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Numerical Analysis of Hygrothermal effect on Laminated Composite Plates

Pranoti Hunungare

Pranoti Hunungare, PG student, Department of Civil Engineering S.S.D.G.C.T.'s Sanjay Ghodawat Group of Institutions, Atigre, Kolhapur– 416118, Maharashtra, India.

Abstract – *A numerical modeling/analysis, which incorporates shear deformation as well as transverse normal thermal strains is studied and assessed for the hygrothermal stress analysis of cross-ply laminates subjected to linear or gradient thermal profile across thickness of the laminate. Results from numerical analysis using finite element tool ABAQUS [1] in terms of displacement and stresses are compared with those of analytical solutions published in most of previous investigations [2, 3]. Hygrothermal response due to a variation in temperature and moisture concentrations has been studied for multi-layered angle ply composite plates with symmetric and antisymmetric lamina stack. The numerical analysis fairly predict the performance of Laminated Composite Plate (LCP) as that of given by various numerical and analytical methods/theories.*

***Key Words*: LCP, ABAQUS, Numerical solution, Hygrothermal analysis, transverse shear.**

1. Introduction

Composites are increasingly used for fabrication of lightweight components. Thin plates and shells are often used in aircraft wings, fuselage, auxiliary devices and construction field. In the analysis or design of laminated structures the critical quantities of interest like maximum transverse deflection, stress, buckling load, first ply failure load etc. have to be evaluated accurately. Accordingly, this study is intended to study Hygrothermal environmental effect on composite laminated plates.

Moisture and temperature changes affect the stiffness and strength of composites, and generate tensions between bonded sub-components [3, 4]. Their static and dynamic behaviour can depend significantly on such hygrothermal conditions. The combination of both phenomena is usually known as hot-wet (H/W) conditions. This state is characterized by moisture absorption by the matrix due its exposure to humid air and high temperature, which reduces the mechanical properties of the laminate as stated by Chang et al. [5]. Additionally, this absorption causes a volume increase and consequently internal tensions between elements and interfaces. Experimental results show the influence of the temperature in moisture absorption, so this phenomenon should be analyzed for different thermal load cases and hygrothermal effects should be considered in any design and optimization process. Thermal stress analysis is important in composite laminates due to high transverse stresses and different thermal expansion coefficients in the orthotropic layers of laminate. It should be noted that research on hygrothermal behavior of laminated composite plate seems to be somewhat scarce.

The analysis of composite laminated structures is in general more difficult in comparison with conventional single-layer structures due to the exhibition of soft transverse shear modulus and discontinuous material properties across the thickness of laminates. In view of this situation, a number of two-dimensional theories [6], which are simpler and more efficient compared to three-dimensional theories, have been proposed to study the thermal behavior of laminates. The classical laminated plate theory [7] and the first-order shear deformation theory [8] are typical deformation theories for the analysis of laminated composite plates. The first order theories assume a constant transverse shear strain across the thickness direction, and a shear correction factor is generally applied to adjust the transverse shear stiffness for the static and stability analyses.

Benkhedda et al. [9] assessed an approximate model to evaluate hygrothermal stress in laminated composite plates during moisture desorption taking into account the change of mechanical characteristics induced by the variation of temperature and moisture. Chakrabarti and Singh [10] investigated hygrothermal analysis of laminated composite plates by using an efficient higher order shear deformation theory. Kant and Shiyekar [11] carried out complete analytical model, which incorporates shear deformation as well as transverse normal thermal strains for the thermal stress analysis of cross-ply laminates subjected to linear or gradient thermal profile across thickness of the laminate. Zhang et al. [12] investigated a progressive failure analysis model involving hygrothermal effects for predicting failure of composite structures in hygrothermal environments. Chang et al. [13] conducted a detailed experimental and numerical investigation on absorption and shear behaviors of stiffened composite panel subjected to hygrothermal environment.

Mantari et al. [14] discussed a new trigonometric shear deformation theory for isotropic and composite laminated and sandwich plates. Zenkour [15] presented a sinusoidal shear deformation plate theory to study the response of multi-layered angle ply composite plates due to a variation in temperature and moisture concentrations. Matsunaga [2] studied a two-dimensional global higher-order deformation theory and presented for the evaluation of interlaminar stresses and displacements in cross-ply multi-layered composite and sandwich plates subjected to thermal loadings. Zhen et al. [3] has analyzed a four-node quadrilateral plate element based on the global–local higher order theory (GLHOT) proposed to study the response of laminated composite plates due to a variation in temperature and moisture concentrations. Ganapathi et al. [16] were investigated the effect of moisture concentration and the thermal gradient on the free flexural vibration and buckling of laminated composite plates.

