Stiffness Optimization of Composite Laminate

Yogesh Shilote[1], Prof. N.S. Kulkarni[2]
[1] Post Graduate Student
[2] Asst. Professor Mechanical Engg. Dept
[1, 2] VIT Pune

Abstract- *In this study, Stiffness of composite laminate is maximized by minimizing the displacement of a laminate. Laminates taken for this study have symmetricity about middle ply. Three different laminates having different thickness have considered for analysis. Laminate with constant ply thickness is used for thickness maximization while ply angles in discrete form are considered as design variables. It is observed that for given ply thickness maximum stiffness can be achieved by varying the ply orientation. In this study, optimization is carried out using genetic algorithm available in Hyperstudy. These FEA results are verified by experimental means and FEA model is validated. The validated FEA model is then utilized for Bi-axial load conditions and maximum stiffness is obtained and validated with published results.*

Keywords- Symmetric Composite Laminate, Stiffness, Optimization, Genetic algorithm

I. INTRODUCTION

Composite material is the combination of two or more materials at macroscopic level which are insoluble into each other. It consists of matrix and reinforcements in form of fibers. The fibers can be oriented at any angle to suit the application. Both fibers and matrix combine to form a single lamina which is a building block of laminate.

Composite material is now used in many industries like aircraft, marine, medical, space etc. There are different kind of stresses applied on the material. It is needed to increase the stiffness of the laminate so that it can bear maximum load. Composite laminate generally bears the multi-axial stresses. So, in this paper biaxial stresses on the composite laminate is also studied.

Three different composite laminates are considered for the unidirectional stress in given study. These three laminates are balanced symmetrical laminates having symmetry about middle ply. These laminates consist of different number of plies. Laminates have 6, 8 and 10 plies. Thickness also varies as number of plies changes. On these laminates force is applied at one end while at another end laminate is hold fixed.

For the bidirectional stresses published results from the work of Daniel are taken and these results are optimized for the maximum stiffness.

Optimization done by using the discrete ply orientation as a variable and ply thickness is taken as constant. Displacement of the laminate varies as the orientation of the plies changes. Hyperstudy used for the optimization. In hyperstudy, optimization is carried out using genetic algorithm.

Zeid Hasan presented general approach to analyzre composite laminate in uniaxial and biaxial loading using Tsai hill and Tsai Wu theories. [1]. Mohammed Torabizadeh investigated behavior of glass epoxy composite laminate under static loading.[2] C. S. Verma analyzed strength and stiffness of bamboo composite [3] Soden presented details of the mechanical properties of the matrices and unidirectional laminae used in the failure exercise.[4] Rowlands analyze stress and failure analysis of glass epoxy composite plate using strain gauges and FEA.[5] Fereidoon studied progressive failure of glass epoxy laminate under tensile stress.[6] Hisao Fukunaga, Studied failure of composite laminate using statistical method.[7] P. D. Soden analyzed composite laminates having different ply orientation for the biaxial stresses.[8] Daniel studied behavior of graphite epoxy plate under biaxial loading using strain gauges.[9] DV Hemelrijck tested and optimized biaxial stress using the cruciform specimen. [10] M. J. hinton Studied biaxial strength of laminate using laminate theory and simple progressive model. [11] Irina compared mechanical properties of carbon and E- glass fibers with hybrid polymers. [12]

II.PROBLEM IDENTIFICATION

From Literature review it is clear that tensile stress is generally applied on the composite material. In this study, stiffness of the laminate is increased by decreasing the displacement in the laminate. Optimization is carried out using genetic algorithm by considering discrete ply angles such as 0^0, $\pm 45^0$, 90^0 for different load cases mentioned in Table 1.

TABLE 1 Uniaxial load cases [1]

Sr. NO.	NO. of plies	Thickness (mm)	Force (N)
1	6	4	9500
2	8	6.5	3800
3	10	7	8000

Before proceeding for actual analysis, it is necessary to understand about stress and strain in composite laminate.

