Proceedings of the International Conference in Recent Advances in Mechanical Engineering
August 25-27, 2022, Indian Institute of Technology, Jodhpur, Rajasthan, India
ICRAM2022–PAPER NO. 4371

An Experimental and Numerical Approach to Free Vibration Analysis of Woven Fibre Laminated Composite Shells

***Jagesh Kumar Prusty**
Department of Mechanical Engineering, National Institute of Technology Rourkela, Odisha-769008, India
Email: jageshkumarprusty@gmail.com
Sukesh Chandra Mohanty
Department of Mechanical Engineering, National Institute of Technology Rourkela, Odisha-769008, India
Email: scmohanty@nitrkl.ac.in
*Corresponding Author

Abstract
The research work on free vibration of glass/epoxy and carbon/epoxy laminated composite shell confirming a cantilever boundary condition is presented in this study through experimental and numerical approaches. The experimental modal analysis is performed using an impact hammer technique to validate the simulated free vibration results. To this end, a shell model (S4R) is developed and simulated for free vibration frequencies using ABAQUS finite element simulation software. The recorded experimental and simulated results exhibit similitude within the test domain. The results conclude that the impact of geometrical parameters such as fibre orientation and the number of ply layers on natural frequencies is thoroughly investigated. The present results can be attributed to a comprehensive dynamic analysis of laminated composite shells and can be considered as an experimental benchmark result in the domain of free vibration in civil, mechanical and aerospace engineering applications.

***Keywords**: Natural frequency; Impact hammer method; Laminated composite shell; ABAQUS.*

1.0 Introduction

The composite laminates are lightweight and offer high specific strength, resistance to tear, and good tolerability. Such improved superior characteristics over traditional materials attract a wide utilization of laminated composites in aerospace, marine, automotive, and civil engineering applications. The structural performance significantly improved as the laminated composites facilitate the different tailor-made attributes. To this end, laminated composite shells (LCS) found a wide spectrum of industrial and engineering applications ranging from aircraft fuselage panels, turbine blades, vehicle body panels to deep submersible vehicles and many more. The widespread utilization of LCSs is realized under high amplitude vibrations that lead to the structure's progressive dynamic failure. This stimulated the interest of several researchers in accurately predicting the structural behaviour of LCS.

The significance of LCS can be realized in the compilation work performed by Qatu et al. [1] through 2009. Presenting the numerical solutions through finite element (FE) analysis, Chakravorty et al. [2] offered the free vibration study based on first-order shear deformation theory (FSDT) for the doubly curved LCS. Liu and To [3] developed hybrid strain-based layer-wise shell elements for the free vibration analysis of laminated composite plate and shell structures. Plagianakos and Saravanos [4] laid the FE predictions for the damping of doubly curved LCS. Cugnoni et a*l.* [5] discussed the modal analysis through the FE analysis in the thrust of vibration of multilayered thin and thick LCS structures based on higher-order shear deformation theories (HSDT).

Employing the FSDT, Toorani and Lakis [6] investigated the frequency variation of multilayered anisotropic, open and closed non-uniform cylindrical LCS under free vibration. Amabili and Reddy [7] explored large amplitude vibrations of doubly curved LCS using non-linear HSDT. Asadi and Qatu [8] used the general differential quadrature technique (DQT) to examine thick laminated cylindrical shells' free vibration analysis for various boundary conditions. A general HSDT was proposed by Viola et al. [9] for the free vibration analysis of completely doubly-curved LCS. Thomas and Roy [10] investigated the vibration analysis of functionally graded carbon nanotube-reinforced composite shell structures having a spectrum of geometrical shapes. Tornabene [11] utilized generalized DQT and generalized integral quadrature techniques to employ a layer-wise HSDT for the free vibrations of doubly-curved LCS. Biswal et al. [12] investigated the free vibration behaviour of woven fibre glass/epoxy laminated shallow composite shells under hygrothermal conditions, taking the effects of moisture absorption and temperature into account. Further, this study was extended to the laminated composite cylindrical shells [13]. The static, free vibration and transient behaviour of laminated composite curved panels were explored by Sahoo et al. [14] both numerically and experimentally. Thakur et al. [15] proposed an HSDT for deep and thick LCS by employing an eight-noded isoparametric shell element with seven degrees of freedom at each node.