This paper presents a numerical analysis for analyzing displacements and transvers shear stresses of cross-ply multilayered composite plates subjected to hygrothermal loadings. The continuity conditions at the interface between layers and stress boundary conditions at the top and bottom surfaces are accessed. For multilayered composite plates, the distribution of displacements and transverse shear and normal stresses in the thickness direction has been obtained accurately at the ply level. Present numerical results are compared with those of the published three-dimensional layerwise theory [2, 3] in which both in-plane and normal displacements are assumed to be C^0 continuous in the continuity conditions at the interface between layers. The numerical analysis in the present paper can predict displacement and stress distributions of simply supported laminated composite plates subjected to hygrothermal loadings accurately.

2. Numerical Example

a. *Defining numerical examples*

A numerical modeling for a laminate composite simply (diaphragm) supported on all the sides is presented. The geometry of the laminate is such that the side ‘a’ is along ‘x’ axis and side ‘b’ is on ‘y’ axis. The thickness of the laminate is denoted by ‘h’ and is coinciding with ‘z’ axis. The reference mid-plane of the laminate is at h/2 from top or bottom surface of the laminate as shown in Fig. 1. The lamina reference axes system is also shown in the figure with fiber direction. Figure also illustrates the mid-plane positive set of displacements along (x–y–z) axes. The plate is composed of n orthotropic layers oriented at angles α_1, α_2,…, α_n made by fiber direction to the x-axis. The material of each layer is assumed to posses one plane of elastic symmetry parallel to the x–y plane. Perfect bonding between the orthotropic layers for temperature-independent mechanical and thermal properties may be assumed.

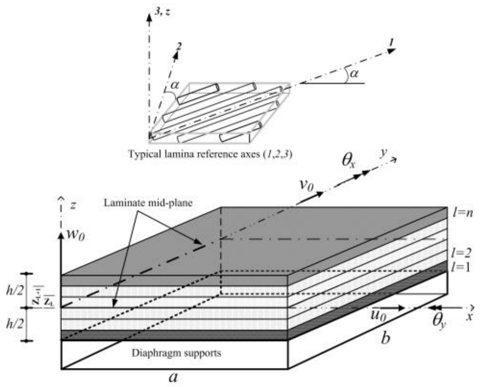

Fig. 1. Laminate geometry with positive set of lamina/laminate reference axes, displacement components and fiber orientation.

b. *Material analyzed (properties)*

The orthotropic material constants of each layer are E_1, E_2, E_3, G_{13}, G_{12} and G_{23}. Poisson’s ratios are given υ_{13}, υ_{23} and υ_{12} other Poisson’s ratios can be obtained by the reciprocal theorem. Although various material properties have been used for parametric studies of numerical examples in the literature, the material properties of the individual layers are taken to be the following two cases for typical of fibrous composites, namely:

Material-1: laminated plates [2]:

$E_1/E_2 = 15$, $E_2 = 10$ GPa, $G_{12}/E_2 = 0.5$, $G_{22}/E_2 = 0.3356$,

$\nu_{12} = 0.3$, $\nu_{22} = 0.49$, $\alpha_1/\alpha_0 = 0.015$, $\alpha_2/\alpha_0 = 1.0$.

In many investigations, material properties of composite laminates are assumed to be independent of temperature. However, the elastic moduli of laminates in general degenerate with the elevation of temperature. The material properties used for LCP subjected to moisture concentration effect are as follows:

Material-2: laminated plates [3]:

$G_{13} = G_{12} = 0.6$; $G_{23} = 0.5{*}G_{12}$; $\upsilon_{12} = 0.3$; $\beta_1 = 0$ and $\beta_2 = 0.44$

$E_0 = 1$ GPa; $T_0 = 300$ K and $\alpha_0 = 10^{-6}$ K^{-1}

For moisture concentration of 0.50:

Elastic moduli $E_1 = 130$ GPa and $E_2 = 9.0$ GPa.

The material properties were assumed to be same in all the layers and the fibre orientations may be different among the layers of laminated plates. The fibre orientations of the different laminae alternate between 0^0 and 90^0 with respect to the x-axis. The thickness of each layer was identified for the 0^0 and 90^0 layers in the laminates. Both symmetric ($0^0/90^0/0^0$) and antisymmetric ($0^0/90^0$) laminations with respect to the middle plane were considered with different aspect ratio of (S = a/h) 5, 10 and 20. In the symmetrical laminates having odd number of layers, the 0^0 layers are at the outer surfaces of the laminate.

