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Elastic Buckling of Composite Laminated Plates: A Numerical Investigation

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Abstract: This paper presents a numerical method using ANSYS to estimate the buckling loads of composite plates. Our approach employs an element based on FSDT that considers out-of-plane shear deformation. We used an Eight node SHELL281 element that is well-suited for analyzing plate and shell structures. The ANSYS results for buckling loads of isotropic and orthotropic layered laminates are in good agreement with other theories from the literature. In this study, we investigated uniaxial and biaxial buckling of the plates and also considered the degree of orthotropy to study its impact on the plates' buckling.

I. INTRODUCTION

Researchers have extensively studied the load-carrying capacity of fiber-reinforced composites in the form of relatively thick plates, considering various loading and boundary conditions to prevent buckling. The following is a list of researchers who have investigated the elastic buckling of laminated composite plates.

Jones [1] investigated the behavior of composite laminated plates, including both macro and micromechanical behavior, and analyzed the plates. Reddy [2] presented different shear deformation theories for composite laminated plates and their finite element formulation, while also analyzing them. Kaw [3] introduced composite materials and analyzed their macro and micromechanical behavior, including failure, analysis, and design of laminates. Gibson [4] studied fiber-reinforced composite laminate, analyzing hygrothermal effects, interlaminate stresses, laminate strength analysis, deflection and buckling of laminates, and selection of laminate design. Ferreira et al. [5] used radial basis function to analyze the static deformations of composite beams and plates. Reddy and Phan [6] studied higher-order shear deformation theory and its application to stability and vibration of composite laminated plates. Kant and Swaminathan [7] presented an analytical solution for composite plates, including the effect of transverse shear deformation, transverse normal strain/stress, and a nonlinear variation of in-plane displacements with respect to the thickness coordinates. Noor et al. [8] used numerical simulations to study the buckling and post-buckling responses and failure initiation of flat, unstiffened composite panels. Reddy and Barbero [9] developed a plate bending element based on the generalized laminate plate theory and presented a method for computing interlaminar stresses. Hsuan and Horng [10] used a sequential linear programming method to maximize the buckling resistance of symmetrically laminated plates with a given material system and subjected to uniaxial compression. Matsunaga [11] analyzed the natural frequencies and buckling stresses of cross-ply laminated composite plates, considering the effects of shear deformation, thickness change, and rotatory inertia. Bert and Devarakonda [12] presented a solution for the buckling of a rectangular plate subjected to a half-sine load distribution on two opposite sides. Akavci et al. [13] studied laminated plates on an elastic foundation, analyzing the bending deflections of symmetric cross-ply laminates. Panda and Ramchandra [14] studied the buckling and post-buckling behavior of simply supported composite plates, including the effect of shear deformation on the buckling load. Khdeir [15] developed an exact solution to the buckling of antisymmetric angle-ply laminated plates, and Shukla et al. [16] estimated critical or buckling loads of laminated composite rectangular plates under in-plane loading. The study by Nemeth and Nemith and Weaver [17] presented non-dimensional parameters and equations that govern the buckling behavior of rectangular symmetrically laminated plates. These equations can be applied to plates made of various structural materials in a general and comprehensive way to represent their buckling resistance. York [18] focused on the benchmark configuration of fully extensionally isotropic laminated plates with matching elastic properties in both extension and bending, as well as some special cases. Ren and Tong [19] reviewed previous research on the elastic buckling of rectangular plates with different boundary conditions and simulated the realistic load and restraining conditions of web plates in I-girders. They analyzed the buckling load of a large number of models under patch load using ANSYS and proposed formulas to predict the elastic buckling coefficients of the webs in I-girders. Their formulas accurately considered the rotational restraints provided by the flanges on the web plates.

