Lecture Notes in Mechanical Engineering

D. K. Maiti · P. Jana · C. S. Mistry ·
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Free Vibration Study of Laminated Composite Shell with Varying Cut-Outs

Soumen Roy, Sandipan Nath Thakur, C. Ajeesh, and Chaitali Ray

1 Introduction

The fiber-reinforced layered composite shell structures are very common in recent engineering applications, e.g., spacecraft, aircraft, submarine, wind turbine blade, defence industry, etc., due to their specific stiffness, lightweight, and other advantageous properties. Shell structures have advantages over plates due to their curvature effect in carrying loads and moments. Cut-outs are the integral parts of most laminated shell structures, although the provisions of cut-outs are unavoidable in most of the engineering structures. The presence of a cut-out makes a structure weak due to the occurrence of stress concentration near the opening. These cut-out structures often initiate failure at comparatively lower stress and sometimes due to resonance. Therefore, the effect of cut-out on the dynamic behavior of laminated shells is to be dealt with carefully.

An HSDT was developed by Reddy and Liu [1] for the bending and vibration analysis of laminated shells with simply supported boundary conditions. Chakraborty et al. [2] presented the vibration behavior of laminated shells with cut-outs using the 8-node isoparametric finite element formulations. Hota and Chakravorty [3] analyzed free vibration characteristics of a conoidal stiffened shell structure with cut-outs using eight-noded curved shell elements. Nanda and Bandyopadhyay [4] presented the nonlinear analysis of undamped vibration of laminated shells with cut-outs using finite element model considering an 8-noded isoparametric element. The solution of semi-analytical analysis for free vibration behavior of laminated shells with cut-out for different geometric configurations was presented by Poore et al.

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[5]. Malekzadeh et al. [6] performed free vibration of homogenous and functionally graded (FG) cylindrical shell panels with cut-out with thermal effect using the 3-D Chebyshev–Ritz method. Hu et al. [7] studied the vibration characteristics of laminated composite shell panels with circular cut-outs at the center and subjected them to axial compressive force using ABAQUS software. Biswas and Ray [8] investigated the free vibration behavior of glass fiber reinforced laminates and hybrid laminates experimentally and numerically. Mandal et al. [9] carried out fundamental natural frequencies of laminated skew plates with cut-outs and without cut-outs. Using third-order shear deformation theory, Chaubey and Kumar [10] studied free vibration behavior of spherical, cylindrical, saddle, elliptical and hyper shells with cut-outs. Mandal et al. [11] also investigated the dynamic behavior of laminated shells with and without cut-outs numerically and experimentally.

In the present work, vibration analysis of six-layered glass fiber laminated composite shell (GFRP) with cut-out has been presented using ANSYS software. The effectiveness of the present model has been verified by validating the solutions with experimental results obtained from Mandal et al. [11] and theoretical results obtained from Chakravorty et al. [2]. Also, a convergence study is carried out to decide the actual mesh size for obtaining a consistent value of natural frequency by comparing with the result taken from Reddy and Liu [1]. Several new results have been obtained using HSDT to check the effect of curvature, thickness ratio, lamination scheme, and boundary condition on the natural frequency with varying cut-out percentages of the shell.

2 Finite Element Formulation

A laminated composite cylindrical shell with cut-outs has been modeled and analyzed using ANSYS software. Triangular element SHELL281 with 6 DOFs per node (u, v, w, θ_x, θ_y, θ_z) is used for the present formulation. Modeling is done by specifying the thickness, material, orientation with a number of integration points through the thickness of the laminates.

Element stiffness matrix $[\mathbf{K_e}]$ and the element mass matrix $[\mathbf{M_e}]$ for an element is expressed as

$$[\mathbf{K_e}] = \iint [\mathbf{B}]^T[\mathbf{D}][\mathbf{B}]\mathrm{d}s\mathrm{d}r = \int_{-1}^{1}\int_{-1}^{1}[\mathbf{B}]^T[\mathbf{D}][\mathbf{B}]|\mathbf{J}|\mathrm{d}\xi\mathrm{d}\eta$$

$$[\mathbf{M_e}] = \iint [\mathbf{N}]^T[\rho][\mathbf{N}]\mathrm{d}s\mathrm{d}r = \int_{-1}^{1}\int_{-1}^{1}[\mathbf{N}]^T\left[\bar{\mathbf{I}}\right][\mathbf{N}]|\mathbf{J}|\mathrm{d}\xi\mathrm{d}\eta$$

where $[\rho]$ is the inertia matrix and $|\mathbf{J}|$ is the determinate of the Jacobian matrix.

Applying the equation of motion for undamped structure, the natural frequencies can be calculated, which is,

$$\omega^2[\mathbf{M}]\{\phi\} = [\mathbf{K}]\{\phi\}$$

where $\{\phi\}$ represent the mode shapes and ω is the natural frequency and the non-dimensional form of the frequency can be expressed as

$$\overline{\omega} = \left(\frac{\omega a^2}{h}\right)\sqrt{\frac{\rho}{E_2}}$$

The free vibration equation is analyzed and modeled using ANSYS 16.0 software package.

