



# Buckling Load Maximization of Laminated Composite Plates

Prashant Bhambe<sup>1</sup>, N.S. Kulkarni<sup>2</sup>  
PG Student<sup>1</sup>, Assistant Professor<sup>2</sup>  
Department of Mechanical Engineering  
VIT, Pune, India

## Abstract:

In the present study, buckling load carrying capacity of laminated plates having midplane symmetry is maximized for a given total thickness. The ply angle in discrete form is considered as design variables with constant ply thickness. Buckling analysis is carried out using the finite element method for uniaxial as well as biaxial loadings. It is observed that for any given ply thickness, buckling load carrying capacity can be improved by optimizing ply angle stacking sequence. The optimum results obtained using finite elements analysis for uniaxial load cases are verified by experimental results and the FEA model is validated. The validated FEA model is then utilized for Bi-axial load conditions and maximum buckling load carrying capacities obtained for various load conditions are compared with already published results. In the current study, unconstrained optimization is carried out using genetic algorithm available in Hyperstudy. It is observed that the removal of constraint like two consecutive plies should have same angle, results in better buckling load factor.

**Keywords:** Symmetric Composite Laminate, Buckling load, Optimization, Genetic algorithm

## I. INTRODUCTION

Fibre reinforced composites are extensively used in many modern engineering applications due to their ability to improve structural performance. Examples include lightweight, strong and rigid aircraft frames, composite drive shafts and suspension components, sports equipment, pressure vessels and high-speed flywheels with superior energy storage capabilities. In composite materials fibres are the main load bearing members, and the matrix, which has low modulus and high elongation, provides the necessary flexibility and also keeps the fibres in position and protect them from the environment. An advantage of using fibre-reinforced composites over conventional materials is that they can be tailored to the requirements of a certain application. Thus, for example, by using the ply angles as design variables, and determining the optimal values to maximize or minimize criterion like strength, mass & buckling load, the most benefit can be obtained from these materials. Due to manufacturing constraints, the sets of values from which the ply angles and layer thicknesses can be selected are generally discrete, and in such cases, the optimization problem becomes one of finding the best permutation of these.

Rectangular thin plate considered in the present study is the basic structural element. When a flat plate is subjected to low in-plane compressive loads, it remains flat and is in equilibrium condition. When magnitude of the in-plane compressive load increases, the equilibrium configuration of the plate is changes to a non-flat configuration and the plate becomes unstable. The compressive load at which the plate gets unstable is called the "critical buckling load." Fibre-reinforced composites are used mostly in the form of thin plate, and therefore the load carrying capability of composite plate against buckling has been mostly considered by researchers under various loading and boundary conditions. In many engineering structures applications like as columns or beams, the failure does not occur because of excessive stresses but from buckling. In operation the composite laminate plates are generally subjected to compression loads that may cause buckling if overloaded. Hence buckling behavior of

composites becomes important factors in safe and reliable design of such structures.

Buckling optimization of laminated composite plate using Genetic Algorithm and generalized pattern search algorithm is carried out by Karakaya & Sykasap [1], by considering ply angle as design variable. Multiobjective optimization of angle ply laminated plates for maximum buckling load subjected to biaxial compressive load is carried out with First-order shear deformation theory by Topal & Uzman [2]. Simulated Annealing approach is used by Erdal & Sonmez [3] for optimum design of laminates to sustain maximum buckling load. Jaroslaw Latalski [4] studied effect of ply thickness tolerances in stacking sequence on multi-layered laminated plate design under uni and biaxial compression for maximum buckling load. Husan-The Hu & Bor-Horng Lin [5] carried out Buckling optimization for symmetrically laminated plates with various geometries and end conditions using sequential linear programming. Experimental and numerical buckling analysis of delaminated hybrid composite beam structures to determine buckling load with ANSYS is carried out by Esfahani, Ghasemnejad and Barrington [6]

This project deals with buckling analysis of symmetrical laminate plates under clamped-free-clamped-free boundary conditions. Initially, developed FEA model is validated with experimental testing. Then same FEA model is used for Bi-axial load cases defined by Karakaya & Omar [1] and the obtained results are compared with reference results. Unconstrained optimization is carried out using genetic algorithm from Hyperstudy in discrete form.