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Chacon et al. [20] proposed a mechanism solution to reproduce the ultimate load capacity of steel girders under patch loading, particularly for steel plate girders with closely spaced transverse stiffening. The authors presented the ultimate load capacity of the girder under patch loading in this paper and a companion paper. Qiao and Shan [21] calculated the local buckling load for fiber-reinforced plastic composite structural shapes. They analyzed the local buckling of rectangular orthotropic composite plates with various boundary conditions and obtained explicit solutions for plate local buckling coefficients in terms of rotational restraint stiffness using a variational formulation of the Ritz method. Ragheb [22] presented an analytical stability model for the local buckling of pultruded fiber-reinforced polymer (FRP) structural shapes under eccentric compression. The model considered each shape as a group of orthotropic plates linked together, and the differential equations that describe the buckling behavior of each plate were solved using Levy's solution. The model was used to investigate the effect of the main parameters governing the local buckling behavior of such shapes. Graciano [23] proposed a methodology to determine buckling coefficients for longitudinally stiffened plate girders under partial edge loading or concentrated loads. They found the optimum parameters that govern the transition from a global buckling mode to a more local buckling mode after an extensive parametric analysis. The results showed that the location and relative flexural/torsional rigidity of the stiffener were relevant parameters that governed the final buckling shape, and the authors presented an expression for the buckling coefficient used to determine the critical buckling load for longitudinally stiffened girder webs. Chacon et al. [24] analyzed hybrid girders under patch loading in detail, focusing on longitudinally stiffened steel girders with transverse stiffening plates.

II. FINITE ELEMENT ANALYSIS USING ANSYS

The research utilized an Eight node SHELL281 element, which is well-suited for analysing plate and shell structures due to its six degrees of freedom at each node as shown in Figure 1. Additionally, this element can be employed for modelling laminated composite shells and sandwich constructions that have layered applications. The software program ANSYS, which employs the Mindlin-Reissner theory, specifically the First Order Shear Deformation Theory, was used to model SHELL281. The ANSYS student version was utilized in the investigation.

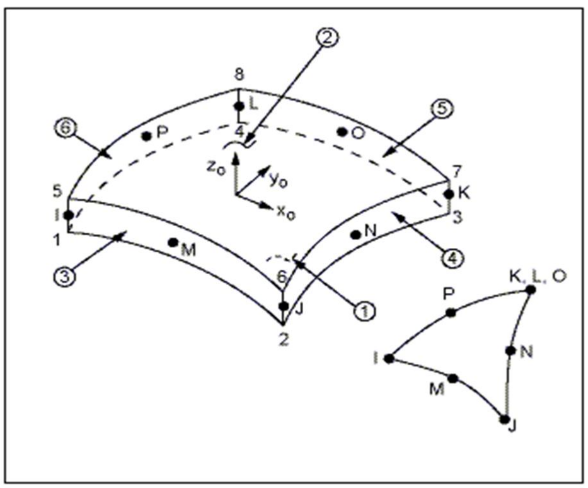

Fig. 1. SHELL281 Element [25]

III. NUMERICAL EXAMPLES

A. Effect of Aspect Ratios on Buckling load of Isotropic Plate

In this section, isotropic rectangular plates with three different aspect ratios a/b = 0.4, 1, 1.4 are chosen to compute the, buckling loads for uniaxially and biaxial loaded plates. Here ‘a’ and ‘b’ denote the plate in-plane dimensions and’ h’ denotes the plate thickness. We consider three side-to-thickness a/h ratios. Table 1 presents the comparison of uniaxial buckling loads, of the simply supported rectangular plate. The ANSYS modeling is shown in Figure 2. The normalization for the buckling load is used as per the following.

$$\bar{N} = \frac{\bar{N}_{xx} b^2}{\pi^2 D}, \qquad \bar{N}_{xy} = 0, \qquad \bar{N}_{yy} = 0$$

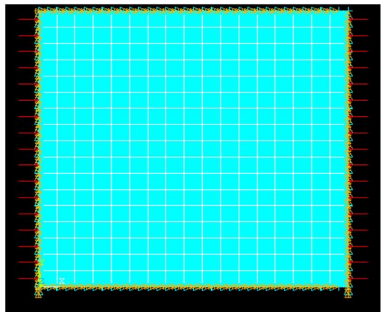

Fig. 2. Uniaxial Load, Simply Supported Boundary Condition, a/b =1, a/h =10

Table 1**.** Uniaxial buckling load of simply supported isotropic rectangle plates

a/h= 5	a/b = 0.4	a/b = 1.0	a/b = 1.4
Present ANSYS (FSDT)	6.7922	3.8132	3.2634
Ferreira et al. [5] Radial Basis Method 19x19 [5]	4.6468	3.2654	3.8160
Reddy and Phan (HSDT) [6]	4.6466	3.2653	3.8206
CLPT	8.410	4.0000	4.470
a/h= 10			
Present ANSYS (FSDT)	7.5881	4.7040	5.0838
Ferreira et al. [5] Radial Basis Method 19x19 [5]	6.9840	3.7744	4.2737
Reddy and Phan (HSDT) [6]	6.9853	3.7865	4.2876
CLPT	8.410	4.0000	4.470
a/h= 100			
Present ANSYS(FSDT)	8.022	5.3683	6.4467
Ferreira et al. [5] Radial Basis Method 19x19 [5]	8.3666	3.9411	4.2859
Reddy and Phan (HSDT) [6]	8.3928	3.9977	4.4682
CLPT	8.410	4.0000	4.470

