

BUCKLING ANALYSIS OF CFRP COMPOSITE CYLINDRICAL SHELL WITH CUTOUTS IN BENDING

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ABSTRACT

Composite materials have many advantages when compared to metallic structures due to their better mechanical properties such as high specific stiffness and strength, high fatigue endurance and better impact properties. In addition, they offer higher corrosion and chemical resistance, better dimensional stability and design flexibility over metallic materials. Especially, in aerospace industry carbon fiber reinforced polymer (CFRP) composite is widely used because of its lightweight and high fatigue strength properties.

The work presented in this study includes the effect of different size cutouts at both sides of the CFRP composite cylinder under pure bending. The results of a parametric study, concerning on the effects of a pair of cutouts symmetrically located at $\pm 90^\circ$ positions with respect to the vertical axis perpendicular to the bending axis, varying size of the cutouts and evaluating their effects on the buckling and maximum load levels of circular cylindrical shell were presented.

The analysis methods that were used for the evaluation of the buckling and failure characteristics of shells include linear buckling analysis and nonlinear failure analysis using Riks method. During the nonlinear analysis, the imperfections coming from the buckling eigenvalue analysis were included at rates of 1%, 2.5%, 5% and 10% of the shell thickness to investigate the effect of imperfections. Analyses were performed using the commercial FEM solution ABAQUS. In that model, the stacking sequence was defined to be 24 layers of conventional fiber orientation angles.

Keywords: Laminated Composite, Buckling, Nonlinear Failure Analysis, Cylindrical Shell.

ÜZERİNDE PENCERE KESİTLERİ BULUNAN POLİMER SİLİNDİRİK KOMPOZİT KABUKLARIN EĞİLME YÜKÜ ALTINDA BURKULMA ANALİZİ

ÖZET

Havacılık/uzay ve otomotiv sektöründe, karbon fiber takviyeli kompozit malzemelerin kullanımı son yıllarda hızla artmaktadır. Metallere göre daha yüksek özgül mukavemet ve katılığa sahiptirler, ayrıca daha hafif olmalarından dolayı da, kompozitler metallere göre havacılık ve uzay alanında daha çok tercih edilmeye başlanmıştır.

Bu çalışmada, silindirik katmanlı kompozit bir yapıda, silindirin her iki yanına dikey eksene göre $\pm 90^\circ$ 'lik pozisyonda simetrik olarak açılan dairesel pencerelerin bileşik yükleme altındaki burkulma ve hasar yüküne olan etkisi incelenmiştir. Silindirik kabuk üzerine açılan dairesel pencerelerin çapları değiştirilerek analizler gerçekleştirilmiş ve sonuçları tablolar ve grafikler halinde sunulmuştur.

Silindirlerin burkulma ve hasar karakteristiklerinin tespit edilebilmesi amacıyla lineer burkulma analizi ve Riks metodu kullanarak lineer olmayan hasar analizleri yapılmıştır. Lineer olmayan analizler gerçekleştirilirken burkulma analizinden teorik olarak elde edilen kusurlar silindirik kabuğun kalınlığının %1, %2.5, %5 ve 10'u oranında analize dahil edilerek kusurların etkileri de incelenmiştir. Analizler gerçekleştirilirken ticari Sonlu Elemanlar Metodu (SEM) programı olan ABAQUS kullanılmıştır. Silindirik kompozitlerdeki pencereler için tanımlanan her bir ölçü için lineer olmayan hasar analizleri yapılarak kusurların ve kesit ölçülerinin hasara olan etkileri incelenmiştir.

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Anahtar Kelimeler: Katmanlı Kompozit, Burkulma, İlerlemeli Hasar Analizi, Silindirik Kabuk.

1. INTRODUCTION:

Composite materials have many advantages when compared to metallic structures due to their better mechanical properties such as high specific stiffness and strength, high fatigue endurance and better impact properties. They can be manufactured as smart materials to be used in structural health monitoring systems with the help of embedded sensors. In addition, they offer higher corrosion and chemical resistance, better stability and design flexibility over metallic materials. On the other hand, the manufacture cost of the composite materials is still higher and production of high quality reliable composite parts is highly knowledge and experience dependent.

