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Research paper

Numerical investigating of the effect of material and geometrical parameters on the static behavior of sandwich plate

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Abstract

Studying the behavior of sandwich panels is very important due to their widespread use in different industries. Therefore, over the past decades, various theories have been proposed to study the behavior of these panels. In this paper a higher order global-local theory with 3D equilibrium-based corrections is presented to study behavior of thick and thin sandwich plate with flexible and auxetic core. In addition to correcting the results with 3D elasticity equations, another important advantage of the presented theory is the ability to consider the transverse core deformation of the sandwich panels. It should be mentioned that to study the behavior of thick sandwich panels, especially with soft core, the existence of this feature is very necessary and has a great effect on the accuracy of the obtained results. Comparison of the obtained results with those existing in valid references showed that the formulation of the provided finite element had a very good accuracy even for thick and thin sandwich plates. Finally, the effect of different material and geometrical parameters on the behavior of sandwich plates are carefully investigated using the presented theory.

1. Introduction

Over the past few decades, the advancement of science and technology has inspired researchers to find new materials, such as auxetic materials. An important feature of these materials is that when pressed, they tend to contract in other directions in contrast with the usual materials. On the other hand, over the past decades, the use of sandwich plates has expanded extensively in various industries, such as aerospace, marine, automotive, and the like.

One of the structures that have attracted many researchers is sandwich structures with cores of auxetic materials. On the other hand, due to the increasing growth of composite structures in various industries, the evaluation of interlayer stresses is as important as the calculation of other stresses [1]. Sandwich plates are one of the most important structures in different industries. Since the three-dimensional analytical solution of sandwich plates has many limitations, the analysis of such structures based on the two-dimensional theory of plates and shells is very practical and noteworthy.

The basis of these theories is to convert three-dimensional models to two-dimensional by eliminating the dependence of the model on thickness. For this purpose, various methods such as equivalent single-layer theories, layer wise theories, and theories based on the principle of superposition (zigzag and global-local) have been proposed [2]. However, some of the theories presented also have shortcomings. For example, if there are significant changes between the properties of the layers or if the structure is made up of a large number of layers, global theories will not be able to properly assess local displacements. As a result, calculated strain and stress by these theories will not be accurate. Thus, equivalent single-layer theories such as CLassical Theory (CLT), First-order Shear Deformation Theory (FSDT), and Higher-order Shear Deformation Theory (HSDT) [3-6] do not provide accurate results in such cases. Equivalent single-layer theories [7-10] are commonly used to analyze the overall behavior of structures.

In layer wise theories, each layer of the plate or shell is considered as an independent layer, and in each layer, the description of the displacement field is used independently. The resulting models are also called layered (local) or local theories [11-14]. Although this theory has good accuracy and correctly displays the zigzag effects of displacement in composites, the number of independent parameters depends on the number of layers and therefore the time of their calculations is high [15].

Therefore, theories based on the principle of superposition were presented that in addition to considering the global and local behavior of the sandwich plate, it has fewer independent parameters and independent of the number of layers and therefore requires less time to analyze the structure [16]. It should be noted that different methods have been presented for converting three-dimensional models of multilayered sheets into two-dimensional models (removal of thickness dependence) with the proper selection of in-plate variables of these structures. Some of the most important of these studies are the following. Shariayat [17-19] examined the dynamic buckling of imperfect plates with piezoelectric sensors and operators under mechanical, electrical, and thermal loads while considering the dependence of material properties on temperature by presenting a finite element formulation based on the high-order theory of shear deformation, along with an effective numerical algorithm for solving nonlinear equations. Dafedar et al. [20] also proposed a mixed, higher-order analytical theory for solving composite face sheets. Similarly, Dehkordi et al. [21] used a multi-layered theory to investigate nonlinear buckling of damaged composite faces. Malekzadeh et al. [22] presented an improved high-order theory for analyzing the dynamic behavior of a sandwich plate with flexible core.

In this method, the first order theory was employed in surface and the theory of elasticity is used in the core. In 2009, Carrera et al. [23] examined and evaluated the accuracy of all kinds of two-dimensional theory including single-layer equivalent, layered (first to seventh order), zigzag and mixed when it came to the static and vibratory analysis of sandwich plates. Brischetto et al. [24] examined the results of bending of the sandwich plate for different geometric ratios and different rigidity ratios of surface to core by adding the zigzag function to the first and third shear theory. Kapuria et al. [25] evaluated the accuracy of general-local theories in terms of the bending and vibration analysis of laminated and sandwich sheets.

Also, in 2013, Botshekanan et al. [26] used a mixed theory, based on the CUF model, including equivalent single-layer theory and layered theory with different degrees in order to carry out a static analysis of sandwich sheets. Li and Liu [27] developed the Zigzag theory to employ the double superposition principle. Shariyat [28] added the effect of vertical transverse strains to the double superposition theory of Li and Liu. Chakrabarti et al. [29] presented a two-dimensional finite element model based on the high-order zigzag theory to analyze multilayered and sandwich sheets. In the proposed model, the fourth-order functions were used for the transverse core displacement and the surface deformation was considered to be fixed when it came to in-plane displacements of the surfaces and the degree polynomial core. In this study, the inter-layer continuity of transverse stresses was also considered. Demasi [30] presented a semi-zigzag theory, based on the CUF theory, for the analysis of composite and sandwich sheets. In this research, the effect of the type of theory (equivalent single-layer or zigzag) and the degree of displacement field on three direction of length, width and thickness of the sheet were considered in the accuracy of the results of the sheet. The results indicate that as far as thick sheets are concerned, the use of plate displacement field and Zigzag term will have good results.

Khalili et al. [31] presented a new high-order theory for analyzing sandwich shells with a transversally deformed core. They calculated the behavior of the surfaces from the elasticity relations using the classical and core theory, and extracted the governing equations and boundary conditions based on the energy method and the Hamilton principle. Grover et al. [32] investigated the static and buckling analysis of multilayered and sandwich sheet using the reverse hyperbolic shear deformation theory. This theory was developed based on nonlinear functions of shear strain while considering shear stress on developed surfaces as zero. Kapuria et al. [33] evaluated the accuracy of general-local theories in the bending and vibration analysis of multilayered and sandwich sheets.

In this research, the results of theories of zigzag, general-local and three-dimension are presented for composite and sandwich sheets with different layers and hybrids. The results show a fairly good accuracy of general-local theory for sheets consisting of more than 3 layers with the same material, but it does not provide good results for hybrid and sandwich sheets, while Zigzag's theory shows the accurate results in the analysis of bending and frequency of composite and sandwich sheets. In 2013, khandelwal et al. [34] analyzed the sandwich plate with soft core statically by using a developed high order zigzag theory. They considered the sandwich plate as 3 layers and to analyze its buckling behavior, they employed a third-order plate and zigzag displacement field for all three layers and a second-degree transverse displacement field for the core as well as the fixed displacement field for surfaces. Also, Botshekanan et al. [35] used a mixed theory, based on the CUF model, including Equivalent Single-Layer theory (ESL) and Layer-Wise theory (LW) with different orders to analyze sandwich plates statically. Different samples of sandwich sheets are analyzed using the proposed theory (from one to four orders) and are compared with three-dimensional solution and high-order theories. The results of the stress and displacement of the 4th order mixed theory correspond very well with 3D solution when it comes to thick sandwich sheet with soft core.

In general, providing a powerful and highly accurate model is very important for modeling and analyzing these structures for their optimal design. The use of powerful theories and advanced software are inexpensive and fast compared to the traditional methods of empirical measurement of deformation and strain. Hence, in this paper, a general-local high-order theory, which is proposed based on the minimum total potential energy equation and is corrected based on the three-dimensional elasticity equations, is employed for the analysis of thin and thick sandwich plates, the accuracy of which corresponds to the obtained results from the three-dimensional solution.