3 Results and Discussions

A convergence study is performed to decide the actual mesh size ($\overline{n} \times \overline{n}$) for obtaining a consistent value of the natural frequency of laminated composite shell using ANSYS 16.0 software. A simply supported anti-symmetric cross-ply (0°/90°) laminated composite shell is chosen for this study. The radius to lateral dimension ratio (R/a) is considered as 5 and thickness to lateral dimension ratio (h/a) is taken as 0.1. The results in terms of the non-dimensional fundamental frequency are presented in Table 1 and it may be observed from Table 1 that the numerical value of non-dimensional fundamental frequency converges approximately at $\overline{n} = 16$. Thus, a mesh division of 16 × 16 is considered for the subsequent comparison studies and parametric studies of laminated composite shells.

Example 1. Free vibration study of laminated shells with cut-outs is carried out in the present study. Six layers of bidirectional symmetric cross-ply glass fabrics of average thickness 0.5 mm each layer is used for the laminates. The composite laminated cylindrical shells of projected plan area 250 × 250 mm and radius of curvature 145 mm have been analyzed. Two straight edges of the shell model are simply supported (only θ_y is free) and the other two curved edges are kept free. The fundamental natural frequencies with varying cut-out sizes are determined using the SHELL281 element available in ANSYS. The numerical results of modal analysis obtained from the ANSYS software package have been compared with the experimental results in Table 2 and the comparison shows good agreement with each other.

Table 1 Convergence study of non-dimensional frequency parameter ($\overline{\omega}$) of simply supported cross ply (0°/90°) cylindrical shells (R/a = 5, h/a = 0.1)

Mesh size	Present formulation	Reddy and Liu [1]
12 × 12	8.88	8.9
14 × 14	8.88	8.9
16 × 16	8.89	8.9
18 × 18	8.89	8.9
20 × 20	8.89	8.9

Table 2 Fundamental natural frequencies of a glass fiber laminated shell having straight edges simply supported (only θ_y is free) and curved edges free with varying cut-out sizes

Cut-out (%) (X-direction)	Cut-out (%) (Y-direction)	Fundamental natural frequency		Deviation percentage (ANSYS-experiment)/experiment
		Experimental frequency [11] (Hz)	Frequency using ANSYS (Hz)	
0.2a	0.2b	271.58	280.98	3.46
0.4a	0.4b	255.34	267.14	4.62
0.2a	0.4b	272.29	279.54	2.66

Table 3 Non-dimensional fundamental frequency $\omega a^2/h\sqrt{(\rho/E_2)}$ for a cross-ply (0°/90°)$_4$ laminated cylindrical shell (h/R$_x$ = 1/300, R$_x$ = R, a = b, a/h = 100)

Cut-out (%) (Y-direction)	Cut-out (%) (Y-direction)	Fundamental natural frequency		Deviation percentage (ANSYS-theory)/theory (%)
		Frequency using ANSYS (Hz)	Chakravorty et al. [2]	
0.1a	0.1b	27.138	27.042	0.355
0.3a	0.3b	28.161	27.913	0.888
0.5a	0.5b	29.858	29.472	1.309

Example 2. A laminated cylindrical shell having a thickness ratio, a/h = 100, with a cut-out at the center with simply supported boundary condition has been investigated here. The material properties are taken as $E_1 = 25E_2$, $G_{12} = G_{13} = 0.5E_2$, $G_{23} = 0.2E_2$, $\gamma_{12} = 0.25$ (Chakravorty et al. [2]). The vibration results in terms of fundamental frequencies calculated using the present model are shown in Table 3. The results show good agreement with those results published by Chakravorty et al. [2]. Furthermore, we can observe that the fundamental frequency increases with the increase of cut-out size due to the reduction of mass.

4 Parametric Study

Several parametric studies have been presented in this section to check the effect of curvature, thickness ratio, lamination scheme, and boundary condition on non-dimensional frequency with varying cut-out percentage of the shell. The material properties used for the entire parametric study presented in Tables 4, 5, 6 and 7 are as follows: $E_1 = 25E_2$, $G_{12} = G_{13} = 0.5E_2$, $G_{23} = 0.2E_2$, $\gamma_{12} = 0.25$ and the cut-out percentage varies from 0 to 0.6. The effects of curvature, thickness ratio, and boundary condition have been studied for the symmetric lamination scheme

Table 4 Effect of curvature on the non-dimensional frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1 and a/h = 100) shells with varying cut-out percentages

R/a	Cut-out ratio	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
0.5	0	10.044	21.312	22.067	36.36	40.812
	0.2	10.018	21.5	22.09	36.088	39.657
	0.4	9.9147	21.963	23.191	31.034	38.633
	0.6	10.222	16.542	20.213	21.949	38.223
1	0	30.27	53.564	54.794	56.517	84.129
	0.2	29.546	49.237	55.767	56.522	82.501
	0.4	28.024	35.168	48.349	56.613	61.356
	0.6	32.567	33.35	48.564	53.629	55.385
1.5	0	32.7	45.342	56.927	58.764	72.227
	0.2	31.706	43.152	57.94	58.666	70.707
	0.4	29.953	35.792	47.628	57.649	58.966
	0.6	34.954	35.918	52.322	55.936	57.399
2	0	33.42	41.83	55.293	57.075	62.605
	0.2	32.469	40.395	56.526	57.167	60.851
	0.4	30.963	36.059	47.178	52.483	57.559
	0.6	35.63	36.7	53.352	56.273	56.51

$(0°/90°)_{2\,s}$. Figure 1 shows a schematic view of the shell with a cut-out at the center and coordinate system (Fig. 2, 3, 4 and 5). Figures 6, 7, 8, 9 and 10 show the mode shapes with square and rectangular cut-outs.