Composite materials are used in wide variety of applications. Especially, in aerospace industry it is widely used because of its lightweight and high fatigue strength properties. CFRP composites have the ability to replace aluminum alloys since they weigh less per unit of strength. In recent years, the use of composites has been extended to the fuselage and wings because of its lightweight and resistance to corrosion compared to the metallic materials that have traditionally been used in aircraft. Not only will the use of composites help save the weight but also there will be benefits to the passengers as well with higher cabin pressure and more humidity [1].

While designing composites where strength constraints are considered, one must be sure that the failure load is beyond the buckling load. Khani et al. [2] used a conservative failure envelopes based on Tsai-Wu failure criterion for strength evaluation. A circular cylinder under bending and an elliptical cylinder under axial compression, which were tailored circumferentially, were modeled and verified using nonlinear buckling analysis in the commercial FEM tool Abaqus. Another finite element analysis on the response of composite cylinder shells with cutouts and subjected to internal pressure and axial compression were presented by Ismail et al. [3]. The objective of the study was to improve the buckling load by applying the internal pressure while applying compression load. They also investigated the effect of local stress concentration distributed around the cutout region. In addition, Shi et al. [4] investigated the initial buckling and post-buckling responses of axially loaded composite cylindrical shells with reinforced rectangular or circular cutouts. A nonlinear analysis procedure was proposed to predict the nonlinear buckling response of the cylindrical shell. Stress analysis of composite cylindrical shells with an elliptical cutout was investigated by Öterkuş et al [5]. They presented a semi analytical solution method for determining the stress and deformation fields in a thin, laminated-composite cylindrical shell with an elliptical cutout. Blom [6] investigated the structural

response of the cylindrical laminated composite shells under bending and performed testing to correlate the test results with the numerical study.

The work presented in this study includes the effect of cutouts located on symmetrical sides of the cylinder with different sizes on conventional cylindrical CFRP composite shells under pure bending. The results of a parametric study, concerning on the effects of a pair of cutouts symmetrically located at $\pm 90^\circ$ positions with respect to the vertical axis perpendicular to the bending axis, varying size of the cutouts and evaluating their effects on the buckling load and maximum load levels of a circular cylindrical shell, were presented. During nonlinear failure analyses, effect of imperfection was investigated. Therefore, several imperfection ratios obtained from most critical buckling eigenvalue were included in the analyses. The main difference from previous works is that in this parametric study, the nonlinear progressive failure analysis was applied while introducing cutouts into the cylindrical shells. In addition, in this study the imperfection effect on the buckling load was displayed.

The analysis methods that were used for the evaluation of the buckling and failure characteristics of shells include linear buckling analysis and nonlinear failure analysis using Riks method [7]. During the nonlinear analysis, the imperfections coming from the buckling eigenvalue analysis were included at rates of 1%, 2.5%, 5% and 10% of the shell thickness to investigate the effect of imperfections. Analyses were performed using the commercial FEM solution ABAQUS [8].

2. CYLINDER GEOMETRY AND CUTOUT CONFIGURATION

The structure under consideration is a circular cylinder with a radius R of 304.5 mm, length of 813 mm and a shell thickness of 4.392 mm as shown in Figure 1.

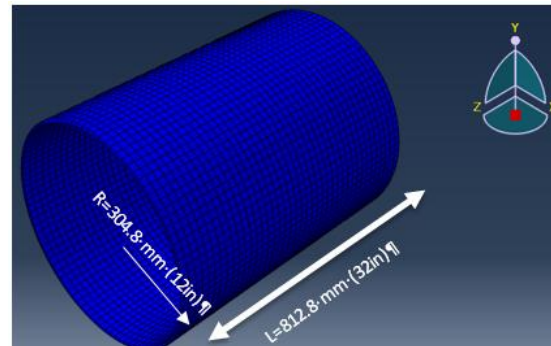


Figure 1. Cylinder geometry

In that model, the stacking sequence was defined to be 24 layers of conventional fiber orientation angles. The laminate is symmetric and balanced. The laminate

stacking sequence is $[\pm 45, 02, 902, 0, \pm 45, \pm 45, 90]_s$ as shown in Figure 2.