The discussions made from the above works of literature broadly enumerate the attempts made for vibration of LCS through numerical solutions, but the experimental aspect is scarcely addressed. This is because of the LCS exhibits complex geometry and requires focused attention during fabrication. Besides, the experimental work on LCS is far from complete and, thus, the focused objective of the present research. The woven fabric laminated composite shells are fabricated in ambient conditions, and arrangments are made towards achieving the cantilever boundary condition. The free vibration frequencies are recorded through an FFT analyzer and compared against the numerical outcomes. The FE predictions are made through the ABAQUS simulation platform. The parametric investigations concerning fibre orientation and the number of plies for a cantilever boundary condition are presented.

2.0 Experimental Analysis

The glass/epoxy and carbon/epoxy laminated composite shells(LCS) are prepared in line with Biswal et al. [13]. To this end, the woven fabric bidirectional glass and carbon fibres are procured and cut into specified sizes. Fibre stacking is done using an epoxy resin matrix prepared by blending 90% epoxy with 10% hardener. The proportion of woven fabrics to epoxy resin measures 50:50 by weight. A Cylindrical steel rigid panel with a diameter of 0.1524 m are utilized as a mould for manufacturing cylindrical LCS. The laminated composite cylindrical panels are cured for three days at room temperature under constant uniform loads. After proper curing of laminates, the specimens are cut with a diamond impregnated wheel for the tensile and free vibration tests.

2.1 Tensile Test for Evaluation of Material Constants

The elastic properties of glass/epoxy and carbon/epoxy laminated composites are obtained by carrying out the tensile test on the specimens. To this end, the laminated samples are prepared following the guidelines laid by ASTM-D3039/D3039M-14 [16]. Furthermore, following this standard code of practice, the INSTRON 8862 universal testing machine is served for tensile tests, as shown in Fig. 1, to obtain the elastic moduli of glass/epoxy and carbon/epoxy composite laminates. The present study utilized industry-driven bi-directional woven glass and carbon fabrics; thus, the elastic constants E_{11} and E_{22} exhibit equal magnitude in tensile test results. The shear modulus G_{12} was determined in line with Jones [17]. The obtained material properties are presented in Table 1.

Fig.1 Tensile test using Universal Testing Machine INSTRON 8862

Table 1. Material properties of glass/epoxy and carbon/epoxy laminated structure from tensile test.

Material properties	**glass/epoxy laminated composite**		**carbon/epoxy laminated composite**	
Modulus of elasticity	E_{11} (GPa)	16.02	E_{11} (GPa)	41.62
	E_{22} (GPa)	16.02	E_{22} (GPa)	41.62
	E_{45} (GPa)	8.27	E_{45} (GPa)	11.16
Poisson's ratio	$\upsilon_{12} = \upsilon_{23} = \upsilon_{13}$	0.27	$\upsilon_{12} = \upsilon_{23} = \upsilon_{13}$	0.29
Modulus of rigidity	$G_{12} = G_{13} = G_{23}$ (GPa)	2.79	$G_{12} = G_{13} = G_{23}$ (GPa)	3.63
Mass density	ρ_m (kg/m^3)	1630	ρ_m (kg/m^3)	1683

