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Numerical frequency analysis of skew sandwich layered composite shell structures under thermal environment including shear deformation effects

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Abstract. The numerical thermal frequency responses of the skew sandwich shell panels structure are investigated via a higher-order polynomial shear deformation theory including the thickness stretching effect. A customized MATLAB code is developed using the current mathematical model for the computational purpose. The finite element solution accuracy and consistency have been checked via solving different kinds of numerical benchmark examples taken from the literature. After confirming the standardization of the model, it is further extended to show the effect of different important geometrical parameters such as span-to-thickness ratios, aspect ratios, curvature ratios, core-to-face thickness ratios, skew angles, and support conditions on the frequencies of the sandwich composite flat/curved panel structure under elevated temperature environment.

Keywords: frequency; FEM; HSDT; skew angle; sandwich; curved panel

1. Introduction

System In the present modern world, a huge number of structures and/or structural components are being made from sandwich materials. These materials possess high strength and stiffness to weight ratios as well as other good properties like **heat resistance** and sound insulation. The sandwich structural components are broadly used in modern industries like automotive, aerospace, submarine, locomotives, and low cost building blocks. These components have been used for the thermal protection system in general and the sandwich flat/curved panels are exposed high temperature in some of the cases which may cause due to the aerodynamic heating during their working period. This, in turn, influences the modal responses considerably. In addition, this type of structure demands additional attention for the modeling and accurate prediction of the frequency parameter under the elevated thermal environment. Hence, to improve the understanding of sandwich structural behavior under the elevated environment, a comprehensive number of current and the past selective studies are discussed briefly considering the model kinematics and solution techniques.

The free vibration responses of skew laminated plates are investigated by (Gurses *et al*. 2009) using the discrete singular convolution method in the framework of the first-order shear deformation theory (FSDT). Chandrashekhar and Ganguli (2010) analyzed the nonlinear frequency responses of the laminated and sandwich plates based on Reddy's third order theory by considering von-Karman nonlinear strain terms. The dynamic responses of the isotropic, laminated composite and sandwich plate are studied via a new trigonometric shear deformation theory (Mantari *et al*. 2012), an accurate higher-order theory (Zhen *et al*. 2010) and layer-wise theory with the help of a generalized differential quadrature (GDQ) method (Ferreira *et al*. 2013). The vibration and acoustic behavior of a sandwich plate subjected to a concentrated harmonic force under a thermal environment are analyzed (Liu and Li, 2013) based on the equivalent non-classical theory. Civalek (2014) used the continuum-based approach and derived the governing equations via discrete singular convolution (DSC) to study the buckling behavior of the skew shaped single-layer graphene sheets. There are several literatures (Zhang *et al*. 2015, Pandey and Pradyumna, (2015), Solanki *et al*. 2015, Sayyad and Ghugal 2015, 2017, Tornabene *et al*. 2017a, b) carried out on layered and sandwich structures to study the structural analysis (e.g., bending, vibration and buckling) using various shear deformation theories with the help of the finite element method (FEM). Zhang *et al*. (2017) studied the vibration responses of the sandwich beams with honeycomb-corrugation hybrid cores using the homogenization method with the FEM. Similarly, Han *et al*. (2017) considered the foam-filled composite corrugated sandwich plate under the temperature loading condition to obtain the frequency and buckling parameters using the refined shear deformation theory. The vibration behavior of micro-beams made of functionally graded (FG) materials under the temperature conditions are examined (Akgoz and Civalek 2017) based on the hyperbolic shear deformation beam and modified couple stress theories. Kolahchi (2017) and co-authors (2018) studied the static, vibration, buckling and dynamic behavior of the carbon nanotube (CNT) sandwich nano-plate structures using the refined zigzag theory (RZT), sinusoidal shear deformation theory (SSDT),

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classical plate theory (CPT) and the FSDT with differential cubature (DC), differential quadrature (DQ) and harmonic differential quadrature (HDQ) methods. The vibration responses of the advanced composite and FG structures are investigated by (Taleb *et al*. 2018, Abualnour *et al*. 2018, Sadoune *et al*. 2018) using a hyperbolic shear deformation theory, a quasi-3D trigonometric and sinusoidal shear deformation theories. Baltacloglu and Civalek (2018) examined the vibration responses of functionally graded and CNT reinforced (CNTR) circular cylindrical panel using the HDQ and DSC methods based on Love's shell theory and the FSDT. Recently, Sharma *et al*. (2018) investigated the acoustic radiation responses of laminated sandwich structures subjected to harmonic loading in an elevated thermal environment based on the higher-order shear deformation theory (HSDT).

It is understood from the above literature survey that researchers have used various analytical and numerical methods for plate and shell structures. However, it is also noticed that relatively fewer studies have been available to analyze the free vibration responses of layered sandwich composite panel structures. In addition, to the best of authors' knowledge, it is the first time the higher-order shear deformation theory with all the higher-order nonlinear terms associated have been used for the numerical solution for free vibration problem of skew sandwich shell panels. The aim of the present article is focused on free vibration problems of skew sandwich shell panel under uniform thermal loading. It is also important to mention that the core of the sandwich has been considered as an equivalent homogenous continuum layer so that the sandwich itself can be considered as an orthotropic multi-layered panel. A nine-noded quadrilateral Lagrangian element with 10 degrees-of-freedom (DOF) per node is considered for the discretization purpose and the governing equation has been obtained using Hamilton's principle and a direct iterative method adopted to obtain the vibration responses. The validity of the presently proposed model is demonstrated by obtaining the responses via a home-made computer code (MATLAB) for different mesh size to check the convergence and comparing the results with the available literature. Finally, the influence of the various geometrical parameters is explored and discussed in detail by computing a few numerical examples.

2. Theory and general formulation

In this study, the frequency responses are obtained for the skew sandwich shell panel geometry (length '*a*', width '*b*' and total thickness '*h*') with isotropic core and the laminate facings as presented Fig. 1. Here, the total thickness *h* consists of the core thickness h_c and the face sheet thickness h_f. In addition, the radii of the curvature of the sandwich panel are denoted as R_1 and R_2 in respective directions. Further, the curved shell panel can be categorized in general based on their curvature parameter i.e. spherical ($R_1 = R_2 = R$), elliptical ($R_1 = R$; $R_2 = 2R$), hyperbolical ($R_1 = R$; $R_2 = -R$), cylindrical ($R_1 = R$; $R_2 = \infty$), and flat ($R_1 = R_2 = \infty$).

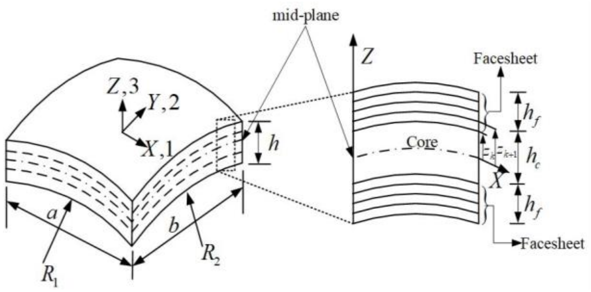

Fig. 1 Sandwich composite configuration

2.1 Kinematic model

In the present work, the HSDT with the thickness stretching is considered to model the skew sandwich composite shell. The displacement field can be represented as (Katariya and Panda 2018):

$$\left.\begin{aligned} \bar{U} &= u_1 + z\theta_1 + z^2\varsigma_1 + z^3\psi_1 \\ \bar{V} &= v_1 + z\theta_2 + z^2\varsigma_2 + z^3\psi_2 \\ \bar{W} &= w_1 + z\theta_3 \end{aligned}\right\} \tag{1}$$

where $\bar{U}$, $\bar{V}$ and $\bar{W}$ are the displacement of any point within the panel along *X*, *Y,* and *Z*-directions, respectively. In addition, the rotations of normal to the mid-plane and extension terms respectively are θ_1, θ_2 and θ_3. Further, the remaining symbols ς_1, ς_2, ψ_1 and ψ_2 are the higher-order terms of Taylor series expansion in the mid-plane of the shell panel.

