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Stress and buckling analysis of multilayered composite plates with different cut-outs using finite element method

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***Abstract*— This study is a numerical analysis where multiple layers of plates with different orientations were combined to form a composite plate. Within this study, the concept of in-plane tensile loading and buckling upon an orthotropic multi-layered plate with different cut-outs is discussed. The finite element method is used to conduct modeling and analysis of the composite plate where the plate has different geometric shape cut-outs to test for parameters such as deflection, stress-strain distribution, buckling, and other effects of cut-outs on the cross-section of the plate.**

***Keywords*— Finite element method, stress analysis, buckling analysis, multi-layered composite plate, cut-out.**

I. INTRODUCTION

Increased demand for composite materials by industries means that accurate knowledge about the material properties, characteristics, and behavior such as deflections, stress, and strain distribution factors require thorough revision. Composite materials are created by combining two or more materials with varying physical and chemical properties. They could be designed to provide strength, reduce weight, resist electricity or fire, and other needed factors. They can also improve stiffness. Firstly, it was known that stress distribution is not uniform through the cross-section of a plate under loading especially when there are changes in the geometry of the plate. That could be a plate with a circular cut out or any geometrical shape cut out [1].

Stress evaluation for square and rectangular cut-outs in symmetric laminates yields that the maximum stress and its coordinates are based on the loading condition [2]. Similarly, isotropic plates reinforced with high elastic modulus inclusions are good at resisting stress concentration, and a smooth-shaped hole makes sense for reducing the stress concentration factor [3]. Sudden changes in stress around structural holes have significant practical implications because they frequently serve as the starting point for fractures to form and spread in a zone of concentrated stress which typically makes the cause of failure. Wu and Mu [4] suggested a straightforward computation method based on scale factors to calculate the stress concentration factors of cylinders or plates with circular cut-outs that are isotropic or orthotropic and have finite widths under tension that are either uniaxial or biaxial. The finite element (FE) method has been used to model three-dimensional multi-layer orthotropic plates in two-dimensional settings in past cases. A study by Jaśkowiec [5] on three-dimensional modeling of laminated glass bending on two-dimensional in-plane mesh employed FEM23 for numerical analysis of a 3D model of laminated glass. FEM23 is a numerical technique to analyze a 3D problem using a 2D FE mesh. Plucinski et al. [6] employed FEM23 to model a multilayered plate and analyze it. Angle ply orientations can be symmetric or antisymmetric, and this affects how many layers need to be stacked together. Contrary to antisymmetric angle ply, symmetric angle ply has layers of odd numbers [7]. Ukadgaonker and Kakhandki [8] studied different in-plane loading effects on the stress distributions of an orthotropic plate with irregular cut-outs. Analysis of the buckling of composite plates is critical for safe design. Buckling occurs when a material has met its stiffness limits. Composite plates buckling deformations are more complex when compared to anisotropic plates. A greater stress value comes from increased flexural rigidity [9]. Buckling load for thin plates is affected by various parameters out of which is the plate boundary conditions. A study done by Kanta Prajapat and team [10] suggested that buckling load for thin plates is governed by the plate's boundary conditions and the size of the cut-out. For their work, a rectangular plate with a circular cut-out of stainless-steel material was tested for different specimens with varying aspect ratios. Similarly, a study on the elastic buckling of plates containing eccentrically located circular holes was done by Sabir and Chow [11]. The boundary conditions were set to be simply supported or clamped outer edges. Moreover, to identify the presence of residual stresses when buckling plates, a study was done by the University of Tokyo, Japan on a welded square column with plate elements [12]. With theoretical knowledge of elastic and plastic buckling of plates, the research team used ASTM A7 and A 514 sheets of steel for the plate elements. The buckling behavior of orthotropic plates under non-uniform in-plane loads with different boundary conditions using a FE methodology can out-weight the quality of results obtained from numerical analysis methods as they can produce overestimated values for buckling loads [13]. Weaver and Nemeth [14] proposed an improved model for buckling analysis of orthotropic plates under combined loading.

