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Effect of nano glass cenosphere filler on hybrid composite eigenfrequency responses - An FEM approach and experimental verification

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Abstract. The effect of an increasing percentage of nanofiller (glass cenosphere) with Glass/Epoxy hybrid composite curved panels modeled mathematically using the multiscale concept and subsequent numerical eigenvalues of different geometrical configurations (cylindrical, spherical, elliptical, hyperboloid and flat) predicted in this research article. The numerical model of Glass/Epoxy/Cenosphere is derived using the higher-order polynomial type of kinematic theory in association with isoparametric finite element technique. The multiscale mathematical model utilized for the customized computer code for the evaluation of the frequency data. The numerical model validation and consistency verified with experimental frequency data and convergence test including the experimental elastic properties. The experimental frequencies of the multiscale nano filler-reinforced composite are recorded through the impact hammer frequency test rig including CDAQ-9178 (National Instruments) and LABVIEW virtual programming. Finally, the nano cenosphere filler percentage and different design associated geometrical parameters on the natural frequency data of hybrid composite structural configurations are illustrated through a series of numerical examples.

Keywords: modal responses; nano glass cenosphere; hybrid composite; FEM; experimental analysis

1. Introduction

Composite is one of the fastest growing industrial material, which demonstrating a significant impact on today's material world. There has been an extraordinary revolution in composite usages, which, in turn, fuels the research and subsequent application. The application of layered structure including the new fillers also improves the structural characteristics due to their inherent properties. Moreover, the multiscale material and their analysis not only the need of hour but also challenging. In this regard, glass cenosphere are one of the available low cost filler material with differently abled capabilities for the structural implementation. In general, glass cenospheres are hollow spheres and its diameters usually vary from 1 to 1000 micrometers, although the sizes can range from 100 nanometers to 5 millimeters for a wide range of applications in areas like medicine, research, consumer goods and various industries. The hollow glass cenosphere (glass bubbles) have unique properties i.e., low density, high energy absorption capacity and low plateau strength with unique smooth spherical surface (Birla *et al.* 2017), which enable to use widely in polymers and ceramics matrix as the reinforcement fillers. In this line, effort have been made by different researchers to show the effects of cenospheres in the polymer composites and provided in the following lines.

Zhang *et al.* (2018) studied the effect of glass cenosphere in 5A03 aluminum matrix syntactic foam on the properties of strength and energy absorption under the dynamic loading and compared with quasi-static results. Xia *et al.* (2014) investigated the distribution and effects of cenospheres on the mechanical properties of aluminium foams. Birla *et al.* (2017) discussed in details the effect of cenosphere content on the compressive deformation behaviour due to variable amounts of cenosphere (18, 25, 30 and 35 vol%) content. Similarly, the metal matrix syntactic foam load bearing capacity including cenosphere under the cyclic loading and the mechanical properties reported in the recent past (Kotana *et al.* 2017, Lin *et al.* 2016). Jena *et al.* (2014) studied the influence of cenosphere filler content on the damping properties of the bamboo epoxy laminated composite. Ferreira *et al.* (2013) analysed the influence of nanoclay reinforcement and water presence in the epoxy matrices on the fatigue behaviour of the composite. Sivasaravanan and Raja (2014) investigated the change of impact properties of the epoxy/ glass fibre