4.1 Curvature Effect

The curvature effect on the fundamental frequencies of cylindrical laminated shells is studied with simply supported boundary conditions (straight edges simply supported and curved edges are free) with (a/b = 1, a/h = 100) and presented in Table 4 as well as Fig. 2. The value of R/a is varied from 0.5 to 2. For cylindrical laminated shells with R/a = 1, 1.5, and 2, the value of non-dimensional frequency initially starts decreasing with an increase in the cut-out percentage and gets reversed after reaching the cut-out percent of 0.4. The cylindrical shells with R/a = 0.5 have no significant change in the non-dimensional frequency as the cut-out percent increases. It can be observed that for the same cut-out percentage, the non-dimensional frequency value increases with an increase value of R/a. The increase is generally due to the reduction of curvature of the shell which will result in the increase of vibration of the shell.

Table 5 Effect of a/h on the non-dimensional natural frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1, and R/a = 0.5) shells with varying cut-out percentage

a/h ratio	Cut-out ratio	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
a/h = 5	0	74.184	106.2	133.44	134.32	182.73
	0.2	74.032	109	131.9	136.38	183.63
	0.4	75.363	112.74	113.53	138.51	180.47
	0.6	82.974	93.407	115.19	125.21	140.22
a/h = 10	0	61.777	96.704	115.26	121.33	169.66
	0.2	61.461	98.597	116.07	119.63	171.59
	0.4	61.393	99.16	102.28	119.7	165.11
	0.6	66.221	78.021	103.93	105.24	126.46
a/h = 25	0	35.39	66.971	73.028	93.501	128.09
	0.2	35.136	67.608	72.973	92.016	123.33
	0.4	34.395	69.268	70.701	75.876	119.32
	0.6	36.015	47.346	64.017	69.621	91.272
a/h = 50	0	19.4	39.86	41.938	64.284	76.41
	0.2	19.301	40.17	41.876	63.533	73.804
	0.4	18.933	41.049	43.774	49.366	71.679
	0.6	19.581	28.501	37.183	40.919	63.532
a/h = 100	0	10.044	21.312	22.067	36.36	40.812
	0.2	10.018	21.5	22.09	36.088	39.657
	0.4	9.9147	21.963	23.191	31.034	38.633
	0.6	10.222	16.542	20.213	21.949	38.223

4.2 *Effect of Thickness Ratio*

The effect of the a/h ratio on natural frequency is observed for the cylindrical shell (a/b = 1, R/a = 0.5) and shown in Table 5 as well as in Fig. 3. The support condition used for the study is straight edges simply supported and curved edges are free. The results are obtained with different a/h ratios and different cut-out percentages. The a/h ratio varies from 5 to 100, and it can be observed that the value of the non-dimensional frequency increases with a decrease in a/h value. This is because of the phenomenon that as a/h ratio increases the thickness of the panel decreases and the frequency value decreases for a thin structural element. It is observed from Fig. 2, that with the increase of cut-out percent above 0.4 the non-dimensional fundamental natural frequency is subjected to a significant increase for a/h ratio 5 and 10 of the cylindrical shells when compared with the a/h ratios (25, 50, and 100).

Table 6 The effect of lamination schemes on the non-dimensional natural frequency on cylindrical shells (a/b = 1, a/h = 100 and R/a = 0.5) with varying cut-out percentages

Lamination schemes	Cut-out ratio	Orientations	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Symmetric	0.2	0°/90°/90°/0°	8.8157	19.582	19.837	33.312	35.61
		30°/−30°/−30°/30°	7.3722	16.54	17.733	29.209	30.166
		45°/−45°/−45°/45°	8.01	16.973	18.244	28.93	31.729
	0.4	0°/90°/90°/0°	8.8808	20.204	20.931	29.572	34.975
		30°/−30°/−30°/30°	7.4081	17.153	18.062	26.433	29.35
		45°/−45°/−45°/45°	7.8077	17.311	18.398	25.197	30.115
	0.6	0°/90°/90°/0°	9.1409	15.788	18.477	20.121	35.861
		30°/−30°/−30°/30°	7.4861	14.946	15.985	17.965	29.57
		45°/−45°/−45°/45°	7.7429	14.208	15.782	17.752	28.738
Anti-symmetric	0.2	0°/90°/0°/90°	9.8106	20.711	21.447	34.418	38.361
		30°/−30°/30°/−30°	8.3396	18.855	20.03	33.253	33.733
		45°/−45°/45°/−45°	9.0472	19.632	19.784	32.485	35.13
	0.4	0°/90°/0°/90°	9.6242	21.082	22.417	29.1	37.375
		30°/−30°/30°/−30°	8.3446	19.493	20.418	29.81	33.04
		45°/−45°/45°/−45°	8.7424	19.792	20.203	28.01	33.823
	0.6	0°/90°/0°/90°	9.9546	15.624	19.533	21.156	36.271
		30°/−30°/30°/−30°	8.4417	16.78	18.015	20.308	33.432
		45°/−45°/45°/−45°	8.771	15.64	17.682	19.471	32.596

4.3 Effect of Lamination Scheme

The lamination scheme effects on the non-dimensional frequency are observed for cylindrical shells (a/b = 1, a/h = 100, R/a = 0.5) with support condition straight edges simply supported and curved edges are free used for the study are shown in Table 6 as well as Fig. 4**.** The lamination schemes used are symmetric [(0°/90°/90°/0°), (30°/−30°/−30°/30°) and (45°/−45°/−45°/45°)] and anti-symmetric [(0°/90°/0°/90°), (30°/−30°/30°/−30°) and (45°/−45°/45°/−45°)], respectively. It can be seen that the anti-symmetric laminates are having higher frequencies when compared with symmetric laminates. It also shows that the (0°/90°/0°/90°) laminate have higher non-dimensional frequencies when compared with the other schemes. For cylindrical angle-ply [(45°/−45°/−45°/−45°), (45°/−45°/45°/−45°)] shells, the non-dimensional natural frequency decreases with increase in cut-out size, whereas it is reverse trends for cross-ply [(0°/90°/90°/0°), (0°/90°/90°/0°)] schemes of cylindrical shells. The increase is less significant for the angle-ply ply [(30°/−30°/−30°/30°), (30°/−30°/30°/−30°)] symmetric and anti-symmetric laminated shells.