The main advantage of this theory is to satisfy the continuity conditions of shear transverse stresses between the layers and taking into account the deformation along the thickness. Also, another benefit is the low cost of computing in spite of the high accuracy of the results and considering the local components of stress and displacement of each layer. Another important feature of this theory is to consider the changes in the thickness of the plate.

Therefore, a very high precise study of the behavior of thick sandwich sheets or sandwich sheets with soft and flexible core is also possible through this theory. Also, due to the aforementioned characteristics, the use of this theory to study the sandwich sheets with auxetic core materials is also appropriate and has led to accurate results. After verifying the proposed model, the behavior of sandwich plates in different models and with different Poisson's ratios under transverse static load is evaluated carefully.

2. Equations and units

The sandwich plate is a square-shaped plate with three layers, whose origin of the coordinate system is in its middle plane, and the z axis is considered to be positive upward. The length and width of the plane along *x* and *y* are *a* and *b* respectively and the thickness of the total plate is *h*. Also, the thickness of the upper layer is considered to be h_1, the thickness of the core is considered to be h_2 and the thickness of the lower layer is regarded as h_3. The in-plane displacement components of the plate are considered as a combination of two local and general sections.

$$\begin{cases} u(x,y,z) = u_G(x,y,z) + u_L^k(x,y,z) \\ v(x,y,z) = v_G(x,y,z) + v_L^k(x,y,z) \end{cases} \quad (k=1,2,3) \tag{1}$$

u_G and v_G are the general components of the displacement field which are considered as follows.

$$\begin{cases} u_G(x,y,z) = u_0(x,y) + z\varphi_x(x,y) \\ \qquad + z^3\lambda_x(x,y) \\ v_G(x,y,z) = v_0(x,y) + z\varphi_y(x,y) \\ \qquad + z^3\lambda_y(x,y) \end{cases} \tag{2}$$

Also, u_L and v_L are local components of displacement and include:

$$\begin{cases} u_L^k(x,y,z) = u_0^k(x,y) + z\varphi_x^{(k)}(x,y) \\ v_L^k(x,y,z) = v_0^k(x,y) + z\varphi_y^{(k)}(x,y) \end{cases} \quad (k=1,2,3) \tag{3}$$

In the above equations, the index k represents the layer number. Also, u_0^k, v_0^k, $\varphi_x^{(k)}$ and $\varphi_y^{(k)}$ are respectively the local displacement of the middle plane of each layer and the local rotation of each layer. φ_x and φ_y are also the general rotation of the middle plane of the core. λ_x and λ_y are also related to the changes in curvature of the distribution of displacement components along the thickness. By applying the continuity conditions and simplification, Eqs. (4-6) will ultimately be achieved:

- ✓ For the 1th layer ($z_1^u \le z \le z_2^u$):

$$\begin{cases} u_1 = u_0 + z\varphi_x + z^3\lambda_x(x,y) \\ \quad + (z - z_1^u)\varphi_x^{(1)} + z_1^u\varphi_x^{(2)} \\ v_1 = v_0 + z\varphi_y + z^3\lambda_y(x,y) \\ \quad + (z - z_1^u)\varphi_y^{(1)} + z_1^u\varphi_y^{(2)} \end{cases} \tag{4}$$

- ✓ For the 2th layer ($z_1^l \le z \le z_1^u$):

$$\begin{cases} u_2 = u_0 + z(\varphi_x + \varphi_x^{(2)}) + z^3\lambda_x(x,y) \\ v_2 = v_0 + z(\varphi_y + \varphi_y^{(2)}) + z^3\lambda_y(x,y) \end{cases} \tag{5}$$

- ✓ For the 3th layer ($z_2^l \le z \le z_1^l$):

$$\begin{cases} u_3 = u_0 + z\varphi_x + z^3\lambda_x(x,y) \\ \quad + (z - z_1^l)\varphi_x^{(3)} + z_1^l\varphi_x^{(2)} \\ v_3 = v_0 + z\varphi_y + z^3\lambda_y(x,y) \\ \quad + (z - z_1^l)\varphi_y^{(3)} + z_1^l\varphi_y^{(2)} \end{cases} \tag{6}$$

It is observed that the final deformation of the plate is calculated based on the superstition principle. One of the advantages of the current paper is to consider the second-order variations for the transverse displacement component of the core as follows:

$$\mathscr{L}_1(z)\, w_u + \mathscr{L}_2(z)\, w_m + \mathscr{L}_3(z)\, w_l \tag{7}$$

where w_u, w_l and w_m are displacement at the top, bottom and middle of the core respectively, and $\mathscr{L}_1$, $\mathscr{L}_2$, and $\mathscr{L}_3$ are parabolic interpolation functions. Thus, the three-layer sandwich plate has a total of 15 independent displacement parameters. These parameters are:

$$u_0, v_0, \varphi_x, \varphi_y, \lambda_x, \lambda_y, \varphi_x^{(1)}, \varphi_y^{(1)}, \varphi_x^{(2)}, \varphi_y^{(2)}, \varphi_x^{(3)}, \varphi_y^{(3)}, w_u, w_m, w_l$$

It should be noted that the displacement in the face sheets of sandwich plates is considered to be fixed, which is reasonable with respect to the thickness and stiffness of the face sheets. According to the above equations, the total displacement field of the sandwich plate can be written in the following matrix form (in which $\psi^i(x,y,z)$ represent the displacement field governing the layers of the sandwich plate):

$$\psi(x,y,z,t)=\begin{bmatrix} 1 & 0 & z & 0 & z^3 & 0 & z-z_1^u & z_1^u & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & z & 0 & z^3 & 0 & 0 & z-z_1^u & z_1^u & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & z & 0 & z^3 & 0 & 0 & z & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & z & 0 & z^3 & 0 & 0 & 0 & z & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & L_1 & 0 & 0 & L_2 & L_3 \\ 1 & 0 & z & 0 & z^3 & 0 & 0 & z_1^l & 0 & 0 & 0 & z-z_1^l & 0 & 0 & 0 \\ 0 & 1 & 0 & z & 0 & z^3 & 0 & 0 & 0 & z_1^l & 0 & 0 & z-z_1^l & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{Bmatrix} u_0 \\ v_0 \\ \varphi_x \\ \lambda_x \\ \varphi_y \\ \lambda_y \\ \varphi_x^{(1)} \\ \varphi_x^{(2)} \\ \varphi_y^{(1)} \\ \varphi_y^{(2)} \\ w_u \\ \varphi_x^{(3)} \\ \varphi_y^{(3)} \\ w_m \\ w_l \end{Bmatrix}$$

$$=\mathrm{H}(z)\Phi(x,y,t) \tag{8}$$

If the problem has a greater number of layers, it is possible to expand the equations for a higher number of layers. For example, the in-plane components of the displacement field for the case in which the composite plate has 5 layers are:

$$\begin{cases} u_1=u_0+z^3\lambda_x+\left(z-\dfrac{h_3}{2}-h_2\right)\varphi_x^{(1)}+h_2\varphi_x^{(2)} \\ +\dfrac{h_3}{2}\varphi_x^{(3)} \\ v_1=v_0+z^3\lambda_y+\left(z-\dfrac{h_3}{2}-h_2\right)\varphi_y^{(1)}+h_2\varphi_y^{(2)} \\ +\dfrac{h_3}{2}\varphi_y^{(3)} \end{cases}$$