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composite when nanoclay filler added to composite. Rohatgi *et al*. (2006) studied the effect of processing variables and compressive properties on the composites was characterized and performed the compressive tests on the different volume fractions of hollow fly ash particles metal matrix composites. Khoshnoud and Abu-Zahra (2015) studied the effect of different loadings of cenosphere fly ash in the rigid PVC foam composite on the thermal, mechanical and morphological properties were characterized. Thakur and Chauhan (2015) investigated the effect of cenosphere particulates of the glass fibre reinforced vinylester composite on the tribological characteristics under water and dry lubricated sliding conditions and also discussed the applied normal forces, sliding speeds and particle content effects on the tribological behaviour. Dalbehera (2016) investigated the effect of cenosphere on the tribological and mechanical propertied of the natural fiber reinforced hybrid composite. Reegan and Arulmurugan (2016) studied the effect of different weight fractions of nanoclay particulates on the vibration and mechanical properties of polymer composites. Kushnoore *et al*. (2018) presented experimentally the effect of different weight fractions of cenosphere particulates on the mechanical characteristics of cenosphere reinforced epoxy composites. Bhattacharjee and Nanda (2018) studied extensively the effect of variation of various design parameters on the damping property of glass fiber reinforced epoxy composite. The free vibration frequencies were obtained by using Ritz method where the four displacement components are assumed as the series of simple algebraic polynomials in case of functionally graded clamped plates and investigated this theory by comparing with the those of first-order and the other higher-order theories (Benachour *et al*. 2011). Bennoun *et al*. (2016) proposed a new five variable refined plate theory for the analysis of free vibration on functionally graded sandwich plates and compared this developed theory with the other higher order theories. An efficient and simple refined shear deformation theory is presented for the vibration and buckling of exponentially graded material sandwich plate resting on elastic foundations under various boundary conditions (Meziane *et al*. 2014). Belkorissat *et al*. (2015) presented a new nonlocal hyperbolic refined plate model for the analysis of free vibration properties of functionally graded plates. Szekrényes (2014) developed a novel analytical model to solve the free vibration problem for the delaminated composite beam type structural components. Similarly, Levy type boundary conditions adopted by Szekrényes (2016) to perform the free vibration responses of the delaminated composite plate using Kirchhoff plate theory. Arani *et al*. (2017) examined the effect of various parameters like small-scale, surface stress, visco-Pasternak medium, electric fields and composite layers on the nonlinear frequency of the smart micro sandwich structure and obtained the nonlinear frequency by using differential quadrature method. Arani *et al*. (2013) investigated the nonlinear vibration and instability of embedded double-walled boron nitride nanotubes (DWBNNTs) conveying viscous-fluid under under combined electro-thermo mechanical loadings, using DQM based on piezoelasticity cylindrical shell theory. Arani *et al*. (2016) analysed the nonlinear transverse vibration of an embedded piezoelectric plate reinforced with single walled carbon nanotubes (SWCNTs). Mohammadi and Ghannadpour (2011) conducted vibration behaviour of nano Timoshenko beams sing Eringen's nonlocal elastic theory. Ghannadpour (2018a) developed a variational approach is developed to obtain bending, buckling and vibration finite element equations of nonlocal Timoshenko beams, to investigate the behavior of nano-beams with complex geometry, material property and different boundary conditions. Ghannadpour *et al.* (2013) attempted to study the bending, buckling and vibrational analysis of the Euler beams, using Ritz method with arbitrary boundary conditions along them. In order to consider the small scale effect in the vibration analysis of the Nano/micro Euler beams, Rayleigh–Ritz technique is used (Ghannadpour and Mohammadi 2010). Moreover, the eigenvalue (vibration and buckling) and bending behaviour of different beam type structural components are studied including the nonlocal elasticity parameter to count the size effect via the analytical and numerical techniques (Taghizadeh *et al*. 2015, 2016, Ghannadpour and Mohammadi 2010, Ghannadpour 2018b). A mathematical model for to optimize the frequency using classical laminate plate theory (CLPT) and modified feasible direction (MFD) method. A program using FORTRAN developed to find the optimal frequency parameter of the symmetrically laminated angle-ply via the general quadrilateral and trapezoidal techniques (Topal 2009). Topal and Uzman (2006) adopted the first-order shear deformation theory (FSDT) to develop a generic mathematical model for the free vibration frequency responses of the simply supported laminated composite plate. The computational responses calculated using the proposed mathematical model via the customized MATLAB code. Topal (2006) conducted the modal frequency analysis of a simply-supported equal-sided sector of a laminated spherical shell using the commercial finite element package program (ANSYS), where the mathematical model follows the FSDT kind of kinematic model. Buckling and free vibration of functionally graded CNT reinforced composite (FG-CNTRC) truncated conical shell is analysed by Mehri *et al*. (2016) using nonlinear equations of motion derived on the basis of Novozhilov nonlinear shell theory and Green-Lagrange geometrical nonlinearity when subjected to axial compression and external pressure simultaneously. To analyze the free vibration and nonlinear thermal stability of shape memory alloy hybrid composite beams, Asadi *et al*. (2013) introduced an exact solution using the first order-shear deformation theory which incorporates the transverse shear deformation.

From review of above articles, we seen that effect of cenosphere filler on the various properties of composite material, especially on the strength and energy absorption capacity which are clearly explaining that cenosphere filler in turn effect the structural behaviour of composite like Bending, Vibration and Buckling resistance capacities etc. Till yet, many authors are using theories like CLPT and

