Nonlinear Buckling Analysis of Axially Loaded Composite Cylindrical Shells with Cutouts

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Abstract - *The laminated composite materials are widely used in almost every engineering field due to its high strength, stiffness, corrosion resistance, thermal insulation and many more. Laminated composite cylindrical shells are one the most common structures and depending on their usage they may face several loading condition. One of the most popular failures of these structures is buckling under axial compression. The application of cylindrical shells in variety of structures demands the creation of cut outs in shells, such as for access openings, pipeline passages etc. Hence there will be an invariable reduction in the strength due to the cut outs of the laminated composite cylindrical shell. The effect of cut-out is that it not only introduces stress concentration but also significantly reduces buckling load. In present study, the nonlinear buckling analysis of laminated composite cylindrical shells under axial loading has been investigated. The analysis is carried out using ANSYS software. The results show how the imperfections like cutouts affect the buckling behavior of the shells.*

Key Words: Laminated Composite Cylindrical Shell, Axial Loading, Nonlinear Buckling, Cutouts, ANSYS

1. INTRODUCTION

Thin walled cylindrical shells find wide application in various fields of engineering such as civil, mechanical, aerospace and nuclear engineering fields as primary structural members. These shells are also extensively used in underwater, surface, air and space vehicles as well as in construction of pressure vessels, storage vessels, storage bins and liquid storage tanks. Earlier such shells were made of conventional materials such as steel. The dead weight of steel shells is much larger than the shells made of a new engineered material, the laminated composite. The composite gives superior properties than original materials including strength, fatigue life, stiffness, corrosion resistance, thermal insulation, wear resistance, thermal conductivity and weight. The buckling is the most important failure mode in most of the thin-walled structures. Buckling is a form of failure that occurs under compressive stresses, before the material reaches its compressive strength. When a structure undergoes visibly large displacements transverse to the load then it is said to buckle. The application of cylindrical shells in variety of structures demands the creation of cut outs in shells, such as for access openings, pipeline passages etc. The effect of cutout is that it not only introduces stress concentration but also significantly reduces buckling load. The loading conditions for these shells are quite varied depending on the specific function of the shell. Axial compression, global bending, external or internal pressure and wind loading are some of the most common loading forms in practical structures. A cylindrical shell under uniform axial compression is one of the most common applications. Axial compression in a cylinder arises from many different causes. For heavy structures like towers and chimneys, self-weight provides uniform axial compression. For a silo, the frictional force between the solids and shell wall imposes substantial axial compression. For a shell with a closed roof, axial compression is caused by the weight of the roof. In addition, many shells under other loading conditions can also induce or include either symmetrical or unsymmetrical axial compression.

Hence, the buckling response and material failure characteristics of composite cylindrical shells must be understood and accurately predicted in order to develop efficient, safe design. Therefore, in designing the tanks and marine structures, it is essential to find out the effect of cut outs on the loading capacity and buckling behavior of cylindrical shells. In this regard, wide investigations have been conducted by the researchers.