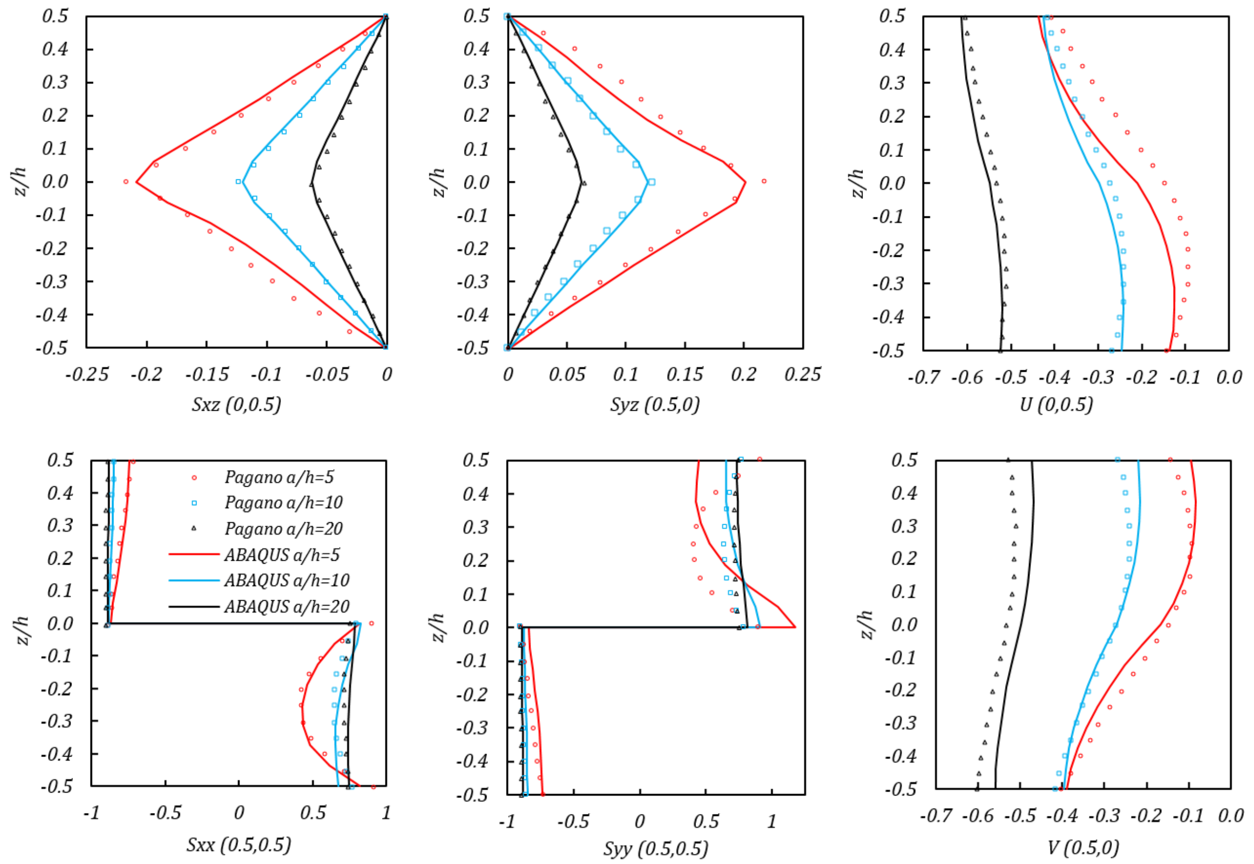

Fig. 2. Displacement and stress distributions of 2-layer antisymmetric cross-ply laminated composite plates with constant temperature load (a/b = 1, [$0^0/90^0$]) for Case-1: $T_0 = T_{11}^{(0)}$ *(*ABAQUS Plots – Present)*

c. Hygrothermal loading effect

The plates were assumed to be subjected to a sinusoidal hygrothermal load ($T_{rs}^{(n)}$ and $M_{rs}^{(n)}$). The first two terms $T_{rs}^{(0)}$ and $T_{rs}^{(1)}$ were considered in the following analysis.

Two Cases are studied, in line with Matsunaga H. [2];

Case-1: With Constant temperature load along the thickness direction: Temperature will be Constant along the thickness ($T_{rs}^{(0)}$ i.e. +1 from +h/2 to –h/2).

Case-2: With Gradient temperature load along the thickness direction ($h^*T_{rs}^{(0)}$ i.e. +1 at +h/2 - top surface; 0 at h=0 - mid-plane; and -1 at –h/2 - bottom surface).