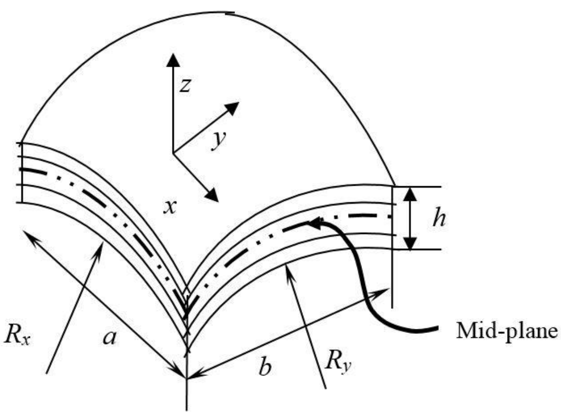


Fig. 1 Doubly curved composite shell configuration

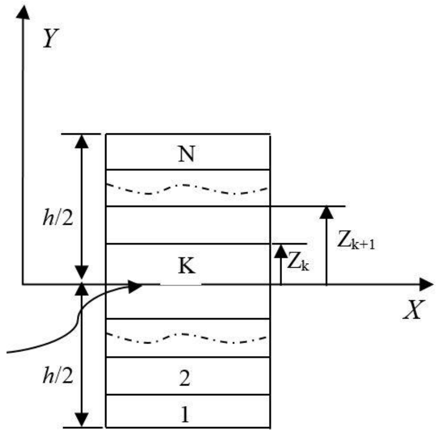


Fig. 2 Laminate configuration

FSDT to find the best preferred parameters to design final finished structural components made of composite material (beam and plate) by neglecting the Higher order shear deformation. Though we know its effect is not that much on the structure, still the author wants to study whole effect by considering Higher order shear deformation also. In this present work the author is going to present the effect of increasing the percentage Cenosphere in Glass/Epoxy laminated plate on modes of frequency responses by numerically as well as experimentally by using HSDT.

2. Mathematical modelling

2.1 Geometry and configuration

Consider a layered composite structure of length a, width b and thickness h with a finite number of orthotropic layers of uniform thickness as shown in Fig. 1 and laminate configuration shown in Fig. 2. Based on the HSDT kinematics (Reddy 2004), the author assumed the displacement field within the laminate where in-plane displacements are elaborated as cubic/linear functions of the thickness coordinate while the transverse displacement varies either linearly and/or constant through the panel thickness.

2.2 Displacement field and strain displacement relation

As we discussed earlier, two different shear deformation kinematic model have been employed for the mathematical modelling. The mathematical model is developed based on the HSDT kinematics using the displacement field (Mehar *et al*. 2015) as shown in below

Model:

$$\begin{aligned} u(x,y,z,t) &= u_0(x,y,t) + z\theta_x(x,y,t) + z^2\phi_x(x,y,t) \\ &\quad + z^3\lambda_x(x,y,t) \\ v(x,y,z,t) &= v_0(x,y,t) + z\theta_y(x,y,t) + z^2\phi_y(x,y,t) \\ &\quad + z^3\lambda_y(x,y,t) \\ w(x,y,z,t) &= w_0(x,y,t) \end{aligned} \tag{1}$$

Further, the constitutive relations for any k^{th} lamina oriented at an arbitrary angle "θ" about any arbitrary material axes are given by

$$\{\sigma\} = \left[\overline{Q}_{ij}\right]\{\varepsilon_j\} \tag{2}$$

where, $\{\sigma\}$, $\left[\overline{Q}_{ij}\right]$ and $\{\varepsilon_j\}$ are the corresponding stress tensor, reduced stiffness matrix and strain tensor, respectively. Further the strain tensor for any material panel can be written as

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = \begin{Bmatrix} u,_x \\ v,_y \\ u,_y + v,_x \\ u,_z + w,_x \\ v,_z + w,_y \end{Bmatrix} = \begin{Bmatrix} \left(\dfrac{\partial u}{\partial x} + \dfrac{w}{R_x}\right) \\ \left(\dfrac{\partial v}{\partial y} + \dfrac{w}{R_y}\right) \\ \left(\dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} + \dfrac{2w}{R_{xy}}\right) \\ \left(\dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial x} - \dfrac{u}{R_x}\right) \\ \left(\dfrac{\partial v}{\partial z} + \dfrac{\partial w}{\partial y} - \dfrac{v}{R_y}\right) \end{Bmatrix} \tag{3}$$

where, R_x and R_y are the principal radius of curvature in x and y-axis, respectively and R_{xy} ($\sim\infty$) is the twist radius at the mid-plane of the panel structure.

2.3 Finite element formulation

The displacement fields for different assumed kinematic models are expressed in terms of desired field variables and the necessary discretisations have been performed with the help of suitable FEM steps. Now, the displacement vector "d" at any point on the mid-surface for the discussed model is expressed as in following

$$d = \sum_{i=1}^{n} N_i(x,y)\, d_i \tag{4}$$

where, $\{d_i\} = \left\{u_{0_i}\ v_{0_i}\ w_{0_i}\ \theta_{x_i}\ \theta_{y_i}\phi_{xi}\ \phi_{yi}\ \lambda_{xi}\lambda_{xi}\right\}^T$ is the nodal displacement vectors for Model and N_i is the corresponding interpolating functions associated with the i^{th} node.

Now, the strain is presented in the matrix form after introducing the FEM concept and conceded to the following form

$$\{\varepsilon\} = [T]\{\bar{\varepsilon}\} \tag{5}$$

Where $\{\bar{\varepsilon}\}$ is the mid-plane strain and $[T]$ is the thickness coordinate matrix and the mid plane strain vector can be further reduced as

$$\{\bar{\varepsilon}\} = [B_L]\{d_i\} \tag{6}$$

where, $[B_L]$ is a general strain displacement relation matrix according to the type of the displacement field model.