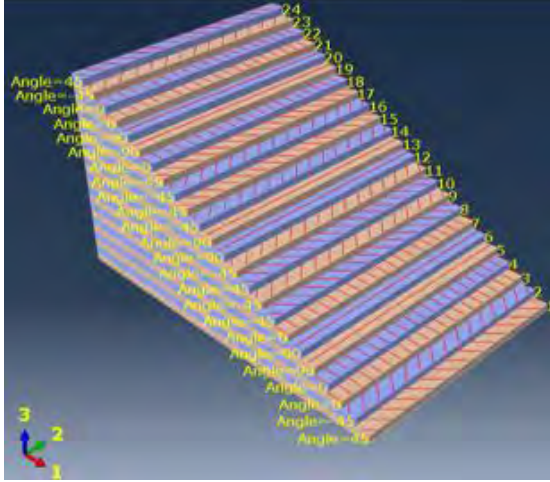


Figure 2. Ply stacking sequence

The material properties used for the design studies are Hexcel IM7/8552 unidirectional prepreg with properties as provided in Table 1 [9].

Table 1. IM7/8552 Lamina Mechanical Properties

t_{ply}	0.183 mm
E_1	158.510 GPa
E_2	8.963 GPa
G_{12}	4.688 GPa
G_{13}	4.688 GPa
G_{23}	3.9735 GPa
ν_{12}	0.316
ρ	1580 kg/m ³
F_1^t	2500.7 MPa
F_2^t	64.05 MPa
F_1^c	1716.4 MPa
F_2^c	285.719 MPa
F_{12}^s	91.15 MPa

The cutout shape is defined as circular when the cylinder is opened into a planar form and centered longitudinally at the mid-length of the shell. The circumferential location is at $\pm 90^\circ$ positions from the top of the cylinder, containing a symmetric cutout on the both sides of the shell as depicted in Figure 3.

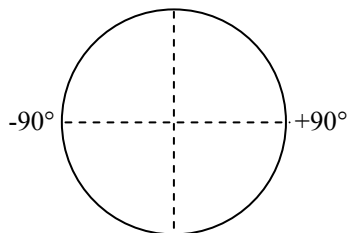


Figure 3. Cutouts location

Cutout size $r=iR$, represented by the radius of the circular cutout in relation to the radius of the cylindrical shell ($i=\{0.1, 0.2, 0.3, 0.35, 0.40, 0.45, 0.5\}$). These sizes are assumed to represent typical window or door sizes in an aircraft fuselage. Cutout

configurations are represented as the size designation followed by the circumferential location in the form iR/β , such as '0.3R/90' for the $r=0.3R$ cutouts located at the $\pm 90^\circ$ positions of the cylinder.

3. IMPERFECTION ANALYSIS

In linear buckling analysis, the presence of geometrical imperfections are not taken into account, and that could have a large influence on the experimental buckling load of thin-walled cylindrical shells. If the exact geometric imperfection is not known, an imperfection consisting of multiple superimposed buckling modes may be introduced and usually first buckling mode is the dominant one. The radial displacements of the nodes under the effect of the bending moment cause the cylinder to deviate from perfect cylinder and create geometric imperfections. The first buckling mode is accepted to provide the most critical imperfections, therefore, usually these are scaled and added to the perfect geometry to create the perturbed mesh. The magnitudes of the perturbations used are typically some percent of a relative structural dimension such as shell thickness [8]. Riks method can be used to perform a geometrically nonlinear load-displacement analysis to determine the collapse loads, especially for imperfection-sensitive structures in which the applied load produces significant geometric instability. Therefore, imperfections obtained from linear buckling analysis were applied in the nonlinear failure analysis.

During the buckling stability study, initially, eigenvalue analysis is used to obtain estimates of the buckling loads and modes. Using imperfections suggested by the eigenvalue analysis, the second phase of the study is the performance of load-displacement analyses, using the Riks method. Before continuing to the nonlinear analysis with cutout, a series of analyses were performed on the cylinder without cutout to see the effect of the imperfections in the shape of buckling eigenmodes from the linear buckling analysis. Imperfections, in the form of first buckling eigenmodes with 1%, 2.5%, 5% and 10% of the shell thickness were applied during nonlinear analyses. Linear and nonlinear finite element analyses were performed using an ABAQUS-Python script. In all analyses, the Hashin failure criterion [10] was checked and no fiber failure initiations were observed before buckling.