The amplitude of thermal loadings T_0 is equal to $T_{rs}^{(0)}$ or $h^*T_{rs}^{(0)}$ according to uniform temperature or temperature gradient, respectively.

T(z) obtained by considering equal rise and fall of the temperatures at top and bottom of the laminate surface as:

$$T\left(x, y, \pm\frac{h}{2}\right) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} T_{mn} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right)$$

Similarly, M(z) obtained by considering equal rise and fall of the moisture at top and bottom of the laminate surface as:

$$M\left(x, y, \pm\frac{h}{2}\right) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} M(z)_{mn} \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right)$$

Where, $T(z)_{mn}$ and $M(z)_{mn}$ as amplitude for Sin loads.

All the numerical results shown in the dimensionless quantities were defined as follows:

$(S_{xx}; S_{xy}; S_{yy}; S_{xz}; S_{yz}; S_{zz}) =$

$(S_{11}; S_{12}; S_{22}; S_{13}; S_{23}; S_{33}) / (\alpha_0 T_0 E_0)$;

$(U; V; W) = (u, v, w) / (\alpha_0 T_0 h)$;

Where $\alpha_0 = 10^{-6}$/K and E_0 = 1 GPa as reference thermal expansion coefficient and elastic coefficient, respectively. The amplitude of thermal loadings T_0 equal to $T_{rs}^{(0)}$ or h $T_{rs}^{(1)}$ according to uniform temperature or temperature gradient, respectively.

Composite laminated plate is modelled as solid plate with shell homogeneous section in ABAQUS [1]. The model discretized using SC8R (8-node quadrilateral continuum shell, reduced integration) shell elements, as shown in Fig. 4.

The maximum transverse displacement for composite laminated plate was analysed, having dimension 1000mmx1000mm simply supported square laminated plate of side 'a' and thickness 'h' was composed of equal thickness layers oriented at $[0^0/90^0$ and $0^0/90^0/0^0]$ subjected to doubly sinusoidal temperature load with unit temperature which will increase as amplitude for m=1, n=1. Following table will show the comparison of results (in terms of displacement and stress) obtained based on current study in ABAQUS and published documented results from open literatures.