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Tenenbaum et al. [15] presented an analytical solution for buckling analysis of thin orthotropic rectangular plates. Holston [16] investigated the buckling of orthotropic plates with one free-edge boundary condition. Shuleshko [17] solved the buckling problem of several plates using a reduction method. The presented solution reduced the problem of an orthotropic plate to an isotropic problem. Bourada et al. [18] proposed a new plate theory for buckling analysis of isotropic and orthotropic plates. Nazarimofrad and Barkhordar [19] investigated the buckling of rectangular orthotropic plates located on a Pasternak foundation using the Frobenius method. Qolipour et al. [20] presented an analytical solution for the buckling analysis of isotropic annular/circular plates based on the first-order shear deformation theory. Rouhi et al. [21] employed molecular dynamics simulations to investigate the elastic characteristics of gallium nitride nanosheets and determine its Young and bulk moduli. Naeini et al. [22] studied the effect of carbon fiber-reinforced plastic and glass fiber-reinforced plastic plates on a reinforced-concrete beam with a T-shaped cross-section using the FE method. Omidi Bidgoli et al. [23] optimized different sunken compartments using the FE method under buckling conditions to reduce the weight of the structure.

In this study, ANSYS is used to model and analyze the problem since it can solve complex structural problems. FE solvers available in ANSYS provide the flexibility to manipulate parameters that can put our designs in multiple scenarios that can be analyzed. Multi-layered plate analysis for a whole plate has been encountered previously in many cases; however, analysis of different cut-outs on it is a rare scenario. The analysis is conducted for a differently shaped cut-out however, the aspect ratio of the size area of the cut-outs will not vary, only the shape of the cut-outs and the orientation combinations of the plates.

II. Implementation Results

In this study, ANSYS is used to model the plate. For this purpose, SHELL 181 is used which is an element with four nodes and six degrees of freedom at each node. The mesh pattern is determined using the try and error to optimize the mesh dimension and increase the accuracy of the results. The governing equation for a complete multilayered plate according to the classical plate theory can be determined as follows [24]:

$$D\nabla^2\nabla^2 w(x,y) = p_z(x,y) \tag{1}$$

where D is the transformed flexural rigidity of the laminated plate, and it is determined as follows:

$$D = \frac{\Phi\Omega - \Upsilon^2}{\Phi}; \quad \Phi = \sum_k \frac{E_k}{1-\nu_k^2}(z_k - z_{k-1}) \tag{2}$$

$$\Upsilon = \sum_k \frac{E_k}{1-\nu_k^2}\frac{z_k^2 - z_{k-1}^2}{2}; \Omega = \sum_k \frac{E_k}{1-\nu_k^2}\frac{z_k^3 - z_{k-1}^3}{3}$$

Where E_k and ν_k are Young's modulus and Poisson's ratio of the k^{th} layer, respectively. The stability equations can be determined for the buckling analysis using the adjacent criteria. The geometry of the plate has been shown in Fig. 1.

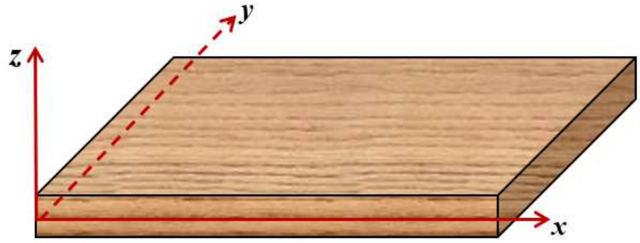

Fig. 1 Geometry of plate

TABLE I. PROPERTIES OF MATERIALS IN PLATES [6]

	Orthotropic – Carbon-Fiber Reinforced Plastic (A)	**Orthotropic – Titanium Honeycomb Structure (B)**	**Isotropic – Foam Made of Polyvinyl Chloride (C)**
E_1^k (N/mm^2)	157,900	191.5	104
E_2^k (N/mm^2)	9,584	191.5	-
E_3^k (N/mm^2)	9,584	1,915	-
ν_{12}^k	0.32	0.00658	0.3
ν_{13}^k	0.32	0.00643	-
ν_{23}^k	0.49	0.00643	-
G_{12}^k (N/mm^2)	5,930	0.0000423	40
G_{13}^k (N/mm^2)	5,930	365.1	-
G_{23}^k (N/mm^2)	3,227	1,248	-

A. Validation

To establish that this result complies with any activity, the validation of this document's methodology was evaluated with the results of Plucinski et al. [6] for the bending analysis of multi-layered orthotropic plates. Within Piotr Pluciski's literature, the square multi-layered plate of length 2 m and a total thickness of 0.1 m, with constant loading of 0.1 N/mm^2 was investigated by applying the Hellinger Reisner refined zigzag theory. The multi-layered plates were simulated to represent materials of orthotropic carbon-fiber-reinforced plastic, orthotropic titanium honeycomb structure, and isotropic foam made of polyvinyl chloride. The materials with their respective mechanical properties are reported in TABLE I. The subscripts 1, 2, and 3 are directions x, y, and z, respectively. Two plates were evaluated with a varying sequence of thickness, these being the one consisting of three and nine layered plates. The orthotropic direction is equal to zero for each layer. The results for a plate with sequence A/C/A with a total of 3 layers are presented in Fig. 2. The graph lines illustrate the displacement in the z-direction against the plate's half-length distance. It seems that the results are in good agreement with the results obtained by Plucinski et al. [6]. To further validate the results a second configuration of the plate with sequence A/C/A/C/B/C/A/C/A is modeled. The plate is with the same geometries, boundary conditions, and loading as mentioned above. Hence, the result of the displacement in the z-direction versus the x-axis is plotted in Fig. 3 which shows a good accuracy of the presented method.