During linear buckling analyses that were performed for the non-cutout cylinder, deformations of nodes for linear buckling eigenvalues were recorded in a file. Then, the deformations obtained from buckling eigenvalues were applied at certain fractions in nonlinear analyses to decide the imperfection value for the analysis cases with cutouts. Different imperfection cases were analyzed only for non-cutout cylindrical shell.

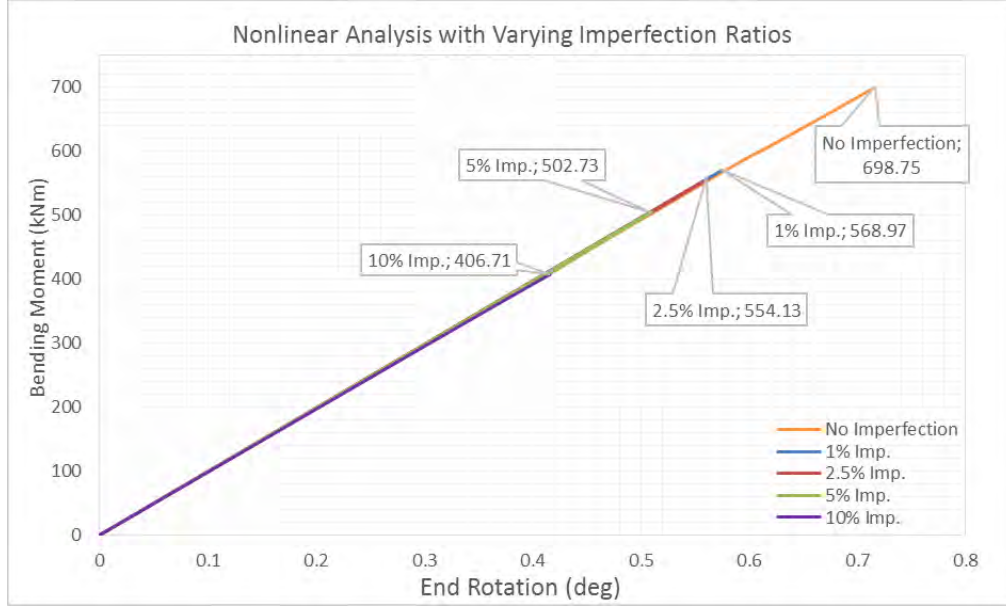


Figure 4. The rotation of the end plates with different imperfections in bending

The load/displacement curve of nonlinear analyses results are shown in Figure 4. The end rotations decreases with the increasing imperfection values, however, the response behaviors for all cases follow the same trend. The decrement in the end rotations is due to the decrement in the buckling load.

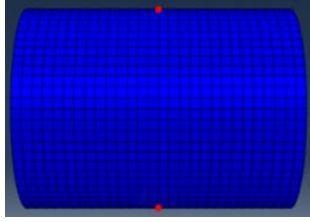


Figure 5. Top and bottom node locations

The displacements of the top and bottom mid nodes shown in Figure 5 in the vertical direction under the effect of the bending moment are given in Figure 6 and Figure 7. Since the top node is in the tension side of the cylinder, the vertical displacement remains linear, however, due to the effect of the imperfection, decrease in the buckling load and vertical deflection were observed. On the other hand, the bottom node has a vertical deflection greater than the top node and the increment is nonlinear because of the compression at the bottom side of the cylinder. Although, after the critical load the vertical displacement in top node stops, the bottom node continues to increase.

