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TECHNICAL PAPER

Bending and buckling analysis of corrugated composite sandwich plates

Mohammad Mahdi Kheirikhah[1] · **Vahid Babaghasabha**[2]

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Abstract In this paper, bending and buckling behavior under uniaxial load of corrugated soft-core sandwich plates with laminated composite face sheets are explored. To this aim, analyses via three-dimensional finite element method are performed using ANSYS 12.0. The core is assumed as a soft isotropic material completely bonded to two stiff laminated composite face sheets. In particular, linear uniaxial critical buckling loads of sandwich plates with sinusoidal and trapezoidal corrugation are analyzed. The through-thickness displacement, normal and shear stresses at the important points of the sandwich plates under uniform transverse loading conditions are obtained. A series of numerical solutions are performed to study the contribution of corrugation shape, face sheet lay-up architecture, boundary conditions and length/thickness ratio of the plate on the bending behavior and linear uniaxial buckling loads of the sandwich plates. For the sake of verification, the linear uniaxial critical buckling loads of the corrugated sandwich plates are then compared with those of flat sandwich plates previously reported in the literatures. It has been shown that the linear uniaxial buckling capacity of sandwich plates is considerably improved by introducing corrugation on both face sheets. The improvement was found to be more significant in the case of trapezoidal corrugation than that of sinusoidal one. Moreover, comparing with corrugated sandwich plates, the contribution of the lay-up architecture to linear uniaxial critical buckling load was negligible in the case of plates with constant thickness.

Keywords Bending analysis · Buckling analysis · Composite sandwich plates · Corrugation · Soft core · 3D finite element modeling

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✉ Mohammad Mahdi Kheirikhah
kheirikhah@qiau.ac.ir

1 Faculty of Industrial and Mechanical Engineering, Qazvin Branch, Islamic Azad University, Nokhbegan Blvd., Qazvin, Iran

2 Young Researchers and Elite Club, Qazvin Branch, Islamic Azad University, Qazvin, Iran

1 Introduction

Composite sandwich plates are widely used in engineering applications due to their high stiffness and strength, and low weight. Sandwich plates are commonly consisted of a light thick core bonded to two thin stiff face sheets. In sandwich plates, the core keeps the face sheets at an adequate distance and transmits the shear and normal loads. The core of composite sandwich plates is usually consisted of a honeycomb or foam polymer, while composite laminates are used as face sheets. Keeping in mind the superior advantage of sandwich plates, an overall understanding of mechanical behavior under different situations is required. Static analysis is commonly used to properly design composite sandwich plate structures. Bending and buckling analyses are two common static analyses which are performed for sandwich plates under uniform transverse load and in-plane compressive forces, respectively.

To date, there has been different approaches to analyze the behavior of sandwich plates to inspect their dynamic and static responses including 3D elasticity solution, layer wise (LW) approaches and equivalent single layer (ESL) theories. Based on the 3D theory of elasticity, Pagano [1] derived the bending response of composite sandwich plates. For uniaxial buckling of simply supported sandwich panels with composite sheets, Noor et al. [2] presented the

3D elasticity solutions. Higher-order ESL theories were presented by Kant and Swaminathan [3] for studying the mechanical behavior of composite sandwich plates. For thick laminated or sandwich plates, the ESL theories can give inaccurate results and are not suitable for predicting the local behavior of sandwich plates such as delamination, matrix cracking or wrinkling. To model thick laminated plates in a better manner and to evaluate their local behaviors, Carrera and Demasi [4] extended the mixed LW theory for sandwich plates. In these models, the number of unknowns depend on the number of the composite layers and it becomes larger as the number of the layers increases.

Layer-wise theories need so much computational time and efforts that their application becomes impractical, occasionally. To overcome this problem, zigzag theories with linear or high-order local functions were proposed. Di Sciuva [5] proposed a refined zigzag plate theory in which the unknowns for the in-plane displacements at each layer were assumed in terms of those at the reference plane, and the transverse displacement was assumed constant along the plate thickness. Most zigzag theories satisfy the transverse shear continuity conditions, but in these theories, the transverse stresses continuity was not enforced in the governing equations. Post-processing method based on equilibrium consideration has to be adopted to calculate the transverse shear stresses. Shariyat [6] introduced a high-order global–local theory that guarantees the continuity conditions of all displacements and transverse stress components and considered the transverse flexibility of sandwich plates. Kheirikhah et al. [7, 8] presented a new improved higher order theory using the third-order plate theory of the face sheets and quadratic and cubic functions for transverse and in-plane displacements of the core for bending and buckling analysis of composite sandwich plates.

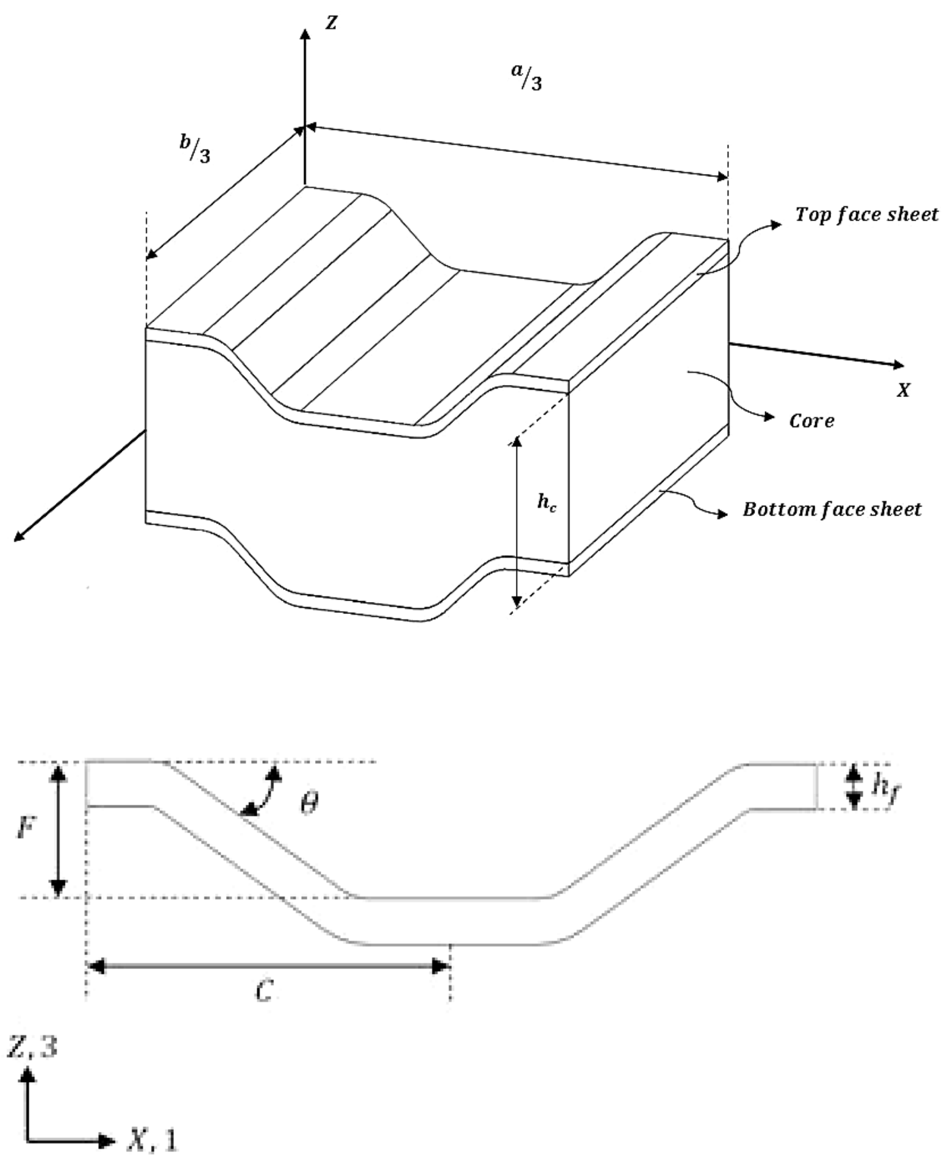
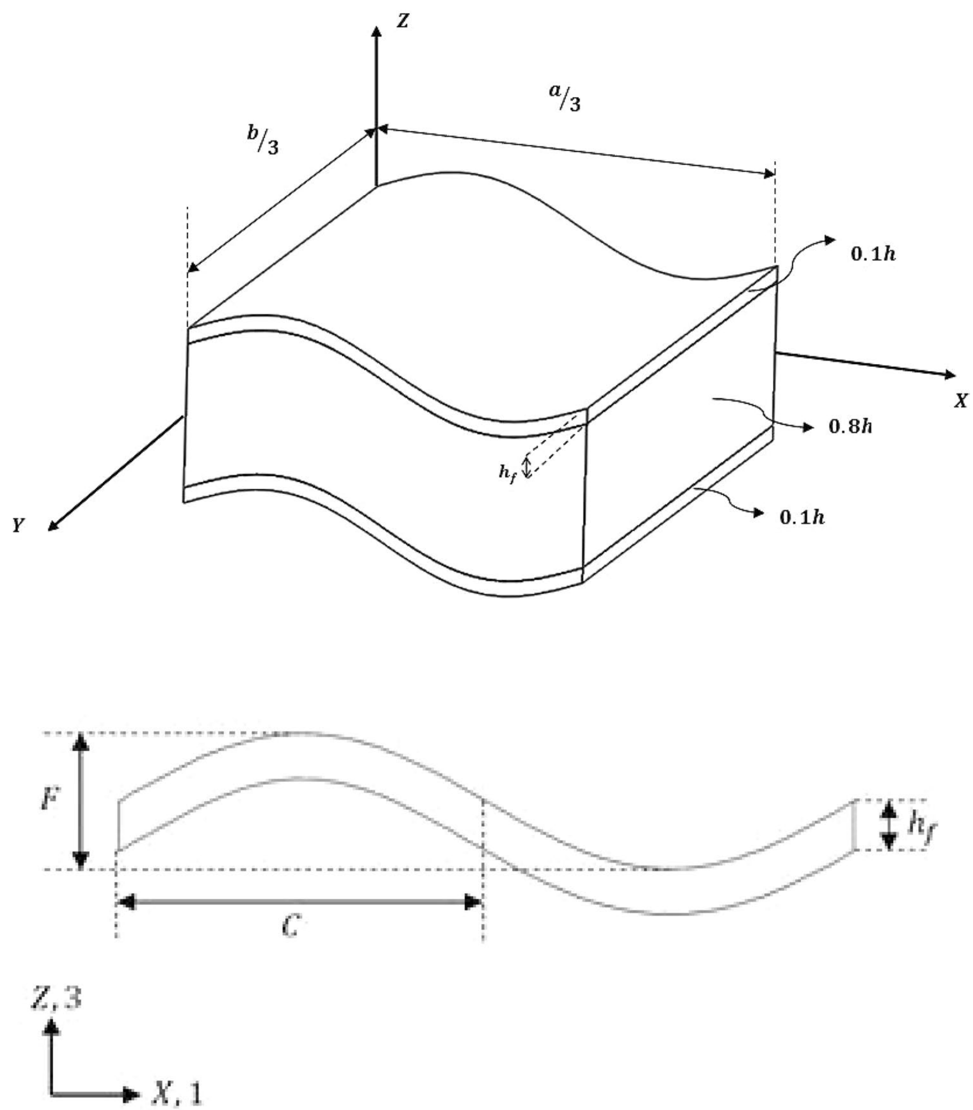