$$for\quad \frac{h_3}{2}+h_2\le z\le\frac{h_3}{2}+h_2+h_1 \tag{9}$$

$$\begin{cases} u_4=u_0+z^3\lambda_x+\left(z+\dfrac{h_3}{2}\right)\varphi_x^{(4)}-\dfrac{h_3}{2}\varphi_x^{(3)} \\ v_4=v_0+z^3\lambda_x+\left(z+\dfrac{h_3}{2}\right)\varphi_y^{(4)}-\dfrac{h_3}{2}\varphi_y^{(3)} \end{cases}$$

$$for\quad -\frac{h_3}{2}\le z\le-\frac{h_3}{2}-h_4$$

$$\begin{cases} u_5=u_0+z^3\lambda_x+\left(z+\dfrac{h_3}{2}+h_2\right)\varphi_x^{(5)}-h_4\varphi_x^{(4)} \\ -\dfrac{h_3}{2}\varphi_x^{(3)} \\ v_5=v_0+z^3\lambda_x+\left(z+\dfrac{h_3}{2}+h_4\right)\varphi_y^{(5)}-h_4\varphi_y^{(4)} \\ -\dfrac{h_3}{2}\varphi_y^{(3)} \end{cases}$$

$$for\quad -\frac{h_3}{2}-h_4\le z\le-\frac{h_3}{2}-h_4-h_5$$

It should be noted that all the theories of sandwich and composite plate, including global-local theory, are two-dimensional, and two-dimensional finite element method must be used to solve them. In this research, non-linear and rectangular plate elements were employed to mesh the plate. Using the finite element method, displacement is written in the following form:

$$\Phi(x,y,t)=\mathbf{N}\,(x,y)\Phi^{(e)}(t) \tag{10}$$

where N and $\Phi^{(e)}$ are the matrix in the form of functions and the vector of nodal displacement values respectively:

$$\mathbf{N} = \begin{bmatrix} \hat{\mathbf{N}} & \mathbf{0} & \cdots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{N}} & \cdots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \hat{\mathbf{N}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} & \hat{\mathbf{N}} \end{bmatrix} \quad (11)$$

Thus, based on Eqs. (9 and 10):

$$\begin{aligned} \psi(x,y,z) &= \mathrm{H}(z)\mathbf{N}(x,y)\Phi^{e} \\ &= \Gamma(x,y,z)\Phi^{e} \end{aligned} \quad (12)$$

On the other hand, the strain matrix form in each layer is:

$$\begin{aligned} \varepsilon = \begin{Bmatrix} \varepsilon^{(1)} \\ \varepsilon^{(2)} \\ \varepsilon^{(3)} \end{Bmatrix} &= \begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix} \Psi(x,y,z) \\ &= \begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix} \Gamma(x,y,z)\Phi^{(e)} \\ &= \Lambda(x,y,z)\Phi^{(e)} \end{aligned} \quad (13)$$

in which:

$$\varepsilon^{(i)T} = \left\langle \varepsilon_{xx}^{(i)} \quad \varepsilon_{yy}^{(i)} \quad \varepsilon_{zz}^{(i)} \quad \gamma_{xy}^{(i)} \quad \gamma_{xz}^{(i)} \quad \gamma_{yz}^{(i)} \right\rangle, \quad (i = 1,2,3)$$

$$\boldsymbol{e}^{(i)} = ¶ \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}^{(i)} = ¶\boldsymbol{d}^{(i)}, ¶ = \begin{bmatrix} \partial_x & 0 & 0 \\ 0 & \partial_y & 0 \\ 0 & 0 & \partial_z \\ \partial_y & \partial_x & 0 \\ \partial_z & 0 & \partial_x \\ 0 & \partial_z & \partial_y \end{bmatrix} \quad (14)$$

The stress components are also calculated according to Hooke's law:

$$\begin{aligned} \sigma = \begin{Bmatrix} \sigma^{(1)} \\ \sigma^{(2)} \\ \sigma^{(3)} \end{Bmatrix} &= \begin{bmatrix} C^{(1)} & 0 & 0 \\ 0 & C^{(2)} & 0 \\ 0 & 0 & C^{(3)} \end{bmatrix} \begin{Bmatrix} \varepsilon^{(1)} \\ \varepsilon^{(2)} \\ \varepsilon^{(3)} \end{Bmatrix} \\ &= \widehat{Q}\varepsilon = \widehat{Q}\Lambda(x,y,z)\Phi^{(e)} \end{aligned} \quad (15)$$

in which $C^{(i)}$ is the matrix of elastic coefficients in the rotated coordinate system of the plate. Structural equations are obtained using the minimum total potential energy principle. If the strain energy and external force work are represented by the symbols U and V, respectively, it could be describe as:

$$\int_0^T (\delta U - \delta V)dt = 0 \quad (16)$$

where:

$$\begin{aligned} \delta U &= \int_{\Omega} (\delta\varepsilon)^T \sigma d\Omega \\ &= \int_{\Omega} (\delta\Phi^{(e)})^T \Lambda^T \widehat{Q} \Lambda \Phi^{(e)} d\Omega \end{aligned} \quad (17)$$

$$\begin{aligned} \delta V &= \int_A q\,\delta w_u dA \\ &= \int_A q(\delta\Phi^{(e)})^T (R\mathbf{N})^T dA \end{aligned} \quad (18)$$

in which: A, Ω and q are the surface area and the volume of the element and the intensity of the external load imposed on the plate respectively. By placing the Eqs. (17 and 18) in Eq. (16) could be written:

$$(\delta\Phi^{(e)})^T [\int_{\Omega} \Lambda^T \widehat{Q} \Lambda \Phi^{(e)} d\Omega - \int_A q(R\mathbf{N})^T dA] = 0 \quad (19)$$

Since $\delta\Phi^{(e)}$ is an arbitrary and non-zero vector, the structural equation of the sandwich plate will be:

$$[\int_{\Omega} \Lambda^T \widehat{Q} \Lambda d\Omega]\Phi^{(e)} = \int_A q(R\mathbf{N})^T dA \quad (20)$$

or in its compressed state:

$$K\Phi^{(e)} = F \quad (21)$$

3. The modification of transverse shear stresses using three-dimensional elasticity equations

Here, after calculating the in-plane stresses, the values of transverse stresses are calculated using three-dimensional equilibrium equations. Therefore, the contiguity condition between the layers and the condition of having zero transverse stresses in free surfaces are well established and there is no need to use shear correction coefficient. In this case, not only the transverse stresses along the thickness are not fixed, but also have a nonlinear distribution.

4. Results and discussion

In this section, in addition to verifying the obtained results, the problem is analyzed parametrically. In addition to verifying the obtained results with the 3D solution results presented in valid references, the convergence of the finite element results and the independence of mesh sizes are also carefully considered for different parameters and in different geometries. In all the proposed results, the size of the elements is chosen in such a way that the change in their number does not have a significant effect on the results of any geometry. Finally, it could be say that the size of meshing 40 × 40 provides more accurate and more appropriate results in all samples.

4.1. Verification of obtained results

First, the verification of the proposed theory results is analyzed using a static analysis of the sandwich plate with isotropic surfaces and cores under sinusoidal loading. In this example, a square symmetric sandwich plate, in which the composite face sheets have the same thickness, equivalent to 0.1 of overall thickness and core thickness is equivalent to 0.8 of the total thickness of the plate are analyzed using the proposed model and compared with the results in the reliable references.

