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EFFECT OF THERMAL ENVIRONMENT ON TRANSIENT RESPONSE OF LAMINATED SHALLOW SHELLS WITH DIFFERENT BOUNDARY CONDITIONS

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Abstract

The current work discussed a transient response according to the first- order shear deformation shallow shell theory of forced vibration analysis for fiber reinforced composite laminated spherical shallow shells with different boundary conditions in a thermal environment. The novelty includes implementation of Levy type solution for investigation under different thermos-mechanical loading for anti-symmetric and symmetric cross- ply thick and thin laminated shallow shells. The results were presented for many designed characteristics such as the number of laminates, curvature, and thickness ratios on the dynamic behaviour of shallow shell subjected. The effects of a distributed load with various forms of loading, such as sine and triangle pulses are investigated. The validity of the current Matlab R2019b codes is confirmed by comparing it to other works' solutions. Results show that the transient response increase as the length to thickness ratios (a/h), shallowness ratios (R/ a), aspect ratios (a/b) increase while decrease when the layers number and modular ratio increase with increasing the temperature to 100 °C.

Keywords: Laminated shallow shell, Levy-type approach; Thermal environment, Transient response.

1. Introduction

In different applications of engineering structures, including a submarine, aircraft, spacecraft, automotive, naval, and civil applications, stiffened cylindrical shells are commonly used today. In particular, the doubly curved stability of composite shallow shells that are normally exposed to extreme thermal environments and loadings has been studied. The use of thermoelastic behaviour of spherical shells subject to intense changes in temperature is very important for the design of modern engineering structures. In composite structures, temperature variations are very common both during manufacturing and when used. In some spherical shell applications, a situation occurs when a body is exposed to transient loading with heating or cooling in thermal environments. Therefore, to maintain the safety and performance of these shells, the study of the dynamic analysis of composite spherical shells under external thermo-mechanical loading was used for a various composite shell theories in the present section.

Reddy and Khdeir [1] used the principle of third-order shell theory to investigate the transient response behaviour of doubly curved cross-ply shallow shells. The method accounts for cubic variance through the thickness for in-plane displacements. A geometrically responses analysis of laminated composite shell under transient dynamic loads by using the hybrid strain-based β at the finite element of the triangular laminated composite shell has been discussed by To and Wang [2]. Lee [3] presented the analytical solutions with finite element method of composite shell and plate structures using smart material for lamina to investigate vibration and deflection analysis. A transient response of nonlinear geometric for the doubly curved laminated composite shells employing the finite element method has been investigated by Kundu and Sinha [4]. Al-Azzawy [5] used a general higher- order theory for simply supported cross-ply cylindrical panels to study free and transient analysis. Maleki et al. [6] studied the static and transient response of symmetric and asymmetric cylindrical shell with moderate thick. The transient response governing equations were obtained in addition to Newmark method and different boundary conditions were used with mixed boundary condition.

Ghavanloo and Fazelzadeh [7] used "Noviozhilov's linaear theory" to improve the vibration analysis for the simply supporting laminated shallow shells with doubly curved. Analytical solutions to the dominant equations through of the length scales development to get the frequencies of the shallow shells. The generalized differential quadrature approach was used by Kurtaran [8] to carry out transient analysis of shallow shells which considered relatively thick. Sahoo et al. [9] improved higher- order theory to examine free vibration, static as well as transient response analysis for lamented curved.

Pham-Tien et. al. [10] proposed a new method to improve the convergence and accuracy rate of finite element method for shells and plates in static and force vibration analysis based on triangular element. El-Helloty [11] applied the finite element system with ANSYS16 to analyse the influence of the orientation angle, layers number and support conditions on dynamic response behaviour for composite shells. Kareem and Majeed [12] used a new function of higher order theory to study the transient response for simply supported cross-ply shallow shell. The transient response and eigenvalue problem of composite spherical and cylindrical shells under hygrothermal environments employing the finite element method has been studied by Nanda and Pradyumna [13] and Fu et. al. [14].

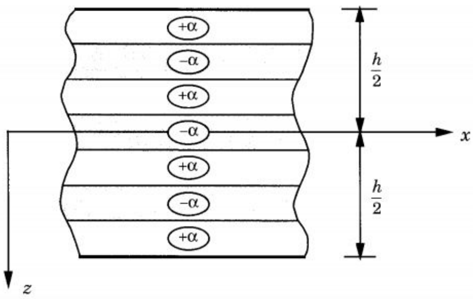
Sheng and Wang [15] studied the nonlinear vibrations analysis of cylindrical shells exposed to the combined influence of mechanical excitations with thermal environments using the non-linear theory of von Karman, including rotary in-plane inertia. A nonlinear dynamic study of thin shallow shells with temperature-dependent properties and subjected to temperature and mechanical load has been described by Duc and Quan [16]. Rivera and Reddy [17] studied thermo-mechanical response of shells and rectangular plates using shell finite element model with high-order spectral basis functions of first-order shear deformation theory for shell element.