The Eq. (1) can be written in the matrix form as follows:

$$\{\delta\} = [f]\{\delta_0\} \tag{2}$$

where, $\{\delta\} = \{\bar{U}\ \bar{V}\ \bar{W}\}$ represents the displacement field vector of any point, [*f*] is the thickness coordinate matrix and, $\{\delta_0\} = \{u_1\ v_1\ w_1\ \theta_1\ \theta_2\ \theta_3\ \varsigma_1\ \varsigma_2\ \psi_1\ \psi_2\}$ represent the displacement field vector within the mid-plane.

Now, the skew sandwich flat panel as shown in Fig. 2 is considered with the skew angle 'ϕ'. Here, one of the edges is not parallel to the global axis system (*X* and *Y*). Therefore, it is essential to do the transformation at the element level via suitable transformation of the nodal unknowns of the skew edges from global axes system (*X* and *Y*) to local axes system (*X*' and *Y*'). At an elemental level, the transformed matrices are formed and further, it has been assembled to obtain the global matrices using the FEM. It is also important to mention that the elements that lie over the normal edges do not require the transformation. Now, the transformed nodal coordinates are defined using the transformation matrix $[T_S]$ in a Cartesian coordinate system and represented as Katariya and Panda (2018):

$$\{\delta_0^*\} = [T_S]\{\delta_0\} \tag{3}$$

2.2 Strain-displacement relations

The kinematic behavior of any material continuum is evaluated via strain-displacement relations and in the

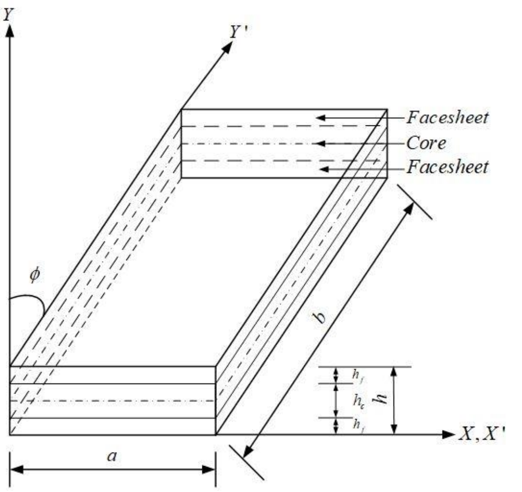

Fig. 2 Skew sandwich composite configuration

present model the following relations have been used as in Singh and Panda, 2014)

$$\{\varepsilon\}=\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix}=\begin{Bmatrix}\dfrac{\partial u}{\partial x}+\dfrac{w}{R_1}\\ \dfrac{\partial v}{\partial y}+\dfrac{w}{R_2}\\ \dfrac{\partial w}{\partial z}\\ \dfrac{\partial v}{\partial z}+\dfrac{\partial w}{\partial y}-\dfrac{v}{R_2}\\ \dfrac{\partial u}{\partial z}+\dfrac{\partial w}{\partial x}-\dfrac{u}{R_1}\\ \dfrac{\partial u}{\partial y}+\dfrac{\partial v}{\partial x}\end{Bmatrix} \tag{4}$$

$$\text{or}\,\{\varepsilon\}=[T]\{\bar{\varepsilon}\}$$

where, $[T]$ represents the thickness coordinate matrix and the mid-plane strain vector is denoted as $\{\bar{\varepsilon}\}$ and can be further defined in terms of nodal displacement vector as (Katariya and Panda, 2018):

$$\{\bar{\varepsilon}\}=[B]\{\delta_0^*\} \tag{5}$$

where, $[B]$ is product form of the differential operators and the shape functions in the strain terms.

2.3 Constitutive relation

The thermo-elastic constitutive relations for any sandwich panel is expressed as (Jones, 1975):

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{Bmatrix}=\begin{bmatrix}Q_{11}&Q_{12}&Q_{13}&0&0&0\\ Q_{21}&Q_{22}&Q_{23}&0&0&0\\ Q_{31}&Q_{32}&Q_{33}&0&0&0\\ 0&0&0&Q_{44}&Q_{45}&0\\ 0&0&0&Q_{54}&Q_{55}&0\\ 0&0&0&0&0&Q_{66}\end{bmatrix}\left(\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix}\right) \tag{6}$$

$$\text{or}\quad \{\sigma\}=[Q]\{\varepsilon\}$$

2.4 Strain energy

The strain energy (U) of the skew sandwich shell panel can be expressed as

$$U=\frac{1}{2}\iint\left[\int_{z_{k-1}}^{z_k}\{\varepsilon\}^T[Q]\{\varepsilon\}\,dz\right]dxdy \tag{7}$$

Now, Eq. (7) can be rearranged by substituting the stresses and the strains from Eqs. (4) and (6) and rewritten as:

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

where

$$[D]=\int_{z_{k-1}}^{z_{k-1}}[T]^T[Q][T]\,dz .$$

2.5 Kinetic energy

The expression of kinetic energy (K_e) of the skew sandwich shell panel can be written as

$$K_e=\frac{1}{2}\int_V\rho\{\delta_0^*\}^T\{\dot{\delta}_0^*\}dV \tag{9}$$

where, the density is represented as ρ. $\{\delta_0^*\}$ *and* $\{\dot{\delta}_0^*\}$ are the corresponding displacement vector and the first-order differential of the displacement vector with respect to time, respectively.

Using, Eq. (2), the kinetic energy (K_e) expression of the skew sandwich shell panel can be expressed in the following form (Katariya and Panda, 2018)

$$\begin{aligned}K_e&=\frac{1}{2}\int_A\left(\int_{z_{k-1}}^{z_k}\{\dot{\delta}_0^*\}^T[f]^T\rho[f]\{\dot{\delta}_0^*\}dz\right)dA\\ &=\frac{1}{2}\int_A\{\dot{\delta}_0^*\}^T[m]\{\dot{\delta}_0^*\}dA\end{aligned} \tag{10}$$

where, $[m]=\int_{Z_{k-1}}^{Z_k}[f]^T\rho[f]dz$ is the mass inertia matrix.

2.6 Finite element formulation

It is well known that the FEM has been widely employed numerical tool for any complex structural problems because of their adaptive nature. In the present study, a nine noded isoparametric quadrilateral Lagrangian element with ten degrees of freedom (DOF) per node is employed for the discretization of the domain. Further, the mid-plane displacement vector $\{\delta_0^*\}$ at any point on the mid-surface can be expressed as (Cook *et al*. 2009)

$$\{\delta_0^*\}=\sum_{i=1}^{9}N_i\{\delta_{0i}^*\} \tag{11}$$

where, $\{\delta_{0i}^{*}\}$ $\{u_1\ v_1\ w_1\ \theta_1\ \theta_2\ \theta_3\ \varsigma_1\ \varsigma_2\ \psi_1\ \psi_2\}^T$ is the nodal displacement vector and N_i represents the interpolating functions of the 'i^{th}' node.

2.7 Governing equation

The governing equation of free vibrated skew sandwich shell panel is obtained through Hamilton's principle and conceded as

$$\delta\int_{t_1}^{t_2}(K_e - U)\,dt = 0 \tag{12}$$

By substituting the values of the strain energy (U) and the kinetic energy (K_e) in Eq. (12), the final form of the equation can be expressed as

$$[M]\{\ddot{\lambda}\}+[K]\{\lambda\}=0 \tag{13}$$

where, $[K]=[B]^T[D][B]$ and $[M]=[N]^T[m][N]$ are the global stiffness and mass matrices, respectively.