The boundary conditions of the plate are simple support for all edges and the top plate of face sheet is under distributed sinusoidal pressure loading. The properties of the face sheets and core material are as follows [29]:

$$E_f = 73GPa \quad , \quad \nu = 0.34 \rightarrow$$
$$E_f / E_c = 10 \Rightarrow \quad E_c = 7.3GPa \quad , \quad \nu = 0.34$$
$$E_f / E_c = 10^5 \Rightarrow \quad E_c = 0.73MPa \, , \quad \nu = 0.34$$

The analyses were carried out on two cases of sandwich plate with stiff core ($E_f/E_c = 10$) and with soft core ($E_f/E_c = 10^5$) in three cases of thick ($a/h = 4$) thin ($a/h = 10$) and very thin ($a/h=100$). As it was mentioned in section 2 the length and the total thickness of the sandwich panel is a and h respectively. Displacements and stresses have become dimensionless using the following relationships:

$$W = w\frac{100E_f h^3}{a^4 q_0} \, , U, V = (u, v)\frac{-10^4 E_f h^2}{a^3 q_0} ,$$
$$S_{xx}, S_{yy}, S_{xy} = \frac{h^2}{q_0 a^2}(\sigma_{xx}, \sigma_{yy}, \sigma_{xy}) ,$$
$$S_{yz}, S_{zx} = \frac{h}{q_0 a}(\sigma_{yz}, \sigma_{zx})$$

At first the mesh independency of the obtained results should be checked. For this reason, plates were meshed using various types of meshes such as 5x5, 10x10, 20x20, 30x30 and 40x40 and their results were examined. The obtained results were analyzed for all three kinds of thin, very thin and thick plates with a/h ratio of 100, 10 and 4 respectively. Various results such as non-dimensional transverse stresses and dimensionless transverse displacement were investigated.

Fig. 1 depicts the comparison of the obtained results for all three ratios of plate thickness and their comparison with the three-dimensional results existing in the references. The results show that the transverse displacement of the plate converges with the element size of 40x40. The obtained results show that the very thin plate (a/h=100) converges faster than the other two cases; however, in all three cases with mesh size 40x40, the results are independent of the meshes number.

Fig. 2 and Fig. 3 also show the convergence of the results for dimensionless transverse shear stresses in both cases of thick and thin plate conditions. As can be seen, the results of most transverse shear stresses with the element size of 40x40 converge in both cases. The picture of the meshed plate is shown in Fig. 4. In the case of a square plate, the number of elements in the length and width of the plate is equal.

Verification of the converged results is shown in Table 1.
The obtained results are compared with the three-dimensional result of the elasticity existing in reference [36]. The investigations showed that for all three cases of very thin plate, ordinary plate and thick plate, the results calculated by the proposed theory are acceptable and have very good accuracy. Finally, the obtained results showed that the mesh size 40x40 led to the provision of converged results, and the further increase in sandwich plate elements did not have a significant effect on the results. Also, comparing the obtained results with those existing in reference [36] made it clear that the theory has an acceptable accuracy.
In order to further examine the proposed theory precisely, the results obtained from solving the example of a three-layer composite plate with three layers [0/90/0] are compared and verified with the results presented in valid references. To solve the reference, the exact solution provided by Pagano [37] has been used.

Table 1. The results of most displacement and maximum dimensionless shear stresses of sandwich plate with soft core for different mesh sizes.

	Approach	Mesh size	*a/h=4*	*a/h=10*	*a/h=100*
Dimensionless transvers shear stress	Present Theory	10×10	0.00931	0.1398	15.824
		20×20	0.01049	0.1581	16.024
		30×30	0.01121	0.1659	16.215
		40×40	0.01128	0.1661	16.207
	3D [36]	-	0.0111	0.1627	16.039
Dimensionless transvers displacement	Present Theory	10×10	1114.2	1051.2	124.94
		20×20	1204.8	1140.9	126.35
		30×30	1268.2	1203.2	127.85
		40×40	1272.5	1207.67	128.01
	3D [36]	-	1299.4	1230.6	126.7

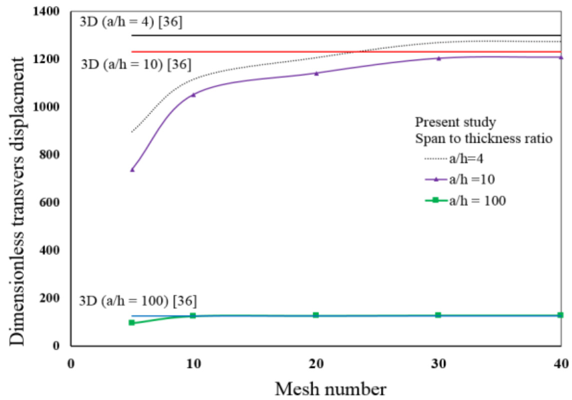

Fig. 1. Mesh independency of the dimensionless transverse displacement for different a / h ratios.

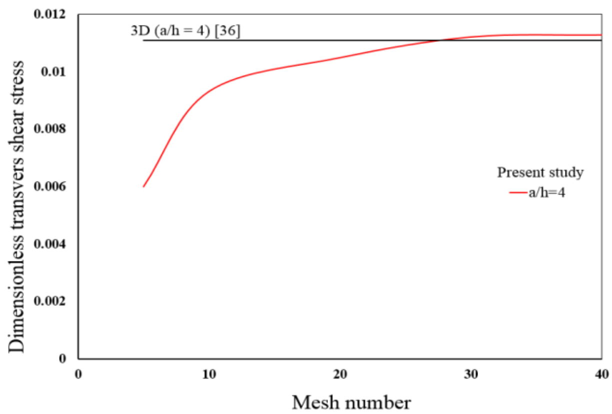

Fig. 2. Mesh independency of the dimensionless transverse shear stress for thick sandwich plate (a/h=4).

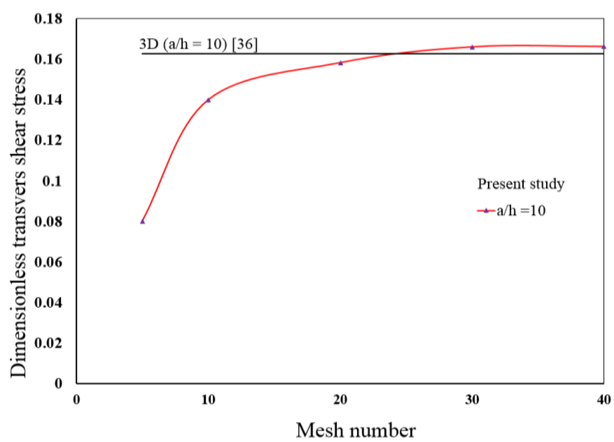

Fig. 3. Mesh independency of the dimensionless transverse shear stress for thin sandwich plate (a/h=10).

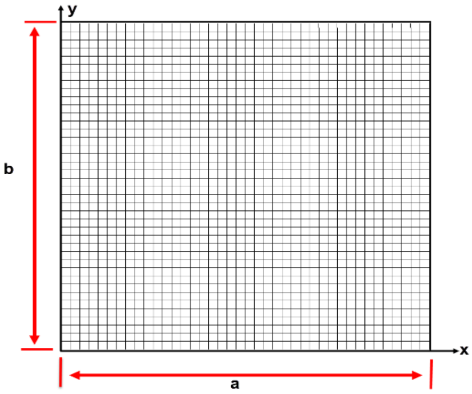

Fig. 4. Plate with the appropriate meshing for analysis.

All edges of the supporting plate are considered as simply support; also, the properties of materials of all three layers include:

$$E_1/E_2 = 25;\ G_{12}/E_2 = G_{13}/E_2 = 0.5;$$
$$G_{23}/E_2 = 0.2;\ \nu_{12} = \nu_{23} = \nu_{13} = 0.25$$

The results obtained from the presented equation have become dimensionless too. The load is also applied in a sinusoidal way in the form of extensive pressure on the top surface of upper face sheet. The obtained results are compared with those of other references such as the results of other references such as Reddy [38], Kant and Swaminathan [39], Mantari et al. [40] and Karama et al. [41] in Table 2. From the comparison of the obtained results, it can be observed that the obtained results of the present theory have a very good consistency with the available results of the exact solution.