The total strain energy of the layered panel can be expressed as

$$U = \frac{1}{2}\iint \left[\int_{-h/2}^{+h/2} \{\varepsilon\}^T\{\sigma\}dz\right] dxdy \tag{7}$$

Eq. (7) can be rewritten by substituting strains and stresses as

$$U = \frac{1}{2}\iint (\{\bar{\varepsilon}\}^T[D]\{\bar{\varepsilon}\})\, dxdy \tag{8}$$

where, $[D] = \int_{-h/2}^{+h/2}[T]^T\left[Q_{ij}\right][T]dz$

The kinetic energy of the laminate can be expressed as

$$T = \frac{1}{2}\int_V \rho\{\dot{\delta}\}^T\{\dot{\delta}\}dV \tag{9}$$

where, ρ and $\{\dot{\delta}\}$ are the mass density and the global velocity vector, respectively.

The final form of governing equation of free vibrated composite panel is obtained by using Hamilton's principle and expressed as

$$\delta\int_{t_1}^{t_2}(T - U)dt = 0 \tag{10}$$

where, T is the kinetic energy and U is the strain energy.

Now, substituting Eqs. (4), (8) and (9) into Eq. (10), the final form of the equation will be conceded as

$$[M]\{\ddot{d}_i\} + [K]\{d_i\} = 0 \tag{11}$$

where, $\ddot{d}_i$ is the acceleration, d_i is the displacement, $[K]$and $[M]$are the stiffness and mass matrices, respectively which can be further expressed as

$$\begin{aligned}[K] &= \int_A [B_L]^T [D][B_L]dA \\ [M] &= \int_A [N]^T[N]\rho dA\end{aligned} \tag{12}$$

Neglecting the required matrices, the eigenvalue form of the governing equation to obtain the natural frequency of the system is conceded as

$$([K] - \omega^2[M])\{d\} = 0 \tag{13}$$

where, ω and Δ are the natural frequency and the corresponding eigenvector, respectively.

The Eq. (13) is solved by using the following sets of support conditions to avoid any rigid body motion as well as reduce the number of unknowns

Simply supported (SSSS):

$$\begin{aligned}&v_0 = w_0 = \theta_y = \theta_z = \phi_y = \lambda_y = 0\\ &\text{at } x = 0 \text{ and } a;\\ &u_0 = w_0 = \theta_x = \theta_z = \phi_x = \lambda_x = 0\\ &\text{at } y = 0 \text{ and } b;\end{aligned} \tag{14}$$

Clamped (CCCC):

$$\begin{aligned}&u_0 = v_0 = w_0 = \theta_x = \theta_y = \theta_z\\ &\quad = \phi_x = \phi_y = \lambda_x = \lambda_y = 0\\ &\text{at } x = 0 \text{ and } a;\\ &\text{at } y = 0 \text{ and } b;\end{aligned} \tag{15}$$

Free (FFFF)

$$\begin{aligned}&u_0 \neq v_0 \neq w_0 \neq \theta_x \neq \theta_y \neq \theta_z\\ &\quad \neq \phi_x \neq \phi_y \neq \lambda_x \neq \lambda_y \neq 0\\ &\text{at } x = 0 \text{ and } a;\\ &\text{at } y = 0 \text{ and } b;\end{aligned} \tag{16}$$

3. Results and discussion

The free vibration responses of cenosphere Glass/ Epoxy laminated composite shell have been obtained numerically with the help of FE-MATLAB code. The model consistency established via the well-known convergence analysis. Further, the multiscale model is extended to compute the frequencies for the validation study and compared with those of the published eigenvalues. In addition to this, different percentages of the Cenosphere Glass/ Epoxy laminated composite plates are fabricated by using hand lay-up method and utilised for the evaluation of frequency responses with the help of experimental set up (CDAQ-9178, National Instrument) at National Institute of Technology Rourkela (NITR), Odisha, India. Also, the author compared these experimental frequency results with the those of numerically obtained results. Moreover, the elastic properties utilized in the current analysis are obtained experimentally for different percentages of nanofiller percentage. Finally, the effect of various geometrical and material parameters on the vibration frequencies of the hybrid layered structure computed to understand the effect of nanofiller on the curved panel.

3.1 Convergence and comparison study

The consistency of presently developed higher order model has been checked by the solving few numerical examples considering the geometrical and material parameters as same as the source data. In this example, the dimensional frequencies are plotted (Fig. 3) for simply

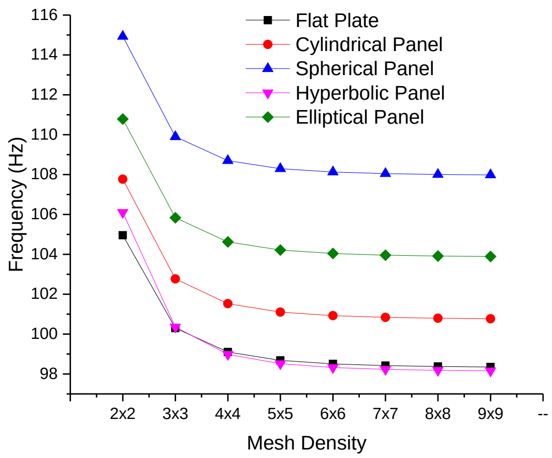


Fig. 3 Convergence behaviour of current higher-order FE model for different geometrical panel using simply-supported symmetric cross-ply laminated composite shell panels (R/a = 40, a/h = 50 and a/b = 1)