III.TENSILE STRAIN DEVELOPED IN COMPOSITE LAMINATE

When the laminate is subjected to the in-plane tensile force strain developed in the laminate

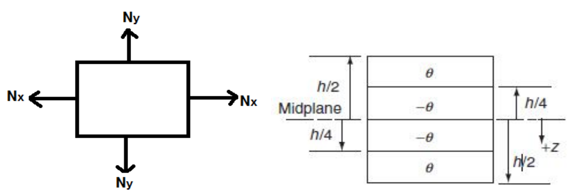

Figure.1 In-plane tensile loading

When there is application of the tensile stress on the laminate strain produced in the laminate. Strain produce in the laminate can be determine by the following formula

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12}/2 \end{bmatrix} = [A] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy}/2 \end{bmatrix} + [B] \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix}$$

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \cdot \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix}$$

$$A_{ij} = \sum_{j=1}^{N} \lfloor Q_{ij} \rfloor_k (h_k - h_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{j=1}^{N} \lfloor Q_{ij} \rfloor_k (h_k^2 - h_{k-1}^2)$$

Here, [A]= extensional stiffness matrix for the laminate and [B]= coupling stiffness matrix for the laminate
ε_x, ε_y = mid plane normal strains in the laminate
K_{xx}, k_{yy} = mid plane shear strains in the laminate
K_{xy} = twisting curvature of laminate
When the symmetric laminate is used at that time [B] i.e. coupling stiffness matrix for the laminate is becomes zero. Hence for this condition only extensional stiffness matrix is remain in existence.
h= total thickness of the laminate and h/2 is distance of extreme ply of symmetry plane.

IV.TENSILE STENGTH ANALYSIS USING OPTISTRUCT

The analysis of composite laminate with tensile strain can be done by loading the material longitudinally with tensile force at one end; while fixing at another end.

After solving this in the FEA, displacement produced in the laminate is obtained. These results are used as input for the optimization.

V.UNIAXIAL LOADING ANALYSIS BY FEM

For uniaxial laminate Tensile strain analysis is carried out using FEM Hypermesh software. For this, standard rectangular composite specimen with dimensions 55×12.5 has taken. Length of the specimen is 55 mm while width is 12.5 mm. The specimen on which experimental tensile test is to be carried out has dumbbell shape with total length of 200 mm. Dumbbell has width of 20 mm.

Three different laminates are prepared to get the required results. Number of plies are varied, in each laminate to get three different thickness laminates. Laminates have 6, 8 and 10 plies.

Tensile stress analysis is done to get the displacement produced in the laminate. For the uniaxial loading one side of the composite laminate is held fixed while tensile load applied on the other side. The load applied on the specimen results in displacement of the laminate. This displacement is minimized to get the maximum stiffness.

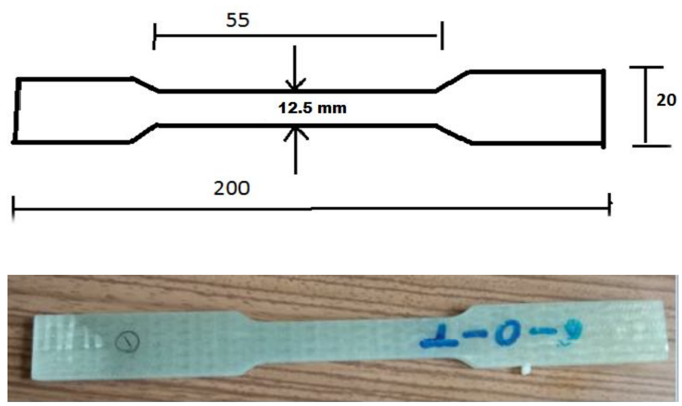

Figure.2 Tensile test specimen

Properties of Laminate:
Properties of laminate are obtained by using Mixture Law,
Fiber and Matrix properties used for making laminates are given in Table 2

TABLE 2 Properties of Glass Fibre & Epoxy [2]

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,

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

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

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

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

The calculated laminate Properties of the test specimen are given in Table 3

TABLE 3 Properties of glass Fibre epoxy laminate [3]

Property	Value
E_{11}	38.5 Gpa
E_{22}	6.5 Gpa
μ_{12}	0.27
G_{12}	2.3 Gpa

Tensile stress Analysis in Hyperstudy 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), (55, 0), (55, 12.5), (0, 12.5). Then 2D surface is created through these nodes. A dimension of the geometry formed is 55×12.5.