## II. PROBLEM IDENTIFICATION

From Literature review it is clear that buckling is the major problem associated with Composite Material. Karakaya & Omar [1] studied maximization of buckling load of balanced symmetric laminate using two-ply stack as a constraint. Optimization is carried out using genetic algorithm by considering discrete ply angles such as  $0^{\circ}$ ,  $\pm 45^{\circ}$ ,  $90^{\circ}$  for different load cases mentioned in Table I.

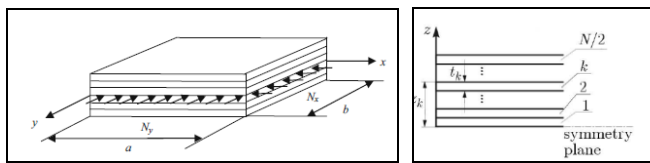
**Table. I. Bi-Axial Load Cases [1]**

Load Case	A (cm)	b (cm)	N <sub>x</sub> (N/m)	N <sub>y</sub> (N/m)
LC1	50.8	25.4	1	1
LC2	50.8	50.8	1	1
LC3	50.8	101.6	1	1
LC4	50.8	25.4	1	0.5
LC5	50.8	50.8	1	0.5
LC6	50.8	101.6	1	0.5
LC7	50.8	25.4	1	2
LC8	50.8	50.8	1	2
LC9	50.8	101.6	1	2

Before proceeding for actual analysis, it is necessary to understand the meaning of buckling and its calculations in case of composite plate. This is explained in next section.

**III. Buckling Load For Composite Laminate**

When the compressive loads reach a certain critical value, the column undergoes a bending action in which the lateral deflection becomes very large with little increase in load. This is called as buckling.



**Figure.1. Composite plate subject to in-plane loading [1]**

Determining the buckling load capacity of a composite plate under in-plane compressive loads is crucial for the design of composite structures. The buckling could yield a premature failure of the structure. The simply supported composite plate subjected to bi-axial in-plane compressive loading is as shown in figure 1. The Buckling factor can be calculated as follows,

$$\lambda^{(mn)} = \left[ \frac{D_{11}m^4 + 2(D_{12} + 2D_{66})m^2n^2(a/b)^2 + 2D_{22}n^4(a/b)^4}{m^2N_x + n^2(a/b)^2N_y} \right]$$

The laminate can buckle into m and n half waves in the x and y directions, respectively when the load amplitude reaches a value  $\lambda^{(mn)}$ , which depends on flexural stiffness  $D_{ij}$  and loads  $N_x$  and  $N_y$ . Variables  $D_{11}$ ,  $D_{12}$ ,  $D_{22}$  and  $D_{66}$  are flexural stiffness's and can be expressed in terms of material invariants  $U_i$  ( $i= 1, \dots, 5$ ) and three integrals  $V_0, V_1, V_3$  as follows,

$$D_{11}=U_1V_0 + U_2V_1 + U_3V_3 \quad D_{12}=U_4V_0 - U_3V_3$$

$$D_{22}=U_1V_0 - U_2V_1 + U_3V_3 \quad D_{66}=U_5V_0 - U_3V_3$$

Invariants  $U_i$  ( $i= 1, \dots, 5$ ) are related to composite material properties

$$U_1 = \frac{1}{8}(3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}) \quad U_2 = \frac{1}{2}(Q_{11} - Q_{22})$$

$$U_3 = \frac{1}{8}(Q_{11} + Q_{22} - 2Q_{12} - 4Q_{66}) \quad U_4 = \frac{1}{8}(Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66})$$