supported laminated cross-ply composite panel structure including the variable geometrical configurations. The required geometrical dimension and the material properties (graphite/epoxy) are similar to the source data (Naidu and Sinha 2007) (E1 = 172.5 GPa, E2 = 6.9 GPa, v12 = 0.25, G12 = G13 = 3.45 GPa, G23 = 1.38 GPa, ρ = 1600 kg/m^3). Fig. 3 shows the consistency of the currently developed higher-order FE model through frequency (Hz) versus the progressive mesh densities. The figure indicates the convergence behavior when the mesh varies from coarse to fine. It can be concluded that a (6 × 6), mesh is sufficient to compute the eigenvalues of a cenosphere-filled hybrid laminated composite.

3.2 Numerical validation

After completion of convergence study, the proposed laminated structure model has to be extended to calculate the non-dimensional fundamental frequency and compared with those available published results. In the process of comparison of present model, an example of free vibration has been solved for two layered (0/90^0) simply supported cylindrical laminated composite shell problem and illustrated in Table 2. The results that are obtained by using geometric and material properties same as in Bhimaraddi (1991) and they are compared with various theories of reference as shown in Table 2. From the table, it is clearly observed that the results are having good agreement with 3-D elasticity solutions. From the results, we can conclude

Table 2 Comparison of non-dimensional natural frequency of two-layered (0/90^0) cylindrical and spherical shell panel (h/a = 0.05, a/b = 1, $1/R_1$ = 0, $\Omega = \Omega a\sqrt{(\rho/Ey)}$)

		Bhimaraddi (1991)							
Shell type	*R/a*	1	2	3	4	5	10	20	∞
Cylindrical (Bhimaraddi 1991)	PSD	0.79993	0.58	0.52516	0.50415	0.49402	0.47997	0.47625	0.47483
	CSD	0.79798	0.57733	0.52222	0.50109	0.49091	0.47677	0.47304	0.47161
	TST	0.8058	0.58723	0.53294	0.51217	0.50216	0.48827	0.48459	0.48317
	3D	0.78683	0.57252	0.52073	0.5011	0.49167	0.47859	0.45709	0.47365
	Present	0.7638	0.565	0.5155	0.4967	0.4877	0.4754	0.4724	0.4716
Spherical (Bhimaraddi 1991)	PSD	1.29835	0.79577	0.64044	0.57419	0.54039	0.49127	0.47812	0.47365
	CSD	1.32595	0.81059	0.64949	0.58038	0.545	0.49341	0.47955	0.47483
	TST	1.32483	0.8087	0.64713	0.57775	0.54219	0.49031	0.47636	0.47161
	3D	1.33	0.81618	0.65602	0.58749	0.55247	0.50149	0.48782	0.48317
	Present	1.3558	0.917	0.7965	0.7494	0.7268	0.6967	0.6901	0.6894

*PSD (parabolic shear deformation theory), CSD (constant shear deformation theory), TST (thin shell theory), 3D Elasticity solution

(a) Nano Cenosphere (b) Epoxy and Hardner (c) Glass fibre (d) Polyvinyl alcohol spray

Fig. 4 Raw materials used for making Hybrid Cenosphere Glass/Epoxy laminated composite

Table 3 Experimental properties of material properties of different percentages of Cenosphere filled Glass/Epoxy composite

Sr. No.	Specimen label	Tensile strain at break (Standard) (%)	Mean	Modulus (MPa)	Mean
1	CG11	3.77339	4.08678667	7629.53339	8438.65687
	CG12	4.16146		9922.16187	
	CG13	4.32551		7764.27536	
2	CG21	3.81244	3.97220333	7607.31812	7468.52417
	CG22	3.76308		7846.70792	
	CG23	4.34109		6951.54648	
3	CG31	4.13018	4.30642333	6248.34328	7338.00011
	CG32	4.51818		9003.80859	
	CG33	4.27091		6761.84845	
4	CG41	4.55738	4.54874667	7764.01901	6958.02193
	CG42	4.47651		6855.87769	
	CG43	4.61235		6254.16908	

that the model results very margin to 3-D elasticity solutions and it is well within expected line.

3.3 Preparation and fabrication of cenosphere laminated composite for experimental analysis

The following raw materials were used to prepare the cenosphere laminated composite (Fig. 4)

(1) Cenospheres
(2) Woven glass fibre
(3) Epoxy and Hardener
(4) Polyvinyl alcohol spray
(5) Mila sheets

The hand layup method is one of the mostly commonly used method for fabrication of laminated composite which was adopted for preparing the cenosphere laminated composite in the current study. The following are the steps for the preparation and fabrication of cenosphere laminated composite.