Further, to obtain the eigenfrequency responses, Eq. (13) can be represented in the following form

$$\left([K]-\omega^2[M]\right)\Delta = 0 \tag{14}$$

where, ω is the eigenvalue (natural frequency) of the skew sandwich shell panel and Δ represents the corresponding eigenvector.

The direct iterative method has been used to solve the governing Eq. (14), and the desired vibration responses are obtained.

3. Results and Discussions

The desired frequency responses of the skew sandwich shell panels are obtained using a home-made computer code developed in a MATLAB environment based on the higher-order mathematical model. Further, the presently proposed and developed mathematical model is verified by comparing the present results with the available published results and the convergence behavior has been checked beforehand. The sets of edge support conditions utilized to avoid the rigid body motion as well as to reduce the number of unknowns in the present analysis are as follows:

(a) Simply supported (S):

$v_1 = w_1 = \theta_2 = \theta_3 = \varsigma_2 = \psi_2 = 0$ at x = 0, a and,

$u_1 = w_1 = \theta_1 = \theta_3 = \varsigma_1 = \psi_1 = 0$ at y = 0, b

(b) Clamped (C):

$u_1 = v_1 = w_1 = \theta_1 = \theta_2 = \theta_3 = \varsigma_1 = \varsigma_2 = \psi_1 = \psi_2 = 0$ and x = 0, a and y = 0, b.

In the present numerical analysis, four different kinds of edge support conditions i.e., SSSS (all edges simply supported), CCCC (all edges clamped), SCSC (two opposite edges clamped whereas the other two simply supported) and CFFF (one edge clamped and other edges free) are employed to examine the vibration responses of the skew sandwich shell panel. The desired frequency responses are computed by using the above mentioned different support conditions and the material properties as mentioned in Table 1.

Table 1 Material properties of sandwich composite

Facesheet:

$E_1 = 132GPa; E_2 = 10.3GPa; G_{12} = G_{13} = 6.5GPa;$

$G_{23} = 3.91GPa; \upsilon_{12} = \upsilon_{23} = \upsilon_{13} = 0.25; \rho_f = 1570kg/m^3;$

$\alpha_1 = 1.2\times10^{-6}/^{\circ}C; \alpha_2 = 2.4\times10^{-5}/^{\circ}C$

Core:

$Ec = 7GPa; \upsilon_c = 0.3; \rho_c = 1000kg/m^3; \alpha_c = 1.8\times10^{-5}/^{\circ}C$

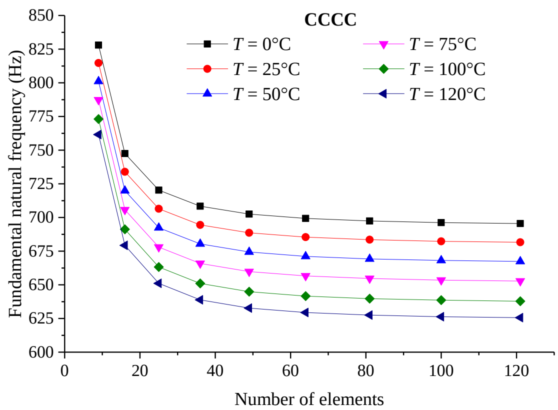

Fig. 3 Convergence study of natural frequency of all edges clamped sandwich composite plate in thermal environment

3.1 Finite element formulation

It is important to check that any model based on the FEM is following the convergence criterion or not. Hence, the convergence behavior of the present solutions of the frequency responses of a skew sandwich plate is examined and presented in Fig. 3. For the computational purpose, rectangular (a = 0.4m, b = 0.3 m and h =0.01m) CCCC sandwich plate has been considered using the material properties as mentioned in Table 1. From Fig. 3, it is clear that the frequency responses converging well with the mesh refinement and the temperature. Based on the convergence study, an (9×9) mesh size has been utilized further for the computational purpose.

Now, the numerical model accuracy is verified through computing the results through an in-house computer code (developed in MATLAB using the formulation) and compared with the published results. The present and the reference data presented in Table 2. The responses are obtained by considering the geometrical and the material parameters similar to the previously discussed example. From the responses, it is understood that the present results agree very well with the previously published results with small differences. The difference between the results are mainly due to the inclusion of mid-plane stretching effect and corresponding geometrical stiffness matrix. In this study the geometrical distortion due to thermal loading

Table 2 Comparison study of natural frequency of all edges clamped rectangular symmetric (0°/90°/C/90°/0°) sandwich plate

Mode No.	Source	Temperature (°C)					
		0	25	50	75	100	120
1	Present	697.4	683.5	669.2	654.7	639.7	627.5
	Sharma *et al*. (2018)	673.5	656.0	638.0	619.4	600.2	584.3
2	Present	1159.4	1146.6	1133.7	1120.5	1107.3	1096.5
	Sharma *et al*. (2018)	1114.4	1093.6	1072.3	1050.6	1028.3	1010.1
3	Present	1626.0	1607.1	1587.9	1568.4	1548.7	1532.8
	Sharma *et al*. (2018)	1570.7	1550.3	1529.7	1508.7	1487.4	1470.1
4	Present	1944.9	1926.5	1907.9	1889.1	1870.1	1854.8
	Sharma *et al*. (2018)	1866.8	1843.6	1820.1	1796.3	1772.1	1752.4
5	Present	1970.9	1959.2	1947.5	1935.7	1923.9	1914.3
	Sharma *et al*. (2018)	1887.6	1865.8	1843.8	1821.4	1798.8	1780.4
6	Present	2593.7	2576.9	2559.9	2542.7	2525.5	2511.6
	Sharma *et al*. (2018)	2477.6	2452.9	2427.9	2402.7	2377.1	2356.5
7	Present	3010.8	2989.7	2968.4	2946.9	2925.3	2907.9
	Sharma *et al*. (2018)	2902.9	2881.0	2859.0	2836.8	2814.4	2796.3
8	Present	3083.5	3072.4	3061.3	3050.1	3038.9	3029.8
	Sharma *et al*. (2018)	2933.4	2911.0	2888.4	2865.7	2842.7	2824.2

modeled using the steps provided in the reference (Cook *et al*. 2009). Moreover, the small strain and large deformation type of problem may unlikely follow the expected line.

3.2 Numerical illustrations

The necessary convergence and validation study shows that the presently developed higher-order finite element model is capable to predict the frequency of skew sandwich structures under thermal environment. Now, the specific numerical examples are solved for various parameters like span-to-thickness ratios (a/h), aspect ratios (a/b), curvature ratios (R/a), core-to-face thickness ratios (h_c/h_f), skew angles (ϕ), and support conditions. In addition, the responses are computed for symmetric (0°/90°/Core/90°/0°) sandwich shell panel with a different skew angle (ϕ = 0°, 15°, 30°, and 45°) using the previously defined material properties under the elevated thermal environment.