Tran et al. [18] examined forced vibration analysis of composite laminated shells with graphene nanoplatelet-reinforced in thermal environments by using the finite element method (FEM). Mousavi et al. [19] investigated dynamic response of the composite laminated cylindrical shell within thermal shock loading and thermal environments and the governing equations are coupled with heat equation.

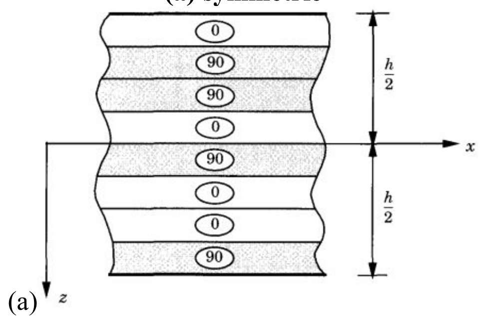
The present work includes investigating the forced vibration analysis for spherical shallow shells in thermal environments with different boundary conditions. Levy type solution is implemented for investigation based on first-order theory under different thermo-mechanical loading (sinusoidal and triangular uniform distributed pressures pulse).

2. Theoretical Formulation of Transient Analysis

The dynamic analysis of symmetric and anti-symmetric cross-ply shallow shell as shown in Fig. 1 has established widespread interest in latest years.



(a) symmetric



(b) anti-symmetric

Fig. 1. Laminated shallow shell [20].

Free vibration and transient response with closed-form solutions have been utilized for the various edge conditions shallow shell. Assume the displacement field form as following [20]:

$$u_1\,(x_1\,,\,x_2, z, t) = u_o(x_1\,, x_2\,, t) + z\phi_1(x_1\,, x_2\,, t)$$
$$u_1\,(x_1\,,\,x_2, z, t) = v_o(x_1\,, x_2\,, t) + z\phi_2(x_1\,, x_2\,, t) \tag{1}$$
$$u_1\,(x_1\,,\,x_2, z, t) = w_o(x_1\,, x_2\,, t)$$

where $(u_o,\; v_o,\; w_o)$ are the displacements of the mid surface at the point $(x_1, x_2, z{=}0)$ and (ϕ_1, ϕ_2) are the rotations to the reference surface. Strain displacement is used throughout the analysis as [21]:

$$\{\varepsilon^o\} = \begin{Bmatrix} \varepsilon_1^0 \\ \varepsilon_2^0 \\ \varepsilon_6^0 \end{Bmatrix}, \{\varepsilon^1\} = \begin{Bmatrix} \varepsilon_1^1 \\ \varepsilon_2^1 \\ \varepsilon_6^1 \end{Bmatrix}$$

$$\varepsilon_1^0 = \frac{\partial u_o}{\partial x_1} + \frac{w_o}{R_1}\;, \varepsilon_2^0 = \frac{\partial v_o}{\partial x_2} + \frac{w_o}{R_2}, \varepsilon_6^0 = \frac{\partial u_o}{\partial x_1} + \frac{\partial v_o}{\partial x_2},\;\; \varepsilon_1^1 = \frac{\partial \phi_1}{\partial x_1}, \varepsilon_2^1 = \frac{\partial \phi_2}{\partial x_2}$$
$$\varepsilon_6^1 = \frac{\partial \phi_1}{\partial x_2} + \frac{\partial \phi_2}{\partial x_1}, \varepsilon_4^0 = \frac{\partial w_o}{\partial x_2} + \phi_2 - \frac{v_o}{R_2}, \varepsilon_5^0 = \frac{\partial w_o}{\partial x_1} + \phi_1 - \frac{u_o}{R_1} \tag{2}$$

Equations under thermal load are:

$$\frac{\partial N_1}{\partial x_1} + \frac{\partial N_6}{\partial x_2} + \frac{Q_1}{R_1} = I_o \frac{\partial^2 u_o}{\partial t^2} + I_1 \frac{\partial^2 \phi_1}{\partial t^2}$$
$$\frac{\partial N_6}{\partial x_1} + \frac{\partial N_2}{\partial x_2} + \frac{Q_2}{R_2} = I_o \frac{\partial^2 v_o}{\partial t^2} + I_1 \frac{\partial^2 \phi_2}{\partial t^2}$$
$$\frac{\partial Q_1}{\partial x_1} + \frac{\partial Q_2}{\partial x_2} - \left(\frac{N_1}{R_1} + \frac{N_2}{R_2}\right) + N_1{}^T \frac{\partial^2 w_o}{\partial x_1{}^2} + N_{12}{}^T \frac{\partial^2 w_o}{\partial x_1 \partial x_2} + N_2{}^T \frac{\partial^2 w_o}{\partial x_2{}^2} = I_1 \frac{\partial^2 w_o}{\partial t^2} \tag{3}$$
$$\frac{\partial M_1}{\partial x_1} + \frac{\partial M_6}{\partial x_2} - Q_1 = I_1 \frac{\partial^2 u_o}{\partial t^2} + I_2 \frac{\partial^2 \phi_1}{\partial t^2}$$
$$\frac{\partial M_6}{\partial x_1} + \frac{\partial M_2}{\partial x_2} - Q_2 = I_1 \frac{\partial^2 v_o}{\partial t^2} + I_2 \frac{\partial^2 \phi_2}{\partial t^2}$$

where:

$$(I_0, I_1, I_2) = \sum_{k=1}^{N} \int_{z_k}^{z_{k+1}} \rho^k (1, z, z^2) dz$$

The normal mode method with Levy type solution was employed to evaluate the transient response of cross-ply and shallow shells with two simply supported edges at x=(0, a) and used arbitrary boundary for other edges at y= ±b/2 as in Fig. 2.