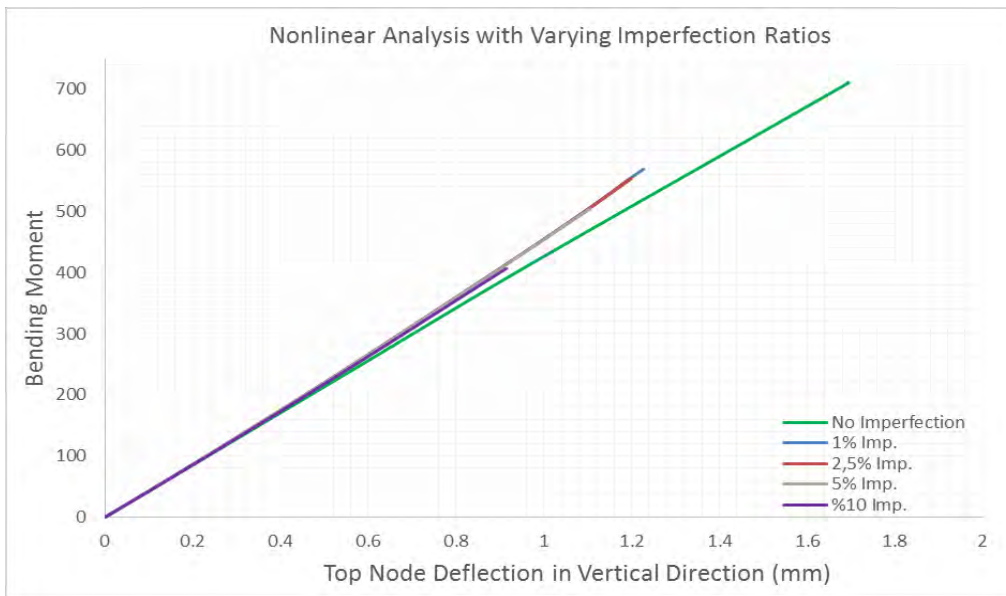


Figure 6. The displacement of the top mid node in the vertical direction

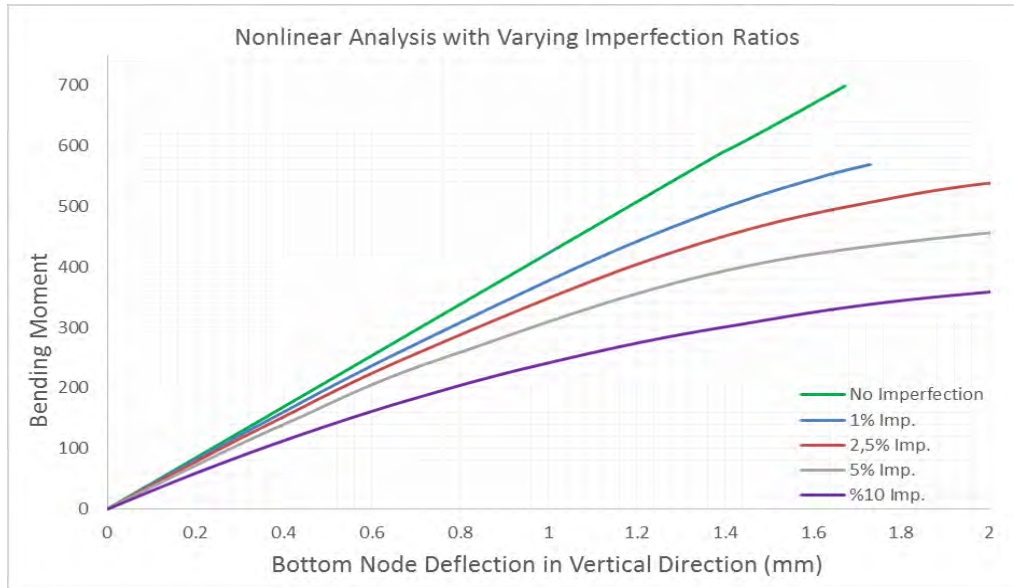


Figure 7. The displacement of the bottom mid node in the vertical direction

The percentage deflection difference between the top and bottom nodes of the cylinder normalized per cylinder radius is given in Figure 8. The peak in the curvature of the graph shows the point when the instability, which cause the failure, starts. After peak point, there is a substantial increase in the deflection at

same load level that indicates the collapse load. It is clear that, for 10 % imperfection, collapse starts around 410 kNm, while this value is 500 kNm for 5% imperfection. That shows the imperfection sensitivity of the shells.