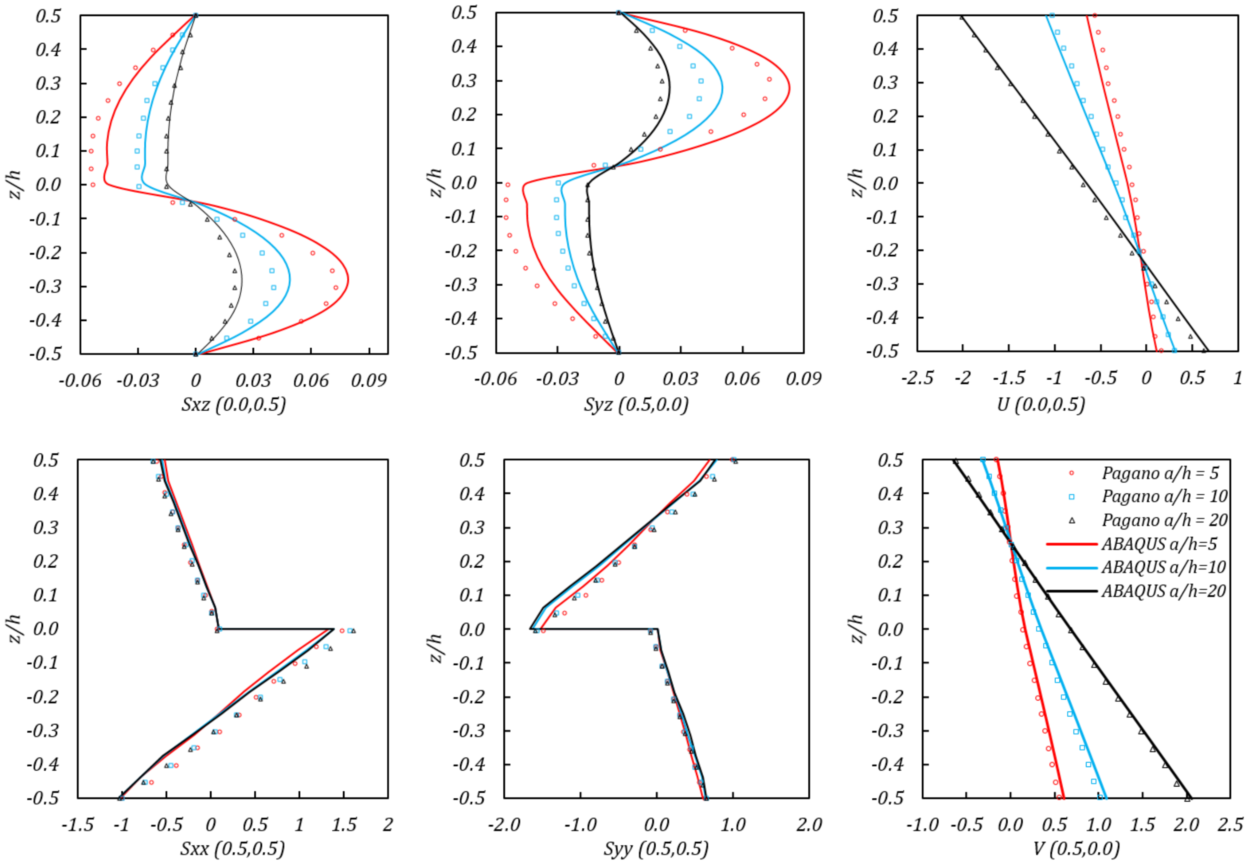

Fig. 3. Displacement and stress distributions of 2-layer antisymmetric cross-ply laminated composite plates with gradient temperature load (a/b = 1, $[0^0/90^0]$) for Case-2: $T_0 = h\, T_{11}^{(1)}$ *(*ABAQUS Plots – Present)*

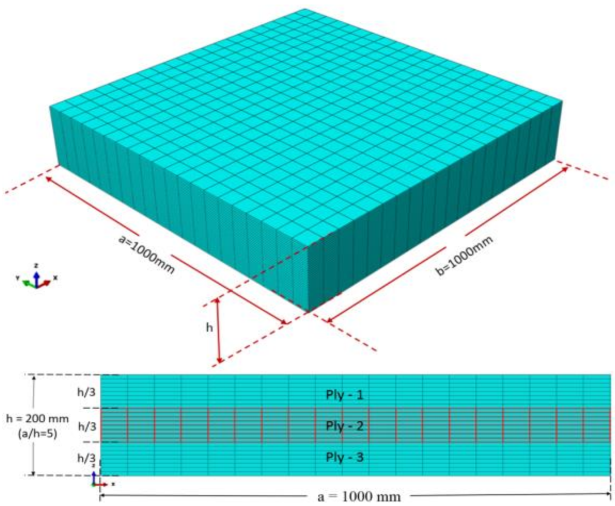

Fig. 4. 3D ABAQUS model of 3-ply sets of lamina/laminate.

3. Numerical results and Discussion

Pagano [17] and Zhen [3] presented effect of temperature and moisture concentration using various shear deformation theory/analytical solutions. In present study same examples (studied by Pagano [17] and Zhen [3]) of composite laminated plate subjected to hygrothermal environment were analysed are analyzed to show the accuracy, capability and applicability of numerical analysis in finite element analysis (FEA) software package ABAQUS v6.14.

The response of composite laminated plate subjected to hygrothermal environment traced numerical analysis using ABAQUS and plotted in terms of normalized stress and displacement. The values of normalized transverse displacement ($\overline{w}$), the normalized in-plane normal stresses ($\overline{\sigma}_x$) and the normalized transverse shear stress ($\overline{\tau}_{xz}$) were presented for different aspect ratio 5, 10 and 20 and compared with the three-dimensional layer wise solutions of Pagano (1970) which was computed by Matsunaga H. [2] and Zhen [3].

