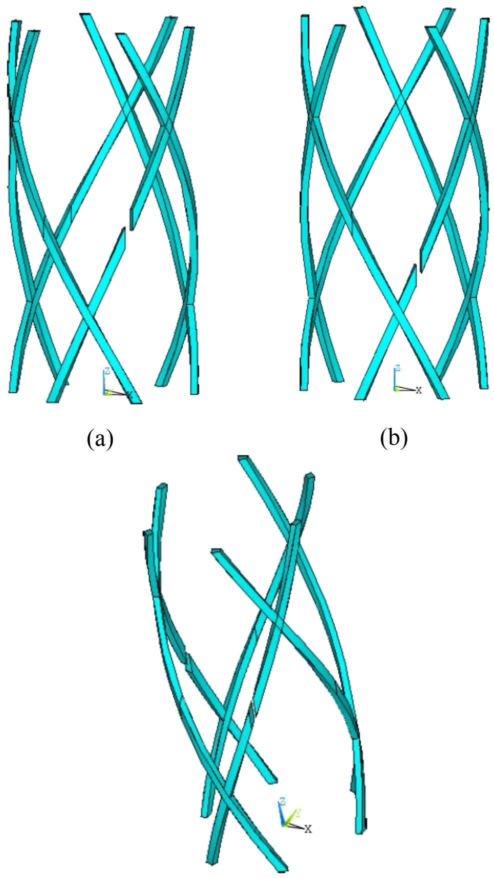


Figure 6. Finite element model of ribs, (a) incision in the center, (b) incision near the lower nodes and (c) model with two incisions in rib

Figure 7a. Global buckling of defective sample

Figure 7b. Local buckling of defective sample

Figure 7c. Local buckling and failure mode of a complete shell

It was observed that at the initial stages of the test, a global buckling occurs, however as the load increases, local buckling starts spreading at different positions of the shell. It was also found that in a perfect shell, local buckling initially occurs at the middle region of the shell and then shifts towards the supports. However, in the defective sample, local buckling initially occurs near the incision area and then expands to the whole sample.

It was observed in all tests that after removal of the load, the shell returns to its original state. The strength and stiffness of ribs are found to be the main reason for the return of the shell to its original position. Images of test samples are shown in Figures 7a-7c.

The results obtained from the finite element simulation showed that the buckling modes of the defective sample occur at positions around the incision area. The same result was also observed during the experiment. These buckling modes were originally created in the intermediate areas and then were observed to shift towards the supports. It was found in the defective samples that buckling modes were created around the incision area and then developed in other parts of the shell. Buckling modes of the complete and defective shells obtained by analytical and experimental methods are shown in Figures 8a and 8b which show good agreements between these two methods.

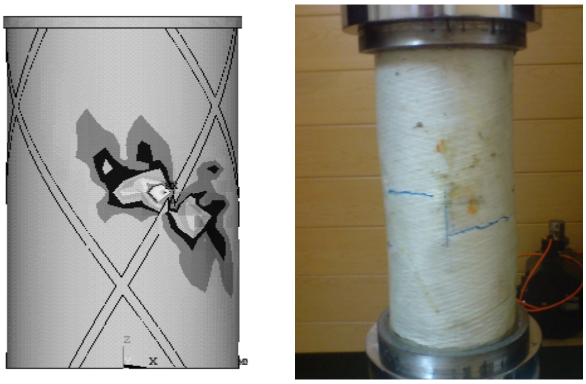


Figure 8a. Buckling mode of a defective shell

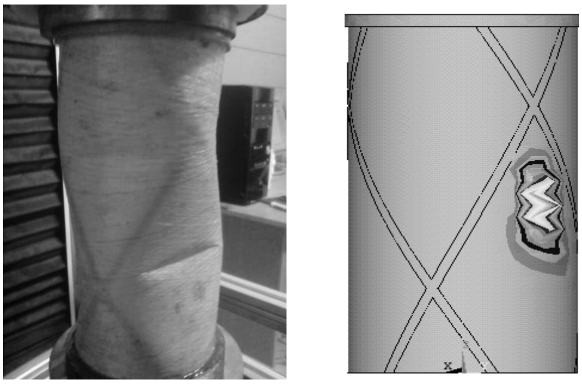


Figure 8b. Buckling mode of a complete shell

Variation of displacement versus applied force for three cases of complete shell, shells with one and two cut off ribs are shown in Figure 9 and a comparison between the finite-element and experimental results is made.