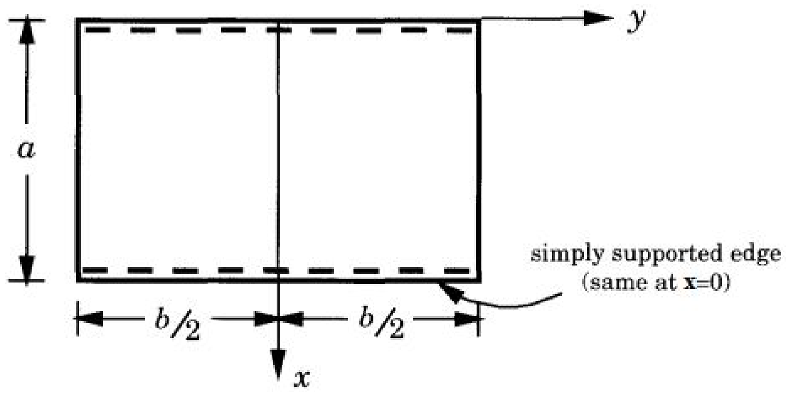


Fig. 2. Geometry and boundary conditions of laminated shallow shell.

For this method, it is suitable to satisfy the boundary conditions when representing the unknown quantities and the displacement field will be characterized as follows:

$$\begin{Bmatrix} u_o \\ v_o \\ \phi_1 \\ \phi_2 \\ w_o \end{Bmatrix} = \begin{Bmatrix} U_m(x_1)\cos\beta_m x_2 \\ V_m(x_1)\sin\beta_m x_2 \\ X_m(x_1)\cos\beta_m x_2 \\ Y_m(x_1)\sin\beta_m x_2 \\ W_m(x_1)\cos\beta_m x_2 \end{Bmatrix} \quad \beta_m = \frac{m\pi}{b} \quad m = (0,1,2,3,\dots) \tag{4}$$

In addition, the loading is stated as:

$$q(x,y,t) = \sum_{m=1}^{\infty} Q_m(y,t)\sin\beta_m x_2 \tag{5}$$

A set of equations is produced by substituting Eqs. (4) and (5) through (3) to get the spatial form as:

$$\{r\}' = [M]\{\ddot{r}\} + [K]\{r\} + \{b\} \tag{6}$$

he eigenvalues and their principles modes related to the free vibration also are obtained. The vector $\{r\}$ was described as:

$$\{r(x_1,t)\} = \{R_m(x_1)\}\,T_m(t) \tag{7}$$

where:

$$\{R'\} = [C]\{R\} \quad ,[C] = [K] - \omega^2{}_m\,[M] \tag{8}$$

A formal solution of Eq. (8) is:

$$\{R\,(x_1)\} = [S]\,\eta(x_1)\,\{I\} \tag{9}$$

where

$$\{I\} = [S]^{-1}\{k\} \quad ,\eta(x_1) = \begin{bmatrix} e^{\lambda_1 x_1} & & 0 \\ & \ddots & \\ 0 & & e^{\lambda_n x_n} \end{bmatrix} \tag{10}$$

At this equation, n=10 for FSDT and λ_i are the eigenvalues of [C] matrix while [S] represents the eigenvectors. To obtain homogeneous algebraic equations, substitute Eq. (9) into the boundary conditions at x_1=∓ a/2:

$$[B\,]\,[S]^{-1}\{\,k\,\} = \{0\} \tag{11}$$

The determinant should be zero for the non-trivial solution of Eq. (11):

$$|\,[B]\;\;[\,S\,]^{-1}\,| = 0 \tag{12}$$

By using the following form of Eq. (12) to avoid ill-conditioned matrices:

$$|\,B\,|/|S| \;= 0 \tag{13}$$

The eigenvalues and corresponding eigenfunctions, respectively, are given by Eqs. (13) and (9). To get the eigenfunctions for the orthogonal set, one must achieve the eigenfunctions of Eq. (8). Nayfeh [22] showed that the adjoint is:

$$\{Z'\} = -[C]^T\,\{Z\} \tag{14}$$

With the related boundary conditions:

$$\{Z\}^T \{Z\} {}^{a/2}_{-a/2} = 0 \tag{15}$$

With a formal solution:

$$\{Z\} = [D]\,[\xi(x_1)]\,\{d\} \tag{16}$$

where

$$[\xi(x_1)] = \begin{bmatrix} e^{\mu_1 x_1} & & 0 \\ & \ddots & \\ 0 & & e^{\mu_n x_n} \end{bmatrix} \tag{17}$$