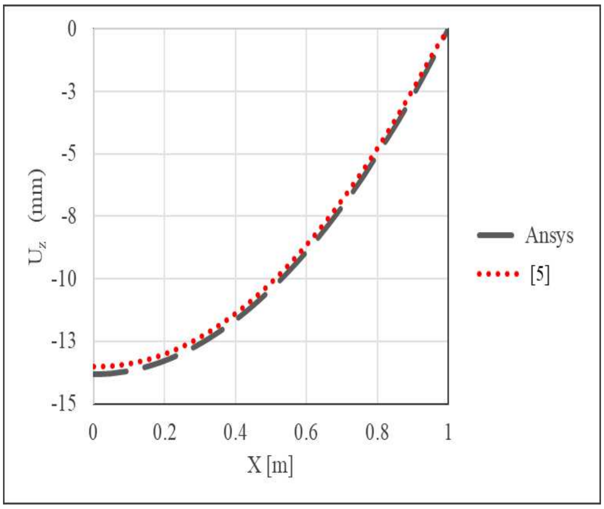

Fig. 2 Comparison of deflection of multilayered plate with three layers

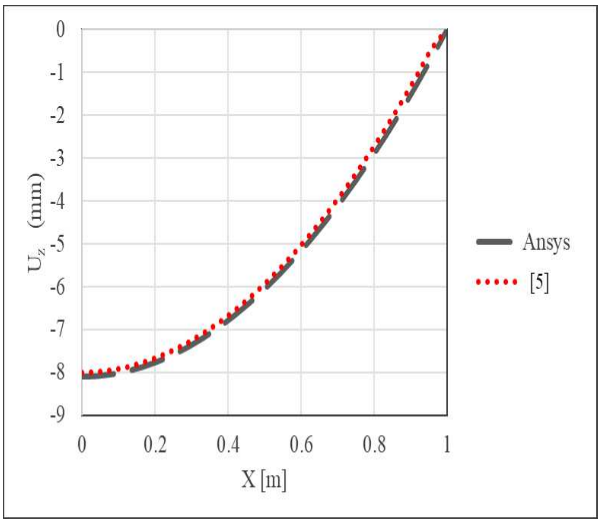

Fig. 3 Comparison of deflection of multilayered plate with nine layers

B. *In-plane tension*

To study the in-plane tension, a square plate with dimensions 300 x 300 x 5 mm is considered. Table II presents the material properties of the plate. The boundary conditions of two far edges are clamped. The plate is subjected to a uniform pressure loading on the other two edges of the plate with a value of 6 N/mm^2. Hence, the pressure case was in the opposite direction, producing an in-plane tensile effect. Moreover, the layers are oriented respectively to the *x*-axis by laying them in varying orientations as shown in Table III. Six orientation combinations were analyzed. The orientation sequence set was placed from the most layers orientated to 0º till the most layered plates orientated towards 90º. As this sequence allows a better comprehension of graphical data than any other alteration sequence. This analysis concerning stress and strain distribution and behavioral patterns is observed when the plate is subjected to tensile pressure in a clamped situation with cut-outs at the center of the plate. These cut-outs are removal of the plate surface area of 15%, as such the plate is analyzed for no-cutouts, circle, square, and triangle cut-outs with the same area of removal of plate substance as illustrated in Fig. 4.

TABLE II. MATERIALS PROPERTIES OF PLATE

Property	**Value**
E_1^k (N/mm^2)	125000
E_2^k (N/mm^2)	7400
E_3^k (N/mm^2)	7400
v_{12}^k	0.34
v_{13}^k	0.34
v_{23}^k	0.37
G_{12}^k (N/mm^2)	4800
G_{13}^k (N/mm^2)	4800
G_{23}^k (N/mm^2)	2700

TABLE III. SEQUENCE OF ORIENTATIONS

Orientation set	**Orientation corresponding to the *x*-axis**
1	All layers are placed at 0º
2	All layers alternating between 0º and 45º
3	All layers alternating between 0º, 45º, and 90º
4	All layers alternating between 0º and 90º
5	All layers alternating between 45º and 90º
6	All layers are placed at 90º