a. Displacement and stress distributions in LCP under Temperature effect

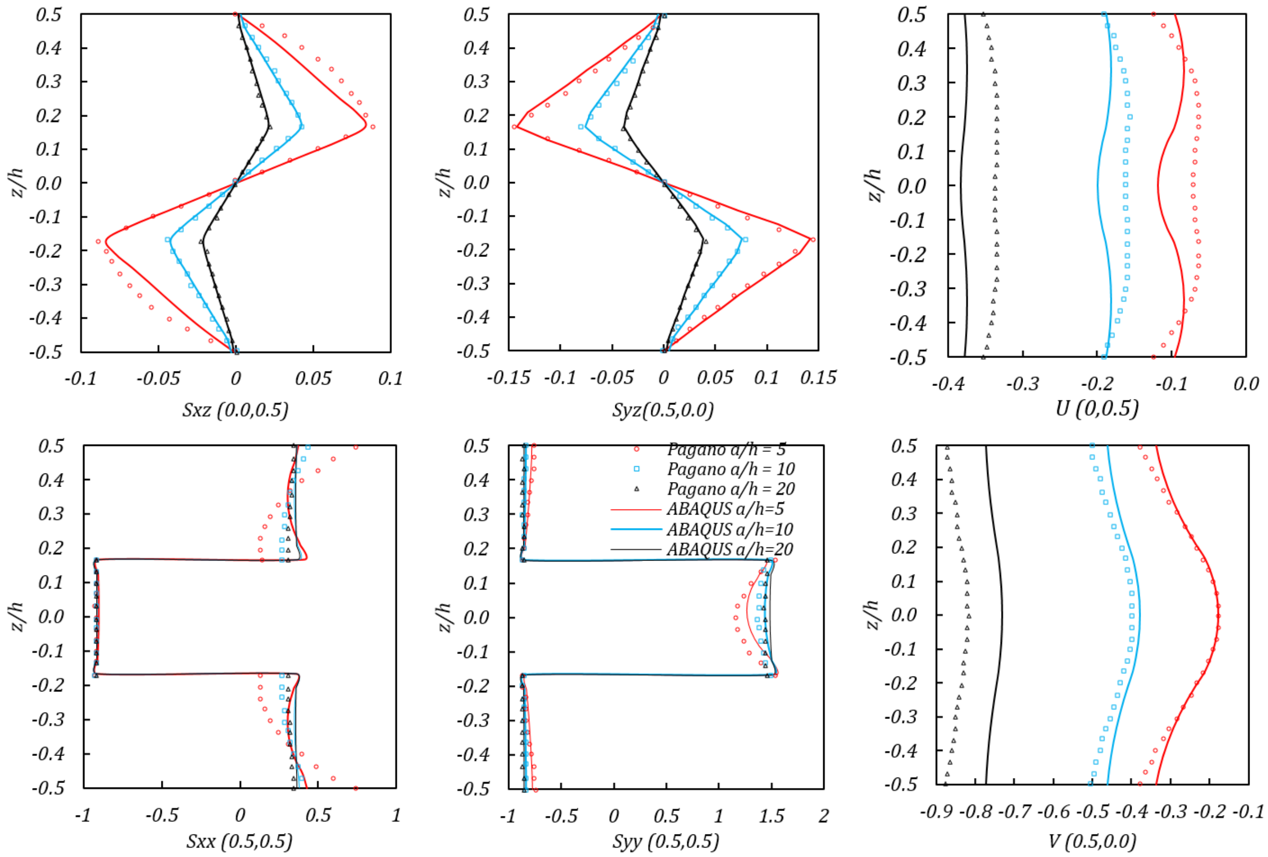

Fig. 5. Displacement and stress distributions of 3-layer symmetric cross-ply laminated composite plates with constant temperature load (a/b = 1, [$0^0/90^0/0^0$]) for Case-1: $T_0 = T_{11}^{(0)}$ *(*ABAQUS Plots – Present)*

For simply supported antisymmetric 2-layer [$0^0/90^0$] composite laminated plates of Material-1, stress and displacement distributions for thermal loadings of constant (case-1) $T_0=T_{11}^{(0)}$ and distributed linearly through the plate thickness (case-2) $T_0=hT_{11}^{(1)}$ are shown in Fig. 2 and Fig. 3 respectively.

Fig. 5 and Fig. 6 shows the distributions of stresses and displacements of simply supported symmetric 3-layer [$0^0/90^0/0^0$] laminated plates subjected to thermal loadings of uniform temperature (case-1) and temperature gradient (case-2), respectively for different aspect ratio 5, 10 and 20.

Compared with the three-dimensional layerwise solutions of Pagano [17], the present results of numerical analysis are quite acceptable even in the case of a very thick laminate. The most important match is the continuity conditions of displacement components at the interface between layers. In case of numerical analysis in ABAQUS, as LCP is modelled as 3D shell elements (SC8R). This shell element is defined by five integration points specified through the thickness of each layer with the models. This provides sufficient data to describe the stress distributions through the thickness of each layer. At the interface between layers there is a sharing of integration point. At interface of layers, shared integration point will represent both layer properties and will reflect the results for both layers. This integration point at interface of layers will help to trace the continuity conditions of displacement and stress components at the interface between layers.

b. Displacement and stress distributions in LCP under Moisture concentration effect

This example studies the effects of moisture concentrations on the material properties and the static response of the simply-supported square plates for a constant moisture distribution across the plate thickness. For relationships between moisture concentrations and material properties are referred from Zhen and Wanji [3]. In order to compare with published results, the entire laminated plate is modelled using 3D shell elements (SC8R).