The homogeneous equations were obtained after substitution of Eq. (16) into the boundary described at $x_1 = \pm\frac{a}{2}$:

$$[E]\{d\} = 0 \tag{18}$$

For the transient response, substitutes Eq. (7) in Eq. (6) and rearranged to obtaining:

$$\int_{-a/2}^{a/2}\{Z_n\}^T (\{R'_m\} - [K]\,\{R_m\})\,dx_1\,T_m(t) - \int_{-\frac{a}{2}}^{\frac{a}{2}}\{Z_n\}^T[M]\,\{R_m\}\,dx_1\ddot{T}_m(t) = \int_{-\frac{a}{2}}^{\frac{a}{2}}\{Z_n\}^T\,\{b_m\}\,dx_1 \tag{19}$$

One gets that Eq. (19) can be simplified to the uncoupled system

$$\ddot{T}_m(t) + \omega_m^2\,T_m(t) = \frac{1}{M_m}\int_{-\frac{a}{2}}^{\frac{a}{2}}\{Z_n\}^T\,\{b_m\}\,dx_1 \tag{20}$$

The state vector {r} for zero conditions is determined using Eq. (7), and the deflection is given by:

$$w(x_1,t) = \sum_{m=1}^{\infty} R_{mw}(x_1)\frac{1}{M_m\omega_m}\int_0^t Q_m(\tau)\,\sin\omega_m(t-\tau)\,d\tau\int_{-\frac{a}{2}}^{\frac{a}{2}}\{Z_n\}^T\,\{b_m\}\,dx_1 \tag{21}$$

3. Results and Discussion

The objective of the present work is to investigate the forced vibration response of spherical shallow shells through the thermal environment with different boundary conditions. Levy type solution is implemented for investigation based on first-order shell theory under different thermo-mechanical loading (sinusoidal and triangular uniform distributed pressures pulse). Also, demonstrate the effects of some design parameters for cross-ply such as modulus ratio, material types, shallowness ratio, layers number, aspect ratio and length to thickness ratio, and lamination schemes using Matlab 2019b. The properties for the lamina material (Epoxy/Carbon fiber) used in current case study are given [20]:

$E_1 = 132$ GPa ; $E_2 = 10.8$ GPa; $G_{12} = G_{13} = 5.56$ GPa; $G_{12} = 3.61$ GPa ; $\nu_{12} = 0.24$
$\nu_{13} = 0.0195$ $\nu_{23} = 0.24$; $\alpha_1 = 5 \times \frac{10^{-6}}{°\mathrm{C}}$; $\alpha_2 = 12 \times \frac{10^{-6}}{°\mathrm{C}}$; $\rho = 1282$ kg/m^3

3.1. Verification of results

The convergence of current case study is a significant method to have the accuracy of the computational. Investigative various numerical examples with Reddy and Khdeir [1] were used to check the current research technique. Figure 3 demonstrates the effect of thickness ratio for thin and thick shells on the response of centre deflection exposed to sine pulse distributed loading in the time domain and varied temperature environments. A larger thickness ratio (a/h) increases amplitude so does the temperature of the environment although its effect is smaller than that for thickness ratio, while the response of SCSC shell is minimum since it has the largest stiffness.

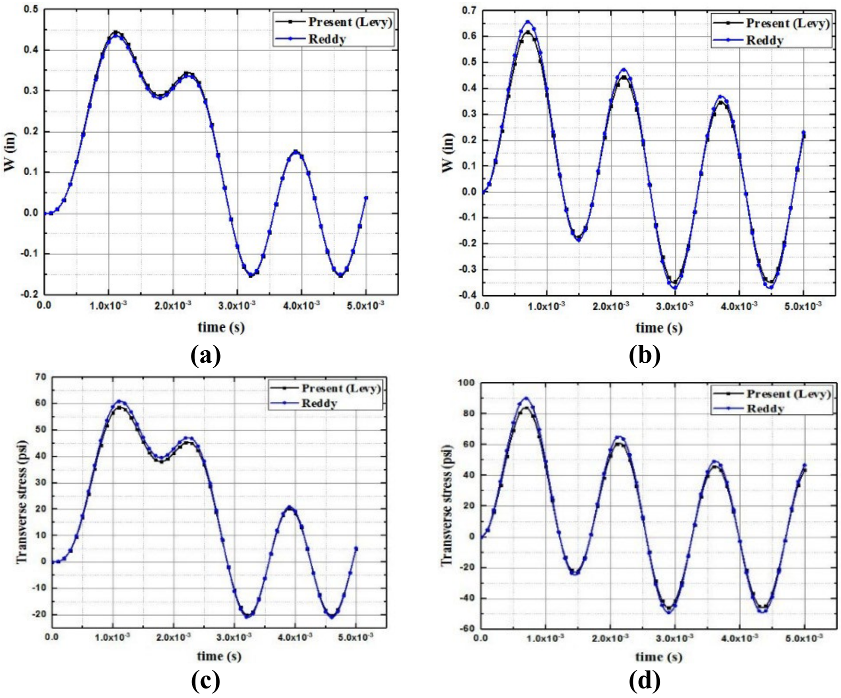


Fig. 3. Centre deflection and transverse stress response for (0/90) simply supported spherical shell subjected to sinusoidal and triangular distributed load a- W-sinusoidal b- W- triangular c- stress-sinusoidal d- stress-triangular.