Table 7 Effect of support conditions on the non-dimensional frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1, a/h = 100, and R/a = 2) shells with varying cut-out percentages

Boundary condition	Cut-out ratio	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
CCCC	0	49.038	63.601	76.24	79.695	97.278
	0.2	46.568	66.249	68.497	77.701	79.789
	0.4	41.031	48.867	61.935	76.923	78.055
	0.6	54.466	56.268	76.041	79.356	89.854
SSSS	0	48.093	63.235	73.782	78.827	97.004
	0.2	45.741	65.639	66.514	77.007	79.658
	0.4	40.559	48.82	59.725	75.93	77.153
	0.6	54.236	56.035	72.683	77.888	83.438
CFCF	0	33.438	41.843	55.309	57.089	62.612
	0.2	32.485	40.409	56.543	57.181	60.856
	0.4	30.98	36.076	47.191	52.492	57.574
	0.6	35.649	36.72	53.391	56.315	56.527
SFSF	0	33.42	41.83	55.293	57.075	62.605
	0.2	32.469	40.395	56.526	57.167	60.851
	0.4	30.963	36.059	47.178	52.483	57.559
	0.6	35.63	36.7	53.352	56.273	56.51

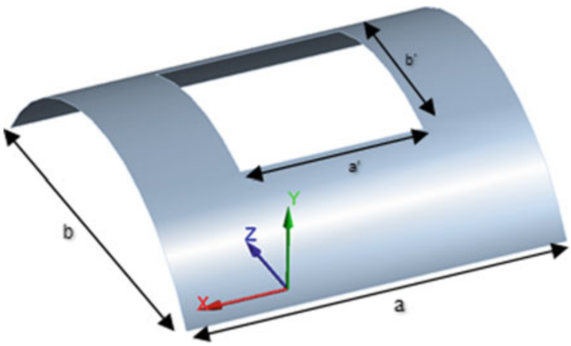


Fig. 1 Schematic view of the shell along with the cutout and coordinate system

4.4 Effect of Support Conditions

The effect of support conditions on the non-dimensional frequencies of cylindrical shells are studied for cross-ply lamination with (a/b = 1, a/h = 100, and R/a = 2) and with varying boundary conditions and different cut-out sizes are shown in Table 7 as well as Fig. 5. The support conditions used for the study are CCCC, SSSS, CFCF, and SFSF, respectively. The non-dimensional frequency of the CCCC composite laminated composite shell is highest for its highest stiffness, and SFSF

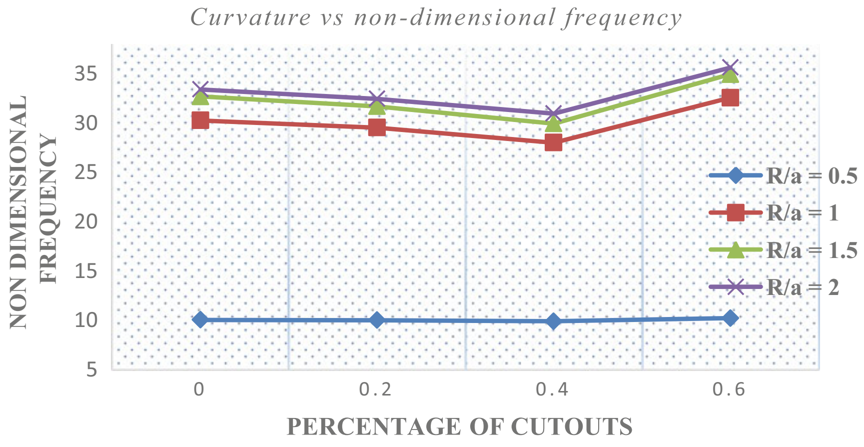


Fig. 2 Curvature effect on the non-dimensional frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1 and a/h = 100) shells with varying cut-out percentages

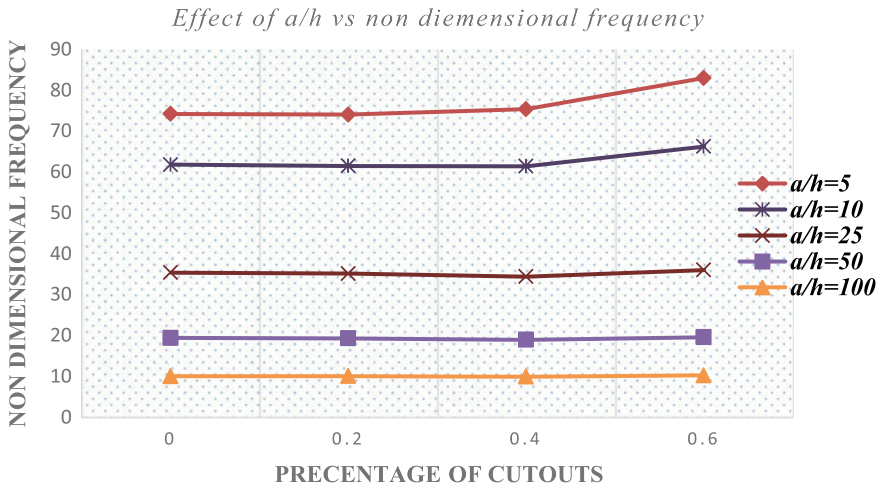


Fig. 3 Effect of a/h on the non-dimensional frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1, and R/a = 0.5) shells with varying cut-out percentage