In the following figures comp, def1, def2 indicate the perfect shell, shell with one and two defective ribs, respectively and the term starting with exp- indicates the corresponding experimental result.

It is observed in Figure 9 that the response curves of the complete shell and defective ones in both finite element and experimental analyses are in good agreement. It is also observed that as the number of ribs cuts increases, the strength of the shell reduces.

Shell thickness is another parameter that plays an important role in the strength of composite lattice structures. In experimental models, the shell with two cut off ribs had the highest value of shell thickness and the shell with one defective rib had the lowest shell thickness. It is observed in Figure 10 that as the shell thickness increases, the strength of the shell increases.

It can be concluded that as the thickness of the shell increases, the ultimate load increases significantly. In any case, the critical loads obtained by the finite element simulations approximately indicates the amount of the load that actually observed by the experimental model. Critical buckling loads for specimens with different thicknesses are calculated and presented in Table 3.

Critical load of the sample with two rib defects was found to be greater than the others mainly due to its larger thickness. It is obvious that the ultimate load reduces as the thickness decreases.

Next, the effect of buckling test repetition on final buckling load of the shell is investigated experimentally and results are shown in Figure 11.

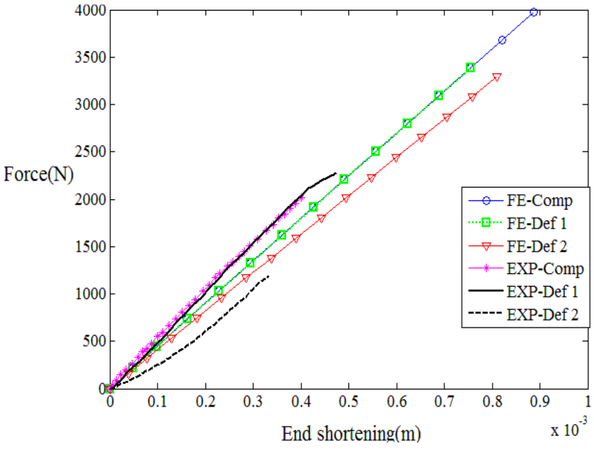


Figure 9. End shortening versus applied force, complete and defective shell

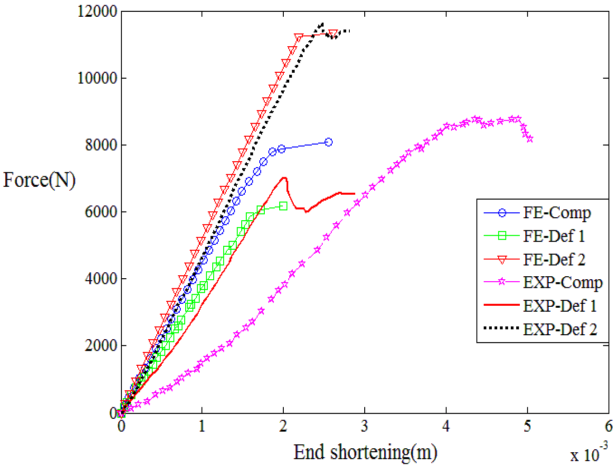


Figure 10. Variation of end shortening with applied force, finite element and experimental results