2.2 Free Vibration Test of the Laminated Composite Shells

The laminated composite shells (LCS) are subjected to non-destructive vibration testing using the impact hammer technique. Concerning the experiments, the free vibration test set-up is presented in Fig. 2. The cantilever boundary condition is achieved through a pre-fabricated iron frame by mechanically clamping one end. The modal hammer and accelerometer are connected to the FFT analyzer's respective channel, and the FFT analyzer is connected to a display unit. The roving hammer method is adopted for the vibration measurement; the accelerometer is fixed at a position, and then the test specimen is excited by moving the modal hammer at different marked points of the specimen. The accelerometer attached to the specimen receives the response generated by the modal hammer. The FFT analyzer receives a time-varying signal from the accelerometer, converts it into a frequency-based signal known as the frequency response function (FRF), and transfers those resulting FRFs to the computer. The display unit with pre-installed Pulse Labshop software captured those FRF spectrums with fine coherence.

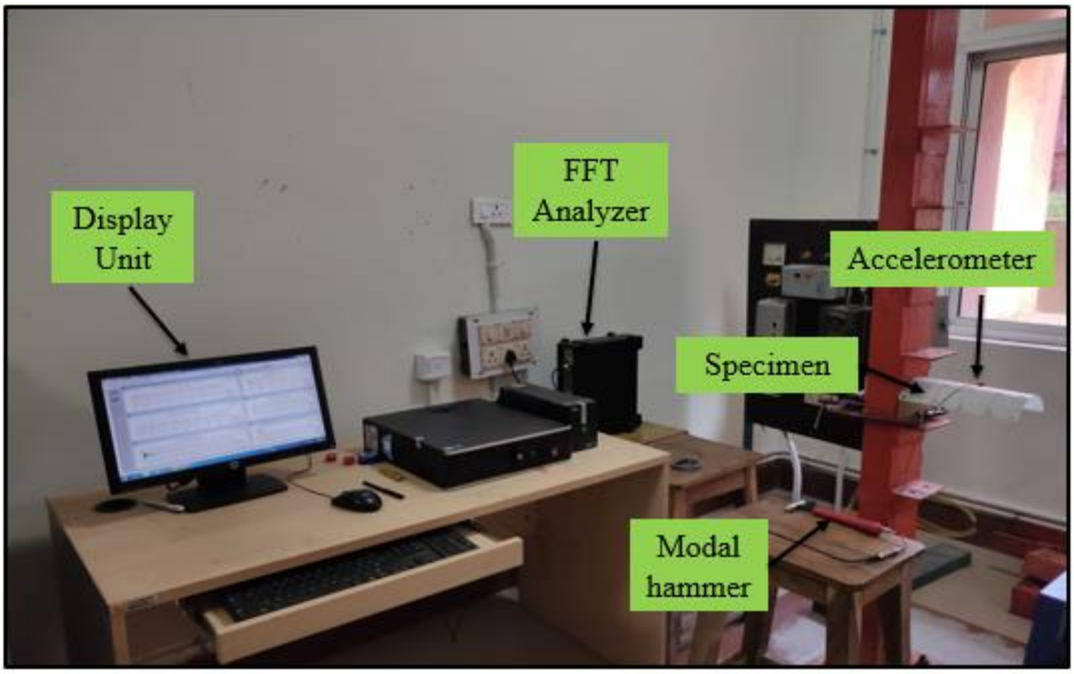


Fig.2 Complete Experimental set-up for free vibration test

3.0 Finite element modelling using ABAQUS

The free vibration simulation analysis is performed on the ABAQUS platform. To this end, a laminated composite shell model is developed on the ABAQUS domain and simulated in the vibration thrust. The modelling for the desired LCS is performed by selecting a shell model (S4R) from the ABAQUS library. The procedure begins with developing the laminated shell's structural geometry, followed by assigning geometrical and material properties to each layer. Modal parameters, including natural frequencies and mode shapes, are obtained using a frequency extraction procedure based on the Lanczos Eigen solver for the cantilever support condition. The flow chart for the numerical simulation procedure is presented in Fig. 3. The mesh division and ply-orientation for a 4-layered LCS with 0^0 fibre orientation are presented in Fig. 4.