$$U_5 = \frac{1}{8}(Q_{11} + Q_{22} - 2Q_{12} + 4Q_{66})$$

Where,

$$Q_{11} = \frac{E_1}{1 - \mu_{12}\mu_{21}} \quad Q_{12} = \frac{\mu_{12}E_2}{1 - \mu_{12}\mu_{21}} = \frac{\mu_{21}E_1}{1 - \mu_{12}\mu_{21}}$$

$$Q_{22} = \frac{E_2}{1 - \mu_{12}\mu_{21}} \quad Q_{66} = G_{12}$$

In above relations  $E_1, E_2, \mu_{12}, \mu_{21}$  and  $G_{12}$  demotes Young's moduli in the fibers direction 1 and lateral direction 2. The

variables  $V_0, V_1$  and  $V_3$  comprise information about fibres orientations about layer thickness and their stacking sequence

$$V_0 = \int_{-h/2}^{h/2} z^2 dz = \frac{1}{3} \sum_{k=1}^N (z_k^3 - z_{k-1}^3) = \frac{2}{3} \sum_{k=1}^{N/2} (z_k^3 - z_{k-1}^3)$$

$$V_1 = \int_{-h/2}^{h/2} z^2 \cos 2\theta dz = \frac{2}{3} \sum_{k=1}^{N/2} (z_k^3 - z_{k-1}^3) \cos 2\theta_k$$

$$V_3 = \int_{-h/2}^{h/2} z^2 \cos 4\theta dz = \frac{2}{3} \sum_{k=1}^{N/2} (z_k^3 - z_{k-1}^3) \cos 4\theta_k$$

Where  $h=N_t$  is the total thickness of the laminate,  $z$  is the distance from symmetry plane as shown in Figure 1.

The pair (m,n) that yields to the smallest value of  $\lambda^{(mn)}$ , is the critical buckling load which varies with the loading conditions, total number of piles considered, material and plate aspect ratio.

**IV. LINEAR BUCKLING ANALYSIS USING OPTISTRUCT**

The Buckling in finite element analysis is solved by applying a reference level of loading  $F_{ref}$  to the structure (this is ideally a unit load that is applied). The unit load and respective constraints, SPC, are referenced in first load step. A standard linear static analysis is carried out to obtain stresses which are needed to form the geometrical stiffness matrix  $K_G$ . The buckling loads are then calculated as a part of second load step, by solving eigen value problem:

$$(K - \lambda K_G) x = 0$$

$K$  is the stiffness matrix of the structure and  $\lambda$  is the multiplier to the reference load. The solution of the eigenvalue problem generally yields n eigenvalue  $\lambda$  (buckling load factor), where n is the number of degrees of freedom. The vector  $x$  is the eigenvector corresponding to eigenvalue. The eigenvalue problem is solved using a matrix method called Lanczos method. Not all eigenvalues are required. Only small number of lowest eigenvalues is normally calculated for buckling analysis. The lowest Eigen value is associated with buckling, the critical or buckling load:

$$F_{crit} = \lambda_{crit} F_{ref}$$

**V. UNIAXIAL LOADING ANALYSIS BY FEM**

For uniaxial laminate Buckling analysis is carried out using FEM Hypermesh software. For this standard rectangular composite specimen with dimensions such that it will satisfy the criteria for Slenderness ratio is used. As per D 695 -02a, Slenderness ratio is ratio of length of a column of uniform cross section to its lease radius of gyration. For specimen of uniform rectangular cross section, the radius of gyration is 0.289 times the smaller cross-sectional dimension. The slenderness ratio should be greater than 16 so that material will fail under buckling.