Fig. 1 Geometry of the trapezoidal corrugated sandwich plate and its parameters

Employing corrugation in the core or face sheets of sandwich plates has been found as an approach to improve the mechanical behavior of these structures against various loading conditions. Sandwich plates which are reinforced with corrugations can achieve a higher stiffness and strength than flat plates, and can thus improve the mechanical behavior and strength/weight ratio of structures that are made of them. There are two types of corrugated sandwich plates which are used in different industries. The first type consists of two flat face sheets and a corrugated core. This type of sandwich plates has been widely studied and used in the last three decades. The second type is corrugated-face sheets sandwich plate which is composed of two corrugated face sheets and a foam-like core that fills the gap between the face sheets [9]. This type of corrugated sandwich plates is relatively new and has not been studied sufficiently at this time. Therefore, the purpose of this paper is to investigate the bending and buckling behavior of the corrugated-face sheet sandwich plates.

The plate theories such as 3D elasticity, ESL or LW are only able to analyze the mechanical behavior of flat sandwich and composite structures without the corrugation. One of the simple and valid ways of analyzing the corrugated metallic or laminated plates is to consider them as orthotropic plates of uniform thickness with equivalent rigidities. Based on this assumption, some researchers investigated the mechanical behavior of corrugated plates. For instance, Seydel's formulation [10] was used for many years to estimate the equivalent rigidities of such structures. These formulas were then improved by Lau [11] and Briassoulis [12]. An analytical model was presented by Shimansky and Lele [13] to analyze the initial transverse stiffness of sinusoidal corrugated plates. Using reduction formulas, Semenyuk and Neskhodovskaya [14] analyzed the stability of

Fig. 2 Geometry of the sinusoidal corrugated sandwich plate and its parameters



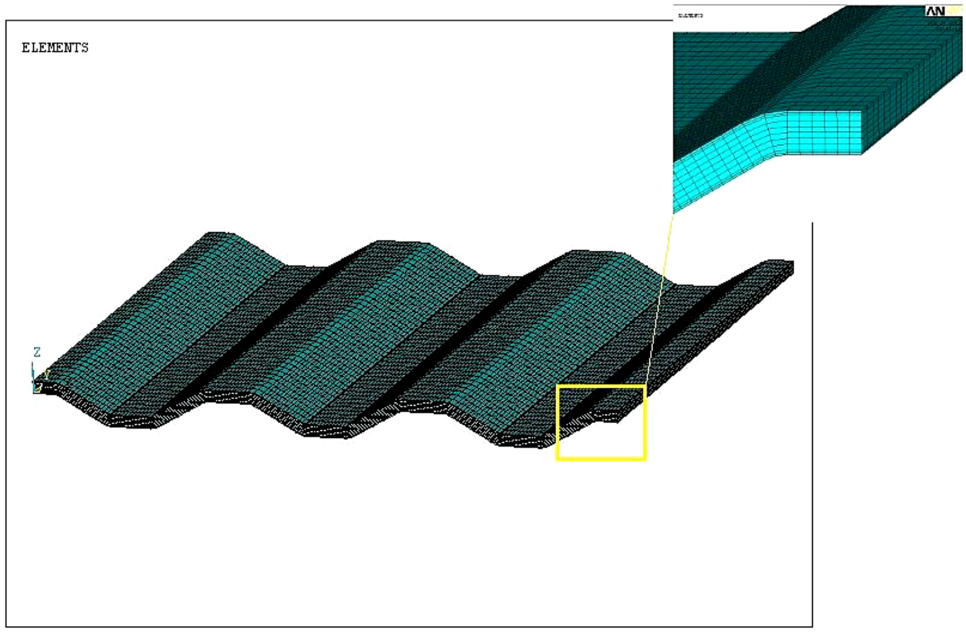


Fig. 3 Complete 3D FE model of the trapezoidal corrugated sandwich plate

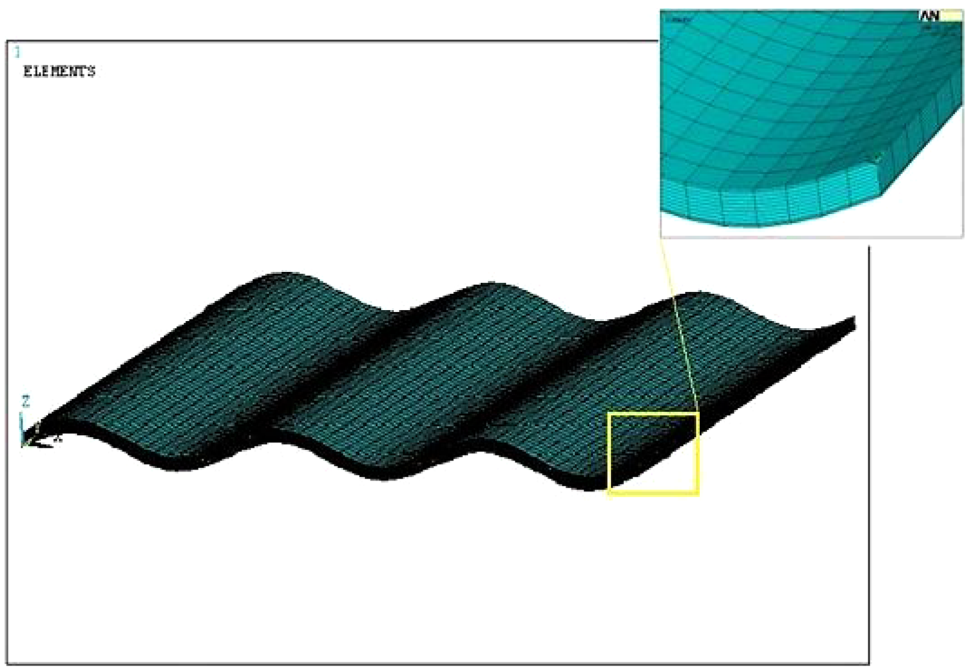


Fig. 4 Complete 3D FE model of the sinusoidal corrugated sandwich plate

Table 1 Material properties used in the present FE modeling

Material set no.	Location	$E_1\,(GPa)$	$E_2\,(GPa)$	$E_3\,(GPa)$	$G_{12}\,(GPa)$	$G_{13}\,(GPa)$	$G_{23}\,(GPa)$	ν_{12}	ν_{13}	ν_{23}
1 Noor [2]	Face sheets	19	1	1	0.52	0.52	0.338	0.32	0.32	0.49
	Core	3.2e−5	2.9e−5	0.4	2.4e−3	7.9e−2	6.6e−2	0.99	3e−5	3e−5
2 Dafedar [27]	Face sheets	131	10.34	10.34	6.895	6.205	6.895	0.22	0.22	0.49
	Core	6.89e−3	6.89e−3	6.89e−3	3.45e−3	3.45e−3	3.45e−3	1e−5	1e−5	1e−5
3 Pandit [26]	Face sheets	0.01	0.01	0.25	2e−3	5e−3	5e−3	0.25	0.25	0.25
	Core	5e−3	4e−4	4e−4	6e−4	6e−4	1.6e−4	0.25	0.25	0.25

longitudinally corrugated cylindrical shells by replacing the corrugated face sheet with an equivalent orthotropic layer.