Mark W. Hilburger (1967) [1] conducted a numerical and experimental study that illustrate the effects of laminate orthotropy on the buckling and failure response of compression-loaded composite cylindrical shells with a cutout. The effects of orthotropy on the overall response of compression-loaded shells were described. Jullien J.F. and Limam A. (1998) [2] studied the influence of circular, square, and rectangular cut outs on the buckling of cylindrical thinwalled shells under axial load and presented a parametric relationship between the shape and dimensions of the cut outs. Poursaeidi E., Rahimi G.H. and Vafai A.H (2004) [3] considered an elastoplastic material and used Abaqus Software to analyse the plastic behaviour of cylindrical shells with cut outs under pure bending. The shell had a circular cross section and both ends had been clamped. The shape of the cut outs in the shells was circular or rectangular. Vartdal (2005) [4] studied simply supported steel tubes with rectangular cutouts of different sizes positioned at their mid-length subjected to axial compression to assess effect of cutouts on the deformation behavior. Han et al. (2006)[5] studied effect of dimension and position of square-shaped cutouts in thin and moderately thick-walled cylindrical shells of various lengths by nonlinear analyses. Schenk and Schueller (2007) [6] have investigated the effect of random geometric imperfections on the critical load of isotropic, thin-walled, cylindrical shells under axial compression with rectangular cut outs. Prabu (2010) [7] studied the effect of variation of size and angle of inclination of dents on buckling strength of the short carbon steel cylindrical shell by FE modelling of cylindrical shell with single dent having different size and angles of inclination. He concluded that the buckling strength of dented cylindrical shell decreases with increase in both diameter and depth of the dent. Mahmoud Shariati and Mahdizadeh Rokhi (2010) [8] Numerical simulation and analysis of steel cylindrical shells with various diameter and length having an elliptical cut out, subjected to axial compression were systematically carried out in this paper. Formulas were presented for the computation of the buckling load of cylindrical shells with elliptical cut outs based on the buckling load of perfect cylindrical shells. Piotr Stasiewicz (2013) [9] investigated buckling of a damaged thin walled cylindrical shell under pure bending. Imperfection of the considered shell had a shape of a circular cut out placed on the upper generatrix of the cylinder. He found from his experiments that the geometrical imperfections had a particularly strong influence on the critical stress value for shells with small cut out. Shanshan Shia, Zhi Suna,b, Mingfa Rena, Haoran Chena, Xiaozhi Hub (2013) [10] presented the initial buckling and post-buckling responses of axial loaded composite cylindrical shells with reinforced rectangular or circular cut outs. The cylindrical shells were reinforced by various local grid configurations near the cut out areas. For unreinforced structures, the results illustrated that shell with a circular cut out possessed a higher global collapse load than that of shell with a rectangular cut out due to the obvious difference in the cut out geometry and thus associated stress concentration. This study aims to investigate the effect of circular cut outs on buckling behaviour of laminated composite cylindrical shells under uniform axial compression. In this study, the effects of different arrangements of the circular cut outs on buckling behaviour of the laminated composite cylindrical shells are investigated.

2. NONLINEAR FINITE ELEMENT ANALYSIS

In this study, the laminated composite cylindrical shells with cutout have been modeled and analyzed using ANSYS 15 software to study the effect of cutout on the loading capacity and buckling behavior of cylindrical shells. The analyses have been conducted by subjecting the structure to the pure axial load. All of the shells were fixed at the bottom and completely free at the top. Herein, the nonlinear static analysis has been used. The composite cylindrical shell with height of 500 mm and radius of 250 mm is considered. The composite shells are considered to be made of Graphite Epoxy with mechanical properties listed in Table 1.

Table -1: Mechanical Properties for Graphite Epoxy

E_{11} (GPa)	E_{22} (GPa)	G_{12}(GPa)	υ_{12}
127.54	11.306	5.998	0.3

The cylindrical shell is assumed to be eight-layered plies each having a thickness of 0.127 mm with different stacking sequences. The 8 node shell 281 elements have been used in modeling. These elements have the capability of considering large displacement and nonlinear behavior of the structural material and therefore are appropriate for solving the problems related to buckling. The elements have six degrees of freedom in each node. Model of laminated composite cylindrical shells with and without cutout is as shown in fig.1. Linear buckling analysis can estimate the maximum load that can be supported prior to structural instability or collapse. However, imperfections and nonlinearities tend to prevent most real structures from achieving their theoretical elastic buckling strength, so the eigenvalue buckling load factors are therefore somewhat overestimated. To get a more accurate answer nonlinear analysis can be undertaken. Non Linear buckling analysis is a static analysis through which we can incorporate the non linearities due to loading, supports and end conditions. Here only the geometric non linearity is considered for the study. Its mode of operation is very simple: it gradually increases the applied load until a load level is found whereby the structure becomes unstable. For this type of analysis, small off-axis loads are necessary to initiate the desired buckling mode.