Two different laminates are prepared to get the required results, in each laminate number of plies are varied to get two different thickness laminates. An Eigen value buckling analysis is carried out to determine critical buckling load. Eigen value buckling analysis predicts the bifurcation point (the critical buckling load) of an ideal linear elastic structure. For the purpose of this project, the Eigen value analysis is an appropriate tool to use since the concern is to see general effects, on critical buckling load, of changing the ply

orientation in each layer. Specimen sizes are as shown in Figure 2,

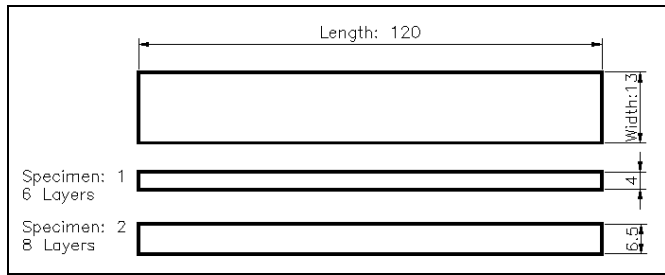


Figure.2. Buckling test specimen [2]

**PROPERTIES OF LAMINATE:**

Properties of laminate are obtained by using Mixture Law, Fibre and Matrix properties are given in below Table,

**Table.2. Properties of glass fibre & epoxy [ii]**

Property	Glass Fibre	Epoxy Resin
Elastic Modulus (Gpa)	72	3.4
Poisson's Ratio	0.2	0.35
Shear Modulus (Gpa)	33	1.2

The Fibre percentage in both the test specimen is around 50%. The laminate mechanical properties can be calculated using following relations,

$$E_{11} = V_f E_f + (1 - V_f) E_m$$

$$\frac{1}{E_{22}} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

$$\mu_{12} = V_f \mu_f + (1 - V_f) \mu_m$$

$$G_{12} = \frac{G_f G_m}{G_f V_f + G_m V_m}$$

The laminate Properties of the Test 1 and Test 2 specimen are given in Table III

**Table.3. Properties of Glass Fibre Epoxy Laminate [Iii]**

Property	Value
E <sub>11</sub>	38.5 Gpa
E <sub>22</sub>	6.5 Gpa
μ <sub>12</sub>	0.27
G <sub>12</sub>	2.3 Gpa

**EIGEN VALUE BUCKLING ANALYSIS IN HYPERMESH HAS FOLLOWING STEPS:**

**1. Build the Model:** Geometry in the Hypermesh can be formed by many ways, such as by using nodes, by using lines, using direct rectangle command. It is easy to form a surface by using nodes. Geometry is formed by using nodes, four nodes are plotted at co-ordinates (0, 0), (120, 0), (120, 13), (0, 13). Then 2D surface is created through these nodes. A dimension of the geometry formed is 120 x 13.

**2. Meshing:**

**a. Element Selection:** Shell elements are generally used for the 2D geometries. Shell elements have 6 degrees of freedom at each node; translations in the x, y, and z directions and rotations about the nodal x, y, and z-axes. The shell element is perfectly suited for composite materials. because it allows entry of up to 250 layers. Each layer has its own thickness, material property, and orientation.

**b. Meshing:** Using automesh command in Hypermesh surface/geometry is meshed. For the meshing the surface elements size of 1 mm is used. It will provide fine mesh.

**3. Material Creation:** In Hyperstudy material is created of orthotropic type and MAT8 as card image.

Laminate properties are as shown above Table III,

**4. Properties:** In Hypermesh property is created with 2D type and PCOMPP as a card image which is used to define composite material. This property is assigned to geometry.

**5. Load collector:**

In Hypermesh boundary conditions, forces are stored in load collector.

**a. Boundary Conditions / constraints:** Constraints are used to restrict degrees of freedom of component, in this case one end of composite plate is kept fixed so that it will restrict all degrees of freedom and other end kept free. This constraint is stored as SPC in Hypermesh

**b. Force:** Compressive force is applied opposite to fixed end; this force is stored as Force in Hyperstudy load collector.

**c. Buckling:** for Eigen value buckling analysis, need buckling as an additional load collector. For buckling load collector EIGRL is selected as card image.

**6. Load step:** Load steps define the type of analysis need to perform on component. There are many type of analysis like linear static, buckling, hormonal etc. For Eigen value buckling analysis, linear static analysis as well as Linear Buckling analysis both are needed, these analyses can be carried out using the optistruct. Optistruct is a solver.