is the lowest. The CFCF and SFSF boundary conditions have almost the same non-dimensional frequency with varying cut-out percentages. It can be noticed that the fundamental natural frequency starts decreasing for all the boundary conditions until the percentage of cut-out reaches 0.4 and then starts increasing. This is due to the effect of mass and stiffness reduction due to cut-outs. For the cut-out percentage of 0.6, the value of natural frequency is highest.

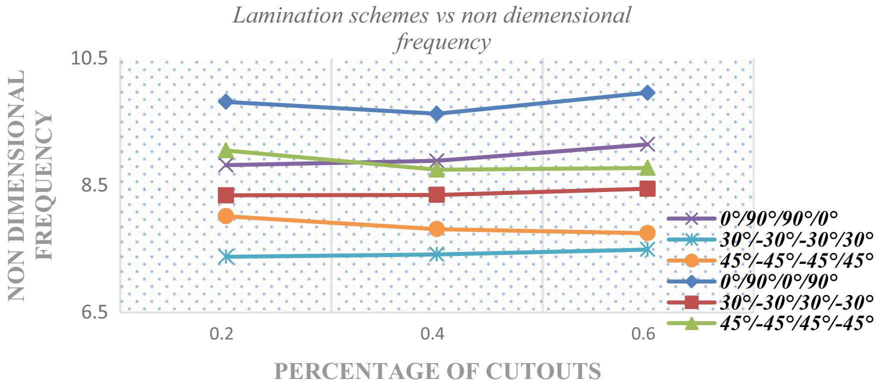


Fig. 4 The effect of lamination schemes on the non-dimensional natural frequency on cylindrical shells (a/b = 1, a/h = 100, and R/a = 0.5) with varying cut-out percentages

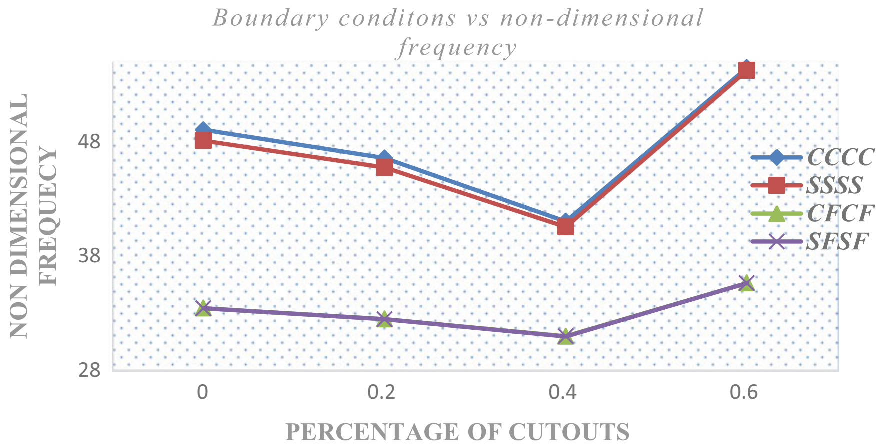
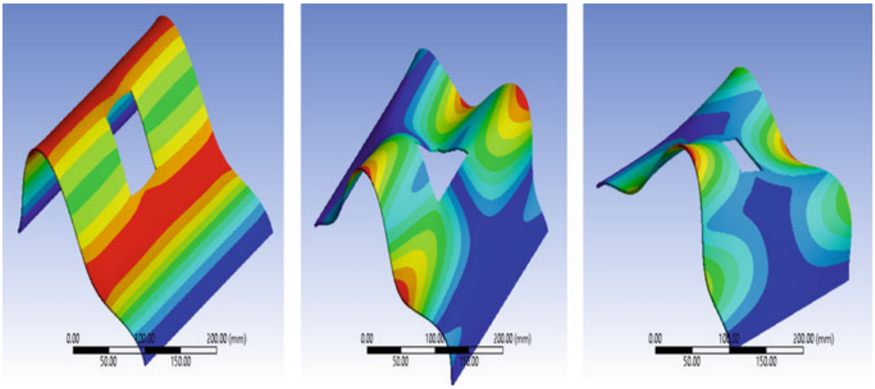


Fig. 5 Effect of support conditions on the non-dimensional frequency of cross-ply symmetric lamination schemes $(0°/90°)_{2\,s}$ and (a/b = 1, a/h = 100, and R/a = 2) shells with varying cut-out percentage