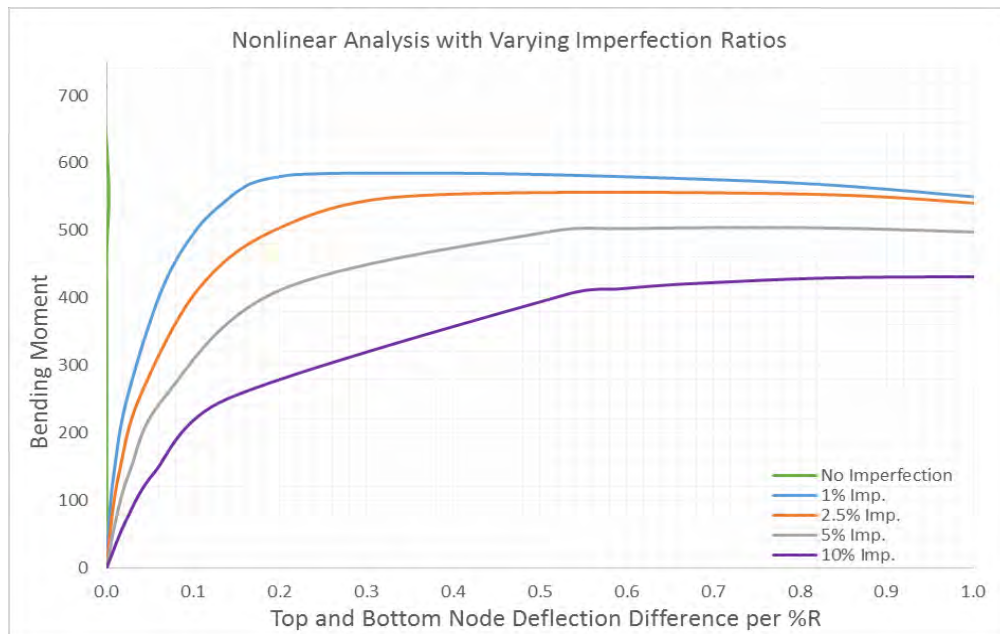


Figure 8. The percent deflection difference between the top and bottom nodes normalized per cylinder radius.

4. LINEAR BUCKLING AND NONLINEAR FAILURE ANALYSIS

Eigenvalue buckling analysis, which is a linear perturbation procedure, was used to estimate the critical (bifurcation) load of the structure. The results of the static buckling analysis and nonlinear analysis as a function of cutout dimension are given in **Figure**

9 where, the buckling load remains unaffected by the presence of the cutout until about 30% of the cylinder radius (0.3R), and then starts decreasing substantially after 35% of the radius (0.35R). Similarly, the nonlinear (NL) analysis failure load also remains almost the same until 0.3R cutout radius and then increases up to 0.35R.

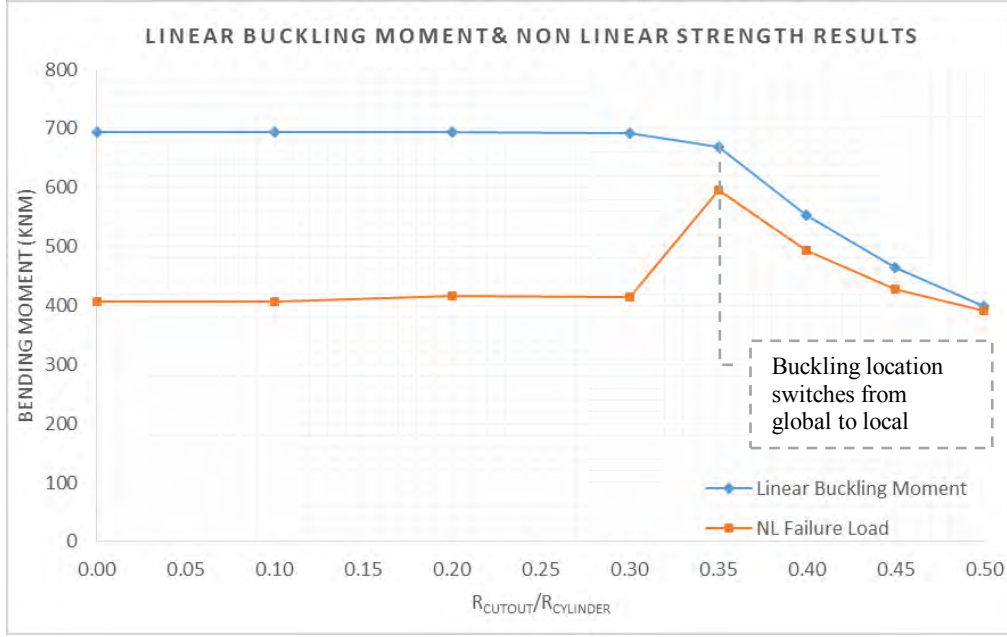


Figure 9. Buckling moment and strength results for given cutout dimensions.