The first example is solved to study the effect of the span-to-thickness ratios (a/h = 5, 10, 15, 20, 25, 30 and 50) on a square SSSS cylindrical and spherical skew sandwich shell panel using the previously defined parameters and presented in Figs. 4 and 5, respectively. For the computational purpose, the necessary parameters are considered as R/a = 10 and h_c/h_f = 20. It is understood from the responses that the frequency values follow the declining type of trend with an increase in the temperature as well as a/h values. Further, it is also important to point out that the values of frequency increase with an increase in the skew angle. Figs. 6 and 7, represent the effect of the aspect ratios (a/b = 1, 1.4, 1.8, 2, 2.4, 2.8 and 3) on an SSSS cylindrical and elliptical skew sandwich shell panel, respectively. The required parameters are taken as a/h = 10; R/a = 10 and h_c/h_f = 20. The results indicate that the frequency values are following the decreasing type of trend with an increase in values of a/b and the temperature. In addition, it is also noticed that an increase in the skew angle shows that the frequency values increase. Now, another problem is considered to demonstrate the effect of the curvature ratios (R/a = 2, 4, 8, 10, 15, 20 and 50) on a square CCCC cylindrical and spherical skew sandwich shell panel and presented in Figs. 8 and 9, respectively. In order to compute the responses, the necessary parameters are taken as a/h = 20 and h_c/h_f = 20. From the figures, it can be easily noticed that the frequencies are decreasing with an increase in the temperature and R/a. Further, it is also essential to point out that, the similar kind of tendency has been noticed for the variation of the skew angle i.e., the frequencies increase with an increase in the skew angle. Now, the influence of the core-to-face thickness ratios (h_c/h_f = 4, 8, 10, 15 and 20) on a square SSSS hyperbolical and elliptical skew sandwich shell panel is investigated with a/h = 50, R/a = 10 and presented in Figs. 10 and 11, respectively. The results indicate that the frequencies are reducing with an increase in the temperature as well as h_c/h_f. Moreover, the results show the similar kind of tendency as seen in the earlier cases for the variation in skew angles. Now, the influence of the edge support conditions (SSSS, CCCC, SCSC, and CFFF) on a square cylindrical skew sandwich shell panel is demonstrated in Fig. 12. In order to compute the responses, the crucial parameters are preferred as a/h = 20; R/a = 10 and h_c/h_f = 20. From the figure, it is clear that the edge support conditions affect the modal responses considerably and the similar kinds of behavior have also been noticed for the variation in skew angle and temperature. Finally, the mode shapes are obtained for a square simply supported (SSSS) sandwich composite-laminated spherical shell panel and presented in Fig. 13. The mode shapes are obtained for (0°/90°/Core/90°/0°) sandwich shell panel with R/a = 10, h_c/h_f = 20 and a/h = 50.

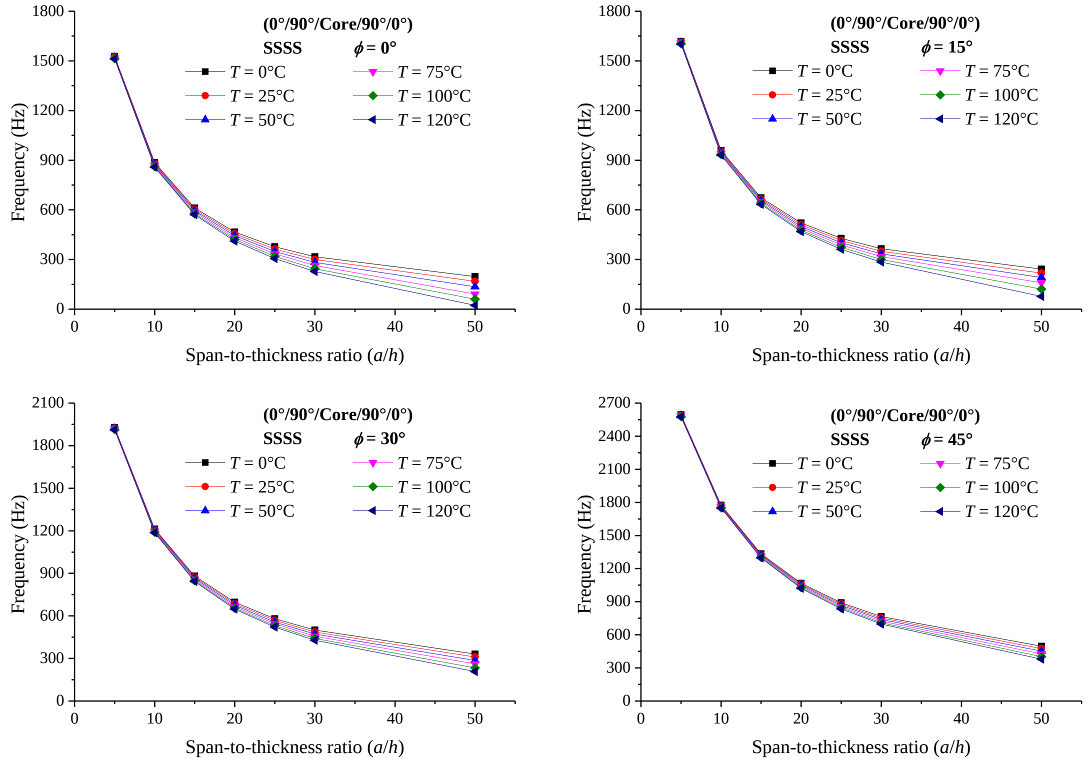

Fig. 4 Influence of span-to-thickness ratios on natural frequency of all edges simply supported skew sandwich composite cylindrical shell panel in thermal environment

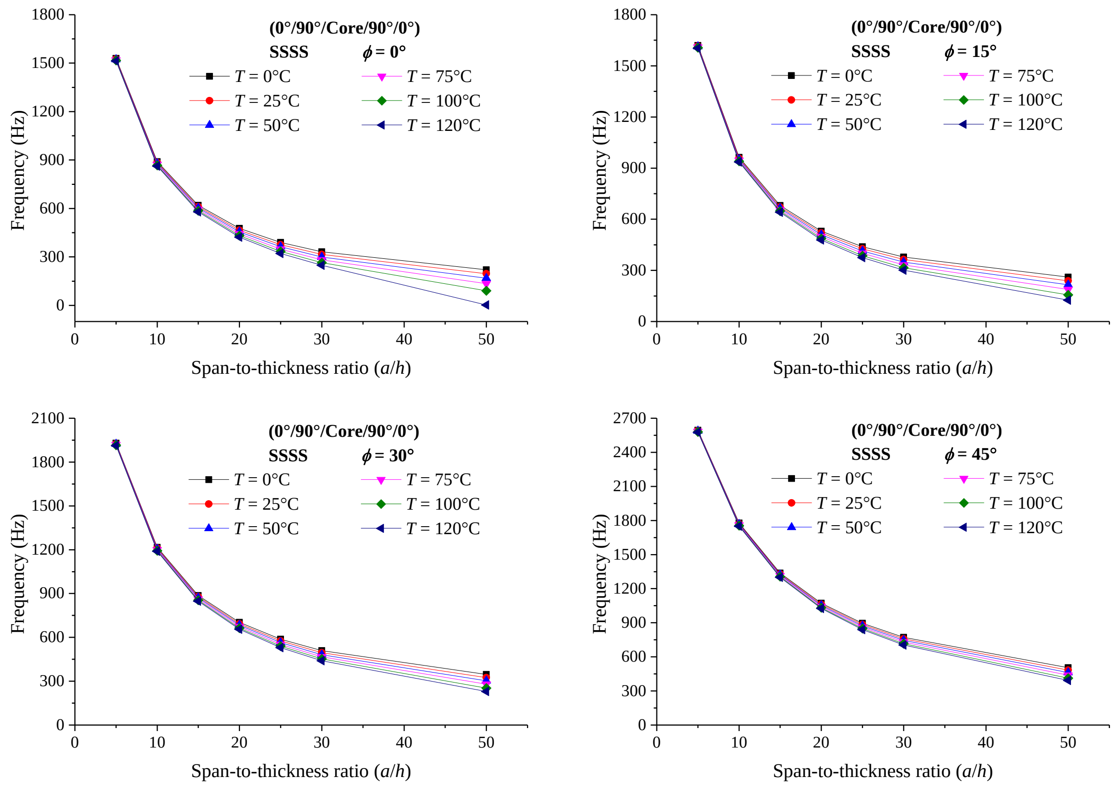

Fig. 5 Influence of span-to-thickness ratios on natural frequency of all edges simply supported skew sandwich composite spherical shell panel in thermal environment