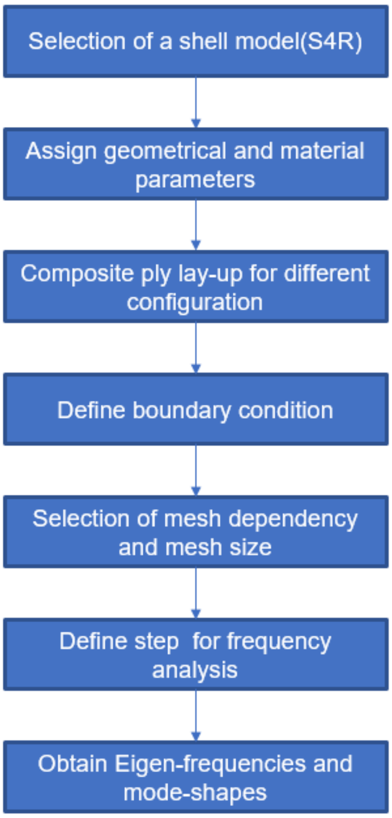


Fig.3 Flow chart for the numerical simulation procedure in the ABAQUS platform

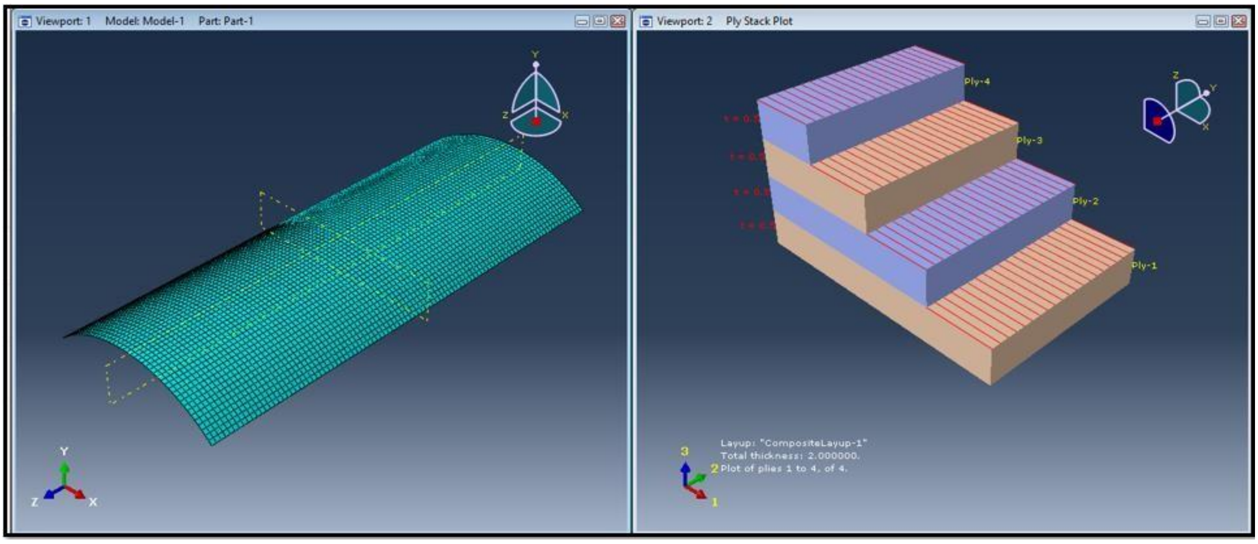


Fig.4 Modelling of the laminated composite shell in the ABAQUS platform

4.0 Results and Discussion

In the present work, the natural frequencies for the LCS are derived experimentally using the Impact hammer method and numerically using the ABAQUS platform. Convergence studies for free vibration of the LCS are performed, and a mesh of 1000 elements demonstrates satisfactory convergence of the numerical solutions. The first five modes of natural frequency obtained by the present ABAQUS simulation for free vibration of LCS are then compared with the literature[12] results. It can be deduced from Fig. 5 that there exists a good agreement between the two results.