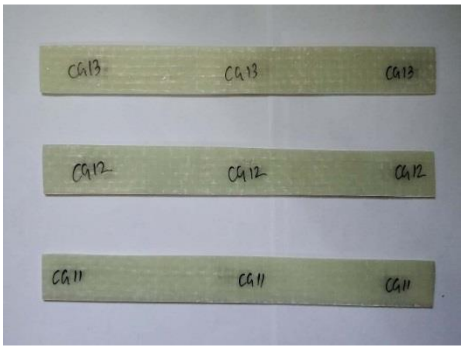
(1) Cut the woven glass fibre mat and Mila sheets of required sizes gently and kept aside.
(2) Now mix the cenospheres in the epoxy thoroughly in the different percentages like 1%, 2%, 3% and 4%.
(3) Next add Hardener to cenosphere epoxy mixture in the ratio of 10:1.
(4) After completion of making of mixture, the Polyvinyl alcohol spray is spread on the mila sheets in order to avoid the sticking of epoxy mixture to sheets.
(5) Now pour and spread the mixture on the sheet which was mounted on strong base and place the glass fibre laminates one by one and repeat the process until four layers has been completed.
(6) Once completion of above step, keep another sheet above of it.
(7) Finally, apply a flat plate of around 50 kg of weight above them and allow it for 3 days for the proper curing.
(8) After adequate curing, take out the laminated composite and prepare the specimens of different sizes based on experimental analysis.

Table 4 The Experimentally evaluated material properties of different volume percentages of Cenosphere

Nano cenosphere %	E_1 (GPa)	G_{12} (GPa)	ν (Crawly 1979)
1%	8.438	2.9533	0.17
2%	7.468	2.6138	0.17
3%	7.338	2.5683	0.17
4%	6.958	2.4353	0.17

3.4 Evaluation of material properties experimentally

Now, the material properties of the cenosphere glass/epoxy laminated composite structure for various percentages of cenosphere composition can be computed by using the universal testing machine (UTM), ASTM D3039 at CIPET Bhubaneswar as shown in the Fig. 5(a). The specimens prepared for test are presented in Fig. 5(b) by fabricated composite plate. In three different directions (longitudinal, transverse and inclined 45^0 from the longitudinal direction), the specimens are cut in order to evaluate the material properties like E_1, E_2 and E_{45}. By using the inclined specimen modulus (E_{45}), shear modulus can be computed given in the formula. Poison's ratio is taken as 0.17 from the source (Crawley 1979) for the calculation of associated material parameter. In order to evaluate the repeatability of the properties, three specimens for each case are tested and averaged to get the final material properties for all four different percentages of cenospheres laminated plates as shown in the Table 3. Further the averaged values data Table 4 is used for computation of the numerical and experimental investiga-

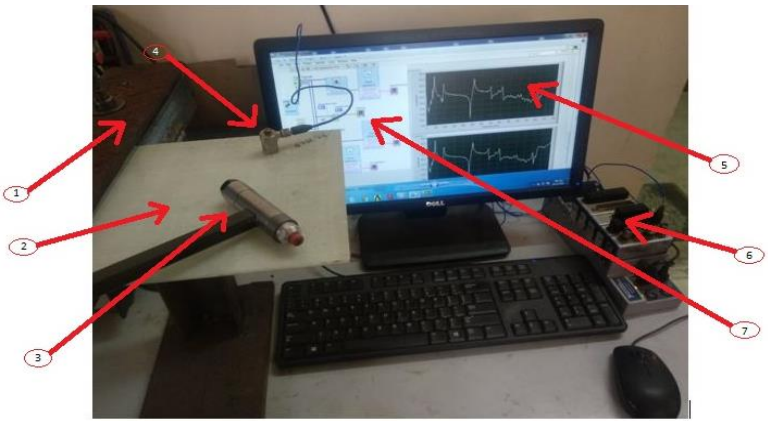


(a) Specimens before testing

(b) Specimens after testing

(c) Universal Testing Machine (Instron, 3382)

Fig. 5 Experimental tensile test details of specimen and machine



1. Fixture 2. Cenosphere Glass-epoxy composite 3. Impact hammer 4. Accelerometer
5. Output window 6. cDAQ 7. Block diagram of the LABVIEW

Fig. 6 Experimental set up for free vibration frequency recording

tion. The following formulae (Jones 1975) is used to obtain the shear modulus of the Cenosphere

Glass/Epoxy

$$G_{12} = 1/\left(\frac{4}{E_{45}}\right) - \left(\frac{1}{E_1}\right) - \left(\frac{1}{E_2}\right) - \left(\frac{2\nu_{12}}{E_1}\right)$$

Now, the averaged material properties set from the experimental data are utilized for the numerical investigation and tabulated in the following Table 4.