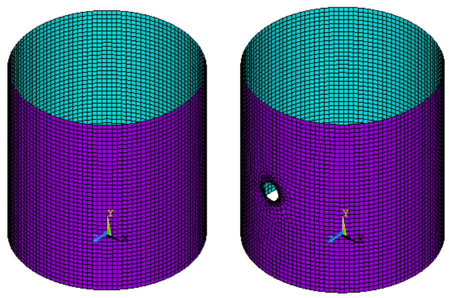

Fig -1: Model of laminated composite cylindrical shell without and with cutout

2.1 Validation

The reliability of the results is checked by comparing them with those available in the literatures. The buckling load of cylindrical shell with square cutout is studied and the results are compared with experimental results reported by Mark W. Hilburger [1]. The composite shell 406 mm in height, 203 mm in radius and eight-layered plies each having a thickness of 0.127 mm is considered. Stacking sequence considered is [±45/0/90]s. Good agreement observed between the results shows the accuracy and precision of FE modeling for laminated composite shell with square cutout.

Table -2: Normalized buckling load of shell with cutout

S. No.	Cutout size	Buckling load	
		Experimental result	Present result
1	25.4 x 25.4	0.49	0.46

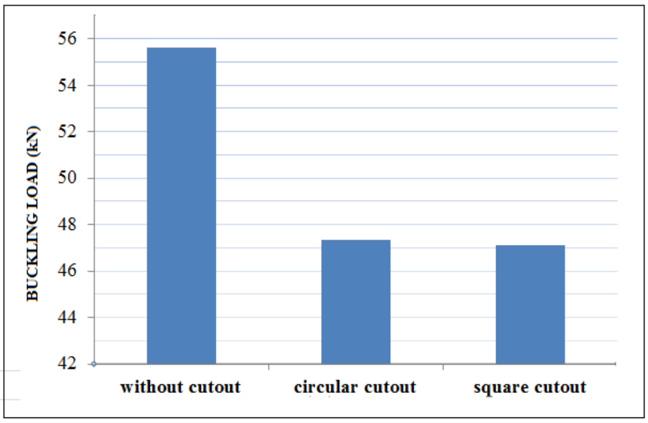

Chart -1: Effect of cutout on buckling load

3. NUMERICAL RESULTS

3.1 Effect of cutout on shell buckling

Cutouts can play an important role in the formation of stress concentration and affect destructively the stability of cylindrical shells. In this study, the effect of circular and square cutouts has been studied on the buckling of cylindrical shells. For this purpose, a circular cutout of diameter 40 mm and a square cutout of size 35.44 x 35.44 mm, both having an area of 1256 mm^2 have been formed and modeled at the midlength of the shell with a stacking arrangement of [+45/45/0/90]s laminate. Then, the models have been subjected to the uniform pure axial loading. The results of this analysis are presented in fig. 2. It can be seen that the buckling load of the shell decreased considerably when a cutout was created in the shell. Buckling load of composite cylindrical shell with circular cutout is slightly higher than the buckling load of shell with a square cutout having same area as that of the circular cutout. So, further studies are conducted for composite cylindrical shells with circular cutouts.

3.2 Effect of ply orientation on shell buckling

Here, a circular cutout with a diameter of 40 mm has been formed and modeled at the shell's mid-length. In order to investigate the effect of ply orientation on the cylindrical shells buckling, three different stacking sequences were considered for the 8-ply shell-wall laminates. These laminates include an axially stiff [+45/-45/02]s laminate, a quasi-isotropic [+45/-45/0/90]s laminate, and a circumferentially stiff [+45/-45/902]s laminate (a 0^o lamina ply and a 90^o lamina ply correspond to plies with fibers aligned along the length of the cylinder and around its circumference, respectively).

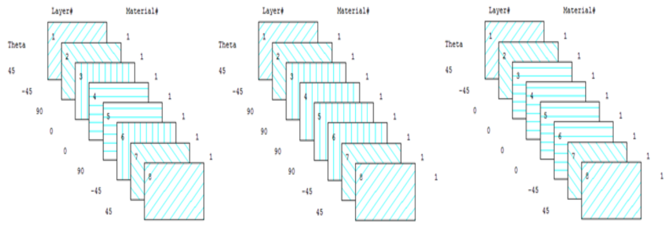

Fig -2: Different ply orientations

Different ply orientations are shown in fig.2. The buckling load of the composite shell is higher for a quasi-isotropic [+45/-45/0/90]s laminate compared to other stacking sequences. Cylindrical shells with a circumferentially stiff $[+45/-45/90_2]_s$ laminate stacking arrangement have the least buckling strength. So, further studies are conducted for composite cylindrical shells with stacking arrangement of [+45/-45/0/90]s laminate. Table 3 shows the effect of ply orientation on buckling of shell.