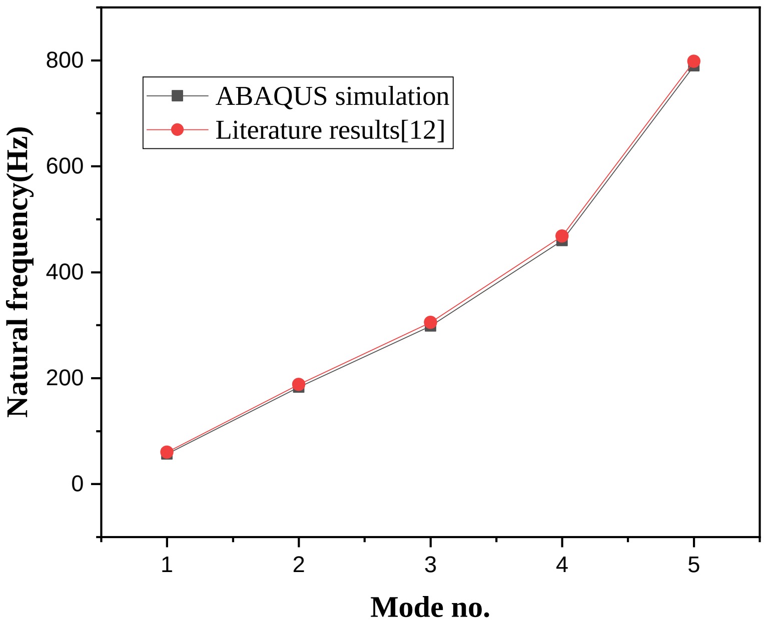


Fig.5 Validation of the present ABAQUS simulation with the available literature

All the arrangements are made for the experimental set-up, and the free vibration test is conducted at room temperature, around 23^0 C. The results are analyzed for the following two parameters.

1. Effect of fibre orientation
2. Effect of number of ply layers

4.1 Effect of fibre orientation

This analysis segment is performed for 0^0, 15^0, 30^0 and 45^0 orientated glass/epoxy and carbon/epoxy LCS. The associated simulated results, along with the experimental results, are presented in Fig. 6. From Fig. 6(a), it is revealed that the glass/epoxy LCS fabricated with a 0^0 lamination scheme for all the layers exhibits higher frequency magnitudes over the 15^0, 30^0 and 45^0 fibre oriented LCS for all modes of vibration. Similar observations are made for carbon/epoxy LCS from Fig. 6(b). Besides, the numerically simulated results are recorded in line with the experimental outcomes.