The LCP study consists of four equal (thickness) layers of same material but oriented in different directions ($0^0/90^0/0^0/90^0$, a/h=5) with antisymmetric arrangement about the mid-plan. In current study, the performance of LCP is analyzed for several of moisture concentrations (ranging from 0.25% to 1.50%) with corresponding material properties.

For simply supported antisymmetric 4-layer composite laminated plates [$0^0/90^0/0^0/90^0$] of Material-2, stress and displacement distributions through the thickness of LCP for moisture concentration loadings are shown in Fig. 7.

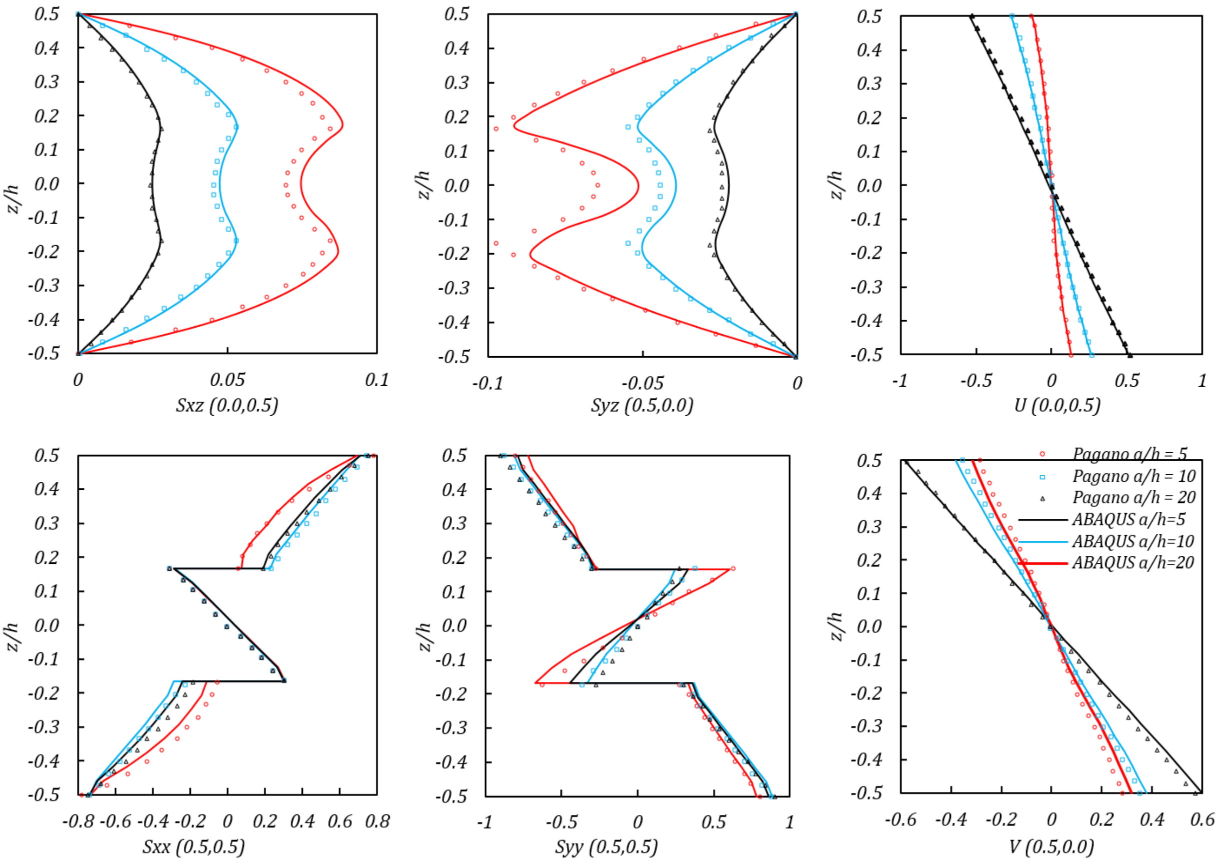

Fig. 6. Displacement and stress distributions of 3-layer symmetric cross-ply laminated composite plates with gradient temperature load (a/b = 1, [$0^0/90^0/0^0$]) for Case-2: $T_0 = h\, T_{11}^{(0)}$ *(*ABAQUS Plots – Present)*

Numerical results in Fig. 7 show that present ABAQUS results agree exactly with the three-dimensional elasticity solutions by Zhen et al. [3]. However, in-plane displacements computed are less accurate in comparison with the exact solution. It is found that the transverse shear stresses predicted from the higher-order theory [10] are discontinuous at the interfaces of laminated plates. Moreover, the first-order theory predicts zero transverse shear stresses for thermal expansion problems which does not agree with the actual situation. This example shows that the numerical analysis can be used effectively in predicting hygrothermal response of laminated plates.