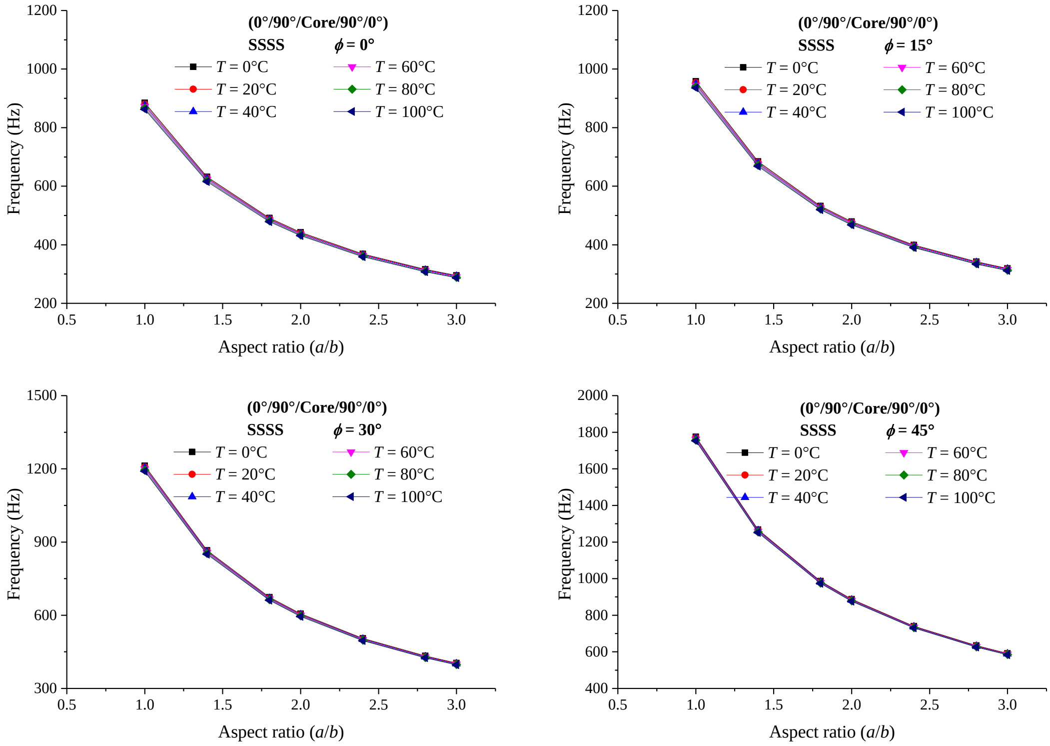

Fig. 6 Influence of aspect ratios on natural frequency of all edges simply supported skew sandwich composite cylindrical shell panel in thermal environment

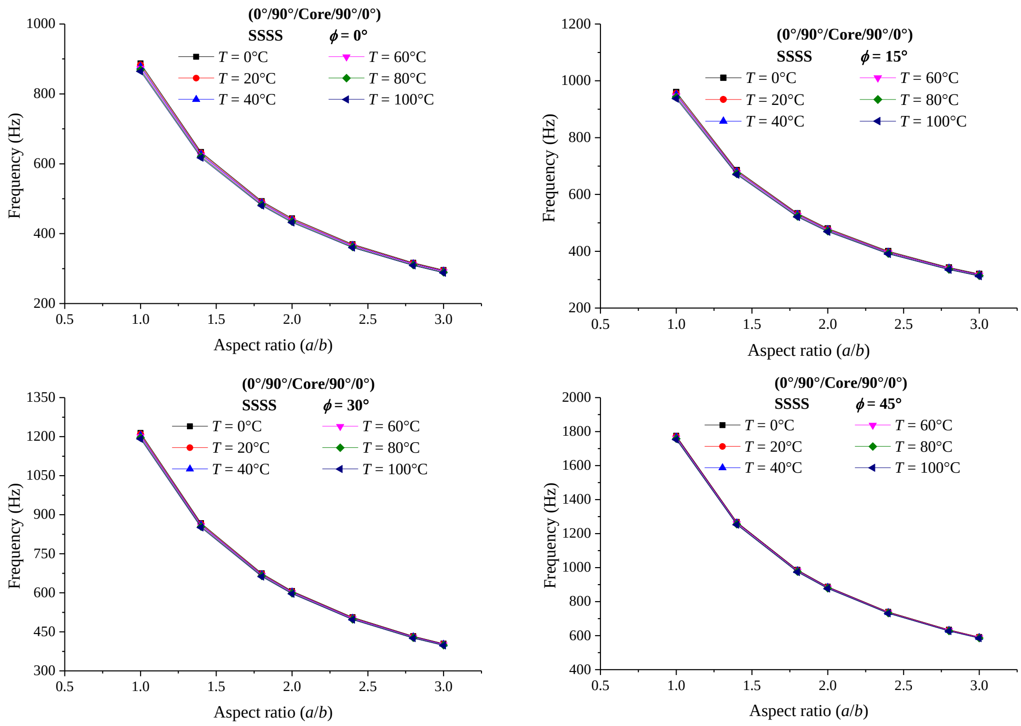

Fig. 7 Influence of aspect ratios on natural frequency of all edges simply supported skew sandwich composite elliptical shell panel in thermal environment

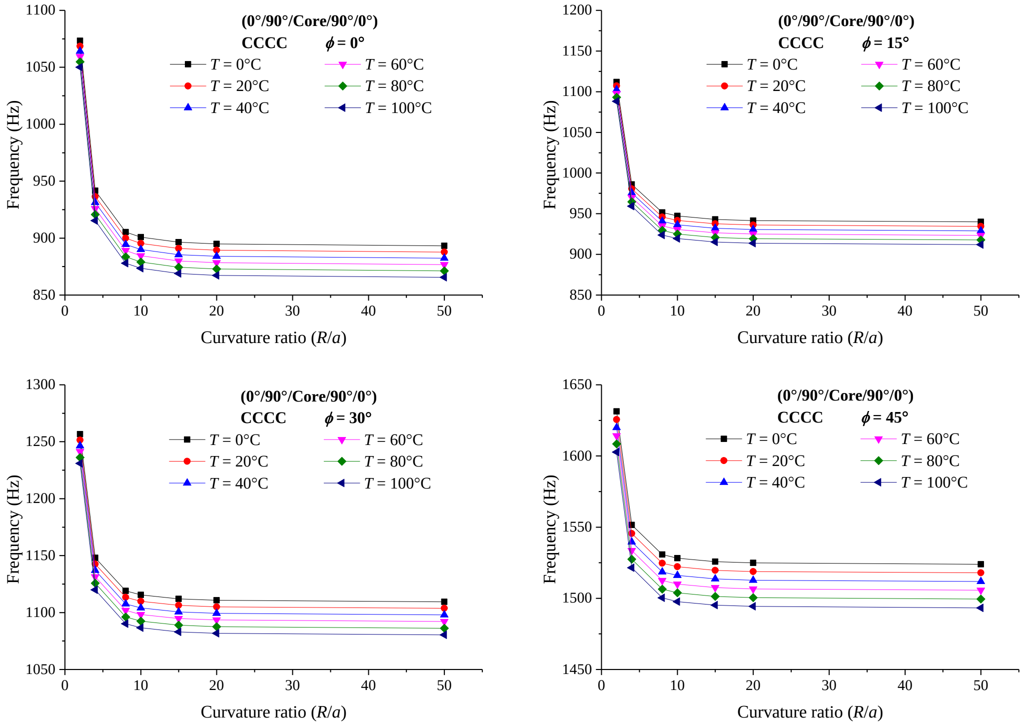

Fig. 8 Influence of curvature ratios on natural frequency of all edges clamped skew sandwich composite cylindrical shell panel in thermal environment