Table -3: Buckling analysis result showing effect of ply orientation

Analysis results	Buckling load (kN)
$[+45/-45/0_2]_S$	33.03
$[+45/-45/0/90]_S$	47.36
$[+45/-45/90_2]_S$	27.25

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3.3 Effect of cutout diameter on shell buckling

Circular cutout with the diameters of d = 30, 40, 50 and 60 mm has been formed and modeled at the mid-length of the shell to investigate the effect of diameter change on the cylindrical shells buckling. The stacking arrangement adopted is $[+45/-45/0/90]_s$ laminate. The influence of radius on buckling load is investigated, keeping length to thickness ratio (L/t) constant equal to 400. The results show that by increasing the cutout size, the buckling load of the composite shell decreases continuously. It is evident from chart 2 that an increase in the cutout diameter when the cutout height is constant causes a considerable reduction in the buckling load of composite cylindrical shells.

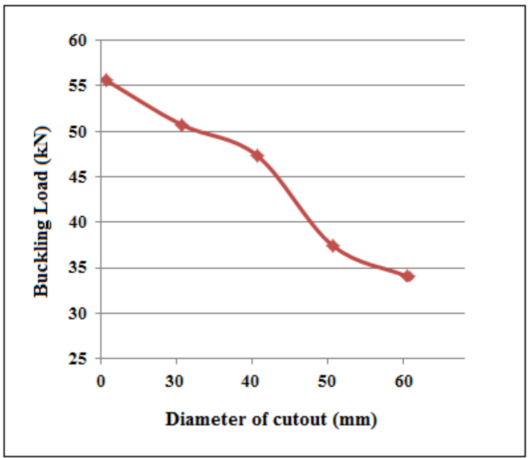

Chart -2: Variation of buckling load with increase in cutout diameter

3.4 Effect of cutout location on shell buckling

A circular cutout of 40 mm diameter has been modeled at a distance of h = L/2, L/4 and L/8 (where L is the length of the cylinder) from the shell bottom to study the effect of change in the circular cutout height from the shell bottom on the cylindrical shell buckling. The stacking arrangement adopted is $[+45/-45/0/90]_s$ laminate.

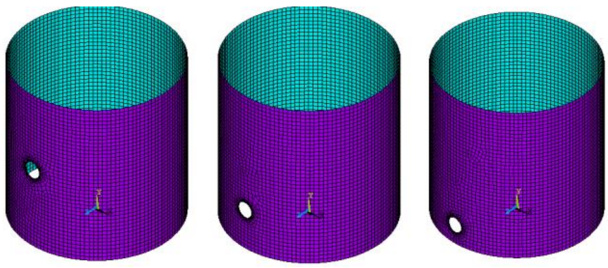

Fig -3: Model of cylindrical shells with cutouts at different locations

From table 4, it is evident that, with changing position of the cutout from shell bottom towards the mid height of the shell, the buckling load gets reduced.

Table -4: Buckling analysis result showing effect of cutout location

Analysis results	L/2	L/4	L/8
Buckling load (kN)	47.24	47.43	55.35

4. CONCLUSIONS

In this study, the laminated composite cylindrical shells with circular cutouts have been subjected to axial compression and the results obtained through nonlinear numerical analysis are summarized as follows:

- The buckling load of the composite cylindrical shell is decreased considerably when a cutout is created in the shell. Buckling load of composite cylindrical shell with circular cutout is slightly higher than the buckling load of shell with a square cutout having same area as that of the circular cutout.
- The buckling load of the composite shell is higher for a quasi-isotropic $[+45/-45/0/90]_s$ laminate arrangement compared to other stacking sequences.
- An increase in the cutout diameter when the cutout height is constant causes a considerable reduction in the buckling load of composite cylindrical shells.
- By changing the position of the cutout from shell bottom towards the mid height of the shell, the buckling load gets reduced.

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