Table 2. Results of dimensionless displacement and square-shaped composite plate stress (a = b) with porcelain layer [0/90/0] under sine load.

a/h	Approach	$\bar{W}(\frac{a}{2},\frac{b}{2}$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2}$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2}$	$\overline{\tau_{xz}}(0,\frac{b}{2}$	$\overline{\tau_{yz}}(\frac{a}{2},0$
4	Present	1.975	0.765	0.542	0.253	0.208
	3D elasticity [36]	2.006	0.755	0.556	0.282	0.217
	Reddy [38]	1.921	0.734	-	-	0.183
	Kant & Swaminathan [39]	1.894	0.764	0.493	-	-
	Mantari et al. [40]	1.943	0.823	0.497	0.245	0.201
	Karama et al. [41]	1.944	0.775	0.502	0.220	0.191
10	Present	0.730	0.585	0.274	0.345	0.110
	3D elasticity [36]	0.740	0.59	0.288	0.357	0.123
	Reddy [38]	0.712	0.568	-	-	0.103
	Kant & Swaminathan [39]	0.715	0.583	0.270	-	-
	Mantari et al. [40]	0.734	0.588	0.276	0.314	0.115
	Karama et al. [41]	0.723	0.576	0.272	0.272	0.108

Table 3. Results of dimensionless displacement and rectangular-shaped composite plate stress (b = 3a) with porcelain layer [0/90/0] under sine load.

a/h	Approach	$\bar{W}(\frac{a}{2},\frac{b}{2},0$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$
4	Present	2.698	1.0912	0.1052
	3D elasticity [37]	2.82	1.1	0.119
10	Present	0.895	0.721	0.0453
	3D elasticity [37]	0.919	0.725	0.0435
50	Present	0.5123	0.6198	0.0253
	3D elasticity [37]	0.5205	0.6276	0.0260

In the following, the intended plate with a different length to width ratio (b=3a) with the same layer was put under the sinusoid load, and then the obtained results were compared with those of Pagano's precise three-dimensional resolution. The results shown in Table 3 represent an excellent match between the results of the existing theory and the exact solution.

4.2. Parametric analysis of sandwich plate with auxetic core under static transverse load

Initially, the effect of Poisson's ratio on the behavior of sandwich plate under different transverse static conditions is investigated. The load is applied to the top of the upper face sheet in the form of a distributed sinusoidal pressure. The plate is investigated in two cases with soft core ($E_f/E_c=10^5$) and stiff ($E_f/E_c=10$) with a thick

geometry (*a/h=4*) and a thin one (*a/h=10*). Other properties of the materials are considered as in the previous section. In order to investigate the Poisson's ratio better and more accurately, in all of the above mentioned cases, the Poisson's ratio of the auxetic core has the following values:
v= -0.3, -0.6, -0.9

In the following, maximum transverse deformation of the sandwich plate in all four samples is studied in order to study more carefully the effect of the existence of auxetic core along with other parameters.

Fig. 5 to Fig. 8 show the maximum deflection of sandwich plates in all four cases of thick (*a/h=4*), thin (*a/h=10*) geometry with soft ($E_f/E_c=10^5$) and stiff ($E_f/E_c=10$) core. It should be noted that the results shown in the following become dimensionless as follows:

$$W = w\frac{100E_{core}h^3}{a^4q_0}, U,V = (u,v)\frac{-10^4E_{core}h^2}{a^3q_0}$$

As can be clearly seen, in general, in all cases, making the core auxetic and the decrease in its Poisson's ratio leads to the reduction of plate increment. In all four cases, the largest out of plane deflection is for the sandwich plate with the normal soft core, while the least transverse deflection, among the four Poisson's ratios, belongs to the Poisson's ratio of -0.9. However, the amount of the deflection variation is another important point for the investigation the effect of using auxetic core.

The largest change in transverse deformation occurred due to the auxetic core in the case of a thick sandwich plate with a stiff core. When it comes to thin plates with stiff and soft cores, the percentage of decrease in deflection is approximately the same.

The reason for this decrease in transverse deformation, which occurs due to making the core auxetic, is the increase in the stiffness of the plate, in a way that the decrease in Poisson ratio from +0.3 to -0.9 leads to an increase of 5 times in the stiffness of the entire plate.

Fig. 9 and Fig. 10 shows the changes in the dimensionless shear transverse stress along the thickness. As discussed in Section 3, the shear stresses were extracted through the correction method using three-dimensional equilibrium equations. Hence, in addition to satisfying the condition of zero shear stresses in the free surfaces of the upper and lower sandwich plate, the continuity condition of shear stresses between the layers, which is not met in many theories and methods, is satisfied perfectly with very high accuracy.

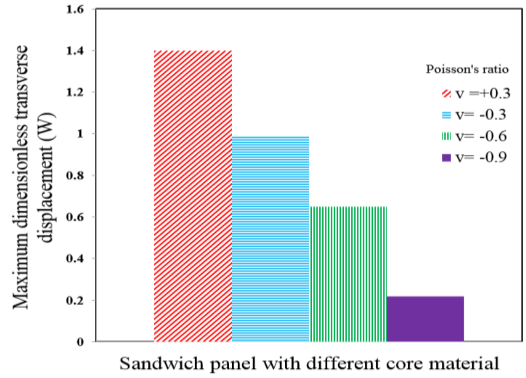

Fig. 5. Maximum dimensionless transverse displacement of thick sandwich plate (*a/h=4*) with stiff core ($E_f/E_c=10$).

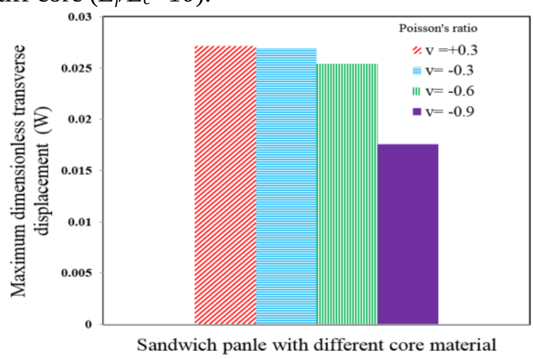

Fig. 6. Maximum dimensionless transverse displacement of thick sandwich plate (*a/h=4*) with very soft core ($E_f/E_c=10^5$).

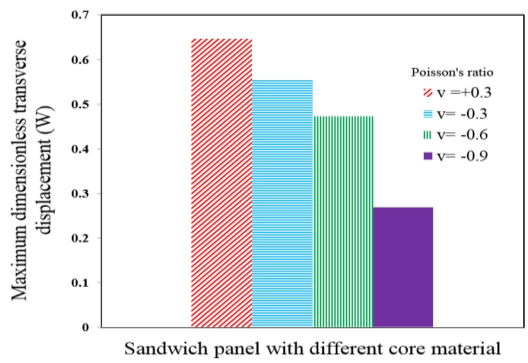

Fig. 7. Maximum dimensionless transverse displacement of thin sandwich plate (*a/h=10*) with stiff core ($E_f/E_c=10$).

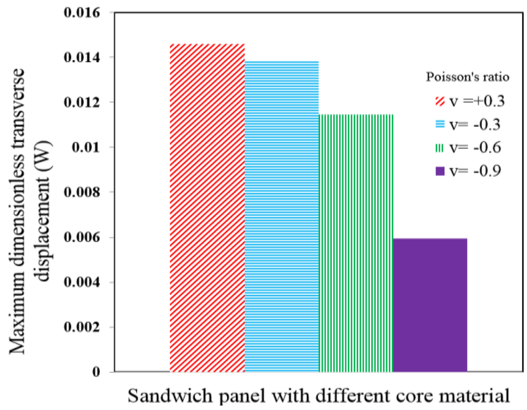

Fig. 8. Maximum dimensionless transverse displacement of thin sandwich plate (*a/h=10*) with very soft core ($E_f/E_c=10^5$).