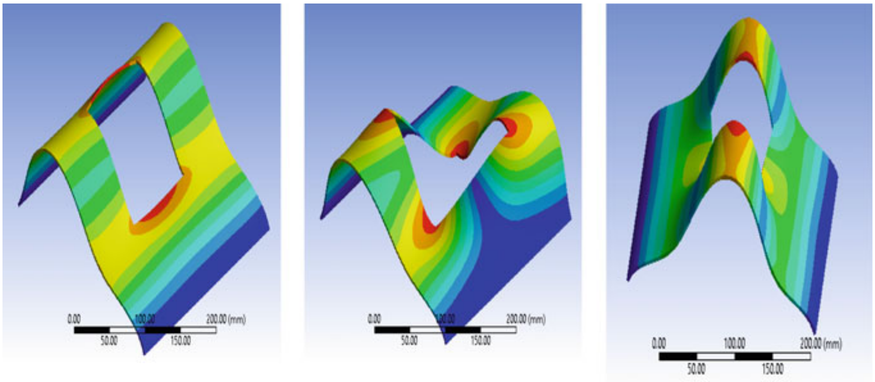
4.5 Mode Shapes

The first three mode shapes of the laminated shell with varying cutouts are obtained by using ANSYS software. Mode shapes with square cutouts (with 0.2, 0.4, and 0.6 cut-out ratios) are shown in Figs. 6, 7 and 8 and rectangular cut-outs are shown in Figs. 9 and 10. Through those figures of mode shapes, the vibration behavior of the laminated shell with cut-out can be more instinctively reflected.



(a) First mode (b) Second Mode (c) Third Mode

Fig. 6 Theoretical mode shape for bidirectional cylindrical shell having straight edges simply supported and curved edges free with 0.2 cut-out ratio

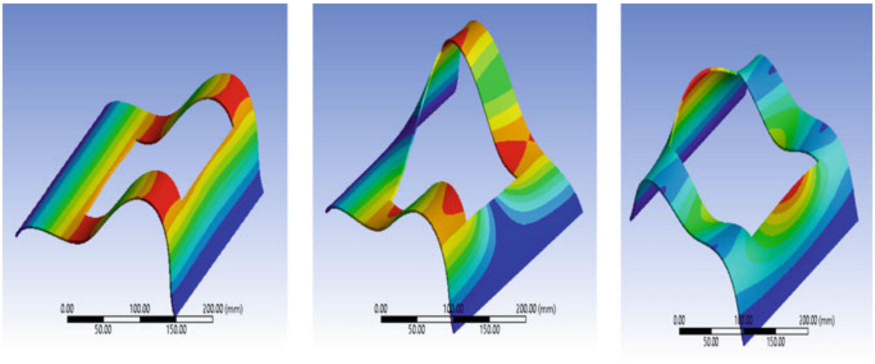


(a) First mode (b) Second Mode (c) Third Mode

Fig. 7 Theoretical mode shape for bidirectional cylindrical shell having straight edges simply supported and curved edges free with 0.4 cut-out ratio

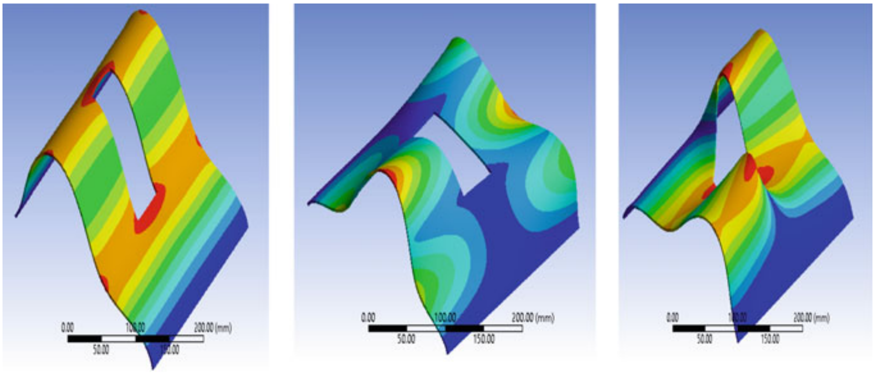
5 Conclusions

The free vibration analysis of laminated composite shells with varying cut-outs is investigated in the present study. The bi-directional cross-ply symmetric glass fiber shells are taken for analysis. The numerical study has been performed using the finite element based software package ANSYS 16.0 using a triangular element with six DOFs per node. The comparison of numerical results with the literature shows very good agreement. A parametric study that includes the effects of the thickness ratio, curvature ratio, lamination schemes, and various support conditions on the non-dimensional natural frequency of cylindrical laminated shells with varying cut-out



(a) First mode (b) Second Mode (c) Third Mode

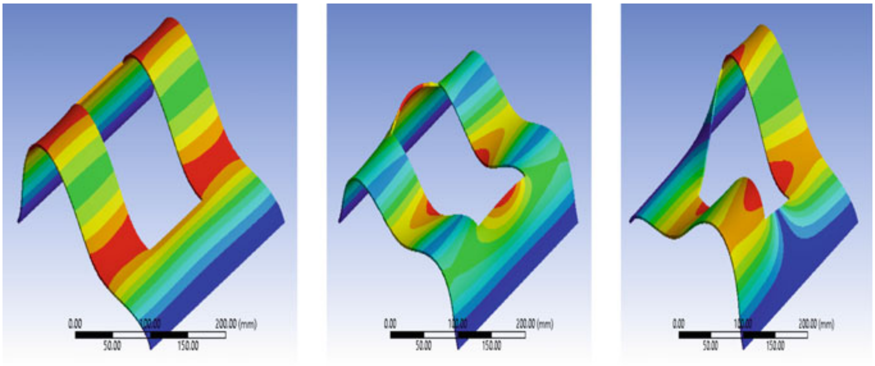
Fig. 8 Theoretical mode shape for bidirectional cylindrical shell having straight edges simply supported and curved edges free with 0.6 cut-out ratio



(a) First mode (b) Second Mode (c) Third Mode

Fig. 9 Theoretical mode shape for bidirectional cylindrical shell having straight edges simply supported and curved edges free with 0.2a × 0.4b cut-out ratio

percentages at the center is examined and can be treated as benchmark results for further research works.