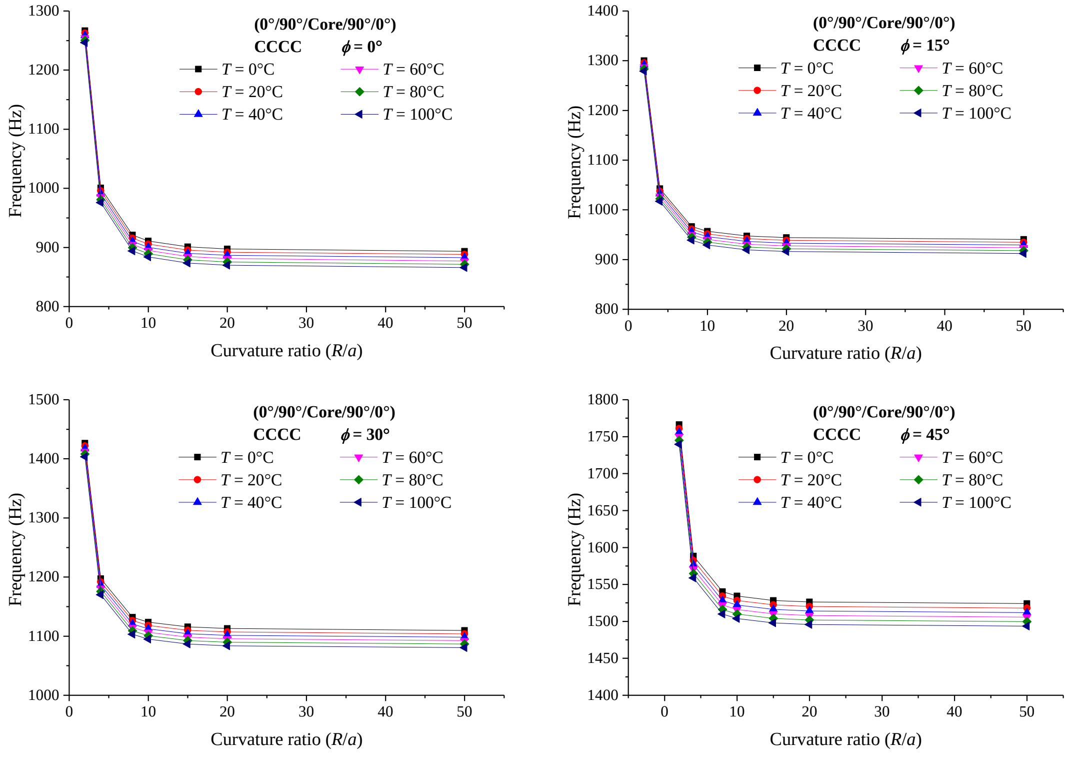

Fig. 9 Influence of curvature ratios on natural frequency of all edges clamped skew sandwich composite spherical shell panel in thermal environment

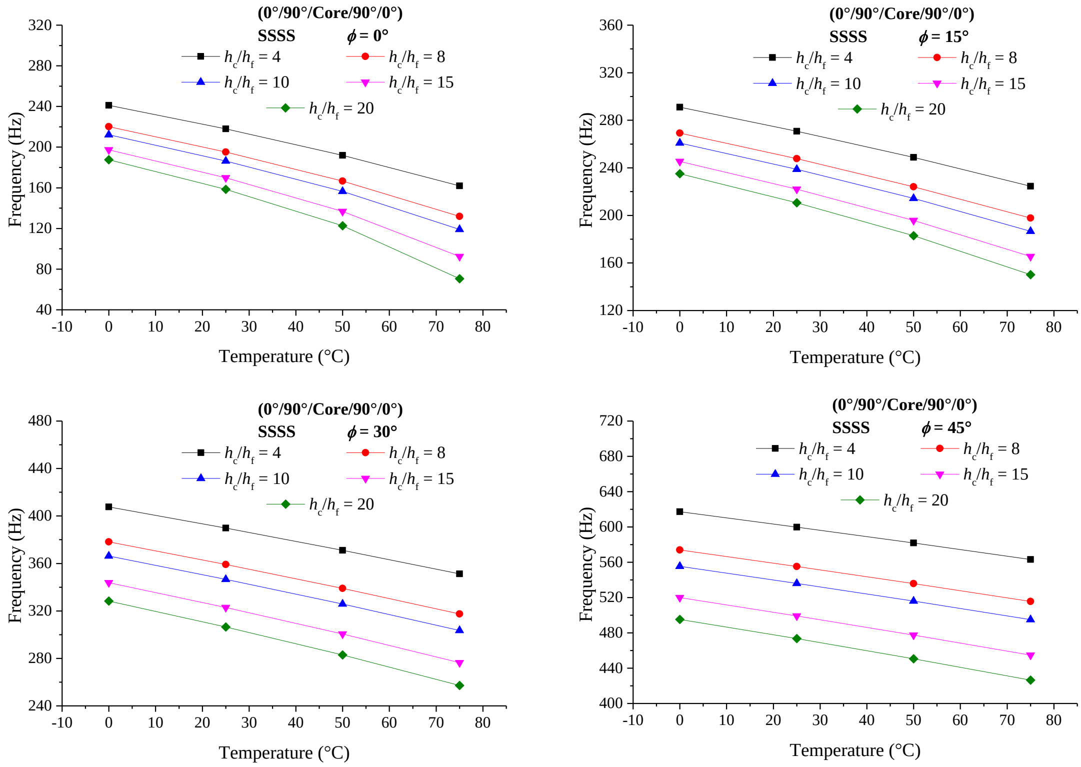

Fig. 10 Influence of core-to-face ratios on natural frequency of all edges simply supported skew sandwich composite hyperbolical shell panel in thermal environment

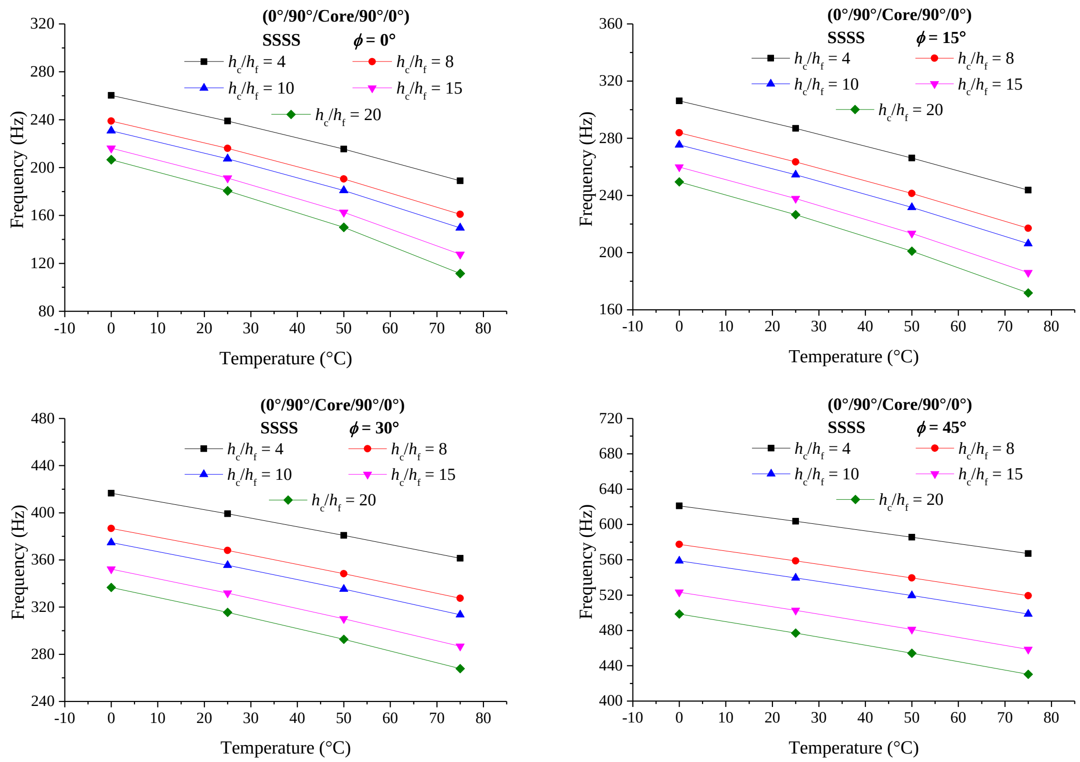

Fig. 11 Influence of core-to-face ratios on natural frequency of all edges simply supported skew sandwich composite elliptical shell panel in thermal environment