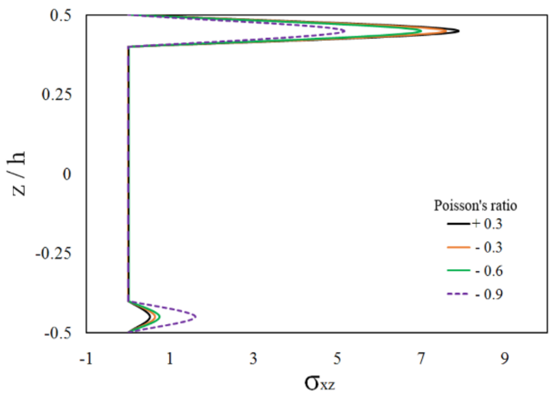

Fig. 9. Effects of the auxeticity of the core material on through-thickness distributions of the dimensionless transverse shear stress (*Sxz*) of the thick sandwich plate with very soft core.

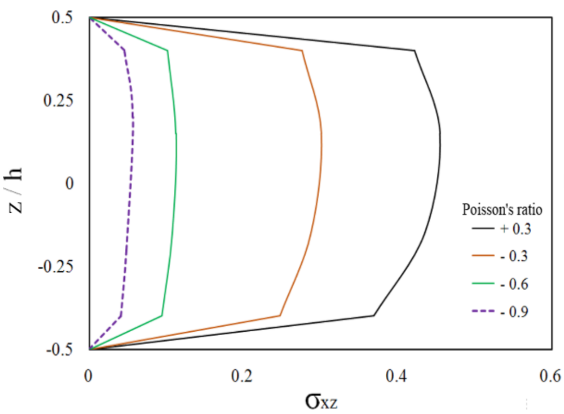

Fig. 10. Effects of the auxeticity of the core material on through-thickness distributions of the dimensionless transverse shear stress (*Sxz*) of the thick sandwich plate with stiff core.

Furthermore, shear stresses possess quite dissimilar and nonlinear distribution. This is of great importance when it comes to the accuracy of the analysis of thick plates, especially plates with soft core. It can be seen from the results that in the cases of the very soft core, the behavior of shear stress is completely different from that of the stiff core. In other words, in terms of those with soft core, cores (in both thick and thin) virtually have a shear stress of zero, while when it comes to plates with stiff core, the core can virtually tolerate significant shear stresses. In general, amounts of the shear stresses produced in thin cases exceed those with thick ones. In the case of a thick sandwich plate with a soft core, the difference between the shear stresses created in the upper and lower layers is significant, while in the case of thin plate, this difference is less between the shear stresses of the upper and lower layers.

As noted above, by changing the Poisson's ratio of the core, the difference between the shear stress of upper and lower of the sandwich plate decreases or even in some cases disappears, in a way that when it comes to thick sandwich plates with a soft core in which the difference between shear stresses between the upper and lower layers is the highest, this change has led to a decrease in the difference, whereas in the case of thin plates with a soft core, the difference is removed thanks to the mentioned change.

As a result, in this example with a Poisson's ratio of (-0.9), the shear stress of the upper and lower layers is the same. Fig. 11 shows the changes in the core equivalent stress at section where it goes through the middle plane of the sandwich panel. (The mentioned contour only shows the equivalent stress in the core and no face sheets are presented in these contours).

As shown in Fig. 9, in this example, the composite face sheets stress is much more than that of the PVC core belonging to the sandwich plate. Therefore, the stress of the face sheets is overlooked to merely obtain the distribution of the equivalent stress in the mentioned section of the core. This figure illustrates thick sandwich plate with both normal and auxetic soft cores. It should be noted that the curvature of the plate is shown with considerable magnification in order to give the better sense. However, the amount of magnification employed in both contours of "a" and "b" is the same. It is well observed that the core deformation has been reduced by the use of the auxetic material, while the core stress level has increased more than ten times.

Also, the stress distribution pattern in the core has also changed due to the use of an auxetic core with a Poisson’s ratio of (-0.9), in a way that when it comes to the sandwich plate with the normal core (Poisson’s ratio of +0.3), the highest equivalent stresses occur in the inner layers of the plate, while because of making the core auxetic and increasing the stiffness of the sandwich plate, the highest equivalent stress occurs in the upper surface of the core.

In the following, the effect of the length-to-width ratio of the plate on its behavior is discussed.

As the “*a* / *b”* ratio changes from 1 to 4, other parameters such as core stiffness as well as plate thickness change too. The effect of the length-to-width ratio is carefully checked for each of the all mentioned cases. All of the dimensionless results are given in Table 4.

It should be mentioned that in these examples, the boundary conditions of all four edges are considered to be simply support (SSSS). Moreover, the load is in the form of uniform distributed pressure applied to the upper surface of the sandwich plate.

The results shown in Table 4 include the dimensionless transverse displacement of the middle point of the sandwich plate in the upper, lower surfaces and in the center of the plate, as well as the in plane dimensionless stress along the length and width in the middle point of the plate located on the upper and lower surfaces of the sandwich plate.

The important point is that, in all (*a*/*b)* ratios, making the core auxetic significantly reduces transverse displacement in all cases. In general, it can be said that the change in the “*a*/b” ratio does not lead to the reduction of this effect, and the negativity of the Poisson's ratio of the core from + 0.3 to -0.5 has a nearly identical effect on all length-to-width ratios. Also, in all 32 investigated cases of the sandwich plate, it can be seen that the change in the “*a*/*b”* ratio has no effect on the behavioral difference between the upper and lower composite face sheets and this behavioral difference between these layers remains constant for all “*a*/*b”* ratios.

The main effect of the change in the length-to-width ratio of the plate is observed in the changes in the amount of in plane stresses $\overline{\sigma_{xx}}$ and $\overline{\sigma_{yy}}$.

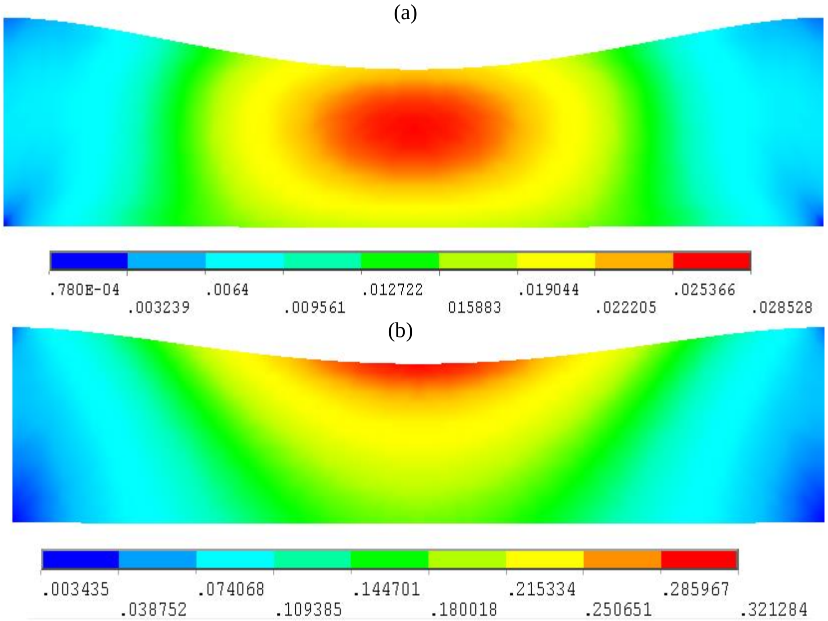

Fig. 11. Distribution of equivalent stress on the mid plane of thick sandwich plate: (a) normal core (v= 0.3) and (b) Auxetic core (v= -0.9).