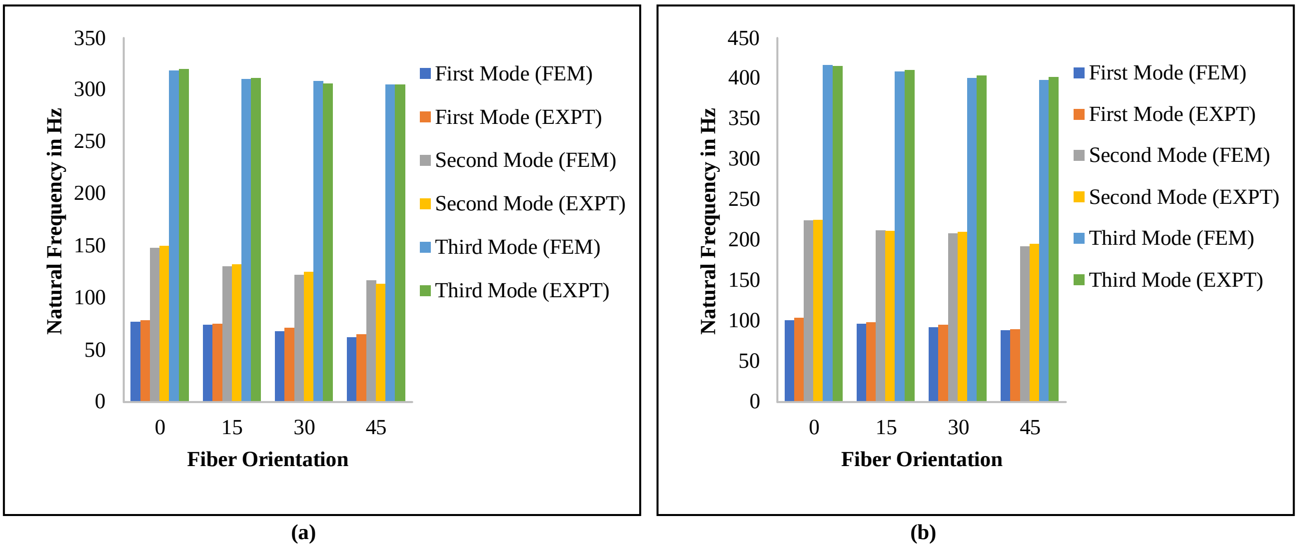


Fig. 6 Natural frequencies upon fiber orientation; (a) glass/epoxyLCS, (b)carbon/epoxy LCS

4.1 Effect of number of layers

The natural frequencies for the first three vibration modes of a 4-layered LCS measured from experimentation and the ABAQUS simulation are presented in Table 2. It can be observed that the experimental results are in excellent agreement with the numerical simulation results. The carbon/epoxy LCS possesses a higher frequency than the glass/epoxy LCS. The 1st three mode shapes of the glass/epoxy LCS under cantilever boundary conditions are presented in Fig. 7.

Table 2. Natural frequencies of the four-layered LCSs for a cantilever boundary condition

Natural frequencies (Hz)				
	Glass/Epoxy LCS		Carbon/Epoxy LCS	
Mode no.	**Experiment**	**Simulation**	**Experiment**	**Simulation**
1	74	77.05	98	101.26
2	156	148.13	218	224.93
3	328	318.51	412	416.59