3.2. Transient analysis in thermal environment

The present work includes investigating forced vibration analysis for spherical shells under thermal loading with different boundary conditions. Levy type solution is implemented for investigation based on first-order theory under different thermo-mechanical loading (sinusoidal and triangular uniform distributed pressures pulse). Also, demonstrate the effects of some design parameters for cross-ply such as modulus ratio, material types, shallowness ratio, layers number, aspect ratio and length to thickness ratio, and lamination schemes, coefficient of expansion ratio, and lamination schemes using Matlab 2019b.

Figure 4 shows the effect of thickness ratio for thin and thick shells on the response for the centre deflection exposed to sine pulse distributed loading of cross ply (0°/90°) subjected to sinusoidal distributed loading (sine pulse) in the time domain with different boundary conditions and different thermal environment. The center deflection response (W) increases when the thickness ratio is increased from 10 to 20 at 100 ° C. This increase in the deflection response results from a decrease in shallow spherical shell stiffness. The center deflection response of clamped boundary shell (SCSC) is lower compared to the simply supported (SSSS) and free (SFSF) boundary conditions.

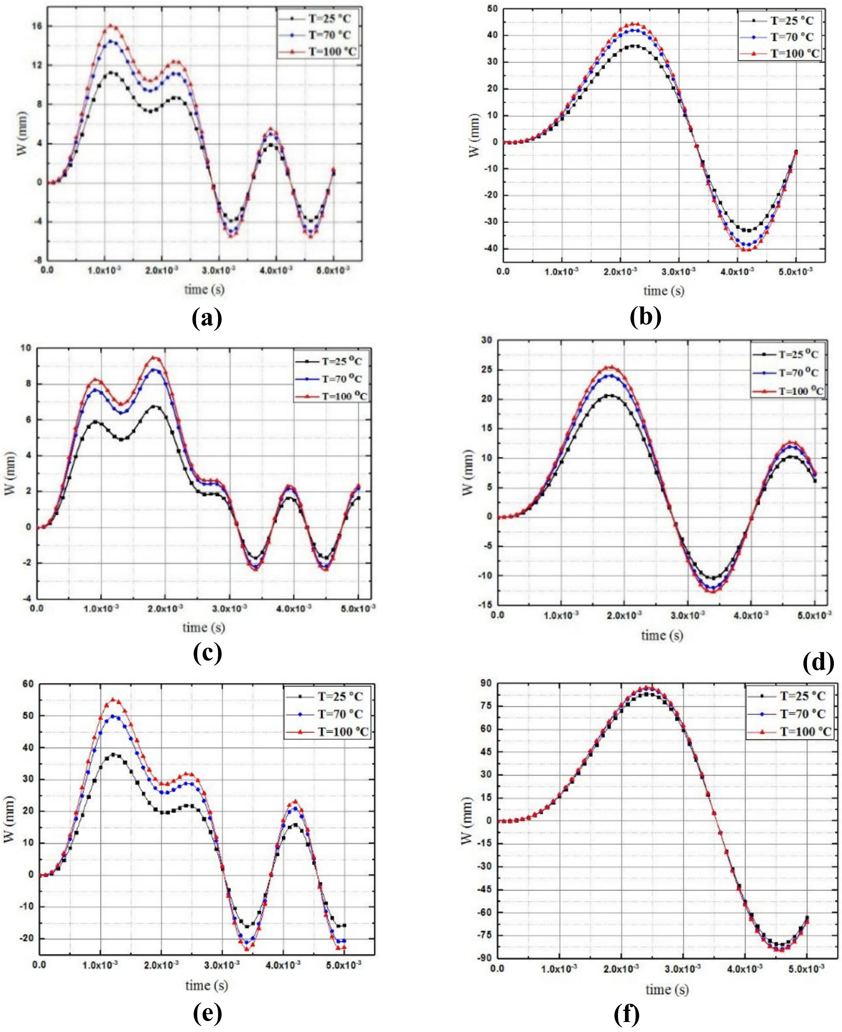


Fig. 4. Effect of length to thickness ratio (a/h) on the centre deflection response with different temperature for (0/90) shell subjected to sinusoidal distributed load (a) SSSS-a/h=10 (b) SSSS-a/h=20 (c) SCSC-a/h=10 (d) SCSC-a/h=20 (e) SFSF-a/h=10 (f) SFSF -a/h=20.

Figure 5 shows the influence of shallowness ratio (R/a) for anti-symmetric shells subjected to sinusoidal distributed load in the time domain with different boundary conditions and different thermal environments. From the result, it is clear that increasing the shallowness ratio from 5 to 10 in addition to increasing the temperature to 100 ° C, a clear increase in the center deflection response. If the shallow ratio increases to more than 10, then the increase in response is small because the shell is closer to the flat plate and the effect of thermal conditions has less effect on the response. The deflection response of clamped boundary (SCSC) is lower compare with simply (SSSS) and free (SFSF) boundaries.