Renhuai and Dong [15] studied the non-linear bending and vibration of corrugated circular plates. Some studies also were done to design an optimum shape for the corrugation of sandwich plates by Cho-Chung et al. [16] and Tian and Lu [17]. Pokharel and Mahendran [18, 19] investigated the local buckling behavior and post-buckling of trapezoidal corrugated steel face sheets sandwich plates experimentally and numerically using FEM. Bending behavior of corrugated core sandwich plates was investigated by Chang et al. [20]. A closed-form solution based on the Mindlin-Reissner plate theory was used to describe the bending behavior of the corrugated sandwich plate. Liew et al. [21, 22] analyzed the buckling behavior of sinusoidal and trapezoidal corrugated plates based on the first order shear deformation theory (FSDT). They also performed a non-linear analysis of the corrugated plates using mesh-free Galerkin method based on the FSDT. Joachim et al. [23] investigated the wrinkling of composite sandwich panels with corrugated face sheets. In particular, semi-circular and sine-wave shaped corrugations on one face sheet were studied. It was shown that the corrugations significantly increased the wrinkling strength. Reany and Grenestedt [24] studied sandwich plates with one corrugated and one flat face sheet with the goal of finding configurations with higher strength and/or stiffness and reduced weight. It was concluded that the corrugations lead to increased bending stiffness in one direction but reduced in another. Numerical analysis predicted the corrugated panel to be 25 % stronger than the flat counterpart in spite of being 15 % lighter. Recently, Kheirikhah et al. [9] studied the natural vibration analysis of corrugated face sheet sandwich plates using 3D FEM. The effects of many parameters such as boundary conditions, geometrical parameters and fiber orientation of the composite face sheets have been assessed.

Many different corrugation shapes have been used for corrugated-core sandwich plates such as: *I*-beam, *Y*-beam, triangular, trapezoidal and sinusoidal. However, to date, only two types of corrugation shapes have been used for corrugated-face sheet sandwich plates: trapezoidal and sinusoidal [9, 10, 15, 21, 22]. Therefore, in the present paper these two common types of corrugated sandwich plates are studied.

However, there are some important points that should be noted about analyzing the corrugated plates using equivalent rigidities and uniform thickness. The first point is that the accuracy of this approach greatly depends on the correct estimation of equivalent rigidities. As an analysis, the results obtained by this theory have to be compared with numerical methods such as finite element method (FEM) for the validation of results [9, 15, 21, 22]. The second point is that this approach cannot inspect and predict the local behavior of materials around the corrugation shapes. These limitations lead scientists to look for numerical methods that can create the real physical model of the corrugated plates with higher accuracy to predict the local behavior of corrugation shapes. Nowadays, FEM is one of the numerical methods in engineering applications which is universally used. The FEM is not only able to predict the mechanical behavior of corrugated sandwich structures accurately, but is also able to consider and analyze the local effects and makes it possible to analyze complex structures with different dimensions and various boundary conditions, easily.

The bending and buckling analyses of sandwich plates with corrugation on both face sheets have not been studied so far. Therefore, this work mainly contributes to understand the bending behavior and linear uniaxial buckling

Table 2 Convergence of the dimensionless linear uniaxi al buckling load

Element numbers $X \times Y \times Z$	Number of core elements	Number of skins elements	Dimensionless linear uniaxial buckling load
$4 \times 4 \times 4$	32	32	8.46
$6 \times 6 \times 4$	72	72	7.91
$8 \times 8 \times 4$	128	128	7.48
$10 \times 10 \times 4$	200	200	7.12
$13 \times 13 \times 4$	338	338	6.78
$15 \times 15 \times 4$	450	450	6.43
$17 \times 17 \times 4$	578	578	6.21
$20 \times 20 \times 4$	800	800	5.93
$25 \times 25 \times 4$	1250	1250	5.74
$30 \times 30 \times 4$	1800	1800	5.61
$35 \times 35 \times 4$	2450	2450	5.42
$40 \times 40 \times 4$	3200	3200	5.26
$45 \times 45 \times 4$	4050	4050	5.17
$50 \times 50 \times 4$	5000	5000	4.96
$60 \times 60 \times 4$	7200	7200	4.84
$70 \times 70 \times 4$	9800	9800	4.72
$80 \times 80 \times 4$	12800	12800	4.61
$90 \times 90 \times 4$	16200	16200	4.61
Dafedar et al. [27]			4.5685

Table 3 Comparison of the dimensionless deflection and stresses at the important points of the simply supported square sandwich plate under double-sinusoidal transverse load

Analysis	$\overline{w}\left(\frac{a}{2},\frac{b}{2},0\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\frac{h}{2}\right)$	$\overline{\tau_{xy}}\left(0,0,\frac{h}{2}\right)$
Present	2.2088	1.1087	0.1060	0.0711
Pagano [1]	2.2004	1.1530	0.1104	0.0707
Kheirikhah [7]	2.1942	1.1981	0.1110	0.0730
Pandit [26]	2.2002	1.1467	0.1084	0.0709
Kant [3]	2.0848	1.1495	0.1042	0.0688

load capacity of composite corrugated-face sheet sandwich plates with a soft core. In this regard, comprehensive 3D finite element (FE) analyses are performed through ANSYS 12. The material of the core is assumed as soft isotropic that is perfectly bonded to two stiff laminated composite face sheets. For the cases studied here, a series of analyses have been carried out on sandwich plates with sinusoidal and trapezoidal corrugation on both face sheets. The effects of many parameters such as boundary conditions, length/thickness ratio of the structures and composite face sheets lay-up on the bending and buckling response of the sandwich plates are investigated. The critical linear uniaxial buckling loads of the corrugated sandwich plates are obtained and then compared to those of flat sandwich plates. Also, the solution for the bending analysis of the corrugated sandwich plates under uniform and double-sinusoidal transverse loads is presented. The through-thickness displacement, normal and shear stresses at the important points of the sandwich plates are obtained.

2 Finite element modeling

Corrugated and flat sandwich plates with the plane dimensions $a \times b$ and total thickness of h are considered. It is assumed that a corrugated isotropic soft core with a thickness of h_c is perfectly bonded to two corrugated composite face sheets with thickness of h_f. The schematic of configuration and geometrical parameters of the trapezoidal and sinusoidal corrugations are drawn in Figs. 1 and 2. The side views of corrugations are depicting the amplitude (F) and the wavelength ($2C$) of the corrugation wave. The trapezoidal angle is considered to be θ as shown in Fig. 1.

As stated previously, the core is considered as a soft isotropic foam-like material and the face sheets are assumed as stiff orthotropic epoxy-based composite material with glass fibers.

3D FE model of the sandwich plates are constructed in the ANSYS 12.0 code. 8-node SOLID185 brick elements were used for the core modeling and SOLID46 layered elements were used for constructing the composite face sheets. The SOLID185 element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has stress stiffening, large deflection and large strain capabilities [25]. The SOLID46 element is the layered version of the SOLID185 element with same node numbers and degree of freedoms. This element has the ability to model layered composite structures. The layered composite specifications including layer thickness, material properties and layer

Table 4 Dimensionless uniaxial buckling load of square sandwich plates with lay-up of $[(0/90)_5/\text{Core}/(90/0)_5]$

h_f/h	a/h	Elasticity [2]	High-order [8]	GLPT [28]	MLW [27]	ESL [27]	Present FEM	Error (%)
0.025	20	2.5543	2.5657	2.5391	2.5390	2.6386	2.64	3.4
	10	2.2376	2.2619	2.1914	2.1904	2.2942	2.37	5.9
	20/3	1.8438	1.8780	1.7961	1.7952	1.8980	1.98	7.4
	5	1.5027	1.5313	1.4449	1.4427	1.5393	1.65	9.8
0.05	20	4.6590	4.6800	4.6387	4.6386	4.7857	4.80	3.0
	10	3.7375	3.7603	3.6770	3.6759	3.8475	3.92	4.9
	20/3	2.7911	2.8310	2.7509	2.7506	2.9222	2.95	5.7
	5	2.0816	2.1007	2.0431	2.0426	2.1977	2.19	5.2
0.075	20	6.4224	6.4403	6.3915	6.3914	6.5644	6.59	2.6
	10	4.7637	4.8236	4.7432	4.7433	4.9580	5.06	6.2
	20/3	3.3729	3.4004	3.3387	3.3385	3.5466	3.52	4.4
	5	2.3973	2.4048	2.3674	2.3672	2.5461	2.12	11.6
0.1	20	7.8969	7.9148	7.8632	7.8631	8.0544	8.09	2.4
	10	5.6081	5.6178	5.5471	5.5463	5.7946	6.11	8.9
	20/3	3.7883	3.7895	3.7430	3.7424	3.9752	4.14	9.3
	5	2.6051	2.6048	2.5791	2.5789	2.7719	2.78	6.7