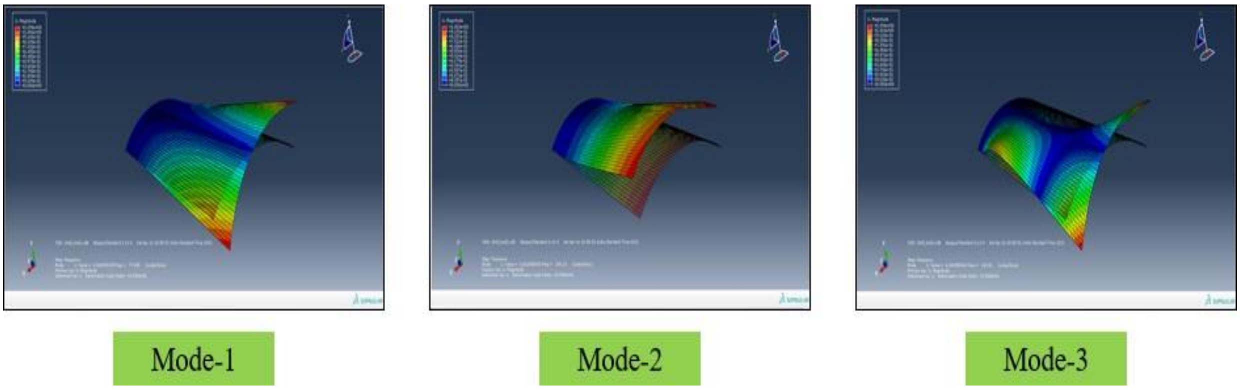
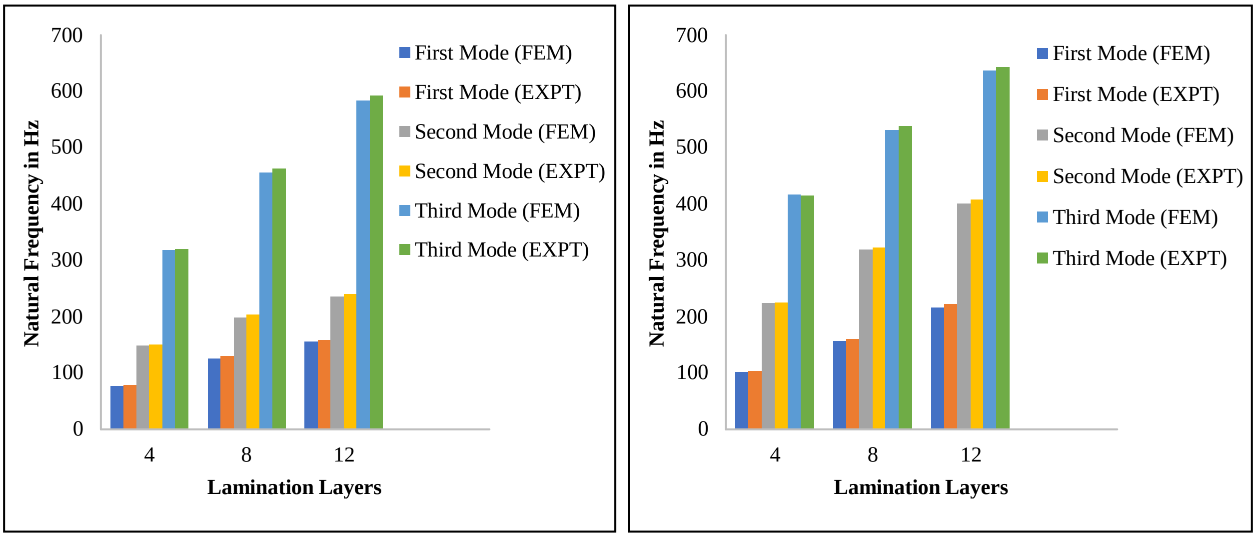


Fig.7 First three mode shapes of the glass/epoxy LCS under a cantilever boundary condition

The above observation is extended to a comparison between 4-layered, 8-layered and 12-layered glass/epoxy and carbon/epoxy LCS towards laying a more affirmative and comprehensive analysis concerning the effect of lamination layers on the natural frequencies. The detailed summarization is presented in Fig. 8. A fine degree of similitude is recorded between the simulation and experiment results from the illustration. Towards the critical observation, the 4-layered LCS exhibits much lesser frequency magnitude with respect to 8-layered and 12-layered LCS. But, the frequency shift from 8-layered LCS to 12-layered LCS is not conspicuous. Thus, concerning the ease of fabrication towards validating the numerical simulation, 8-layered LCS is preferred in this attempt for free vibration study.



(a) **(b)**

Fig 8. Effect of lamination layers on the natural frequencies; (a) glass/epoxy LCS, (b) carbon/epoxy LCS

5.0 Conclusion

The present work details the numerical and experimental attempt for glass/epoxy and carbon/epoxy LCS in the thrust of free vibration concerning a cantilever boundary condition. The parametric studies are erected for fibre orientation and ply lamination layers. In view of the results recorded from ABAQUS simulation and experiments through the impact hammer method, the following conclusions are enumerated for the present work.

- The numerical simulation outcomes are in close agreement with the experimental results.
- The carbon/epoxy LCS possesses a higher frequency than the glass/epoxy LCS.
- LCS fabricated with a 0^0 lamination scheme for all the layers exhibits higher frequency magnitudes over other ply orientations.
- The frequencies increases as the number of layers of LCS increases.