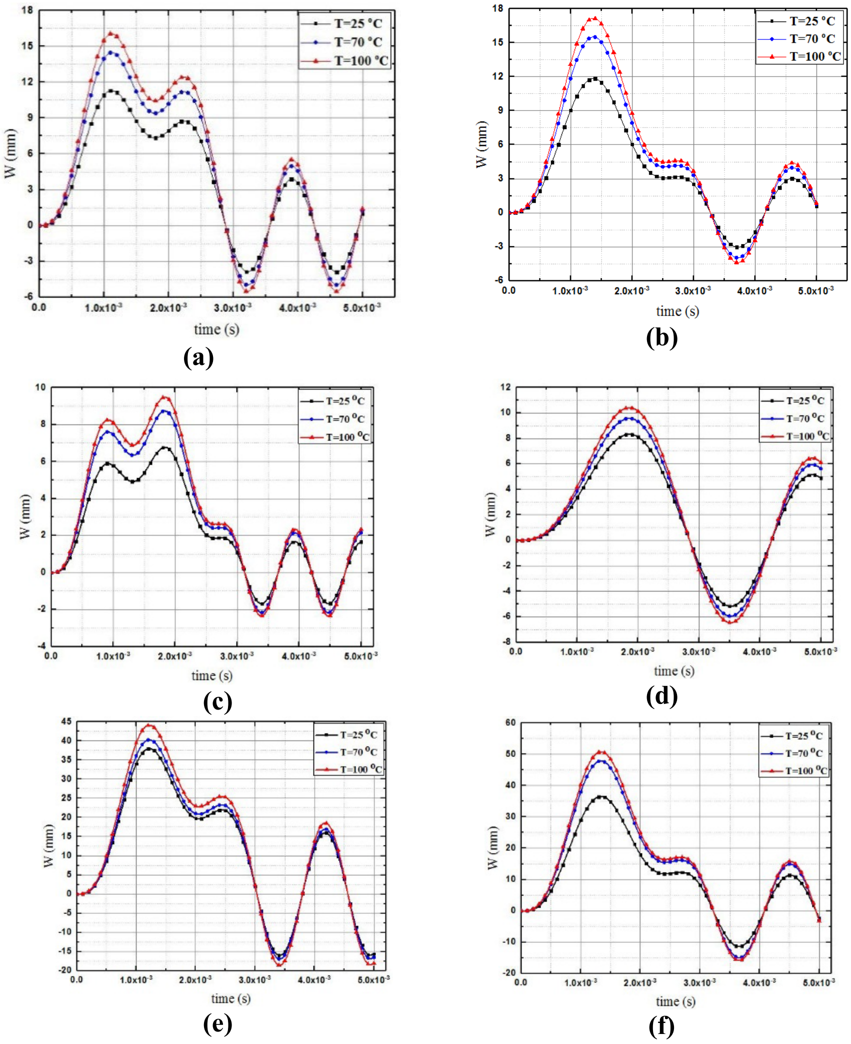
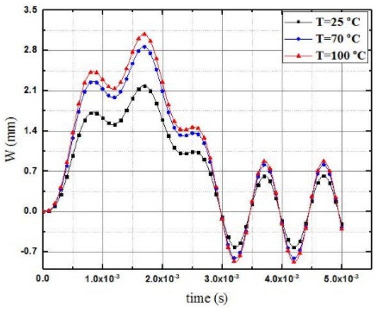
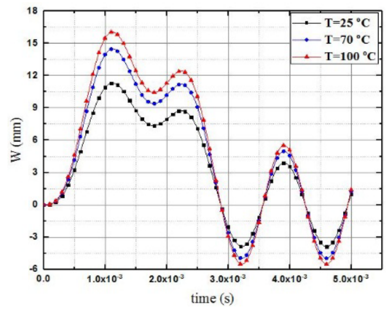


Fig. 5. Effect of shallowness ratio (R/a) on the centre deflection response with different temperature for (0/90) shell subjected to sinusoidal distributed load (a) SSSS-R/a=5 (b) SSSS-R/a=10 (c) SCSC-R/a=5 (d) SCSC-R/a=10 (e) SFSF-R/a=5 (f) SFSF - R/a=10.

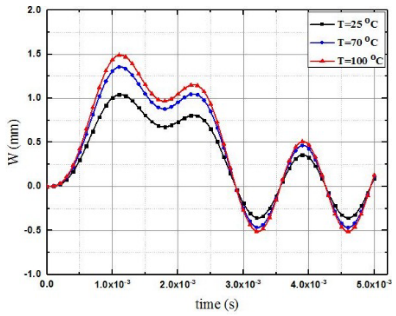
Figure 6 shows the influence of aspect ratio (a/b) on the center deflection response for antisymmetric shells exposed to sinusoidal distributed load in the time domain with different boundary conditions and different thermal environments. From the figure, it is remarked that the increasing aspect ratio from 0.5 to 1 as well as increasing the temperature to 100 ° C, an increase in the center deflection response of the shallow shell occurs and the response becomes minimum at aspect ratio 0.5 and increase with increasing in this ratio to 1, after which the response will decrease due to increase in the shallow shell stiffness. It is clear that as the shape of a structure changes while the boundary conditions and other parameters remain unchanged; the shallow shell structure becomes stronger. As a result, it is possible to say that temperature has a minor influence on the deflections response under mechanical loads in a thermal environment. When using laminated composite shells in a thermal environment, these exceptional results are a reliable recommendation in the design.