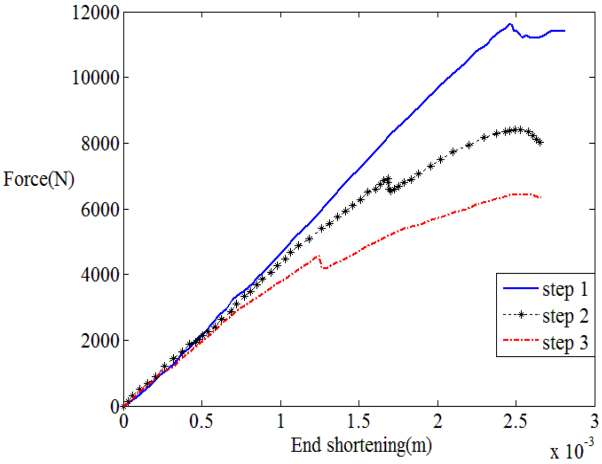


Figure 11. End shortening versus applied force with repetition of tests

TABLE 3. Variation of critical buckling load (N) with defects

	Model with two defective ribs	**Model with one defective rib**	**Complete model**
Thickness (mm)	1.2	0.8	0.9
Numerical results	11343	6180	8080
Experimental results	11420	6542	8163
Relative error (%)	0.67	5.53	1.02

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 in the second stage. It is important to note that as the applied load increases and some critical portions of the cylinder start failing, the general strength of the shell is reduced and as an indication to that the modulus of elasticity is reduced.

In composite cylindrical lattice structures, nodes are considered as one of the most important parameters, since major part of the forces is exerted at these points. Hence, effects of ribs cuts at nodal points on the buckling behavior of these structures are studied. In order to examine this parameter, experimental tests were carried out. The upper three nodes of the sample were considered. Compressive tests on samples with one, two and three ribs cuts were performed and finite element simulations were conducted in accordance with the experimental test data. In this test, the shell with 0.8 mm thickness was tested with axial compressive force of 2450 N. Results of the experimental test and finite element simulations are shown in Figure 12. In the following figure, the notation i-node (i=1, 2, 3) indicates the model with i number of defective nodes.

It is shown in Figure 12 that as the number of ribs cuts at the nodes increases, the shell resistance reduces. It is also found that results of the numerical analysis are in good agreement with experimental results.

In the next study, effects of variation of ribs angles namely 30, 45 and 60 degrees, on the buckling behavior of the shell are examined and results are presented in Figure 13.

It is observed that as the rib angle decreases, the pitch is reduced and hence density of stiffener and the total weight of the structure increases that by itself reduces the flexibility of sample. Hence, it is expected to observe critical buckling modes at smaller rib angle.

It is observed in Figures 13a to 13c that as the angle reduces, ribs performance on reinforcing the shell is reduced. Critical buckling loads of samples with different ribs angles are obtained by finite element analysis and the results are presented in Table 4.

Finally, the effect of the shear force on the buckling behavior of the lattice composite shell is investigated and the results are shown in Figure 14. It is observed form the figure that by application of shear force at the free end, the most critical parts of the shell i.e. regions near the fixed end start yielding at the very early stage of loading.

TABLE4. Variation of critical buckling load (N) with ribs angles

No.	Ribs angle	Model with one defective rib	Complete model
1	30°	8964.14	9751.3
2	45°	7479.43	8936.344
3	60°	7204.3	8080