**7. Ply creation:** In the Hypermesh there is a separate command to form plies. While creating new ply orientation, material and thickness of the plies can be specified. This ply can be applied on selected elements. Material type is considered as Orthotropic, and material is selected as Glass Fiber

**8. Laminate creation:** Laminate is form by using the plies that were created. These plies are used in given order only. There are different options in the laminate creation like symmetry, total, membrane, bending, symmetric membrane etc. Using the symmetric command, symmetric laminate is form using given plies. Plies are get doubled symmetrically. Laminate can also be form by using total command. This command gives plies in order to form a laminate. After the creation of the laminate thickness of the laminate is equal to the total thickness of the plies which are included in the laminate. Laminate gives the 3-D representation. Which is having thickness equal to the total thickness of plies. Sum of thickness of all plies gives us the total thickness of the laminate. In this study all plies of the same thickness.

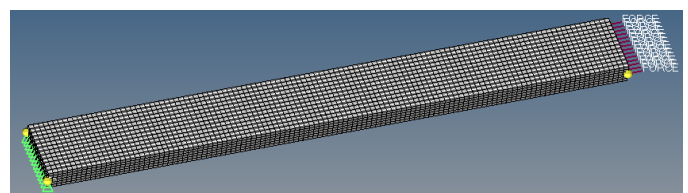


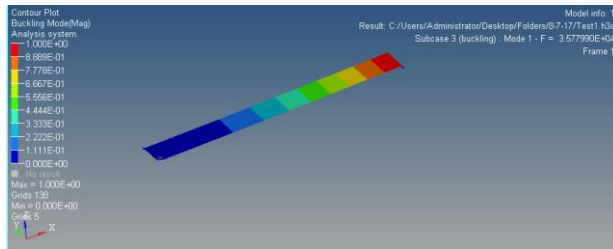
Figure. 3. uniaxial laminate [3]

**9. Analysis:** Analysis is performed for two different laminates having number of plies varies 6 and 8. The details of the laminate are provided in Table IV. Buckling Load calculations

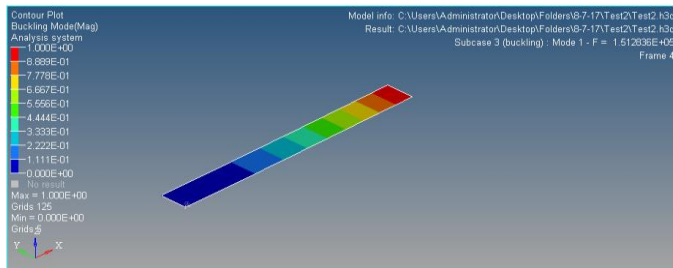
have been done for laminate having random stacking sequence using Hypermesh for both the laminates.

**Table.4. Fibre Epoxy Laminate Specimen Details [IV]**

Sr. No.	No. of Ply	Thickness of Laminate (mm)
Test 1	6	4
Test 2	8	6.5



**Figure. 4. buckling factor for test 1 specimen [4]**



**Figure .5. buckling factor for test 2 specimen [5]**

**Uniaxial Loading Optimization Using Hyperstudy:**

Then this problem is taken in Hyperstudy where optimization is performed. Ply orientation is taken as discrete variables 0°, 45°, -45°, 90°. Genetic algorithm is selected as optimization technique. It is seen that buckling factor is maximum in case of uniaxial fibre laminate when all ply orientation is 0°. The analysis results are summarized in Table V;

**Table.5. Uniaxial analysis results [V]**

Sr. No.	No. Of Ply	Thickness (mm)	Buckling Factor	Buckling Load (N)
Test 1	6	4	35779	465.12
Test 2	8	6.5	151283	1966.68

So it is concluded that buckling factor is maximum when all ply angle is 0°.