Table 5 Cross-sectional area (A) and second moment of cross section area of the flat, sinusoidal and trapezoidal sandwich plates

a/h	Cross-sectional area (mm^2)			Second moments of area, I_{XX} (mm^4)		
	Flat	Sinusoidal corrugated	Trapezoidal Corrugated	Flat	Sinusoidal Corrugated	Trapezoidal Corrugated
100	3600.00	3780.18	3785.66	10800.00	554332.00	624577.67
50	7200.00	7574.14	7584.31	86400.00	918815.93	1209587.00

orientation can be specified in this element [25]. The complete 3D FE model of the sandwich plate is constructed by extruding and meshing the generated cross-section of the plate using two mentioned brick elements along the z-axis [9]. Figures 3 and 4 show the complete generated 3D FE model of the sinusoidal and trapezoidal corrugated sandwich plates.

The effects of the different boundary conditions on the bending behavior and linear uniaxial buckling load of sandwich plates are also studied in this research. The boundary conditions considered herein include all edges simply supported (SSSS) and all edges clamped (CCCC). The boundary conditions applied to the all nodes of the plate edges are defined as follows:

Edges parallel to Y-axis:

$$\text{SSSS}: \ v = w = 0 \quad (1)$$

$$\text{CCCC}: \ u = v = w = 0 \quad (2)$$

Edges parallel to X-axis:

$$\text{SSSS}: \ u = w = 0 \quad (3)$$

$$\text{CCCC}: \ u = v = w = 0 \quad (4)$$

where u, v and w are the node displacements in the X, Y and Z directions, respectively.

3 Model verification

Based on the literature reviews and to the best of our knowledge, sandwich plates with two corrugated face sheets have not been studied. Consequently, before

Table 6 Dimensionless deflection and stresses at the important points of square sandwich plates under uniform transverse load and simply support boundary condition with length/thickness ratio of $a/h = 50$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−6.98419918	−0.693	−0.541	−0.000378	−0.409	−0.409
		−6.98419918	0.542	0.695	−0.0000217		
	30	−5.57981756	−0.6.03	−0.587	0.0004.17	−0.407	−0.386
		−5.57981756	0.422	0.589	0.000858		
	45	−4.88076916	−0.520	−0.715	0.000683	−0.408	−0.381
		−4.88076916	0.348	0.648	0.00113		
	60	−4.73599778	−0.415	−0.902	0.000393	−0.405	−0.390
		−4.73599778	0.304	0.840	0.000809		
	90	−4.96412572	−0.280	−1.10	−0.000360	−0.416	−0.412
		−4.96412572	0.280	1.10	−0.0000397		
Sinusoidal	0	−2.34346604	−0.146	−0.244	−0.0291	−0.184	−0.215
		−2.34412764	0.201	0.180	0.0402		
	30	−2.33034517	−0.205	−0.266	−0.0414	−0.198	−0.227
		−2.32913224	0.221	0.179	0.0440		
	45	−2.26242494	−0.281	−0.255	−0.0562	−0.151	−0.231
		−2.26176338	0.263	0.162	0.0525		
	60	−2.18314881	−0.344	−0.197	−0.0685	−0.111	−0.226
		−2.18303774	0.324	0.138	0.0646		
	90	−2.09405792	−0.363	−0.119	−0.0728	−0.202	−0.206
		−2.09372714	0.365	0.115	0.0726		
Trapezoidal (45°)	0	−1.33502808	−0.0701	0.0492	−0.00040	−0.181	−0.198
		−1.33216132	0.0741	0.0808	−0.00081		
	30	−1.34463145	0.0574	0.0651	−0.00073	−0.168	−0.202
		−1.34124685	0.0527	0.169	−0.00091		
	45	−1.36366522	0.0326	0.143	−0.00096	−0.152	−0.207
		−1.36244596	0.0358	0.501	−0.00146		
	60	−1.37797454	0.0237	0.276	−0.00223	−0.137	−0.211
		−1.37431468	0.0219	0.834	−0.00265		
	90	−1.39754551	−0.0192	0.395	−0.00236	−0.124	−0.214
		−1.39434796	0.0760	1	−0.00284		

analyzing the bending and buckling of the corrugated sandwich plates, the accuracy of the present 3D FE modeling and analyzing is assessed by modeling a flat sandwich plate and its comparison with those of sandwich plates reported in the literature.

In this research, different sets of materials are used for modeling. Table 1 shows the sets of the material properties which are used in the present FE modeling and analysis.

In FEM-based analysis, a convergence study must be performed before obtaining the results to define the proper elements size. In the present research, the convergence study is performed for uniaxial linear buckling load of a flat square sandwich which was studied by Dafedar et al. [27] using mixed layerwise theory (MLW). The plate has lay-up of [0/90/Core/90/0], length/thickness ratio of $a/h = 60$ and $h_c/h_f = 10$. The simply support boundary conditions (SSSS) were applied to the all edges of the plate. Set no. 2 of the material properties in Table 1 is used for modeling. Table 2 presents the variation of the dimensionless linear uniaxial buckling load of the plate versus plate divisions and its total number of elements. The line divisions along plate length (X direction), plate width (Y direction) and plate thickness (Z direction) are given in Table 2. In this analysis, all the studied plates have constant divisions along their thickness direction. The thickness of each face sheet was divided to one portion while the core has two elements along its thickness direction.

The dimensionless linear uniaxial buckling load is expressed as [2, 27]:

$$\bar{N} = \frac{a^2 N_0}{E_2 h^3} \quad (5)$$

Table 7 Dimensionless deflection and stresses at the important points of square sandwich plates under uniform transverse load and simply support boundary condition with length/thickness ratio of $a/h = 100$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−6.7353884	−0.683	−0.535	−0.0000698	−0.353	−0.377
		−6.7353884	0.534	0.684	−0.0000153		
	30	−5.3489826	−0.596	−0.581	0.000723	−0.377	−0.363
		−5.3489826	0.417	0.580	0.000857		
	45	−4.6588802	−0.515	−0.708	0.000991	−0.395	−0.363
		−4.6588802	0.343	0.638	0.00112		
	60	−4.521218	−0.412	−0.893	0.000701	−0.381	−0.367
		−4.521218	0.300	0.830	0.000801		
	90	−4.756856	−0.277	−1.09	−0.0000498	−0.368	−0.382
		−4.756856	0.277	1.09	−0.0000502		
Sinusoidal	0	−0.7467382	−0.0531	−0.0806	−0.0105	−0.141	−0.152
		−0.7449468	0.0748	0.0591	0.0147		
	30	−0.80043886	−0.0806	−0.0989	−0.0161	−0.134	−0.169
		−0.8002735	0.0919	0.0648	0.0179		
	45	−0.81410862	−0.117	−0.103	−0.0231	−0.0799	−0.179
		−0.81399838	0.114	0.0614	0.0223		
	60	−0.7783633	−0.142	−0.0782	−0.0279	−0.0397	−0.175
		−0.77833574	0.136	0.0510	0.0266		
	90	−0.71464458	−0.139	−0.0432	−0.0276	−0.147	−0.162
		−0.71461702	0.140	0.0403	0.0275		
Trapezoidal (45°)	0	−0.40826006	−0.0306	0.0571	−0.000108	−0.0950	−0.148
		−0.4078191	0.0332	0.455	−0.0000516		
	30	−0.44986188	−0.0292	0.0690	−0.000265	−0.0963	−0.157
		−0.44937958	0.0780	0.325	0.000596		
	45	−0.4714827	−0.00259	0.110	−0.000683	−0.0926	−0.00352
		−0.47101418	0.0861	0.219	0.00116		
	60	−0.46329738	−0.0197	0.198	−0.00111	−0.797	−0.159
		−0.46278752	0.0671	0.151	0.00152		
	90	−0.43095572	−0.00918	0.326	−0.00144	−0.0480	−0.159
		−0.43047342	0.0510	0.113	0.00150		

where N_0 is the linear uniaxial buckling load, a is the length of the sandwich plate, h is the total thickness of sandwich plate and E_2 is the transverse elastic modulus of the face sheets. It can be seen that by increasing the number of elements, the buckling load converged to a constant value and further increasing does not affect the results. Also, it can be seen that the obtained result is in good agreement with those of Dafedar et al. [27].

A similar convergence study has been performed for all the analysis and obtained results in this paper.