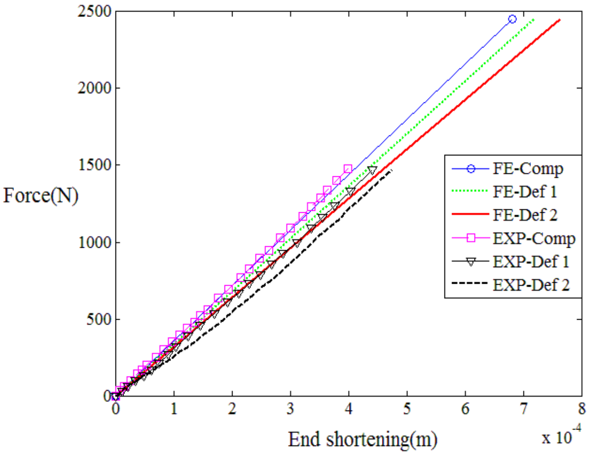
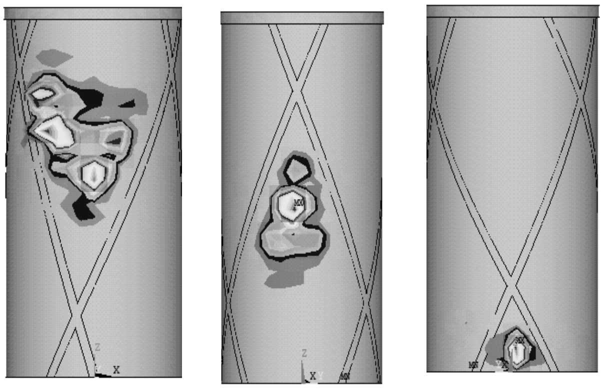


Figure 12. End shortening versus force, effect of node incision



(a)30° (b) 45° (c) 60°

Figure 13. The effect of ribs angles on buckling behavior of the shell

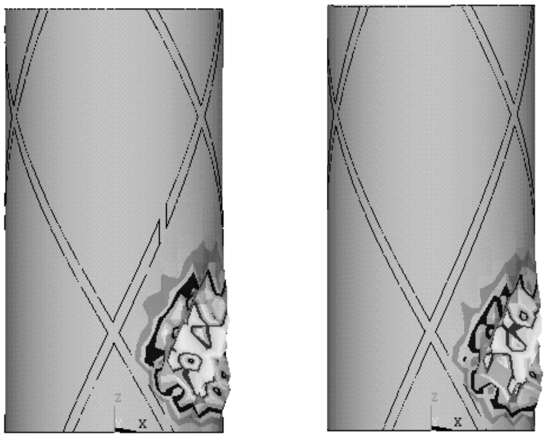


Figure 14. Buckling mode shapes, samples under shear force

TABLE 5. Critical buckling load (N), shear force versus compressive loading

Loading condition	Shell thickness (mm)	Defective model	Complete model
Compressive force	0.8	6180	6995.5
Shear force	0.8	1930	1840

Buckling loads for complete and defective shells under shear force and axial compressive loadings obtained by finite element analysis are shown in Table 5. It is found that the critical buckling load for both complete and defective samples, the critical shear force loading is less than that of the critical compressive load.

6. CONCLUDING REMARKS

In this study, finite element analysis was performed using ANSYS software and the results were compared with the experimental test data. The followings are the main results.

- ✓ A good agreement was observed between the finite element and experimental test results.
- ✓ In defective lattice shells with wider cut off ribs, the buckling modes occurred around the incision area.
- ✓ As the number of defective ribs increases, structural strength and critical buckling load of the shell decreases.
- ✓ It was shown experimentally that with repetition of tests for several times, the ultimate load was reduced in each repetition.
- ✓ As the rib angle reduces, their efficiency in reinforcing the shell reduces.
- ✓ Under shear force loading, the buckling modes were observed to be close to the supports.