Table 4. The effect of a/b on the behavior of thick and thin sandwich plate with soft, stiff and auxetic core.

$\frac{b}{a}$	$\frac{a}{h}$	$\frac{E_f}{E_c}$	υ	$\bar{W}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\bar{W}(\frac{a}{2},\frac{b}{2},0)$	$\bar{W}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$
1	4	10	+ 0.3	-2.163	-2.136	-2.055	-0.580	0.567	-0.580	0.567
			− 0.5	-1.269	-1.185	-1.161	-0.507	0.463	-0.507	0.463
		10^5	+ 0.3	-0.281	-0.226	-0.174	-12.24	9.858	-12.24	9.858
			− 0.5	-0.187	-0.139	-0.094	-11.19	8.257	-11.19	8.257
	10	10	+ 0.3	-0.962	-0.967	-0.959	-0.520	0.516	-0.520	0.516
			− 0.5	-0.731	-0.728	-0.728	-0.461	0.453	-0.461	0.453
		10^5	+ 0.3	-0.046	-0.045	-0.043	-9.909	9.894	-9.909	9.894
			− 0.5	-0.031	-0.030	-0.029	-7.801	7.762	-7.801	7.762
2	4	10	+ 0.3	-3.810	-3.788	-3.689	-1.071	1.054	-0.493	0.474
			− 0.5	-2.317	-2.231	-2.209	-0.908	0.864	-0.410	0.372
		10^5	+ 0.3	-0.432	-0.374	-0.319	-19.12	16.56	-19.02	16.21
			− 0.5	-0.284	-0.232	-0.185	-18.27	15.00	-12.42	11.18
	10	10	+ 0.3	-1.979	-1.987	-1.976	-0.913	0.908	-0.286	0.279
			− 0.5	-1.532	-1.529	-1.529	-0.803	0.795	-0.253	0.246
		10^5	+ 0.3	-0.081	-0.080	-0.078	-18.37	18.35	-1.350	1.343
			− 0.5	-0.054	-0.053	-0.052	-14.34	14.30	-1.128	1.118
3	4	10	+ 0.3	-4.129	-4.106	-4.008	-1.158	1.140	-0.380	0.360
			− 0.5	-2.496	-2.409	-2.387	-0.971	0.928	-0.316	0.280
		10^5	+ 0.3	-0.498	-0.441	-0.386	-23.63	20.97	-9.495	9.432
			− 0.5	-0.316	-0.265	-0.217	-22.00	18.60	-5.739	5.571
	10	10	+ 0.3	-2.206	-2.214	-2.202	-1.054	1.040	-0.338	0.332
			− 0.5	-1.703	-1.698	-1.698	-0.918	0.910	-0.296	0.289
		10^5	+ 0.3	-0.088	-0.087	-0.085	-21.56	21.54	-1.805	1.799
			− 0.5	-0.059	-0.057	-0.056	-16.55	16.52	-1.443	1.433
4	4	10	+ 0.3	-4.141	-4.115	-4.020	-1.157	1.140	-0.337	0.316
			− 0.5	-2.498	-2.412	-2.390	-0.970	0.927	-0.290	0.255
		10^5	+ 0.3	-0.508	-0.451	-0.396	-25.45	22.75	-3.800	3.786
			− 0.5	-0.318	-0.267	-0.220	-23.21	19.77	-2.219	2.099
	10	10	+ 0.3	-2.235	-2.244	-2.232	-1.075	1.070	-0.347	0.341
			− 0.5	-1.721	-1.718	-1.718	-0.934	0.926	-0.303	0.296
		10^5	+ 0.3	-0.089	-0.087	-0.086	-22.14	22.12	-1.895	1.888
			− 0.5	-0.060	-0.058	-0.057	-16.96	16.93	1.5022	1.492

Table 5. The effect of boundary condition on the dimensionless results of squared thick and thin sandwich plate with soft, stiff, normal and auxetic core.

B.C.	$\frac{a}{h}$	$\frac{E_f}{E_c}$	υ	$\bar{W}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\bar{W}(\frac{a}{2},\frac{b}{2},0)$	$\bar{W}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\overline{\sigma_{xx}}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2},\frac{h}{2})$	$\overline{\sigma_{yy}}(\frac{a}{2},\frac{b}{2},\frac{-h}{2})$
CCCC	4	10	+ 0.3	-2.163	-2.136	-2.055	-0.580	0.567	-0.580	0.567
			− 0.5	-1.269	-1.185	-1.161	-0.507	0.463	-0.507	0.463
		10^5	+ 0.3	-0.281	-0.226	-0.174	-12.24	9.858	-12.24	9.858
			− 0.5	-0.187	-0.139	-0.094	-11.19	8.257	-11.19	8.257
	10	10	+ 0.3	-0.962	-0.967	-0.959	-0.520	0.516	-0.520	0.516
			− 0.5	-0.731	-0.728	-0.728	-0.461	0.453	-0.461	0.453
		10^5	+ 0.3	-0.046	-0.045	-0.043	-9.909	9.894	-9.909	9.894
			− 0.5	-0.031	-0.030	-0.029	-7.801	7.762	-7.801	7.762
CFCF	4	10	+ 0.3	-4.088	-4.046	-3.957	-1.123	1.121	-0.079	0.149
			− 0.5	-2.459	-2.373	-2.349	-0.949	0.899	-0.212	0.144
		10^5	+ 0.3	-0.491	-0.432	-0.375	-25.70	22.85	1.773	-1.16
			− 0.5	-0.310	-0.259	-0.211	-23.37	19.80	1.732	-0.66
	10	10	+ 0.3	-2.222	-2.229	-2.219	-1.040	1.039	-0.196	0.205
			− 0.5	-1.699	-1.696	-1.696	-0.907	0.897	-0.233	0.220
		10^5	+ 0.3	-0.088	-0.086	-0.085	-22.26	22.26	-0.300	-0.23
			− 0.5	-0.059	-0.058	-0.056	-17.12	17.08	-0.261	0.248

In all examples, the amount of in-plane stresses $\overline{\sigma_{yy}}$ decreased because of increasing the "*a*/*b*" ratio, while the amount of in-plane stresses $\overline{\sigma_{xx}}$ has increased. Because of using auxetic foam as a sandwich core, the amount of the changes is varied but the total behavior of sandwich panels are the same with the normal core.

By investigating the displacement changes in the central points *(a/2,b/2)* located in the upper surface *(z=h/2)*, the lower surface *(z=-h/2)* and the middle plate *(z=0)* for all cases, including thick and thin sandwich panels, sandwich with very soft and stiff cores, or with normal and auxetic cores, it became obvious that the changes in transverse displacement *(W)* have converged at the ratio "*b/a=3*" and practically "*W*" is not affected by increasing "*b/a*" from 3 to 4.

Also, the difference of transverse displacement between the upper and lower layers in all "*b*/a" ratios remains constant in all cases and changing "*b/a*" does not have an effect on the behavior of upper and lower face sheets. In order to investigate this issue better, Fig. 12 and Fig. 13 show the maximum dimensionless transverse displacement(W)changes of top and bottom of sandwich panels with different "*b/a*" ratios for four kinds of thick sandwich plate (a/h=4) with very soft core ($E_f/E_c=10^5$), normal (v = +0.3) and auxetic (v=-0.5) core, as well as thick sandwich plate (a/h=4) with stiff core ($E_f/E_c=10$), normal (v= +0.3) and auxetic (v = -0.5) core.