The findings of the dynamic exploration of the present study can be used to assess structural integrity or monitor the health of structures. The vibration range could be controlled by understanding the natural frequency in the component. This could assist in designing or manufacturing components which can prevent the component from vibrating at its natural frequency, thus eliminating the risks of resonance occurrence.

REFERENCES

1. Qatu, M.S., Sullivan, R.W. and Wang, W., 2010. Recent research advances on the dynamic analysis of composite shells: 2000–2009. Composite Structures, 93(1), pp.14-31.
2. Chakravorty, D., Bandyopadhyay, J.N. and Sinha, P., 1996. Finite element free vibration analysis of doubly curved laminated composite shells. *Journal of Sound and Vibration*, *191*(4), pp.491-504.
3. Liu, M.L. and To, C.W.S., 2003. Free vibration analysis of laminated composite shell structures using hybrid strain based layerwise finite elements. *Finite elements in analysis and design*, *40*(1), pp.83-120.
4. Plagianakos, T.S. and Saravanos, D.A., 2003. Mechanics and finite elements for the damped dynamic characteristics of curvilinear laminates and composite shell structures. *Journal of Sound and Vibration*, *263*(2), pp.399-414.
5. Cugnoni, J., Gmür, T. and Schorderet, A., 2004. Identification by modal analysis of composite structures modelled with FSDT and HSDT laminated shell finite elements. *Composites Part A: Applied Science and Manufacturing*, *35*(7-8), pp.977-987.
6. Toorani, M.H. and Lakis, A.A., 2006. Free vibrations of non-uniform composite cylindrical shells. *Nuclear Engineering and Design*, *236*(17), pp.1748-1758.
7. Amabili, M. and Reddy, J.N., 2010, January. A New Nonlinear Higher-Order Shear Deformation Theory for Nonlinear Vibrations of Laminated Shells. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 44458, pp. 1017-1025).
8. Asadi, E. and Qatu, M.S., 2013. Free vibration of thick laminated cylindrical shells with different boundary conditions using general differential quadrature. *Journal of Vibration and Control*, *19*(3), pp.356-366.
9. Viola, E., Tornabene, F. and Fantuzzi, N., 2013. General higher-order shear deformation theories for the free vibration analysis of completely doubly-curved laminated shells and panels. *Composite structures*, *95*, pp.639-666.
10. Thomas, B. and Roy, T., 2016. Vibration analysis of functionally graded carbon nanotube-reinforced composite shell structures. *Acta Mechanica*, *227*(2), pp.581-599.
11. Tornabene, F., 2016. General higher-order layer-wise theory for free vibrations of doubly-curved laminated composite shells and panels. *Mechanics of Advanced Materials and Structures*, *23*(9), pp.1046-1067.
12. Biswal, M., Sahu, S.K. and Asha, A.V., 2015. Experimental and numerical studies on free vibration of laminated composite shallow shells in hygrothermal environment. *Composite Structures*, *127*, pp.165-174.13.
13. Biswal, M., Sahu, S.K. and Asha, A.V., 2016. Vibration of composite cylindrical shallow shells subjected to hygrothermal loading-experimental and numerical results. *Composites Part B: Engineering*, *98*, pp.108-119.
14. Sahoo, S.S., Hirwani, C.K., Panda, S.K. and Sen, D., 2018. Numerical analysis of vibration and transient behaviour of laminated composite curved shallow shell structure: An experimental validation. *Scientia Iranica*, *25*(4), pp.2218-2232.
15. Thakur, S.N. and Ray, C., 2021, August. Static and free vibration analyses of moderately thick hyperbolic paraboloidal cross ply laminated composite shell structure. In *Structures* (Vol. 32, pp. 876-888). Elsevier.
16. Standard, A.S.T.M., 2008. Standard test method for tensile properties of polymer matrix composite materials. *ASTM D3039/DM*, *3039*(2008).
17. Jones, R.M., 1998. *Mechanics of composite materials*. CRC press.