3.1 Bending of flat sandwich plate

To demonstrate the accuracy of the proposed FE modeling and bending analysis and compare the obtained present results with those of published results, some dimensionless parameters have been obtained for the important points of a flat square sandwich plate ($a/b = 1$) with plane dimensions of 225 × 225 mm^2. The plate has lay-up of $[(0°/90°)_5/\text{Core}/(90°/0°)_5]$ and the used finite element mesh for this analysis is the same as that used in the convergence study. Set no. 3 of the material constants in Table 1 is used to verify the accuracy of the proposed models. The simply support boundary conditions (SSSS) are applied to all the edges of the plate. The length/thickness ratio of the plate is assumed to be $a/h = 10$ with face sheet thickness ratio of $h_f/h = 0.1$. A transverse double-sinusoidal load is applied to the top surface of the plate to obtain its linear bending behavior. The sinusoidal load relation is defined as:

$$q(x, y) = q_0 \sin(\pi x/a)\cos(\pi y/b) \quad (6)$$

Table 8 Dimensionless deflection and stresses at the important points of square sandwich plates under uniform transverse load and clamped boundary condition with length/thickness ratio of $a/h = 50$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−2.19604842	−0.338	−0.238	−0.000372	0.255	0.255
		−2.19604842	0.237	0.338	−0.0000284		
	30	−1.96295878	−0.319	−0.285	−0.0000673	0.185	0.278
		−1.96295878	0.197	0.328	0.000335		
	45	−1.76504208	−0.268	−0.35	−0.0000206	0.136	0.336
		−1.76504208	0.163	0.357	0.000414		
	60	−1.6241298	−0.196	−0.417	−0.0000884	0.104	0.414
		−1.6241298	0.135	0.412	0.000252		
	90	−1.53559102	−0.117	−0.475	−0.000317	0.0904	0.499
		−1.53559102	0.116	0.475	0.0000827		
Sinusoidal	0	−0.76210609	−0.0606	−0.107	−0.0122	−0.118	−0.0467
		−0.76229354	0.876	0.0724	0.0176		
	30	−0.7004487	−0.0778	−0.11	−0.0158	−0.0838	−0.0699
		−0.70001869	0.0862	0.0669	0.0171		
	45	−0.68180374	−0.107	−0.104	−0.0215	−0.0387	−0.0865
		−0.68148398	0.105	0.0618	0.0208		
	60	−0.66861664	−0.134	−0.0789	−0.0268	−0.00253	−0.103
		−0.66852843	0.129	0.0542	0.0257		
	90	−0.68302762	−0.154	−0.0481	−0.031	−0.0186	−0.118
		−0.68298352	0.153	0.0466	0.0305		
Trapezoidal (45°)	0	−0.44586939	−0.0209	−0.00951	−0.000405	−0.0744	−0.00877
		−0.44478884	0.0381	0.275	0.0000801		
	30	−0.44516437	−0.0154	−0.02678	−0.000573	−0.0915	−0.01635
		−0.44427332	0.0368	0.297	0.000243		
	45	−0.44453341	−0.00931	−0.05379	−0.000672	−0.116	−0.03946
		−0.44353774	0.0352	0.312	0.000427		
	60	−0.44346198	−0.00849	−0.07195	0.000812	−0.127	−0.05813
		−0.44273286	0.0343	0.329	0.000784		
	90	−0.44277108	−0.00752	−0.0946	−0.000918	−0.131	−0.0845
		−0.44160233	0.0332	0.341	−0.000913		

where q_0 is the amplitude of the transverse sinusoidal load. The quantities of the dimensionless normal and shear stress components and deflection at those of mentioned points of the sandwich plate are shown in Table 3. The dimensionless parameters for the normal and shear stress components and transverse displacement are defined as [1, 7]:

$$\left(\overline{\sigma_x}, \overline{\sigma_y}, \overline{\sigma_z}, \overline{\tau_{xy}}\right) = \frac{h^2}{a^2 q_0}\left(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}\right), \quad (7)$$

$$\left(\overline{\tau_{xz}}, \overline{\tau_{yz}}\right) = \frac{h}{a q_0}\left(\tau_{xz}, \tau_{yz}\right) \quad (8)$$

$$\overline{w} = \frac{100 E_2 h^3}{a^4 q_0} w \quad (9)$$

All the normal components of the stress and the transverse displacement are calculated at the point $\left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$. Transverse shear stress components such as $\overline{\tau_{xz}}$ and $\overline{\tau_{yz}}$ are calculated at the points $\left(\frac{a}{2}, 0, 0\right)$ and $\left(0, \frac{b}{2}, 0\right)$, respectively. The obtained results in the present study are compared with those of results obtained by 3D elasticity solution [1], high-order equivalent single layer theory (ESL) [3], high-order zigzag theory [26] and high-order analytical theory [7], as shown in Table 3. It can be seen that the present results are in good agreement with three-dimensional elasticity solutions [1] and other accurate analytical results.

3.2 Buckling of flat sandwich plate

For verification of the linear buckling analysis, a square sandwich plate with lay-up of $[(0°/90°)_5/\text{Core}/(90°/0°)_5]$ is subjected to uniaxial in-plane compressional loading. The finite element mesh for this analysis is the same as that of used in the convergence study. The sandwich plate consists

Table 9 Dimensionless deflection and stresses at the important points of square sandwich plates under uniform transverse load and clamped boundary condition with length/thickness ratio of $a/h = 100$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2}, 0, 0\right)$	$\overline{\tau_{xz}}\left(0, \frac{b}{2}, 0\right)$
Flat	0	−1.9582758	−0.326	−0.231	−0.0000561	−0.197	0.329
		−1.9582758	0.230	0.327	−0.0000247		
	30	−1.7229134	−0.308	−0.276	0.000247	−0.201	0.380
		−1.7229134	0.191	0.315	0.000329		
	45	−1.527513	−0.259	−0.338	0.000333	−0.188	0.484
		−1.527513	0.157	0.343	0.000405		
	60	−1.3946738	−0.189	−0.403	0.000222	−0.171	0.612
		−1.3946738	0.131	0.397	0.000244		
	90	−1.31706484	0.113	−0.461	−0.0000121	−0.142	0.746
		−1.31706484	0.113	0.461	−0.0000878		
Sinusoidal	0	−0.23540374	−0.0256	0.0228	0.00616	−0.176	−0.140
		−0.23533484	−0.0217	−0.0356	−0.00429		
	30	−0.21794448	−0.0288	−0.0394	−0.00577	−0.127	−0.139
		−0.21790314	0.0332	0.0219	0.00647		
	45	−0.21640112	−0.0401	−0.0318	−0.00801	−0.0787	−0.173
		−0.21637356	0.0408	0.021	0.00796		
	60	−0.21477508	−0.0503	−0.0288	−0.00998	−0.00346	−0.00143
		−0.2147613	0.0493	0.0187	0.00968		
	90	−0.22524788	−0.0570	−0.0171	−0.0113	−0.0997	−0.193
		−0.2252341	0.0567	0.0161	0.0112		
Trapezoidal (45°)	0	−0.13296735	−0.00816	0.0158	0.000101	−0.0837	−0.0239
		−0.13281302	0.0109	0.152	−0.0000436		
	30	−0.12747878	−0.00781	0.0216	−0.000133	−0.0732	−0.0224
		−0.12731618	0.0357	0.115	0.000165		
	45	−0.12897391	−0.00088	0.0341	−0.00025	−0.0666	−0.0169
		−0.1288182	0.0407	0.0803	0.000342		
	60	−0.13046353	−0.00549	0.0602	−0.000378	−0.0665	−0.00718
		−0.13031746	0.038	0.0551	0.000443		
	90	−0.13709584	−0.000697	0.093	−0.000454	−0.0725	0.0118
		−0.13696493	0.0363	0.0387	0.000433		

of a soft orthotropic core and two equal laminated composite face sheets. The analysis is carried out for different face sheet ratios ($h_f/h = 0.025$, 0.05, 0.075 and 0.1) and length/thickness ratios ($a/h = 20$, 10, 20/3 and 5). Set no. 1 of the material constants given in Table 1 is used to model the plate. The simply support boundary conditions are applied to all the edges of the plate.

The dimensionless overall buckling loads obtained by 3D elasticity solution [2], high-order equivalent single layer theory (ESL) [27], high-order global–local plate theory (GLPT) [28], mixed layer-wise (MLW) theory [27] and high-order analytical theory [8] are given and compared with those of obtained using present FE analysis in Table 4 together with the percentage of relative error between the present FE analysis and the elasticity solution [2]. It can be seen that the present results are in good agreement with 3D elasticity solutions [2] and other accurate analytical results. The maximum discrepancy between the present results and those of elasticity solutions is <12 % which is occurred in sandwich plate with $a/h = 5$ and $h_f/h = 0.075$.

Finally, based on the obtained results in this section, it can be drawn that the present FE modeling and bending and linear buckling analyses of sandwich plates are sufficiently accurate.