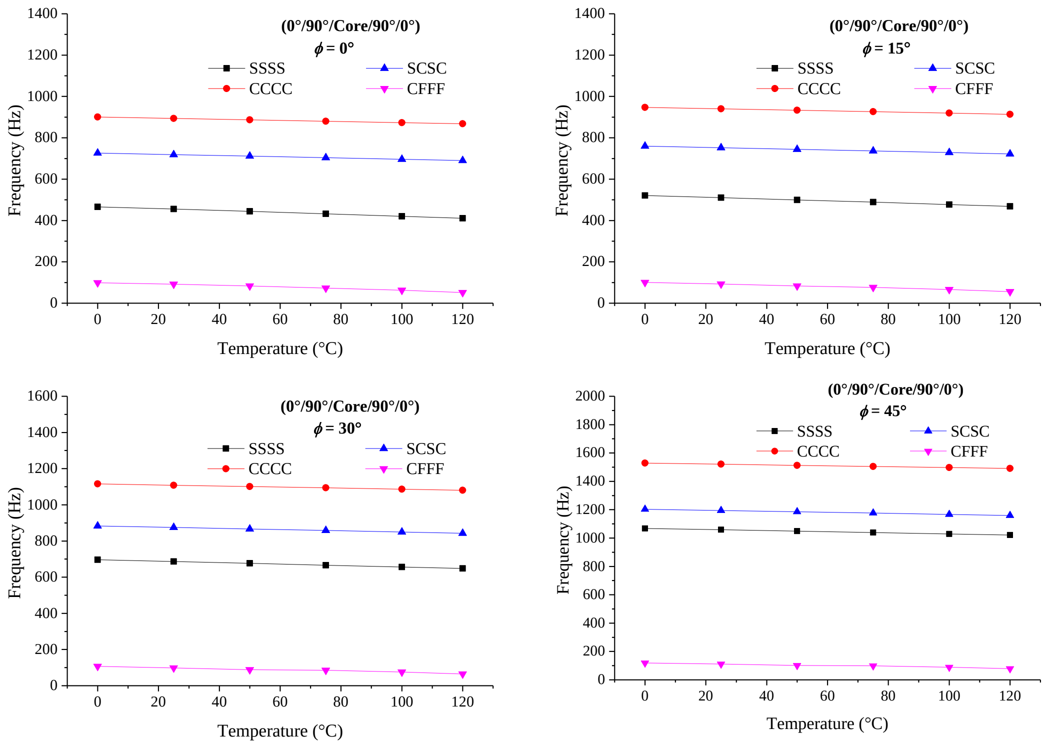

Fig. 12 Influence of support conditions on natural frequency of skew sandwich composite cylindrical shell panel in thermal environment

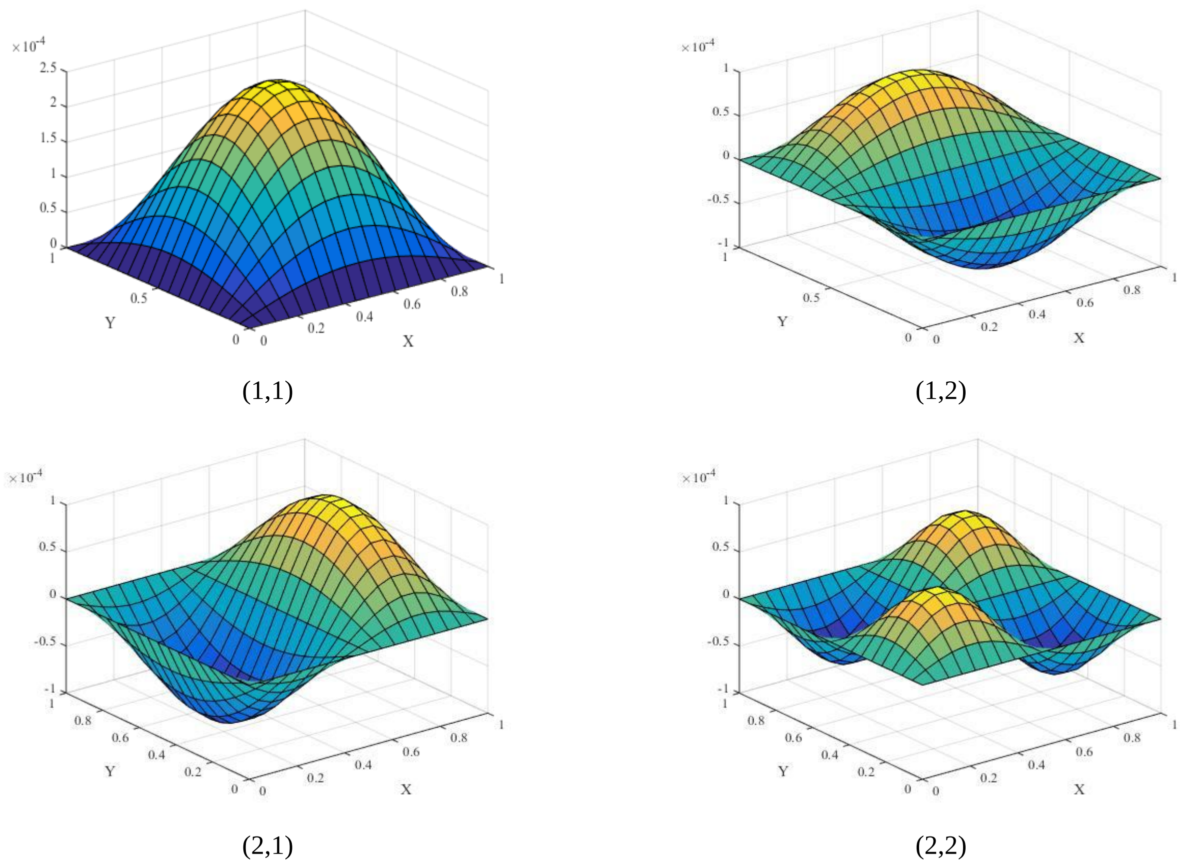

Fig. 13 Mode shapes for SSSS (0°/90°/Core/90°/0°) sandwich composite spherical shell panel

4. Conclusion

In the present article, the vibration behavior of the skew sandwich composite shell panel under thermally elevated environment are studied using the higher-order shear deformation theory. In addition, to attain the exact behavior of the structure, all the higher-order terms associated with the present mathematical model are incorporated in the formulation. The equations of motion for the skew sandwich shell panel has been obtained by using Hamilton's principle, and the finite element steps are used to discretize the domain. Further, the direct iterative method is employed to solve the algebraic equations and the desired responses have been obtained. Based on the present mathematical model, a unique generalized home-made computer code is developed in MATLAB environment to compute the responses. The applicability of the present numerical model has been presented by solving various numerical examples and the important observations are summarized as follows:

- The frequency responses follow a declining type of trend as with an increase in the span-to-thickness ratios, the curvature ratios, and the aspect ratios. This is because of the change in the stiffness of the structure, which affects the responses greatly.
- It is very well known that the structural stiffness changes when the geometrical parameters change and which in turn affect the frequency values significantly.
- It is also interesting to note that the skew angles and the support conditions affect the frequency values of the skew sandwich shell panels considerably. In addition, the frequency values decrease with an increase in the temperature.