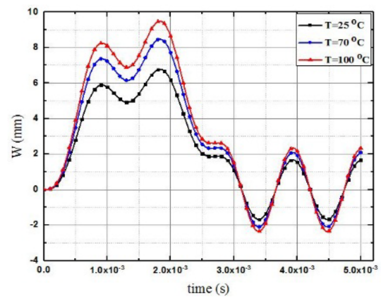
(a)



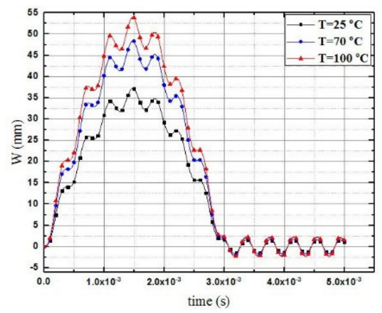
(b)



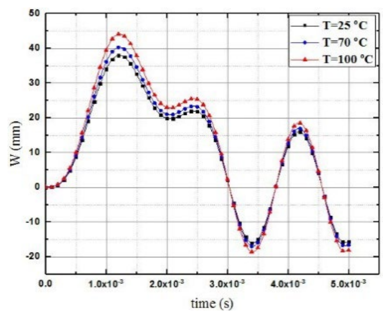
(c)



(d)



(e)



(f)

Fig. 6. Effect of aspect ratio (a/b) on the centre deflection response with different temperature for (0/90) shell subjected to sinusoidal distributed load (a) SSSS-a/b=0.5 (b) SSSS-a/b=1 (c) SCSC-a/b=0.5 (d) SCSC-a/b=1 (e) SFSF-a/b=0.5 (f) SFSF -a/b=1.

The center deflection response is substantially influenced by the number of layers as shown in Fig. 7 with a different temperature for (0/90) simply supported shell subjected to sinusoidal distributed load. The presence coupling of stretching-bending in shell laminates, influences decreasing deflections when the layers number increase for the same total thickness of laminate and the shallow shell becomes stiffer than the shell with a smaller number of layers.

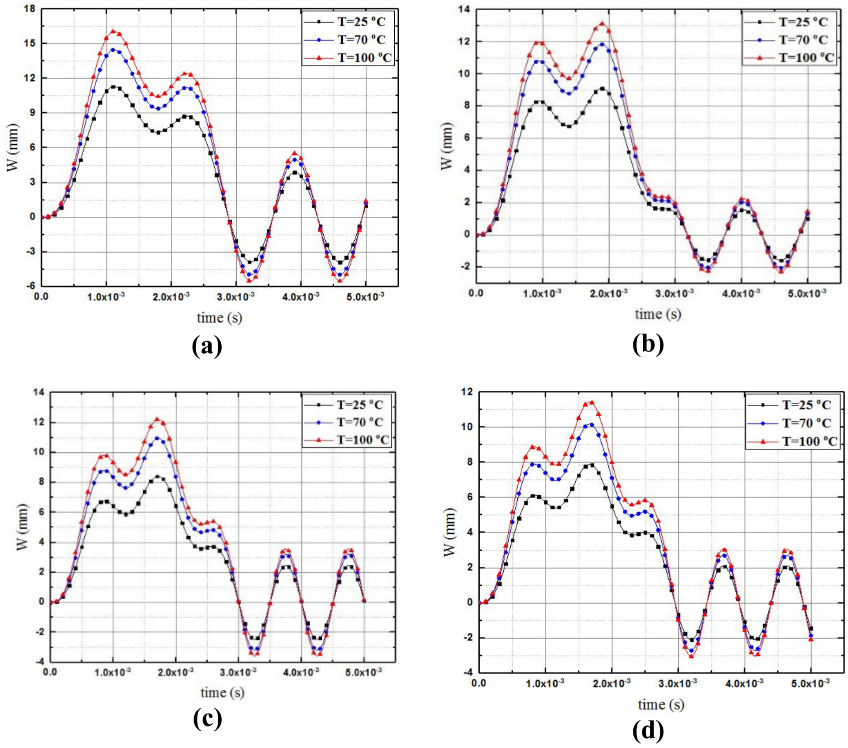
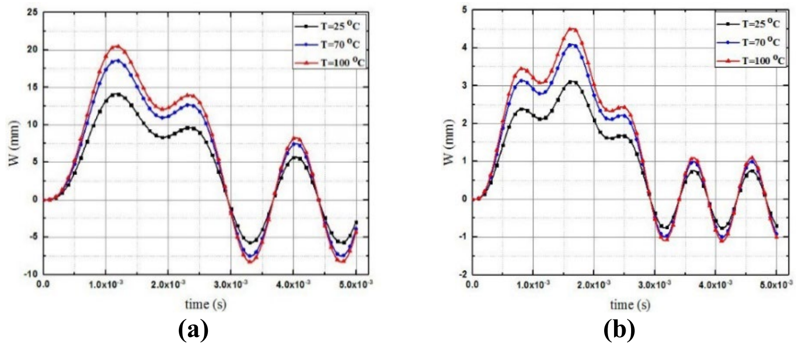