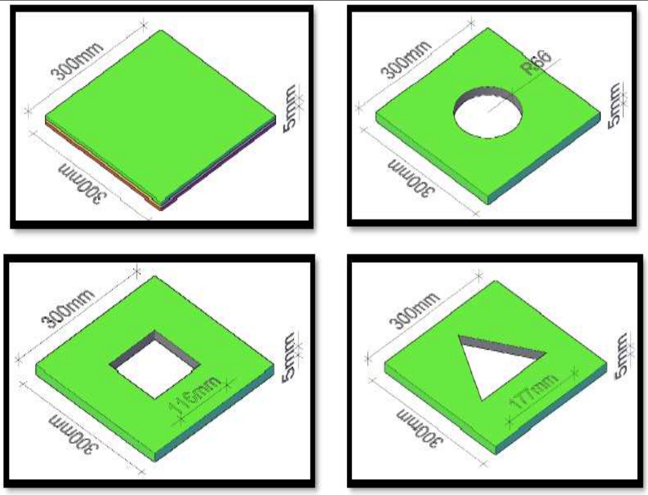

Fig. 4 Geometry of plates with different cutouts

The results of the plate experiencing the in-plane tensile pressure with 4 layers are presented with von Mises strain against the orientation sets for each respective cut-out analysis in Fig. 5. It is seen that the maximum strain occurs for orientation 1 with triangular cutout. It can be concluded that orientations 2, 3, and 4 have less strain than other orientations for the studied range of values. To vanish the effect of the mesh size on the results, an optimum size is determined using trial and error. Fig. 6 reports the effect of the number of layers on the results. Von Mises strain of 4-, 5-, and 6-layer plates with a circular cutout is reported. It is seen that for orientations 1, 2, and 6, the number of layers does not have any significant effect, while, for orientation 5, a plate with 5 layers has the minimum strain. For other cutouts, the same results are determined which are not reported here.

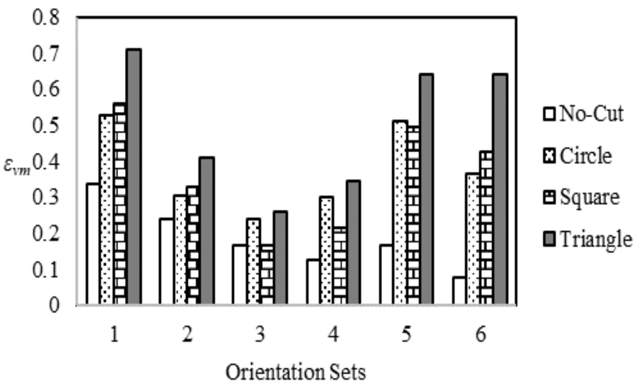

Fig. 5 von Mises strain versus different orientation for plate with 4 layers

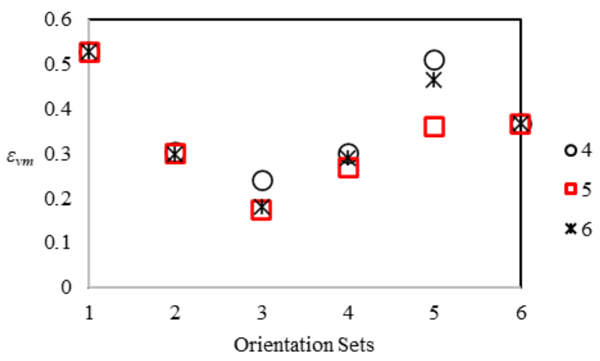

Fig. 6 von Mises strain versus different orientation for plate with 4, 5, and 6 layers and circular cutout

C. *Buckling Testing*

On the same modeling system and geometry, multilayered plates under compression for buckling analysis are discussed. The boundary conditions are clamped at the bottom side and free at other edges. The buckling compression load is applied to the top side of the plate. Since this study aims to determine the buckling load, only the effect of prestresses is important and is considered in the stability analysis. Fig. 7 reports the buckling load of multilayered plates with 4 layers and different cutouts. It is observed that the buckling load for orientations 4, 5, and 6 of the plate without cutout is significantly more than other plates and the minimum buckling load observes for orientation 1 without cutout. Also, it can be concluded that for orientations 1, 2, and 3, the cutout causes an increase in the buckling load while for other orientations the cutout decreases the buckling load. For the other number of layers, the same behavior is observed which they are not reported here. Fig. 8 shows the effect of the number of layers on the buckling load of the multilayered plate with a circular cutout. It is concluded that the maximum buckling load is for a plate with 6 layers and orientation 4. In all the orientations, the plate with 6 layers has the maximum buckling load. For other cutouts, the same behavior is observed, and the results are not reported here. However, for the plate without a cutout, the buckling load is determined for a different number of layers, and it is reported in Fig. 9. Unlike, plates with cutouts, the maximum buckling load occurs in orientation 6 and like plates with cutouts, the plate with 6 layers has the maximum buckling load in all the orientations.