4 Results and discussion

In this section, the composite-face corrugated sandwich plates are studied and the contribution of geometrical parameters of both sinusoidal and trapezoidal corrugation on the bending behavior and linear uniaxial buckling load

Table 10 Dimensionless deflection and stresses at the important points of square sandwich plates under double-sinusoidal transverse load and simply support boundary condition with length/thickness ratio of $a/h = 50$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−4.4181182	−0.474	−0.367	−0.000372	−0.195	−0.194
		−4.4181182	0.367	0.475	−0.0000277		
	30	−3.5404486	−0.418	−0.403	0.00015	−0.197	−0.182
		−3.5404486	0.290	0.412	0.000565		
	45	−3.1016138	−0.359	−0.490	0.000323	−0.198	−0.179
		−3.1016138	0.240	0.451	0.000748		
	60	−3.00469526	−0.284	−0.614	0.000128	−0.194	−0.181
		−3.00469526	0.209	0.574	0.000541		
	90	−3.13380972	−0.189	−0.738	−0.000381	−0.199	−0.190
		−3.13380972	0.189	0.739	−0.0000192		
Sinusoidal	0	−1.49931548	−0.111	−0.167	−0.0221	−0.0894	−0.0858
		−1.4989847	0.153	0.122	0.0308		
	30	−1.48674584	−0.151	−0.186	−0.0303	−0.101	−0.0951
		−1.48608428	0.166	0.121	0.0332		
	45	−1.44209054	−0.203	−0.187	−0.0450	−0.0743	−0.0987
		−1.4416495	0.195	0.109	0.0389		
	60	−1.39070938	−0.248	−0.137	−0.0494	−0.0484	−0.0935
		−1.39048886	0.237	0.0930	0.0473		
	90	−1.3335947	−0.266	−0.0811	0.0534	−0.0955	−0.0837
		−1.33337418	0.267	0.0784	0.0531		
Trapezoidal (45°)	0	−0.86764697	−0.0631	0.0324	−0.000404	−0.0936	−0.0602
		−0.86560716	0.0648	0.551	−0.0000716		
	30	−0.87465975	−0.0524	0.0726	−0.000635	−0.0805	−0.0623
		−0.87267982	0.0627	0.573	−0.000167		
	45	−0.88389165	−0.0461	0.135	−0.000819	−0.0734	−0.0651
		−0.88163736	0.0603	0.618	−0.000452		
	60	−0.89842566	−0.0276	0.214	−0.000951	−0.0681	−0.0672
		−0.89526781	0.0594	0.637	−0.000827		
	90	−0.90327197	−0.0188	0.263	−0.00177	−0.0570	−0.0698
		−0.90102267	0.0587	0.678	−0.00184		

capacity is investigated. The material properties of the foam core and the epoxy-based fiber glass composite face sheets are tabulated in Table 1. Material set no. 2 is used to construct the core and face sheets in all bending and linear uniaxial buckling analysis. Square sandwich plates with plane dimension of 0.6 × 0.6 m^2 and length/thickness ratios of (a/h = 100, 50) are considered. The face sheet thickness ratio is assumed to be constant ($h_f/h = 0.1$). The amplitude and the wavelength of the corrugation configuration are considered to be $F = 0.03$ m and $C = 0.1$ m, respectively.

To quantify and present a fair comparison among the obtained results of the studied sandwich plates, their cross-sectional area and second moment of the cross-section area are presented in Table 5. It can be seen that the trapezoidal corrugated plate has a relatively higher second moment of cross-section area than the sinusoidal one. But, the cross-sectional area of the plates are very close together.

4.1 Bending analysis

In this section, several examples are presented to study the bending behavior of the corrugated sandwich plates. In these analyses, the effects of different parameters such as length/thickness ratio, number of composite layers in each face sheet, fiber orientation in the composite face sheets lay-up and boundary conditions are surveyed.

A square sandwich plate with lay-up of [0/α/C/α/0] is considered in which α is the fiber angle of the face sheets composite layers with X direction. The analysis is carried out for different face sheet layer angles ($\alpha = 0°$, 30°, 45°, 60° and 90°). The plates are subjected to double-sinusoidal and uniform transverse loads and also simply support and clamped boundary conditions are applied to the edges of the plates. For trapezoidal corrugated sandwich plates, the trapezoidal angle is assumed to be $\theta = 45°$.

Table 11 Dimensionless deflection and stresses at the important points of square sandwich plates under double-sinusoidal transverse load and simply support boundary condition with length/thickness ratio of $a/h = 100$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−4.2441022	−0.466	−0.362	−0.0000570	−0.171	−0.179
		−4.2441022	0.362	0.466	−0.0000243		
	30	−3.3838168	−0.412	−0.398	0.000465	−0.190	−0.172
		−3.3838168	0.286	0.403	0.000565		
	45	−2.9518138	−0.355	−0.485	0.000638	−0.201	−0.172
		−2.9518138	0.236	0.442	0.000747		
	60	−2.8592122	−0.281	−0.607	0.000439	−0.190	−0.171
		−2.8592122	0.206	0.566	0.000535		
	90	−2.9931538	−0.187	−0.730	−0.0000719	−0.177	−0.175
		−2.9931538	0.187	0.730	−0.0000281		
Sinusoidal	0	−0.48293388	−0.0446	−0.0561	−0.00881	−0.0702	−0.0549
		−0.48289254	0.0625	0.0411	0.0123		
	30	−0.51466922	−0.0633	−0.0716	−0.0126	−0.0676	−0.0650
		−0.51457276	0.0740	0.0446	0.0145		
	45	−0.52235846	−0.0893	−0.0744	−0.0177	−0.0354	−0.0703
		−0.52228956	0.0900	0.0420	0.0176		
	60	−0.499525	−0.109	−0.0565	−0.0215	−0.0103	−0.0671
		−0.50502322	0.107	0.0351	0.0209		
	90	−0.45989372	−0.113	−0.0104	−0.0224	−0.0712	−0.0589
		−0.45989372	0.113	0.0284	0.0226		
Trapezoidal (45°)	0	−0.2691234	−0.0157	0.0389	−0.000105	−0.0463	−0.0387
		−0.26879268	0.0320	0.317	−0.0000463		
	30	−0.29363802	−0.0127	0.0462	−0.000213	−0.0474	−0.0451
		−0.29329352	0.0636	0.229	0.000384		
	45	−0.30699084	−0.00437	0.0731	−0.000503	−0.0459	−0.0463
		−0.30663256	0.0714	0.156	0.000763		
	60	−0.3020576	−0.00934	0.133	−0.000809	−0.0382	−0.0456
		−0.30169932	0.0619	0.108	0.001		
	90	−0.2820766	−0.00899	0.222	−0.00106	−0.0161	−0.0437
		−0.2817321	0.0569	0.0788	0.000971		

Tables 6, 7, 8 and 9 show the dimensionless deflection and stresses of the flat, sinusoidal corrugated and trapezoidal corrugated sandwich plates under uniform transverse load. Tables 6 and 7 present the dimensionless parameters for the plates with SSSS boundary conditions and length/thickness ratios of $a/h = 50$ and $a/h = 100$, respectively. Also, Tables 8 and 9 show the dimensionless parameters for the plates with CCCC boundary conditions and length/thickness ratios of $a/h = 50$ and $a/h = 100$, respectively.

The dimensionless deflection and stresses of the corrugated sandwich plates under double-sinusoidal transverse load are tabulated in Tables 10, 11, 12, 13. Tables 10 and 11 present the dimensionless parameters for the plates with SSSS boundary conditions and length/thickness ratios of $a/h = 50$ and $a/h = 100$, respectively. Also, Tables 12 and 13 show the dimensionless parameters for the plates with CCCC boundary conditions and length/thickness ratios of $a/h = 50$ and $a/h = 100$, respectively.

Comparison between the obtained results of the flat, sinusoidal corrugated and trapezoidal corrugated plates shows that employment of the corrugation lowered the dimensionless deflection and stresses in all the cases. However, this improvement was more significant in the case of trapezoidal corrugated plates than those of sinusoidal ones. Moreover, it can be seen that sandwich plates with CCCC boundary conditions have smaller dimensionless deflection and stresses than those with SSSS boundary conditions. Therefore, it can be concluded that trapezoidal sandwich plates with CCCC boundary conditions have better behavior and lower dimensionless deflection and stresses than the others.