It is also observed that the frequency values of the spherical type of geometry are higher in comparison to the elliptical, cylindrical, flat and hyperbolical geometry.

References

Abualnour, M., Houari, M.S.A., Tounsi, A., Bedia, E.A.A. and Mahmoud, S.R. (2018), "A novel quasi-3D trigonometric plate theory for free vibration analysis of advanced composite plates", *Compos. Struct*., **184**, 688-697. https://doi.org/10.1016/j.compstruct.2017.10.047.

Akgoz, B. and Civalek, O. (2017), "Effects of thermal and shear deformation on vibration response of functionally graded thick composite microbeams", *Composites Part B*., **129**, 77-87. https://doi.org/10.1016/j.compositesb.2017.07.024.

Baltacloglu, A.K. and Civalek, O. (2018), "Vibration analysis of circular cylindrical panels with CNT reinforced and FGM composites", *Compos. Struct.,* **202**, 374-388. https://doi.org/10.1016/j.compstruct.2018.02.024.

Chandrashekhar, M. and Ganguli, R. (2010), "Nonlinear vibration analysis of composite laminated and sandwich plates with random material properties", *Int. J. Mech. Sci*., **52**, 874-891. https://doi.org/10.1016/j.ijmecsci.2010.03.002.

Civalek, O. (2014), "Elastic buckling behavior of skew shaped single-layer graphene sheets", *Thin Solid Films*., **550**, 450-458. https://doi.org/10.1016/j.tsf.2013.10.021.

Cook, R.D., Malkus, D.S., Plesha, M.E. and Witt, R.J. (2009), *Concepts and Applications of Finite Element Analysis*, Wiley, Singapore.

Ferreira, A.J.M., Viola, E., Tornabene, F., Fantuzzi, N. and Zenkour, A.M. (2013), "Analysis of sandwich plates by generalized differential quadrature method", *Math. Prob. Eng*., https://doi.org/10.1155/2013/964367.

Gurses, M., Civalek, O., Korkmaz, A.K. and Ersoy, H. (2009), "Free vibration analysis of symmetric laminated skew plates by discrete singular convolution technique based on first-order shear deformation theory", *Int. J. Numer. Meth. Engng*., **79**, 290-313. https://doi.org/10.1002/nme.2553.

Hajmohammad, M.H., Nouri, A.H., Zarei, M.S. and Kolahchi, R. (2018), "A new numerical approach and visco-refined zigzag theory for blast analysis of auxetic honeycomb plates integrated by multiphase nanocomposite facesheets in hygrothermal environment", *Eng. Comput*., https://doi.org/10.1007/s00366-018-0655-x.

Han, B., Qin, K.K., Zhang, Q.C., Zhang, Q., Lu, T.J. and Lu, B.H. (2017), "Free vibration and buckling of foam-filled composite corrugated sandwich plates under thermal loading", *Compos. Struct.,* **172**, 173-189. https://doi.org/10.1016/j.compstruct.2017.03.051.

Jones, R.M. (1975),, "Mechanics of Composite Materials", Taylor and Francis, Philadelphia.

Katariya, P.V. and Panda, S.K. (2018), "Frequency and deflection responses of shear deformable skew sandwich curved shell panel: A finite element approach", *Arab. J. Sci. Eng*., https://doi.org/10.1007/s13369-018-3633-0

Kolahchi, R. (2017), "A comparative study on the bending, vibration and buckling of viscoelastic sandwich nano-plates based on different nonlocal theories using DC, HDQ and DQ methods", *Aerosp. Sci. Technol*., **66**, 235-248. https://doi.org/10.1016/j.ast.2017.03.016.

Liu, Y. and Li, Y. (2013), "Vibration and acoustic response of rectangular sandwich plate under thermal environment", *Shock Vib*., **20**, 1011-1030.

Mantari, J.L, Oktem, A.S. and Soares, C.G. (2012), "A new trigonometric shear deformation theory for isotropic, laminated composite and sandwich plates", *Int. J. Solids Struct*., **49**, 43-53.

Pandey, S. and Pradyumna, S. (2015), "A new C^0 higher-order layerwise finite element formulation for the analysis of laminated and sandwich plates", *Compos. Struct*., **131**, 1-16.

Sadoune, M., Houari, M.S.A., Bakora, A., Tounsi, A., Mahmoud, S.R. and Alwabli, A.S. (2018), "Vibration analysis of thick orthotropic plates using quasi 3D sinusoidal shear deformation theory", *Geomech. Eng*., **16**(2). https://doi.org/10.12989/gae.2018.16.2.141.

Sayyad, A.S. and Ghugal, Y.M. (2015), "On the free vibration analysis of laminated composite and sandwich plates: A review of recent literature with some numerical results", *Compos. Struct.,* **129**, 177-201. https://doi.org/10.1016/j.compstruct.2015.04.007.

Sayyad, A.S. and Ghugal, Y.M. (2017), "Bending, buckling and free vibration of laminated composite and sandwich beams: A critical review of literature", *Compos. Struct*., **171**, 486-504. https://doi.org/10.1016/j.compstruct.2017.03.053.

Sharma, N., Mahapatra, T.R., Panda, S.K. and Katariya, P. (2018), "Thermo-acoustic analysis of higher-order shear deformable laminated composite sandwich flat panel", *J. Sandwich Struct. Mater*., https://doi.org/10.1177/1099636218784846.

Singh, V.K. and Panda, S.K. (2014), "Nonlinear free vibration analysis of single/doubly curved composite shallow shell panels", *Thin-Walled Struct*., **85**, 341-349. https://doi.org/10.1016/j.tws.2014.09.003.

Solanki, M.K., Mishra, S.K., Shukla, K.K. and Singh, J. (2015), "Nonlinear free vibration of laminated composite and sandwich plates using multiquadric collocations", *Mater. Today: Proc*., **2**, 3049-3055. https://doi.org/10.1016/j.matpr.2015.07.210.

Taleb, Q., Houari, M.S.A., Bessaim, A., Tounsi, A. and Mahmoud, S.R. (2018), "A new plate model for vibration response of advanced composite plates in thermal environment", *Struct. Eng.*

Mech., **67**(4). https://doi.org/ 10.12989/sem.2018.67.4.369.

Tornabene, F., Fantuzzi, N. and Bacciocchi, M. (2017a), "Foam core composite sandwich plates and shells with variable stiffness: Effect of the curvilinear fiber path on the modal response", *J. Sandwich Struct. Mater*., https://doi.org/10.1177/1099636217693623.

Tornabene, F., Fantuzzi, N., Bacciocchi, M. and Reddy, J.N. (2017b), "An equivalent layer-wise approach for the free vibration analysis of thick and thin laminated and sandwich shells", *Appl. Sci*., **7**(17), https://doi.org/10.3390/app7010017.

Zhang, X., Yu, K., Bai, Y. and Zhao, R. (2015), "Thermal vibration characteristics of fiber-reinforced mullite sandwich structure with ceramic foams core", *Compos. Struct.,* **131**, 99-106. https://doi.org/10.1016/j.compstruct.2015.04.049.

Zhang, Z.J., Han, B., Zhang, Q.C. and Jin, F. (2017), "Free vibration analysis of sandwich beams with honeycomb-corrugation hybrid cores", *Compos. Struct.,* **171**, 335-344. https://doi.org/10.1016/j.compstruct.2017.03.045.

Zhen, W., Wanji, C. and Xiaohui, R. (2010), "An accurate higher-order theory and C^0 finite element for free vibration analysis of laminated composite and sandwich plates", *Compos. Struct*., **92**, 1299-1307. https://doi.org/10.1016/j.compstruct.2009.11.011.

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