However, as the cutout size was further increased, the NL failure load decreases following almost the same trend with linear buckling moment. The region where

there is an increase in the failure load is the transition region of the buckling mode from global buckling into local buckling around the cutout edge.

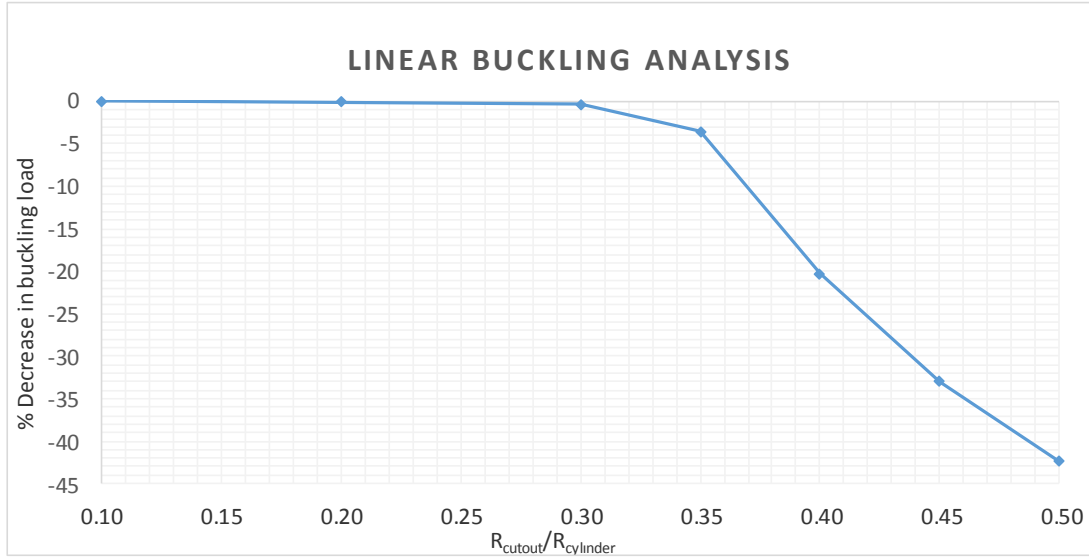
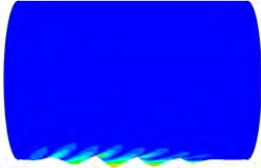
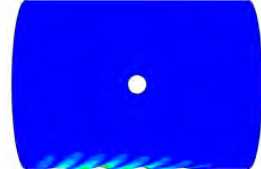
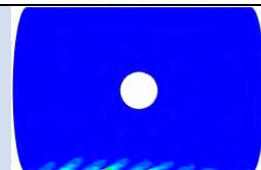
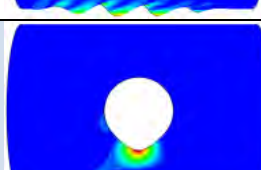
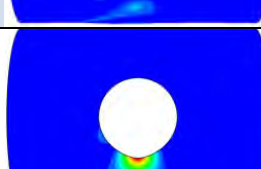
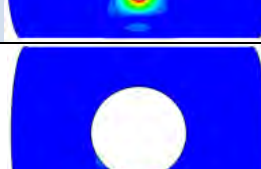


Figure 10. Percent decrease in the buckling moment due to increase in the cutout dimension

Numerical results are tabulated in **Hata! Yer işareti başvurusu geçersiz.** along with the buckling mode shapes. It can be observed that until cutout dimension 0.3R the structure buckles from lower portion of the cylinder that is the compression side. However, after cutout dimension 0.35R the buckling initiates from the lower side of the cutout boundary and the buckling load decreases more than 20% compared to non-cutout buckling load as shown in Figure 10. Until 0.30R

cutout size, the decrement in the buckling load due to the increment in the cutout dimension is less than 4%. However, after 0.35R, the buckling load starts to decrease rapidly and at cutout dimension 0.5R the reduction reaches to 40%. Since linear buckling analysis is usually done for “stiff” structures, it is not generally necessary to include the effects of geometry change in establishing equilibrium for the base state.