B. Effect of Aspect Ratios on Buckling Load of symmetrical composite Laminated Plates

The effect of aspect ration on the buckling load of symmetrical composite laminated plate is presented in this section. In Tables 2, 3 and 4, results are compared with the 3D elasticity solutions given by Noor [8] and a mixed finite element solution by Reddy [2]. Following material properties, $E_1 = 25E_2, G_{12} = G_{13} = 0.5E_2, G_{23} = 0.2E_2, \upsilon_{12} = 0.25$, k_s=5/6 are considered. Results are compared with Reddy [2] and normalized by $\bar{N} = \frac{\bar{N}_{cr} a^2}{E_2 h^3}$.

Table 2. Effect of aspect ratio of the 0^0 composite layer on the Non-dimensional buckling load of the square composite plate.

Uniaxial Compression (k=0)	a/h				
Source	10	20	25	50	100
Present ANSYS (FSDT)	15.73	20.917	21.801	23.14	23.52
Reddy (FSDT) [2]	15.874	20.953	21.800	23.046	23.381
Biaxial Compression (k=1)					
Present ANSYS (FSDT)	7.39	9.77	10.19	10.85	11.068
Reddy (FSDT) [2]	5.837	7.555	7.839	8.257	8.369

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Table 3. Effect of aspect ratio of the [$0^0/90^0/0^0$] composite layers on the Non-dimensional buckling load of the square composite plate

Uniaxial Compression (k=0)	a/h				
Source	10	20	25	50	100
Present ANSYS (FSDT)	13.47	20.01	21.319	23.34	23.95
Reddy (FSDT) [2]	15.289	20.628	21.568	22.958	23.363
Biaxial Compression (k=1)					
Present ANSYS(FSDT)	6.85	9.53	10.02	10.77	11.02
Reddy (FSDT) [2]	7.644	10.314	10.784	11.489	11.682

Table 4. Effect of aspect ratio of the [$0^0/90^0/0^0/90^0/0^0$] layers on the Non-dimensional buckling load of the square composite plate

Uniaxial Compression (k=0)	a/h				
Source	10	20	25	50	100
Present ANSYS (FSDT)	14.919	20.8934	21.9827	23.6740	24.1715
Reddy (FSDT) [2]	16.309	21.125	21.917	23.078	23.389
Biaxial Compression (k=1)					
Present ANSYS (FSDT)	7.5338	10.5504	11.1001	11.9548	12.2054
Reddy (FSDT) [2]	8.154	10.562	10.958	11.539	11.695

Tables 2, 3 and 4 show that, aspect ratio a/h with buckling load for corresponding aspect ratio for uniaxial and biaxial compression of composite laminate plate. Results are for 0^0 ply orientation of laminate with respect to *x* axis. We can clearly observed that, as we increase in aspect ratio i.e. a/h=10, 20, 25, 50,100 non-dimensional buckling load $\bar{N}$ increased. Thinner plate (a/h=100) require more buckling load coefficient $\bar{N}$ to buckle, whereas thicker plate required less non- dimensional buckling load.

C. Effect of Degree of orthography i.e. $\mathbf{E_1/E_2}$ ratio on buckling load

The investigation of the impact of orthotropy on various symmetrical layers of a composite laminated plate is depicted in Figure 3. The study analyzes the critical buckling loads of simply supported square bidirectional composite plates subjected to uniaxial buckling load, considering the degree of orthotropy of each layer and the number of layers present.