**VI. UNIAXIAL LOADING EXPERIMENTAL TESTING**

FEA results for uniaxial case are validated using experimental work. Two specimens with 0° fiber orientation are prepared by using Hand Layup technique. The required size specimens are cut using water jet machining. The specimen is loaded in axial compression using a uniaxial tensile testing machine of 98000N capacity. The specimen is clamped at one ends and kept free at the other ends. All specimens were loaded slowly up to failure. For axial loading, the test specimens were placed between the two extremely stiff machine heads, of which the lower one was fixed during the test, whereas the upper head was moved downwards by servo hydraulic cylinder. The shape of the plate after buckling was shown in below Figure 6 and Figure 7.

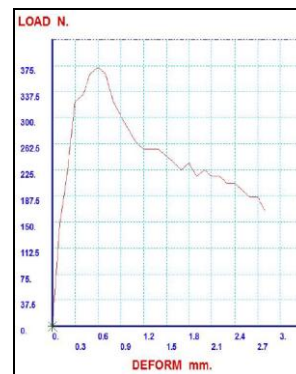


**Figure. 6. Universal testing M/C [6]**

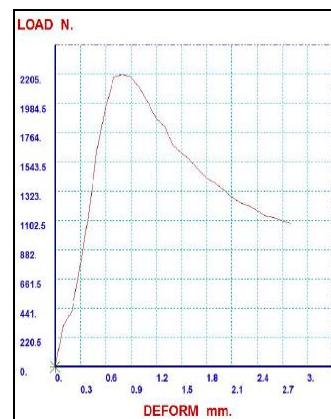


**Figure .7. Plate deformed due to buckling [7]**

**Testing results:** As axial load increases gradually the plate starts to buckle. The obtained experimental results are provided in Figure 8 and Figure 9 for Test 1 and Test 2 specimen respectively.



**Figure .8. graph load vs deformation test 1 specimen [8]**



**Figure .9. graph load vs deformation test 2 specimen [9]**  
The buckling load obtained for Test 1 and Test 2 specimen are provided in Table VI,

**Table 6. Uniaxial loading experimental results [VI]**

Sr. No.	No. Of Ply	Thickness (mm)	Experimental Buckling Load (N)
Test 1	6	4	372.40
Test 2	8	6.5	2205.00

The comparison between obtained by simulation & obtained experimentally is provided in Table VII,

**Table 7. Comparison analysis buckling load and experimental buckling load [vii]**

Sr. No.	Optimized Buckling Load (N)	Experimental Buckling Load (N)	% Difference
Test 1	465.12	372.40	19.93
Test 2	1966.68	2205.00	12.11

It is observed that difference between these two values for a particular specimen is very less. This validates the optimization procedure used for this work. Henceforth, this validated procedure is used for biaxial loading conditions.

**VII. BIAXIAL LOADING ANALYSIS BY FEM**

The Biaxial Hypermesh buckling factor results are compared with the results obtained by Karakaya & Omar [1]. In the reference study, a symmetric laminate consists of 64 plies with two-ply stack in a form of rectangular plate with original length of 508mm and width of 254 mm with total thickness as 8.128 mm made up of Graphite epoxy resin is used for analysis. Fibre orientation in each layer is taken as a design variable. The design variables reduced to 16 from 64 due to symmetrical and two-ply stack lamination. Laminate properties are as mentioned in Table VIII,