3.5 Procedure for experimentation

The following experimental setup (Fig. 6) is used to conduct free vibration analysis on the cenosphere four layered laminate glass/epoxy composite in order get the frequency responses. The setup consists of cenosphere glass/epoxy laminated composite plate (1) which was firmly clamped on fixture (2). The hammer (086C03) (3) is used to give the initial excitation frequency and the acceleration signal will be capture by the accelerometer (352C03) (4)

Table 5 Comparison of frequency data between numerical and experimentation for four layer cross-ply symmetrical panel (a = b = 0.15 m, h = 2.5×10^{-3}m)

Modes	Natural frequency (Hz)							
	Composite-1		Composite-2		Composite-3		Composite-4	
	Num.	Exp.	Num.	Exp.	Num.	Exp.	Num.	Exp.
1	42.4639	43	40.0764	40	39.8538	39.5	38.9336	39
2	102.4501	91.5	96.6826	92	96.152	90	93.9318	93
3	274.7832	254	259.3328	239	257.8902	242	251.9381	236
4	330.7728	344	312.1672	332	310.4418	331	303.2721	313
5	384.937	385.5	363.2721	362	361.2729	358	352.9334	354
6	662.5888	656	625.2886	642.5	621.8501	636	607.4941	648

which was attached on the surface of composite plate. The captured acceleration signal is further transferred with the help of eight-channel compact data acquisition (cDAQ-9178) (5) for the signal conditioning and conversion (analog to digital) process. The virtual instrument (VI) circuit (6) is noted the signal which was made in the LabVIEW platform. Generally, the VI program is used to converting the raw acceleration signal form time domain to frequency domain via fast furrier transformation (FFT). The final acceleration amplitude-frequency graph can be identifying from the output window (7) and records the modes of frequency responses for the comparison purpose.

3.6 Experimental comparison study

Based on the convergence and comparison between the present and reference results, it can easily conclude that the currently developed model is adequate to compute the eigenvalues of hybrid composite. Further, to show the model accuracy the frequency parameters for all four types of composite are recorded experimentally using the available set-up (refer to Fig. 6). Additionally, LABVIEW programming language has been utilized for the virtual programming of frequency analysis. The present FE solution of the first natural frequency including the experimental data for all four types of composite are presented in Table 5. This can be clear from the provided results that the current FE solutions are showing very good agreement with the experimental data. For the computational purpose the necessary geometrical parameters are taken as four layered symmetrical cross-ply cantilever composite square plate (a = b = 0.15 m, h = 2.5×10^{-3}m) similar to the experimental case. Also, it can be concluded that as the percentage of cenosphere composition in glass/epoxy laminated increases, the stiffness of the composite is reducing and the frequency follow the similar line.

4. New illustrations

After the validation of the multiscale model extended to evaluate the frequency parameter for the different variations of the associated structural parameters. The frequency parameters of different geometrical configuration and dimension including the material properties have been checked for the simply supported symmetric cross-ply laminated hybrid structure. The detailed understanding from the numerical examples are discussed including their scientific relevance for the boundary condition has been checked and illustrated in the following examples.

4.1 Effect of curvature ratio (R/a)

In this example, the first mode of frequencies of simply supported hybrid square spherical shell structure are evaluated numerically using the proposed model. The responses are computed for the four layer cross-ply thin (a/h = 50) shell structure. The values of frequency corresponding to different curvature data (R/a = 10, 20, 30, 50 and 80) provided in Fig. 7. This can be concluded from the results that the first natural frequency values are decreasing when the curvature ratio values increase irrespective of filler volume fractions. It is because of the fact curved panel geometries have higher values of stretching energy in comparison to the bending and the structure becomes flat when curvature ratio increases. Similarly, the responses are lower for the Composite-4 in

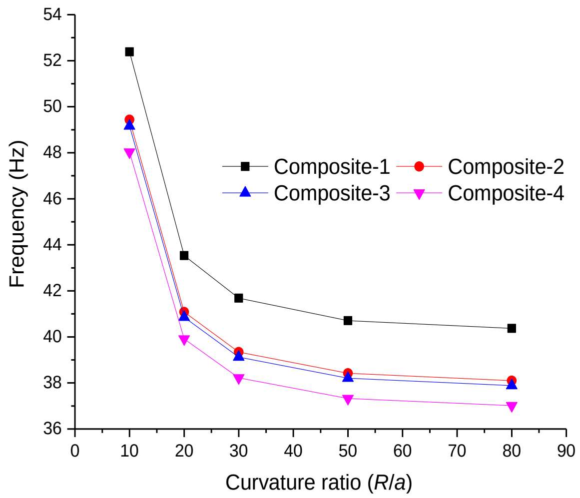


Fig. 7 Curvature ratio effect on free vibration frequency of simply-supported symmetric cross-ply spherical shell structure (a/h=50 and a/b=1)

in comparison to all kind of composite fabricated.

4.2 Effect of Aspect ratio (a/b)

The effect of structural aspect ratio variation on the modal responses for all kinds of composite (Composite-1, Composite-2, Composite-3 and Composite-4) are analyzed considering a simply supported symmetric cross-ply cylindrical (R/a = 40 and a/h = 50) panel problem. The frequencies are obtained using the current higher-order model for different values of aspect ratios (a/b = 1, 1.5, 2, 2.5 and 3). The results are presented in Fig. 8 and follows the expected line i.e. modal values higher for the Composite 1 and lower for the Composite-4. This is because of the elastic modulus data follow a decreasing path when the cenosphere percentage (volume) increases. Similarly, the responses also follow an increasing slope while the aspect ratio increases.