7. REFERENCES

1. Vasiliev, V. and Razin, A., "Anisogrid composite lattice structures for spacecraft and aircraft applications", ***Composite Structures***, Vol. 76, No. 1, (2006), 182-189.
2. Totaro, G. and Gürdal, Z., "Optimal design of composite lattice shell structures for aerospace applications", ***Aerospace Science and Technology***, Vol. 13, No. 4, (2009), 157-164.
3. Vasiliev, V., Barynin, V. and Rasin, A., "Anisogrid lattice structures–survey of development and application", ***Composite Structures***, Vol. 54, No. 2, (2001), 361-370.
4. Wodesenbet, E., Kidane, S. and Pang, S.-S., "Optimization for buckling loads of grid stiffened composite panels", ***Composite Structures***, Vol. 60, No. 2, (2003), 159-169.
5. Morozov, E., Lopatin, A. and Nesterov, V., "Finite-element modelling and buckling analysis of anisogrid composite lattice cylindrical shells", ***Composite Structures***, Vol. 93, No. 2, (2011), 308-323.
6. Kim, T. D., "Fabrication and testing of composite isogrid stiffened cylinder", ***Composite Structures***, Vol. 45, No. 1, (1999), 1-6.
7. Tafreshi, A., "Buckling and post-buckling analysis of composite cylindrical shells with cutouts subjected to internal pressure and axial compression loads", ***International Journal of Pressure Vessels and Piping***, Vol. 79, No. 5, (2002), 351-359.
8. Hilburger, M. W. and Starnes Jr, J. H., "Buckling behavior of compression-loaded composite cylindrical shells with reinforced cutouts", ***International Journal of Non-Linear Mechanics***, Vol. 40, No. 7, (2005), 1005-1021.
9. Frulloni, E., Kenny, J., Conti, P. and Torre, L., "Experimental study and finite element analysis of the elastic instability of composite lattice structures for aeronautic applications", ***Composite Structures***, Vol. 78, No. 4, (2007), 519-528.
10. Craig, K. J. and Stander, N., "Optimization of shell buckling incorporating karhunen-loève-based geometrical imperfections", ***Structural and Multidisciplinary Optimization***, Vol. 37, No. 2, (2008), 185-194.
11. Fan, H., Jin, F. and Fang, D., "Uniaxial local buckling strength of periodic lattice composites", ***Materials & Design***, Vol. 30, No. 10, (2009), 4136-4145.
12. Vasiliev, V. V., Barynin, V. A. and Razin, A. F., "Anisogrid composite lattice structures–development and aerospace applications", ***Composite structures***, Vol. 94, No., (2011), 117-1124.
13. Ansys inc., release 12. User manual.

Buckling Analysis of Composite Lattice Cylindrical Shells with Ribs Defects

R. Akbari Alashti[a], S. A. Latifi Rostami[a], G. H. Rahimi [b]

[a] *Department of Mechanical Engineering, Babol University of Technology, Babol, Iran*
[b] *Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran*

PAPER INFO

Paper history:
Received 15 Agusut 2012
Received in revised form 8 October 2012
Accepted 18 October 2012

Keywords:
Composite
Cylindrical Shell
Buckling
Rib Defect
Finite Element

چکیده

هدف این تحقیق، بررسی اثرات بریدگی ایجاد شده در ریب بر توزیع میدان تنش و رفتار کمانشی سازه‌های مشبک کامپوزیتی استوانه‌ای است. تحلیل اجزای محدود به صورت ۳ بعدی با استفاده از مدل صریح در نرم‌افزار ANSYS انجام پذیرفته است. پارامترهای ورودی در این نرم‌افزار که شامل مشخصات ماده، پیکربندی هندسی و مشخصات ارتوتروپیک پوسته و ریب می‌باشد ، با استفاده از داده‌های مدل ساخته شده در نرم‌افزار اعمال شده است. پوسته های مشبک کامپوزیتی استوانه ای که توسط روش رشته پیچی ساخته شده‌اند، تحت نیروهای فشاری و برشی آزمایش شده اند و نتایج به دست آمده با نتایج اجزای محدود مقایسه شده است. به منظور تحلیل شرایط مختلف، تاثیر پارامترهایی از قبیل زاویه ریب، ضخامت و استحکام پوسته در توزیع میدان تنش و نیز بار کمانشی پوسته مورد بررسی قرار گرفته است.

doi: *10.5829/idosi.ije.2013.26.04a.10*