Fig. 7. Effect of the number of layer (N) on the centre deflection response with different temperature for (0/90) simply supported shell subjected to sinusoidal distributed load (a) N=2 (b) N=4 (c) N=8 (d) N=10.

Figure 8 shows the effect of modular ratio (E1/E2) on the deflection response with different temperatures. In all cases of the deflection response, shell material orthotropicity increased as the modular ratio increased and which changing the shell stiffness greatly.



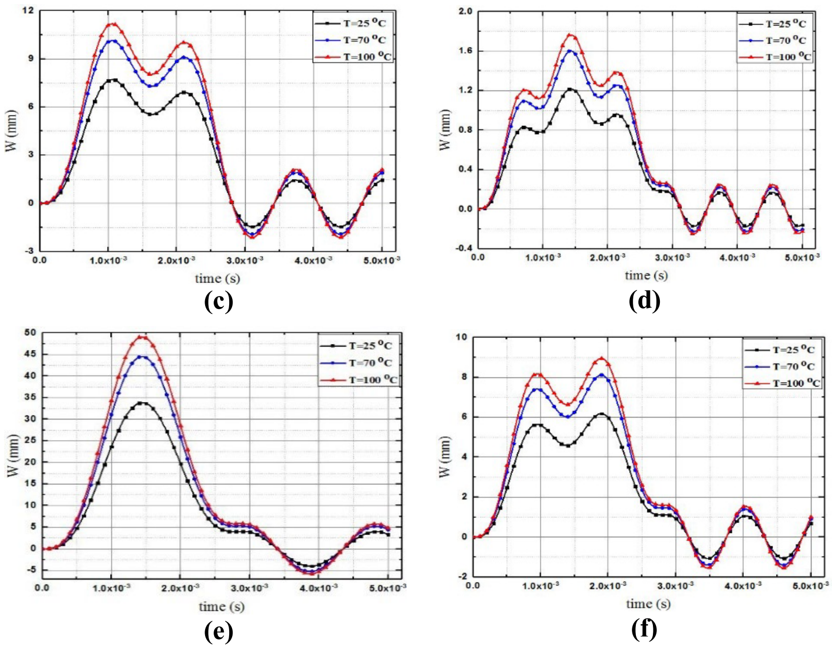


Fig. 8. Effect of Modular ratio (E_1/E_2) on the center deflection response with different temperature for (0/90) shell subjected to sinusoidal distributed load (a) SSSS- E_1/E_2=10 (b) SSSS- E_1/E_2=30 (c) SCSC- E_1/E_2=10 (d) SCSC- E_1/E_2=30 (e) SFSF- E_1/E_2=10 (f) SFSF - E_1/E_2=30.

4. Conclusions

The novelty includes used Levy type approach to investigate the transient response of anti-symmetric and symmetric cross-ply laminated spherical shallow shells with uniform temperature distribution. The investigation offers the following:

- When compared to other methods, the formulation by Levy approach can accurately evaluate the transient response behavior of anti-symmetric and symmetric of cross-ply laminates shallow shell.
- The transient response increase as the length to thickness ratios (a/h), shallowness ratios (R/ a), aspect ratios (a/b) increase while decrease when the layers number and modular ratio increase with increasing the temperature to 100 °C.
- The deflections and stress responses in the thermal environment depending on whether the shell is clamped, simply supported or free support.
- The parametric design such as layers number, (a/h) ratio as well as modular ratio, which has a significant effect on the deflection response also has greatly affected on the stiffness of the shallow shell than the other parameters such as a shallowness ratio (R/a).

Nomenclatures

$[D]$	The eigenvectors
E	Modulus of elasticity, GPa
G	Shear modulus, GPa

N_i	In-plane loading, N
N_i^T	Thermal forces due to the thermal environment, N
Ri	The radii of curvature in the x and y directions, m
$\{r\}$	The state vector
u_i	Displacements of the mid surface, m
$\{Z_n\}^T$	Adjoint eigenfunction
Greek Symbols	
α	Thermal expansion coefficient, 1/°C
ε	strain
μ_i	The distinct eigenvalues
ν	Poisson's ratio
ρ	The density of the kth layer, kg/m^3
$\Phi(x_i)$	The state transition matrix
ϕ_i	The rotations to the reference surface
ω	Frequency, rad/s
Abbreviations	
ES-FEM	Edge-based smooth finite element method
FEM	Finite element method
FRC	Fiber-reinforced composite
FSDT	First-order shear deformation theory
HSDT	High-order shear deformation theory

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