(a) First mode (b) Second Mode (c) Third Mode

Fig. 10 Theoretical mode shape for bidirectional cylindrical shell having straight edges simply supported and curved edges free with 0.4a × 0.6b cut-out ratio

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Numerical Study on Concrete-Filled Steel Tubes with Diagonal Binding Ribs and Longitudinal Stiffeners

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1 Introduction

Concrete-filled steel tubular (CFST) columns have high strength, superior seismic performance, and reasonable construction cost [4]. These are widely used as one of the main structural elements for resisting both vertical and lateral loads in high-rise buildings and bridges [5]. It consists of an outer thin steel tube and inner infilled concrete. If thin steel tubes are adopted, welding and construction will be easy. Also, steel plates tend to be slenderer when adopting high-strength steel. But the materials cannot be fully used. And the ductility is poor when high-strength concrete is used due to local buckling and also the increase in the deformation of the steel tube by the concreting is not negligible. Stiffened CFST have continuous strong confinement from the ribs or stiffeners to both concrete and steel tubes. This can relax the width-to-thickness ratio limit [6] and thus can facilitate the use of thin-walled and high-strength steel and concrete. Openings can act as shear connectors and can avoid the disengagement at interfaces between the concrete and the steel tube. It helps while pouring concrete. The ribs with square openings had larger strength but worse ductility than those with circular openings. Square and rectangular CFST columns [7] have easy beam-to-column connections hence lead to less construction cost. It helps to make flexible building layouts hence facilitate decoration, the layout of architectural space, and fireproof plates. Only a few numerical studies are available related to diagonal rib stiffened CFST columns. So, this paper presents the numerical

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study on the effect of ribs and stiffeners on axial load carrying capacity of nineteen various CFST column models and the seismic performance of three unstiffened square CFST columns and two octagonal CFST columns by nonlinear static analysis using ANSYS Workbench 16.2.

2 Numerical Study of Stiffened and Unstiffened CFST Columns Under Axial Load

2.1 General

The model of diagonal binding rib stiffened CFST column was validated with reference to the paper, "Improved composite effect of square concrete-filled steel tubes with diagonal binding ribs," [3].

A square column with 300 mm side and 900 mm height having 2 mm thick outer steel tube and ribs that are placed diagonally across the cross section. There are 60 mm diameter holes in the ribs at 225 mm center to center spacing. A 40 mm size meshing was provided. A multilinear isotropic hardening model was used. The bottom surface of the column was restrained against all degrees of freedom. The top of the column was free and axial load was applied with displacement control along the Y-axis. Due to the symmetry of geometry and loading, only one fourth of the model was established for efficiency. The axial load taken by the column is plotted against the strain and the failure mode (see Fig. 1).

By comparing experimental results and finite element analysis results by means of ultimate load-carrying capacity of the composite column and by means of strain, percentage variation of 1.92 and 3.03% was found. Thus, the model was validated.

The CFST column models used for further analysis are: unstiffened square columns, stiffened square columns with diagonal binding ribs, stiffened square columns with longitudinal stiffeners [8], and unstiffened octagonal columns. Here, a total of nineteen models are used. Here, on the naming of the models, U stands for unstiffened, R stands for rib stiffened, L stands for longitudinally stiffened, S stands for square-shaped cross section, O stands for octagonal-shaped cross section, the first digit indicates the thickness of steel tube, the second digit indicates the thickness of rib or stiffener, H, H1, and H2 indicates hollow opening with particular diameter and spacing between holes, W and W1 indicate square opening with particular spacing between the openings.

The width of stiffener or rib equals 141.42 mm and its height equals 900 mm. 2, 3, and 6 mm thick steel tubes and stiffeners or diagonal ribs were used. Square or circular openings with different spacing were provided on ribs.

A non-linear static analysis on the stiffened and unstiffened CFST columns was done by using the same method used for validation. The concrete, steel tube, and stiffeners or ribs were modeled by SOLID 186. The contact between steel tube and concrete, steel tube and ribs, ribs and concrete were modeled by CONTA 174. The