Assessment of the obtained results demonstrates that the plates subjected to uniform transverse load have larger

Table 12 Dimensionless deflection and stresses at the important points of square sandwich plates under double-sinusoidal transverse load and clamped boundary condition with length/thickness ratio of $a/h = 50$

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−1.57241786	−0.266	−0.186	−0.000369	0.209	0.209
		−1.57241786	0.186	0.266	−0.0000312		
	30	−1.40383032	−0.251	−0.224	−0.000135	0.161	0.217
		−1.40383032	0.156	0.259	0.000253		
	45	−1.26115388	−0.211	−0.274	−0.0000706	0.130	0.253
		−1.26115388	0.129	0.281	0.000319		
	60	−1.15949416	−0.154	−0.326	−0.000161	0.113	0.306
		−1.15949416	0.107	0.322	0.000199		
	90	−1.09521258	−0.0917	−0.367	−0.000348	0.110	0.365
		−1.09521258	0.0918	0.368	−0.0000521		
Sinusoidal	0	−0.54490492	−0.0555	−0.0854	−.0111	−0.050	−0.00456
		−0.54481671	0.0797	0.0569	0.0160		
	30	−0.49903676	−0.0683	−0.0896	−0.0139	−0.0311	−0.0176
		−0.49876111	0.0784	0.052	0.0156		
	45	−0.48474706	0.116	−0.0844	−0.0185	−0.00388	−0.0287
		−0.48453757	0.0929	0.0479	0.0185		
	60	−0.47505521	−0.115	−0.0640	−0.0230	0.0194	−0.0367
		−0.47497803	0.113	0.0423	0.0225		
	90	−0.48526529	−0.132	−0.0388	−0.0269	0.0155	−0.0412
		−0.48519913	0.133	0.0369	0.0264		
Trapezoidal (45°)	0	−0.32355797	−0.0241	−0.00607	−0.000401	−0.0228	−0.0288
		−0.32264281	0.0378	0.213	−0.0000717		
	30	−0.32283742	−0.0187	−0.00952	−0.000564	−0.364	−0.0204
		−0.32153498	0.0352	0.228	−0.0000916		
	45	−0.32134617	−0.0138	−0.0286	−0.000691	−0.492	−0.0138
		−0.32185736	0.0336	0.245	−0.000264		
	60	−0.32187275	−0.0105	−0.0408	−0.000734	−0.528	−0.00906
		−0.32062487	0.0318	0.252	−0.000438		
	90	−0.32042659	−0.00895	−0.0687	−0.000813	−0.0612	−0.00832
		−0.31948938	0.0298	0.263	−0.000665		

Table 13 Dimensionless deflection and stresses at the important points of square sandwich plates under double-sinusoidal transverse load and clamped boundary condition with length/thickness ratio of *a*/*h* = 100

Sandwich plate type	Layer angle	$\overline{w}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_x}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_y}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\sigma_z}\left(\frac{a}{2},\frac{b}{2},\pm\frac{h}{2}\right)$	$\overline{\tau_{yz}}\left(\frac{a}{2},0,0\right)$	$\overline{\tau_{xz}}\left(0,\frac{b}{2},0\right)$
Flat	0	−1.4081782	−0.256	−0.181	−0.00005	−0.0849	0.251
		−1.4081782	0.181	0.257	−.000029		
	30	−1.23807788	−0.243	−0.217	0.000184	−0.0906	0.276
		−1.23807788	0.151	0.249	0.00025		
	45	−1.09719116	−0.204	−0.266	0.000246	−0.0814	0.341
		−1.09719116	0.125	0.270	0.000314		
	60	−1.0012548	−0.149	−0.316	0.000153	−0.0682	0.426
		−1.0012548	0.104	0.310	0.000193		
	90	−0.94488082	−0.0891	−0.357	−0.0000413	−0.0462	0.516
		−0.94488082	0.0891	0.357	0.0000587		
Sinusoidal	0	−0.17014166	−0.0225	−0.0293	−0.00446	−0.0894	−0.0589
		−0.17014166	0.0322	0.0185	0.00635		
	30	−0.15673372	−0.0281	−0.0340	−0.00559	−0.0592	−0.0605
		−0.15670616	0.0334	0.0175	0.00655		
	45	−0.15519036	−0.0379	−0.0330	−0.00753	−0.0303	−0.0685
		−0.15517658	0.0399	0.0167	0.00783		
	60	−0.15407418	−0.0478	−0.0249	−0.00946	−0.0142	−0.0767
		−0.15407418	0.0479	0.0150	0.00941		
	90	−0.16192878	−0.0562	−0.0141	−0.0112	−0.0421	−0.0849
		−0.16192878	0.0559	0.0134	0.0110		
Trapezoidal (45°)	0	−0.09759547	−0.00883	0.0116	−0.0000993	−0.0280	0.00488
		−0.09746594	0.0196	0.118	−0.0000403		
	30	−0.0928524	−0.00804	0.000124	−0.00648	−0.0219	0.00368
		−0.09271597	0.0325	0.000109	0.0272		
	45	−0.09364337	−0.00285	0.0252	−0.000216	−0.0185	0.00646
		−0.09351246	0.0367	0.0648	0.000239		
	60	−0.09478849	−0.00520	0.0448	−0.000318	−0.0193	0.0126
		−0.09466584	0.0375	0.0446	0.000313		
	90	−0.10002902	−0.00455	0.0694	−0.000387	−0.0241	0.0250
		−0.09992016	0.040	0.0306	0.000297		

Table 14 Dimensionless linear uniaxial buckling load of sandwich plates with simply support boundary conditions (*a*/*h* = 50)

Layers lay-up	Flat	Sinusoidal	Trapezoidal (30°)	Trapezoidal (45°)	Trapezoidal (60°)
(0/0/C/0/0)	1.992	5.623	7.646	7.712	7.990
(0/0/0/0/C/0/0/0/0)	1.992	5.623	7.648	7.747	7.993
(0/15/C/15/0)	2.1568	5.6127	7.6348	7.7043	7.8864
(0/15/0/15/C/15/0/15/0)	2.205	5.617	7.641	7.793	7.892
(0/30/C/30/0)	2.3614	5.607	7.623	7.695	7.738
(0/30/0/30/C/30/0/30//0)	2.412	5.611	7.635	7.865	7.756
(0/45/C/45/0)	2.6701	5.766	7.635	7.932	7.842
(0/45/0/45/C/45/0/45/0)	2.684	5.782	7.668	7.942	7.870
(0/60/C/60/0)	2.8422	6.197	7.648	8.573	8.235
(0/60/0/60/C/60/06/0/0)	2.857	6.241	7.742	8.624	8.278
(0/75/C/75/0)	2.8697	6.2753	7.9152	8.7325	8.7546
(0/75/0/75/C/75/0/75/0)	2.891	6.314	7.962	8.763	8.755
(0/90/C/90/0)	2.8981	6.356	8.293	8.894	9.033
(0/90/0/90/C/90/0/90/0)	2.923	6.383	8.321	8.937	9.088

Table 15 Dimensionless linear uniaxial buckling load of sandwich plates with simply support boundary conditions ($a/h = 100$)

Layers lay-up	Flat	Sinusoidal	Trapezoidal (30°)	Trapezoidal (45°)	Trapezoidal (60°)
(0/0/C/0/0)	2.145	17.845	13.670	26.638	29.892
(0/0/0/0/C/0/0/0/0)	2.147	17.846	13.680	26.649	29.996
(0/15/C/15/0)	2.3476	17.2453	13.2367	27.1548	29.7443
(0/15/0/15/C/15/0/15/0)	2.368	17.285	13.241	27.167	29.754
(0/30/C/30/0)	2.585	16.750	12.959	27.662	29.440
(0/30/0/30/C/30/0/30/0)	2.593	16.782	12.984	27.798	29.470
(0/45/C/45/0)	2.939	16.549	12.234	26.672	28.284
(0/45/0/45/C/45/0/45/0)	2.944	16.581	12.239	26.686	28.312
(0/60/C/60/0)	3.110	17.285	12.534	27.184	28.668
(0/60/0/60/C/60/06/0/0)	3.121	17.394	12.731	27.437	28.736
(0/75/C/75/0)	3.122	17.9253	12.9858	28.1296	29.7807
(0/75/0/75/C/75/0/75/0)	3.138	18.137	13.058	28.372	29.821
(0/90/C/90/0)	3.132	18.711	13.482	28.958	30.193
(0/90/0/90/C/90/0/90/0)	3.143	18.772	13.498	29.027	30.211

Table 16 Dimensionless linear uniaxial buckling load of sandwich plates with clamped boundary conditions ($a/h = 50$)

Layers lay-up	Flat	Sinusoidal	Trapezoidal (30°)	Trapezoidal (45°)	Trapezoidal (60°)
(0/0/C/0/0)	2.945	8.156	11.606	12.831	11.650
(0/0/0/0/C/0/0/0/0)	2.956	8.156	11.606	12.832	11.651
(0/15/C/15/0)	3.1254	8.4329	11.6782	12.8562	11.8412
(0/15/0/15/C/15/0/15/0)	3.168	8.468	11.702	12.861	11.892
(0/30/C/30/0)	3.313	8.713	11.732	12.875	12.161
(0/30/0/30/C/30/0/30/0)	3.427	8.721	11.892	12.895	12.194
(0/45/C/45/0)	3.682	9.107	11.854	12.934	12.550
(0/45/0/45/C/45/0/45/0)	3.649	9.124	12.009	12.953	12.603
(0/60/C/60/0)	4.008	9.468	11.976	12.975	13.032
(0/60/0/60/C/60/06/0/0)	4.011	9.516	12.031	12.986	13.095
(0/75/C/75/0)	4.1315	9.5157	11.9863	12.9942	13.3412
(0/75/0/75/C/75/0/75/0)	4.132	9.531	12.042	13.034	13.343
(0/90/C/90/0)	4.228	9.554	11.991	13.060	13.424
(0/90/0/90/C/90/0/90/0)	4.243	9.562	12.053	13.099	13.483