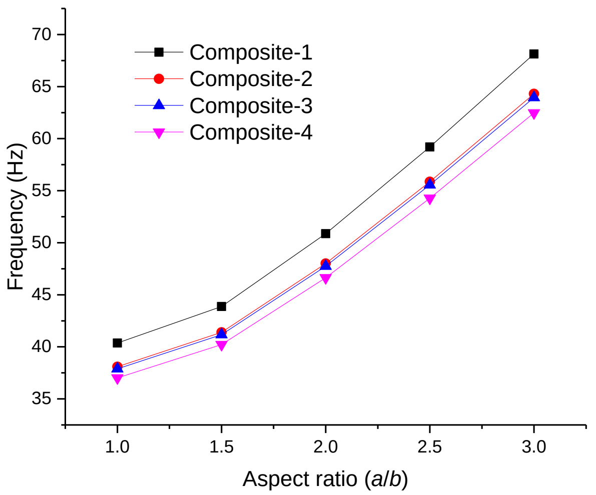


Fig. 8 Effect of cenosphere percentage and aspect ratio on modal responses of simply-supported symmetric cross-ply cylindrical shell structure (R/a = 40 and a/h = 50)

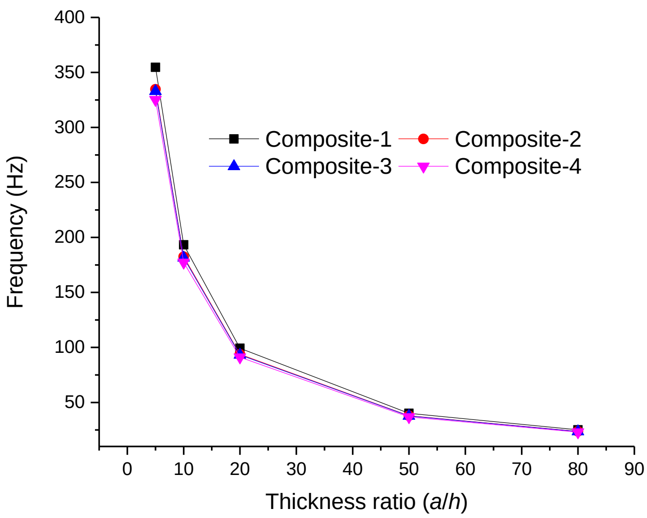


Fig. 9 Variation of thickness ratio on eigenvalues of simply-supported symmetric cross-ply hyperbolic shell structure (R/a = 40 and a/b = 1)

4.3 Effect of thickness ratio (a/h)

In this example, the natural free vibration frequency of a simply supported four layered square hyperbolic (R/a = 40) shell structural problem is solved for six side-to thickness ratios (a/h = 5, 10, 20, 50, 80 and 100). The first natural frequency values for all four kinds composite i.e. Composite-1-4 are plotted in Fig. 9. It can be concluded from the natural frequency data that the structural frequencies are following a decreasing path when the thickness ratio increases. This is because the structural stiffness largely depends on the panel thickness values and the corresponding material strength. Similarly, the responses also follow the expected line i.e. decreasing slope for different volume fractions of the filler material. The reason for the decreasing frequency due to the lower modulus data.

5. Conclusions

The natural frequencies of the cenosphere filled hybrid glass/epoxy laminated composite curved panel structure computed numerically using a higher-order FE model in association with MATLAB. The model accuracy has been checked by comparing the results with different published frequency data i.e. theory and 3D elasticity solution. Also, the model validity verified with the corresponding experimental data obtained through the available impact type frequency analyzer at the parent institute. The experimental properties are obtained for the in-house fabricated hybrid composite of four different volume fractions and the subsequent analysis utilized the experimental elastic data. Lastly, the proposed higher-order polynomial model ability established by computing the frequency responses for different geometrical dimension parameters i.e. aspect ratio, curvature ratio and thickness ratio on frequency responses of different percentages of cenosphere on laminated shell structure evaluated through the variety of numerical examples. Finally, based on numerical results a few conclusions are drawn and reported in the point-wise fashion in the following lines.

(1) The numerical and experimental comparison indicates the validity of the present higher-order polynomial model for the analysis of hybrid composite analysis.
(2) Similarly, the increasing percentages of cenosphere indicate a decreasing tensile strength under the uniaxial tensile test, whereas the ductility of composite increases since the strain at break increases.
(3) The frequency values are showing a decreasing path while the thickness and curvature ratio increases irrespective of the cenosphere volume fractions.
(4) Finally, it is concluded that the presently developed multiscale numerical model is capable of solving

the numerical problems for different geometrical configurations (cylindrical, hyperboloid, elliptical and spherical and flat panel) accurately.

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