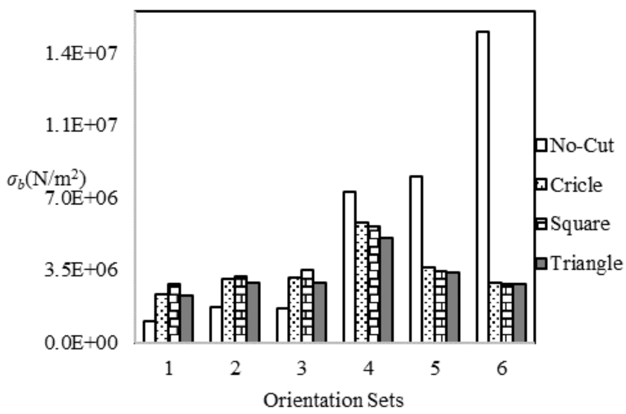

Fig. 7 buckling load versus different orientation for plate with 4 layers

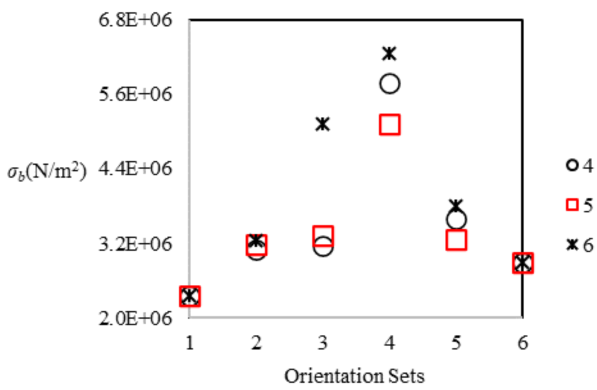

Fig. 8 Buckling load versus different orientation for plate with 4, 5, and 6 layers and circular cutout

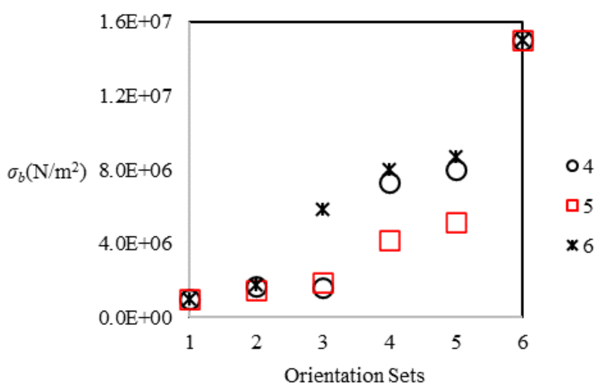

Fig. 9 Buckling load versus different orientation for plate with 4, 5, and 6 layers and no cutout

III. Conclusion

In summation, the multi-layered orthotropic plate was simulated within the ANSYS FE package. Three types of plates with a different number of layers were analyzed accompanied by the orientation sets. The cut-outs were the area equivalent to 15% of the original 0.3 x 0.3 m plate's surface area, while the shape was specified to be a circle, square, or triangle. To validate the procedure used to simulate the analysis, a comparison with another reference was conducted. The effects of orientations, number of layers, and cutouts on the static and buckling behavior of the multilayered plates were discussed. It should be mentioned that the concluded results are determined by the studied range of dimensions and material properties. Some of the most important conclusions can be listed as follows:

- The maximum strain occurs for orientation 1 with a triangular cutout.
- The von Mises strain of orientations 2, 3, and 4 is less than other orientations.
- For orientations 1, 2, and 6, the number of layers does not significantly affect the von Mises strain.
- For orientation 5, a plate with 5 layers has the minimum strain.
- The buckling load for orientations 4, 5, and 6 of the plate without cutout is significantly more than other plates.
- The minimum buckling load observes for orientation 1 without cutout.
- For orientations 1, 2, and 3, the presence of the cutout increases the buckling load while for other orientations it decreases the buckling load.
- The maximum buckling load of the plate with the cutout is for orientation 4 and without the cutout is for orientation 6.
- In all the orientations, the plate with 6 layers has the maximum buckling load.

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