Table 17 Dimensionless linear uniaxial buckling load of sandwich plates with clamped boundary conditions ($a/h = 100$)

Layers lay-up	Flat	Sinusoidal	Trapezoidal (30°)	Trapezoidal (45°)	Trapezoidal (60°)
(0/0/C/0/0)	3.308	24.502	20.491	40.223	43.959
(0/0/0/0/C/0/0/0/0)	3.315	24.503	20.571	40.264	43.959
(0/15/C/15/0)	3.5248	24.8945	19.7541	40.8726	44.7078
(0/15/0/15/C/15/0/15/0)	3.549	24.899	19.755	40.893	44.751
(0/30/C/30/0)	3.797	25.333	18.883	41.019	44.569
(0/30/0/30/C/30/0/30/0)	3.824	25.413	18.926	41.125	44.611
(0/45/C/45/0)	4.271	25.735	18.930	40.616	43.725
(0/45/0/45/C/45/0/45/0)	4.286	25.781	18.957	40.740	43.798
(0/60/C/60/0)	4.661	26.463	19.131	40.669	43.427
(0/60/0/60/C/60/06/0/0)	4.692	26.485	19.438	40.943	43.510
(0/75/C/75/0)	4.7871	26.5314	19.0156	40.4521	43.0445
(0/75/0/75/C/75/0/75/0)	4.803	26.563	19.214	40.702	43.049
(0/90/C/90/0)	4.896	26.609	18.914	40.242	42.390
(0/90/0/90/C/90/0/90/0)	4.916	26.640	18.933	40.395	42.478

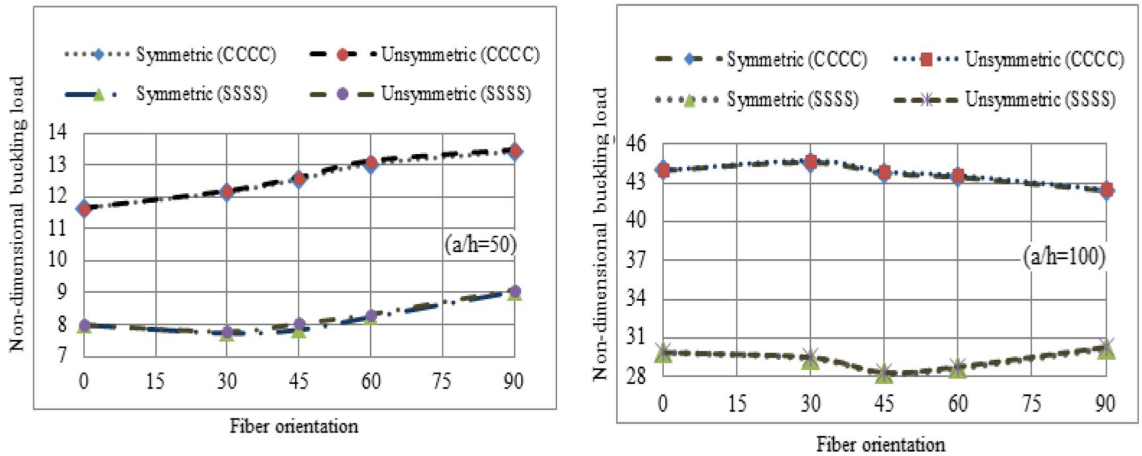


Fig. 5 Dimensionless linear uniaxial buckling load of trapezoidal corrugated sandwich plate with $\theta = 60°$ and length/thickness ratio of **a** $a/h = 50$ and **b** $a/h = 100$

dimensionless transverse displacement than those subjected to double-sinusoidal transverse load. Also, according to the presented Tables, it can be seen that as the length/thickness ratio increases, the dimensionless transverse displacements decreases.

According to the presented results, the dimensionless stresses along X direction ($\overline{\sigma_x}$) are decreased by increment of the face sheet layer angle from 0 to 90 degrees in the case of both trapezoidal and sinusoidal plates. However, this phenomenon had a lower effect on trapezoidal plates than sinusoidal one.

4.2 Buckling analysis

In this section, numerical analyses are performed to investigate the linear uniaxial buckling load capacity of the corrugated sandwich plates. In these analyses, the effects of different parameters such as length/thickness ratio, composite lay-up of the face sheets, fiber orientation in composite layers lay-up and boundary conditions are investigated. A square sandwich plate with two different lay-up ([0/α/C/α/0] and [0/α/0/α/C/α/0/α/0]) is considered. The analysis is carried out for different face sheet layer angles ($\alpha = 0°, 15°, 30°, 45°, 60°, 75°, 90°$) and simply support and clamped boundary conditions are applied to the edges of the plates. Moreover, for trapezoidal corrugated sandwich plates, different trapezoidal angle is assumed ($\theta = 30°, 45°$ and $60°$).

Tables 14 and 15 present the dimensionless linear uniaxial buckling loads for the simply supported sandwich plates with length/thickness ratios of $a/h = 50$ and $a/h = 100$, respectively. The dimensionless linear uniaxial buckling loads of the sandwich plates with clamped boundary condition and length/thickness ratios of $a/h = 50$ and $a/h = 100$ are tabulated in Tables 16 and 17, respectively.

It is generally understood that the introducing of corrugation considerably strengthens the critical linear uniaxial buckling load of sandwich plates. In particular, the improvement in the case of trapezoidal corrugation is more significant than that of sinusoidal corrugation. Distinctively, in the trapezoidal corrugation for higher trapezoidal angles, the critical linear uniaxial buckling load is improved. Also, it can be seen that the dimensionless buckling load is increased by increasing the face sheet layer angle. This phenomenon could be attributed to high stiffness of the face sheets for the bigger lay-up angles. It is noticeable that the linear uniaxial buckling load is more sensitivity to corrugation type rather than the face sheet layer angle. It is also inferred that by increasing the length/thickness ratio (a/h), the dimensionless linear uniaxial buckling load increases. Moreover, the linear uniaxial buckling loads of the plates with clamped boundary conditions are higher than those of the simply supported ones.

In this work, the influence of the face sheet lay-up architecture on the dimensionless linear uniaxial buckling load is analyzed and the corresponding results are presented in Tables 14, 15, 16, 17. Two types of symmetric layers lay-up ([0/α/0/α/C/α/0/α/0] and [0/α/C/α/0]) with different fiber orientations ($\alpha = 0°, 15°, 30°, 45°, 60°, 75°$ and $90°$) are considered. The total thickness of the plates and the thickness of the face sheets for the both plate types are the same. It is generally seen that for a constant thickness of composite face sheets, the contribution of layer numbers are not considerable. It turns out that for practical applications, the thickness of plates should be taken into consideration, rather than the number of the layers in each plate.

The above calculations were based on symmetric lay-up architecture. To study the style of lay-up orientation, antisymmetric lay-up architecture for trapezoidal corrugation with angle of 60° is considered. The dimensionless linear uniaxial buckling load of the trapezoidal corrugation with simply support and clamp boundary condition are shown in Fig. 5a, b for $a/h = 50$ and 100, respectively. Negligible contribution due to anti-symmetrical configuration is observed.

5 Conclusion

The present work contributed to FE modeling and analysis of the critical linear uniaxial buckling load and the bending behavior of the soft-core sinusoidal and trapezoidal corrugated composite sandwich plates. A comprehensive 3D FE analysis was performed for two corrugation configurations including sinusoidal and trapezoidal, through ANSYS 12. The accuracy of the FE modeling and analysis together with the convergence of the results were examined prior to performing the main analysis. The influence of corrugation shape parameters, boundary conditions, fiber orientation in the face sheets composite layers lay-up and length/thickness ratio of the plates on the dimensionless deflection, stresses and linear uniaxial buckling loads of the structures were investigated.

From the presented results, it can be concluded that introducing the corrugation considerably strengthens the critical linear uniaxial buckling load of the sandwich plates. In particular, the improvement introduced by the trapezoidal corrugation was more significant than the sinusoidal one. It became clear that the linear uniaxial buckling load is more sensitivity to the corrugation type rather than the face sheet lay-up angle. Numerical results demonstrated that the global bending behavior of the sandwich plates will be improved by using the trapezoidal corrugation shape as one of the methods to reinforce the sandwich structures against various loading conditions. Moreover, it was found that the dimensionless displacement decreases by increasing the lay-up orientation angle. Numerical results also indicated that introducing corrugation considerably strengthens the bending behavior of the sandwich plates, which reduces the normal and shear stresses.

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