The analysis of buckling load takes into account specific material properties, including E_1/E_2 = 3, 10, 20, 30, 40, an open value for E_1=open, E_2 =8.27 GPa, υ_{12} =0.25, $G_{12} = G_{13}$ =0.6E_2 GPa, G_{23} =0.5E_2 GPa respectively. Here, E_1 represents the Young's modulus in the 1-1 axis, E_2 represents the Young's modulus in the 2-2 axis, υ_{12} represents the Poisson's ratio in the 1-2 axis, and G_{12}, G_{13}, and G_{23} represent the corresponding shear stresses. The density used for the analysis is 1 kg/m^3. Considering only E_2 =3.1 GPa, the presented data is normalized as under.

$$\bar{N} = \frac{\bar{N}_{xx} a^2}{E_2 h^3}, \quad \bar{N}_{xy} = 0, \quad \bar{N}_{yy} = 0$$

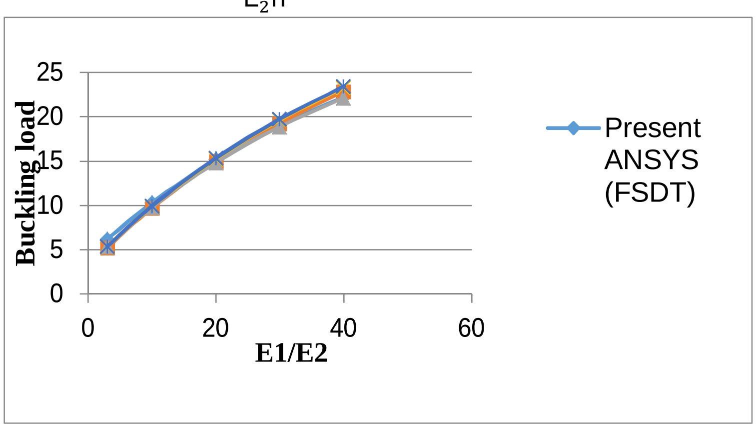
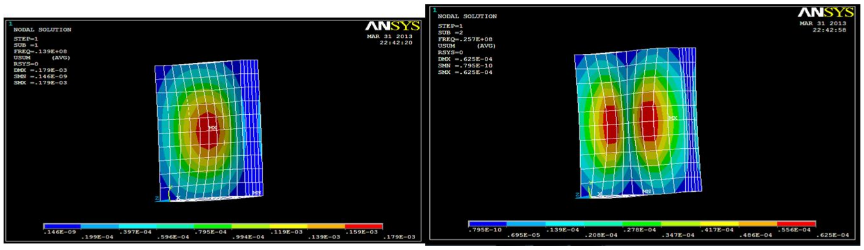


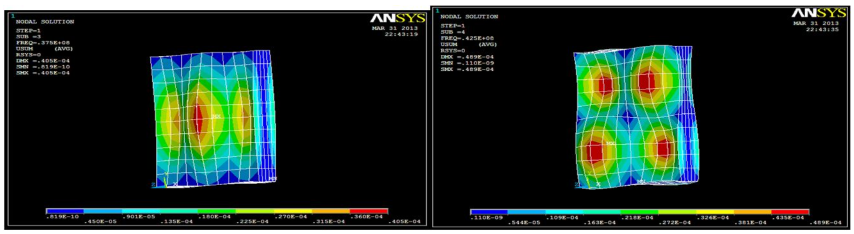
Fig. 3. Effect of degree of orthography of [$0^0/90^0/0^0$] degree layers on buckling load of square composite plate

IV. BUCKLING MODES OF COMPOSITE LAMINATE PLATE

Buckling modes of composite laminates are presented in the following Figure 4.



(a) 1st mode shape, $\overline{N}$=10.6923 (b) 2nd mode shape, $\overline{N}$=19.8069



(c) 3rd mode shape, $\overline{N}$=28.8092 (d) 4th mode shape, $\overline{N}$=32.6538

Fig. 4. Buckling Mode Shapes (a-d): Uniaxial buckling load of simply supported composite plate with a/h=10.

V. CONCLUSION

The aim of this paper is to introduce a numerical method for estimating buckling loads of composite plates using ANSYS. The FSDT element is used in this method considers out-of-plane shear deformation. The following are the conclusions drawn from this study.

1) For uniaxial compression ($\overline{N}_{xx}$), plate with aspect ratio (a/b) = 1 that is (square plate) having less buckling resistance than for aspect ratio 0.4.
2) With an aspect ratio of 1.4, the resistance to buckling is almost equivalent to that of a square plate. This is because the plate's dimensions are planar, and the load applied is in the X-direction. Therefore, when using a square plate or a plate with an aspect ratio of 1.4, the plate does not provide as much resistance in the length direction and buckles at a lower load.
3) By observing different buckling loads for isotropic plates with aspect ratios of 5, 10, and 100, it can be concluded that the thickness of the plate provides stiffness or resistance against buckling.
4) In this study, we conducted a buckling analysis of a composite plate with simply supported boundary conditions under uniaxial compression. The composite plate was examined at various aspect ratios using FSDT. Our findings suggest that the aspect ratio has an impact on the buckling of the plate, which is influenced by the stiffness provided by the plate's thickness.
5) We investigated the influence of the degree of orthotropy on the buckling of a composite plate made up of orthotropic material with different properties in the longitudinal and transverse directions. The results of this study indicate that although the material properties in the X and Y directions are different, the plate exhibits very high stiffness against buckling. Additionally, the E_1/E_2 ratio of the material is such that E_1 is always greater than E_2, providing greater resistance when an applied load is in the X-direction (i.e., the longitudinal direction).