Fig. 12 shows variations of mentioned parameters for a thick sandwich plate with a stiff core. In this example, it can be seen that for different ratio of "*b/a",* the amount of transverse displacement(|W|) of upper and lower point of sándwich are reduce by using auxetic core.

The dimensionless transverse displacement(W) after the "*b/a*" ratio of 3 also converge and remain unchanged. In general, the increase in the "*b/a*" ratio has led to an increase in the amount of transverse displacement(|W|). This effect is visible at both central points of the upper and lower surfaces of the sandwich plate with an auxetic ad normal core.

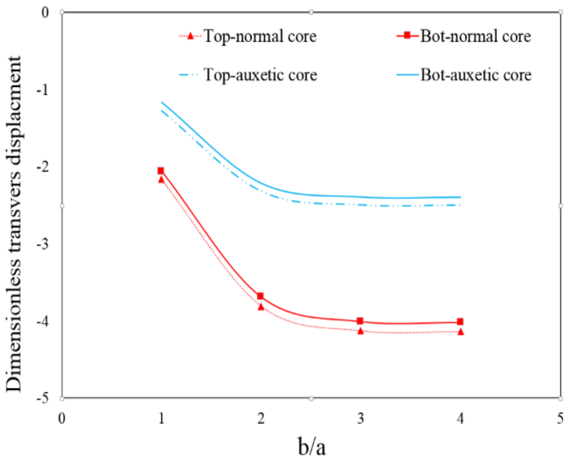

Fig. 12. The effect of the length-to-width ratio of the plate on the dimensionless transvers displacement of the middle points of the upper and lower surfaces belonging to the thick sandwich plate (a/h=4) with a stiff core (E_f /E_c=10) ordinary (v = +0.3) and Auxetic (v = -0.5).

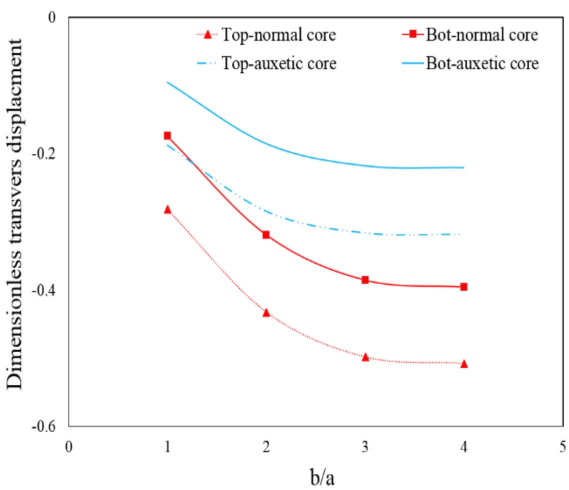

Fig. 13. The effect of the length-to-width ratio of the plate on the dimensionless transvers displacement of the middle points of the upper and lower surfaces belonging to the thick sandwich plate (a/h=4) with a very soft core (E_f / E_c=10^5) ordinary (v = +0.3) and Auxetic (v = -0.5).

Fig. 13 also shows the maximum dimensionless transverse displacement (W) changes for a thick sandwich plate with a soft core. In these examples, using the auxetic material as a sandwich core leads to the reduction of the displacement level caused by the increase in plate stiffness. It should be noted that the increase in "*b/a*" from 1 to 2 leads to the simultaneous increase in the transverse displacement both in the upper and lower surfaces. The difference between the displacement of the top and bottom layers of the sandwich in both sandwich sheets with the normal core and the auxetic core is the same. However, in this example, as in other examples in "*b/a = 3 or 4*" ratios, transverse displacement of upper and lower layers converge to a specific number. And it seems that larger length-to-width ratios of the sheet will not increase transverse displacement. However, in both cases, increasing the ratio of "*b/a*", will increase the transverse displacement.

In the following, the effect of boundary conditions on the behavior of square-shaped sandwich plate in different thick and thin cases with different cores is investigated carefully. The dimensionless results are shown in Table 5 Changing the boundary conditions from CCCC (Clamped on all edges) to CFCF (Clamped-Free-Clamped- Free) has increased displacements in all cases. In general, this change causes an increase in in-plane stresses in the upper and lower layers of the plate. Of course, for a thick plate with a soft core, the above mentioned change led to a change in sign $\overline{\boldsymbol{\sigma}_{yy}}$ both in the upper and lower layers. This is seen in both cases where the core of the sandwich plate is normal or auxetic. The change of stress sign $\overline{\boldsymbol{\sigma}_{yy}}$ stemming from the mentioned changes in the boundary conditions is also seen in the thin sandwich plate with a soft core. However, in this example, the auxetic state of the core leads to the correction of this issue and the uniformity of the sign of stress component in the lower layer.

5. Conclusions

In this paper, the effect of different parameters on the behavior of sandwich plate under transverse static load is studied. Some of these parameters are the thickness of the plate, the length-to-width ratio of the plate, the core stiffness, using the auxetic material as a sandwich core and the various boundary conditions of the sandwich plate. In order to study the mentioned effects on the sandwich plate behavior, a high-order global local theory using the modification of the shear stress based on three-dimensional elastic equilibrium equations is applied.

Also, one of the features of the proposed theory is the nonlinear simulation of the changes in the core thickness, which is essential in studying thick sandwich plates or sheets with a soft core. Before investigating the effects of various parameters, in addition to evaluating the convergence of the obtained results, the accuracy of the obtained results for different plates was evaluated and verified through the three-dimensional solution results existing in valid references and other theories presented in different references. Here are some of the most important results:

- The use of three dimensional elastic correction method along with high-order general-local theory is a highly efficient method for determining the all components of stresses such as shear stresses of sandwich plates, especially the thick sandwich plate with soft core, which in addition to satisfying the continuity condition of changes in transverse stress between the layers, evaluates its changes with great accuracy.
- The use of an auxetic core has a very significant effect on the reduction of in-plane stresses, followed by an increase in the load tolerance capacity of the sandwich plate.
- The assumption of considering transverse displacement constant along the sandwich thickness, which is common in many of the theories presented, can only be used in thin sandwich plates and plates with a stiff core; it leads to significant errors if used for thick sandwich plates or sandwich plates with a soft core.
- The effect of the Poisson's coefficient change from + 0.3 to -0.9 leads to the reduction of shear stresses occurring in different parts, so much so that in some cases, the shear stress of the core was reduced by up to 7 times due to the mentioned change.
- Changes in the length-to- width ratio of sandwich plate have different effects in different cases. In some cases, the change in the "b/a" ratio from 3 to 4 does not affect the increment or in-plane stresses of the upper and lower plates, while in some others, such as a thick sandwich plate with a normal soft auxetic core, there are some changes in stresses and increment due to the mentioned change.
- In general, an increase in the "b/a" ratio leads to an increase in the transverse displacement of the different points of the plate as well as an increase in the stress $\overline{\boldsymbol{\sigma}_{xx}}$ of the upper and lower surfaces of the plate, as well as a decrease in stress $\overline{\boldsymbol{\sigma}_{yy}}$.
- Changing boundary conditions from the mode of CCCC (Clamped on all edges) to CFCF (Clamped-Free-Clamped- Free) leads to an increase in displacements in all cases. The auxeticity of the core has not played a significant role in the mentioned change in the effect. In general, the greatest change in transverse displacement is due to the change of boundary conditions from CCCC (Clamped on all edges) to CFCF (Clamped-Free-Clamped- Free) for a thin sandwich plate with a stiff auxetic core, and the slightest change among the investigated cases belongs to the thick sandwich plate with soft auxetic core.

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