Table 2. Buckling analysis of the shell with cutout

Dimension R=304.5 mm	Linear Buckling Analysis (kNm)	Nonlinear Failure Analysis with 10% imp. (kNm)	Number of Elements	Mode Shapes
0.0R	698.75	406.71	15744	
0.1R	693.79	406.76	15734	
0.2R	693.22	416.5	15725	
0.3R	691.27	414.15	15428	
0.35R	669.08	594.77	15714	
0.4R	553.22	493.81	15032	
0.45R	464.98	427.5	14784	
0.5R	399.76	391.07	15128	

5. CONCLUSIONS

It can be inferred from the study that, there is a very important effect of imperfection on the failure load of cylindrical shells since shells are very imperfection sensitive. The 40 % decrease in the buckling load

with the effect of 10% imperfection shows that one must take into account the imperfections in the shells very carefully.

Another important result is that the effect of cutout on the collapse load of the cylindrical shell. Since the

applied load type is bending, the failure is mostly due to buckling of the cylinder. With increasing size of the cutout, an increase in the collapse load was observed until cutout radius of 0.35R size. That increase was due to the shift of buckling location from global buckling to local buckling around the cutout edge. During local buckling, contrary to global buckling, cylinder was able to carry load further with the strength of fibers at the top and bottom of the cylinder. However, if you keep increase the cutout size the collapse load will start to decrease.

The results of this study shows that, in the design of cylindrical aerospace structures the window or door cutout sizes should be adjusted so that the buckling will tend to start from cutout edge to increase the ultimate failure load. On the other hand, it will better to include combined loading with variable size and location of cutouts for the future studies.

6. REFERENCES

- [1] S. Freissinet, "Worries about new composite made airplane," *www.1001Crash.Com*, 2011. Available: <http://www.1001crash.com/index-page-composite-lg-2.html>.
- [2] A. Khani, M. M. Abdalla, and Z. Gürdal, "Circumferential stiffness tailoring of general cross section cylinders for maximum buckling load with strength constraints," *Compos. Struct.*, vol. 94, no. 9, pp. 2851–2860, 2012.
- [3] M. S. Ismail, B. T. H. T. Baharudin, S. A. Yahya, and H. A. Kahar, "Finite Element Analysis of Composite Cylinder with Centre Cutout under Axial Load and Internal Pressure," *Adv. Mater. Res.*, vol. 701, no. October, pp. 425–429, 2013.
- [4] S. Shi, Z. Sun, M. Ren, H. Chen, and X. Hu, "Buckling response of advanced grid stiffened carbon-fiber composite cylindrical shells with reinforced cutouts," *Compos. Part B Eng.*, vol. 44, no. 1, pp. 26–33, 2013.
- [5] E. Oterkus, M. Erdogan, and M. P. Nemeth, "Stress Analysis of Composite Cylindrical Shells With an Elliptical Cutout," *J. Mech. Mater. Struct.*, vol. 2, no. April, pp. 695–727, 2007.
- [6] A. W. Blom, "Structural performance of fiber-placed, variable-stiffness composite conical and cylindrical shells," TU Delft, Ph.D., 2010.
- [7] E. Riks, "An incremental approach to the solution of snapping and buckling problems," *International Journal of Solids and Structures*, vol. 15, no. 7, pp. 529–551, 1979.
- [8] Dassault Systèmes, "Abaqus analysis user's guide, Abaqus 2016." 2016.
- [9] K. Marlett, "Hexcel 8552 IM7 Unidirectional Prepreg 190 gsm & 35%RC Qualification Material Property Data Report," CAM-RP-2009-015, NIAR, Wichita State University, 2011.
- [10] Z. Hashin, "Failure Criteria for Unidirectional Fiber Composites," *J. Appl. Mech.*, vol. 47, p. 329–334, 1980.

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