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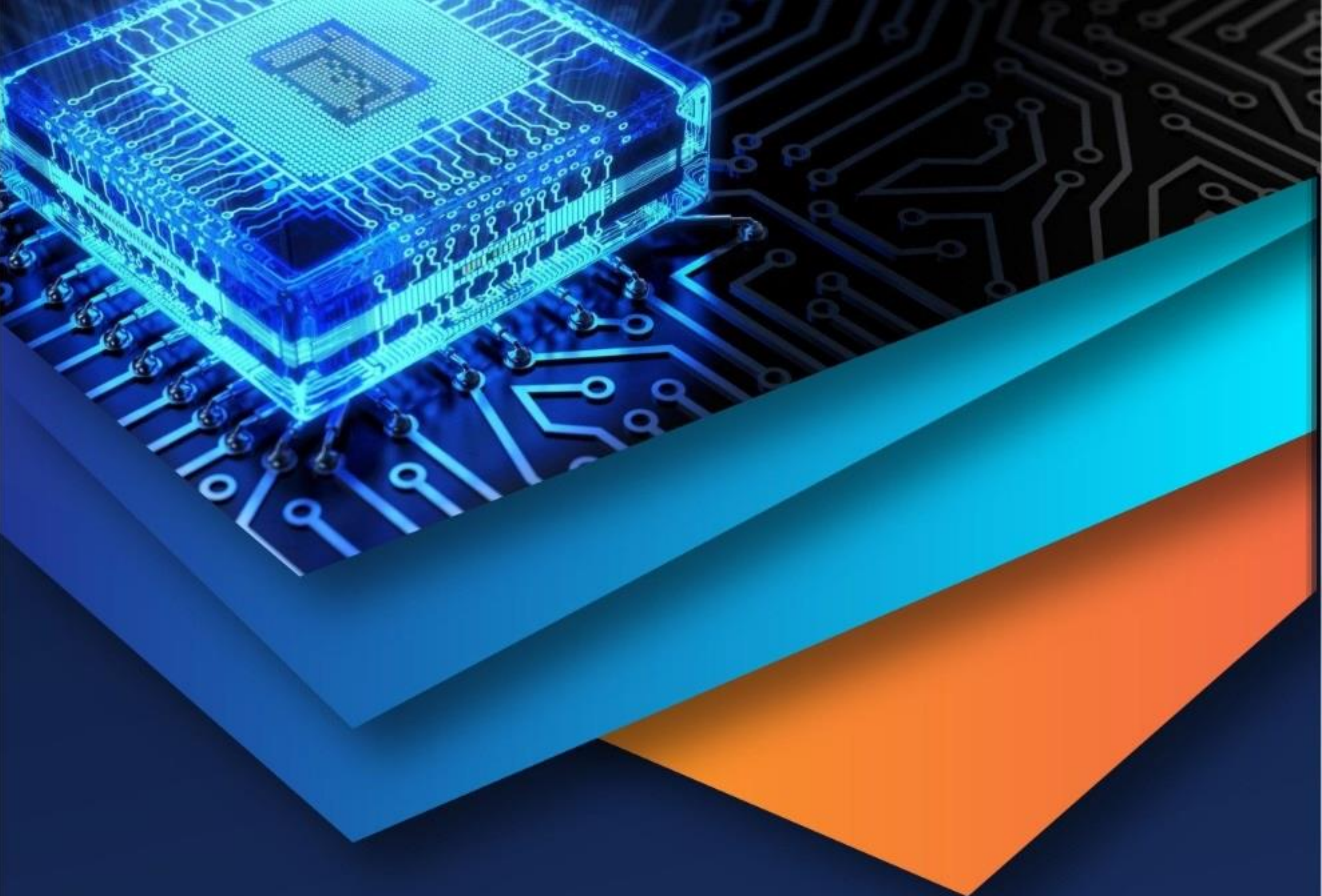

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