**Table 8. Properties of Graphite epoxy laminate [VII]**

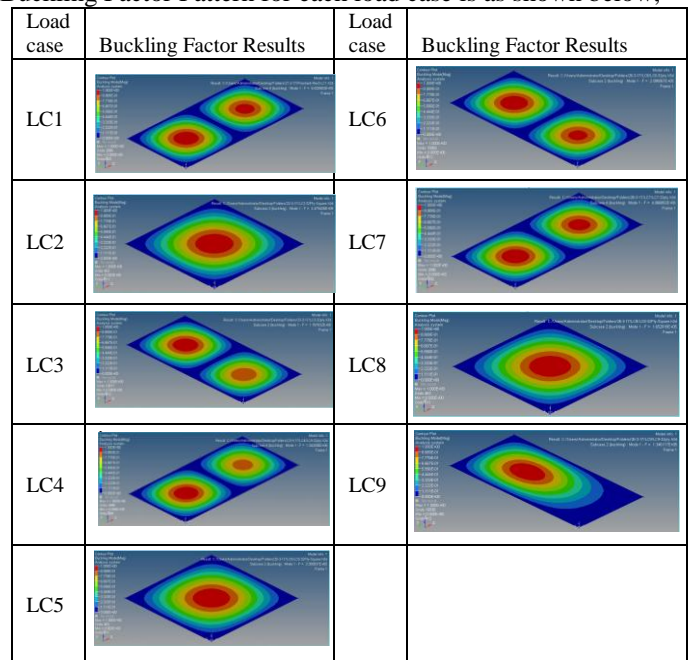
Property	Value
$E_{11}$	127.6 Gpa
$E_{22}$	13.0 Gpa
$\mu_{12}$	0.3
$G_{12}$	6.4 Gpa

The reference paper has considered nine load cases as mentioned in Table I to compare the efficiency of Genetic Algorithm and Generalized Pattern Search Algorithm. In this study, all 9 different load cases modelled in Hypermesh to find out buckling factor for each case as per the stacking sequence considered by Karakaya & Omar [1] for each case. It is seen that buckling factor from Hypermesh for same stacking sequence matches with the buckling factor found out by Karakaya & Omar [1]. This results are provided in Table IX.

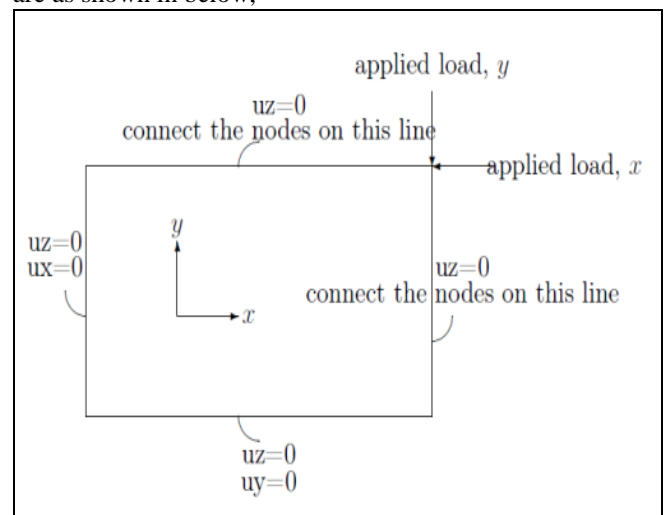
**Table 9. Comparison of hypermesh buckling factor with karakaya & omar [1] buckling factor same stacking sequence [ix]**

Load Case	Karakaya & Omar [1] Stacking Sequence	Karakaya & Omar [1] Buckling Factor	Buckling Factor for Same Stacking
LC1	$[90_{10}/\pm 45_2/90_2/\pm 45_3/90_2/\pm 45_4]_s$	695781.3	682558
LC2	$[\pm 45_{16}]_s$	242823.1	247942
LC3	$[0_{10}/\pm 45_2/0_2/\pm 45_3/0_2/\pm 45_4]_s$	173945.3	176763
LC4	$[90_3/\pm 45_3/90_6/\pm 45/90_4/\pm 45_2/90_2]_s$	1057948	1042698
LC5	$[\pm 45_{16}]_s$	323764	330583
LC6	$[0_{16}/\pm 45/0_6/\pm 45/0_2/\pm 45/0_2]_s$	206492.9	209656
LC7	$[90_{16}/\pm 45/90_6/\pm 45/90_2/\pm 45/90_2]_s$	412985.8	406689
LC8	$[\pm 45_{16}]_s$	161882.1	165291
LC9	$[0_4/\pm 45_5/0_6/\pm 45/0_4/\pm 45_2/0_2]_s$	132243.5	134611