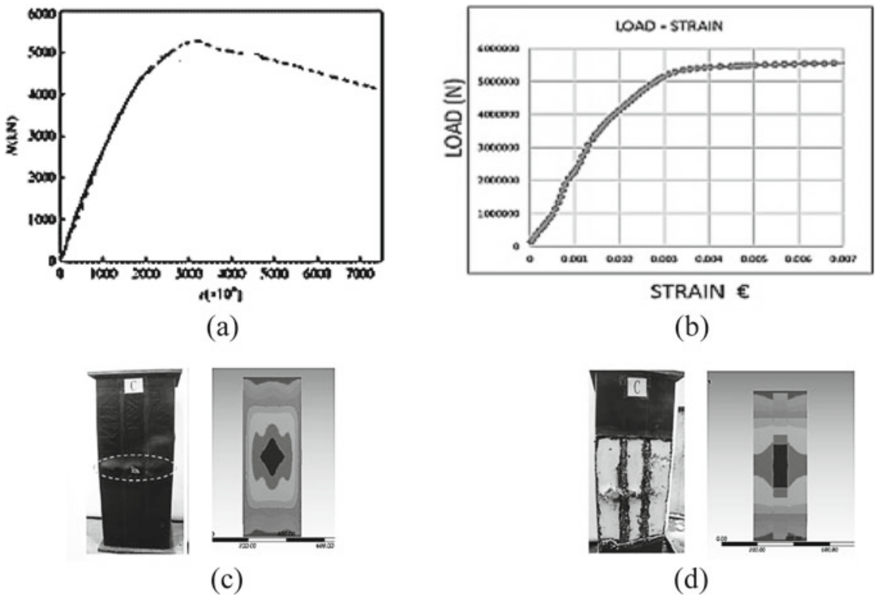

Fig. 1 **a** Load-strain graph from the experimental study [3], **b** load-strain graph from numerical analysis **c** failure mode on steel tube and **d** failure mode on concrete

connection between steel tube and ribs, between steel tube and concrete, between ribs and concrete was provided by using bonded, frictional and frictional, respectively with a frictional coefficient value of 0.2. A nonlinear isotropic hardening model was used. The material properties were as shown in Table 1. The ultimate axial load taken by the columns is plotted against the strain (see Fig. 2) and ultimate load values of different models are as shown in Table 2.

Table 1 Material properties

Type	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
2 mm steel	170	300	200	0.3
3 mm steel	350	490	195	0.3
6 mm steel	320	480	190	0.3
Concrete	60	–	39	0.15

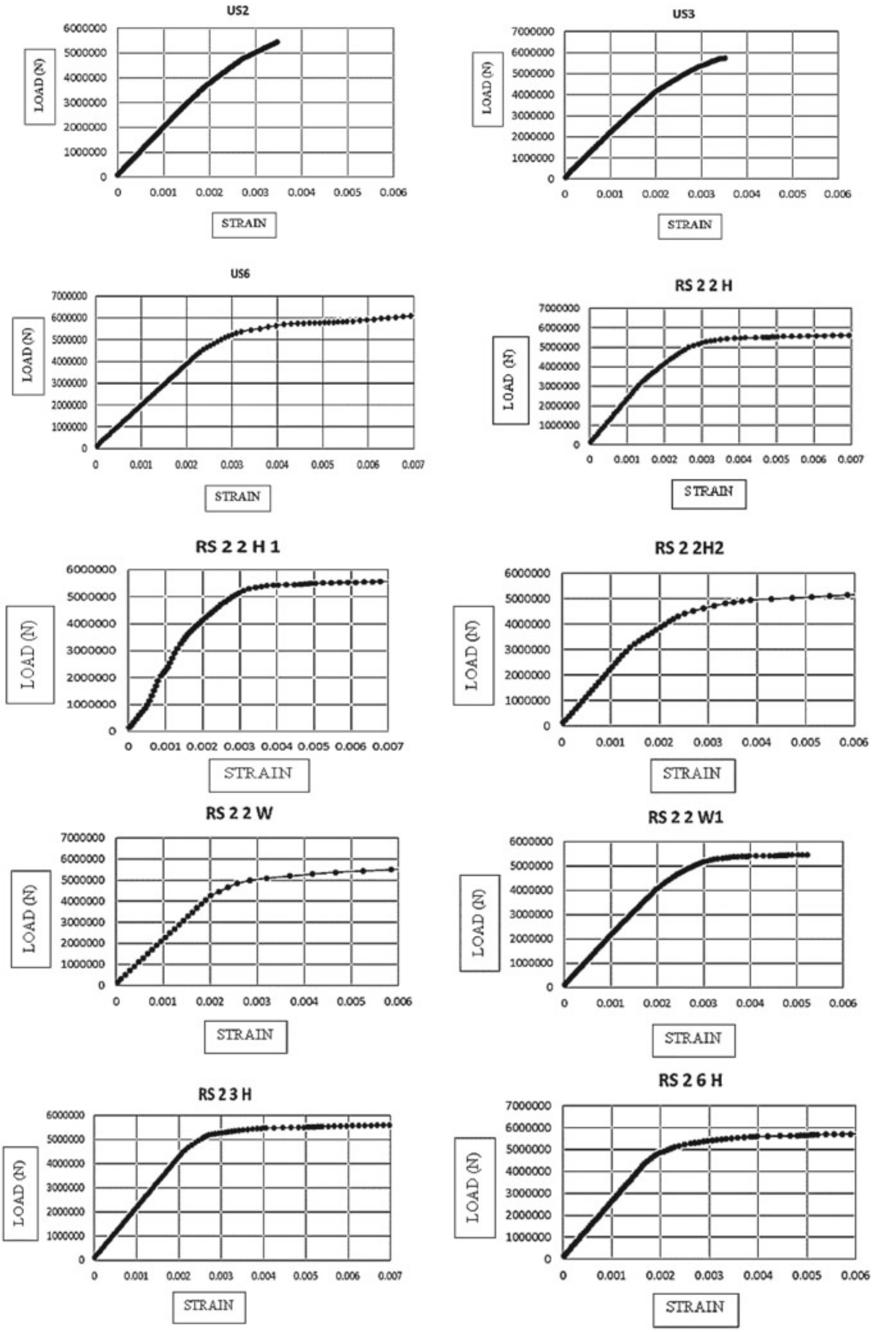

Fig. 2 Load-strain graph of CFST columns under axial load