4. Conclusions

In the present numerical analysis it is observed that, the results for hygrothermal effects on square simply supported LCP for various aspect ratios and orientation from ABAQUS and analytical theories in terms of quantities of non-dimensional transverse displacement, normal stress and shear stress are in well agreement. The continuity conditions at the interface between layers and stress boundary conditions at the top and bottom surfaces are satisfied completely. In line with analytical results, transverse shear stress, as computed from the numerical simulations, persists the effects like, decrease in transverse shear stress with increasing width to thickness ratio (a/h). The current comparative study validate the numerical methodology presented for the analysis of hygrothermal effects on LCP.

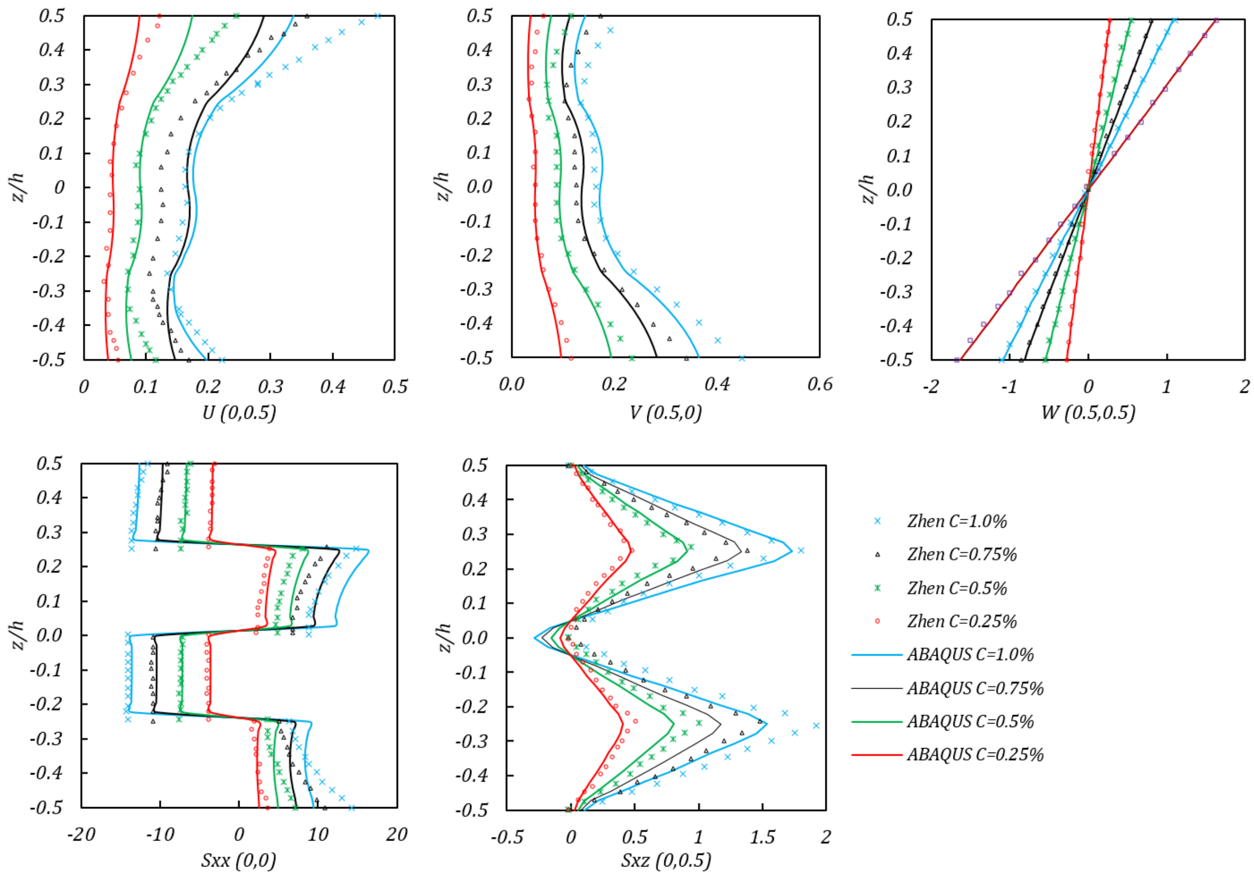

Fig. 7. Comparison of displacements and stresses with different moisture concentrations and material constants (a/b = 1, [$0^0/90^0/0^0/90^0$]) for a/h = 5. *(*ABAQUS Plots – Present)*

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