Buckling Factor Pattern for each load case is as shown below,



Boundary conditions used for simply supported biaxial loading are as shown in below,



**Figure 10. Boundary conditions for SS Biaxial Loading [10]**

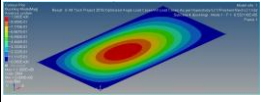
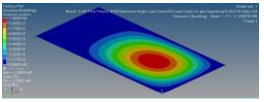
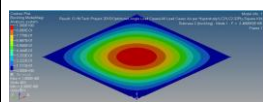
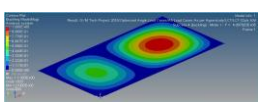
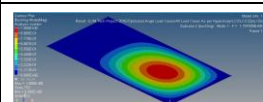
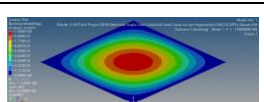
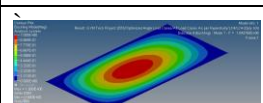
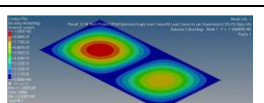
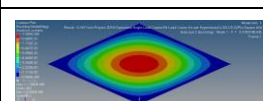
Then all these load cases are considered in Hyperstudy to check possibility to get improved buckling factor if there is no two-ply stack constraint by applying optimization procedure. Comparison of buckling factor obtained after optimization

without any constraints versus buckling factor obtained by Karakaya & Omar [1] are shown in Table X,

**Table .10. Comparison of biaxial loading buckling factor [x]**

Load Case	Optimized Stacking Sequence	Karakaya & Omar [1] Buckling Factor	Buckling Factor per optimized stacking seq.	% Difference
LC1	[-45,90 <sub>9</sub> ,±45,90,45,90 <sub>2</sub> ,45,90,45 <sub>3</sub> ,90,45 <sub>9</sub> ]s	695781.3	716349.3	2.96
LC2	[±45 <sub>15</sub> ,90,-45]s	242823.1	248009.2	2.10
LC3	[0 <sub>3</sub> ,-45,0,-45,0,45 <sub>2</sub> ,0 <sub>10</sub> ,-45,0 <sub>2</sub> ,-45 <sub>10</sub> ]s	173945.3	179793.9	3.36
LC4	[90 <sub>4</sub> ,±45,90 <sub>4</sub> ,45,90,-45,45,90 <sub>2</sub> ,45,90,-45,90 <sub>3</sub> ]s	1057948	1043760	-
LC5	[±45 <sub>13</sub> ,-45,90,-45]s	323764	331027.4	2.24
LC6	[0 <sub>16</sub> ,±45,0 <sub>3</sub> ,-45,0,-45 <sub>9</sub> ]s	206492.9	212392.7	2.85
LC7	[90 <sub>16</sub> ,±45,45,90 <sub>6</sub> ,-45,90 <sub>3</sub> ,-45,90 <sub>2</sub> ]s	412985.8	409756.3	0.78
LC8	[±45 <sub>13</sub> ,-45,90,-45]s	161882.1	165508.9	2.24
LC9	[±45,-45,0 <sub>5</sub> ,-45,0,±45,-45,45,0,±45,0,-45,0 <sub>2</sub> ,-45,0,-45,90,-45 <sub>2</sub> ]s	132243.5	135488.2	2.45

Optimized Buckling Factor Pattern for each load case is as shown below,

Load case	Buckling Factor Results	Load case	Buckling Factor Results
LC1		LC6	
LC2		LC7	
LC3		LC8	
LC4		LC9	
LC5			

### VIII. CONCLUSION

In the present article, buckling load maximization of composite laminate is carried out using genetic algorithm for uniaxial as well as biaxial load conditions. The optimum results obtained using Hyperstudy for uniaxial load conditions are validated by experimental means. Then the similar methodology is used for different biaxial load conditions provided by Karakaya and Omar [1]. It is observed that removal of two ply stack condition results in improved buckling load carrying capacity.

### IX. REFERENCES

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