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.

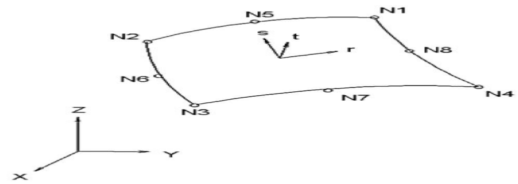

Figure 3. Shell element

b. Meshing: Using automesh command in Hypermesh surface/geometry is meshed. For 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 is 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

TABLE 4 Boundary conditions and constrains [4]

SR. NO.	Entity	Definition
1	Force	FORCE
2	Constrain	SPC

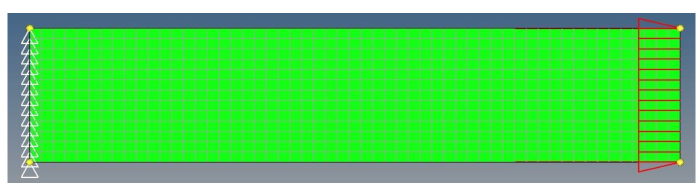

Figure 4. Boudary conditions

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

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 tensile strain analysis, it needs to select the linear static analysis, 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 formed 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 formed using given plies. Plies 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 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 the total thickness of the laminate. In this study, all plies of the same thickness are used.

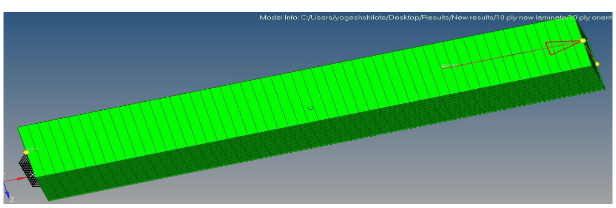

Figure 5. Uniaxial laminate

9. Analysis:

Analysis is performed for three different laminates with number of plies 6, 8 and 10. The details of the laminate are provided in Table 5. Tensile stress calculations have been done for laminate with random stacking sequence using Hypermesh for both the laminates.,

TABLE 5 Fibre epoxy laminate specimen details [5]

Sr. NO.	NO. of plies	Thickness (mm)
1	6	4
2	8	6.5
3	10	7

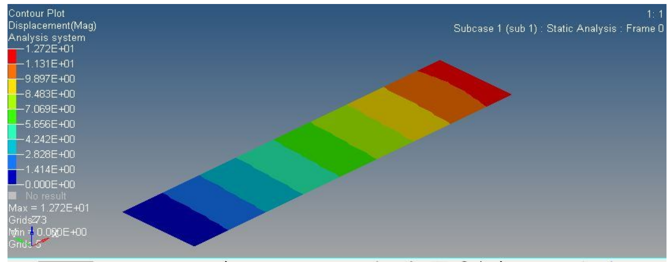

Figure 5. Displacement for 6 ply laminate

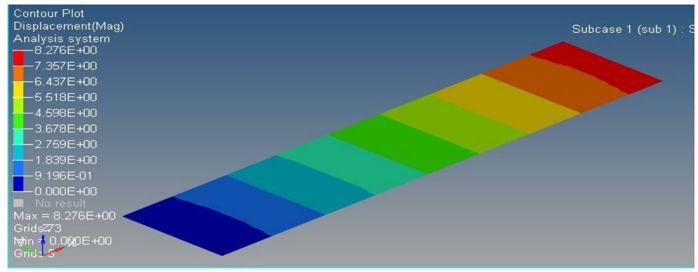

Figure. 6. Displacement for 8 ply laminate

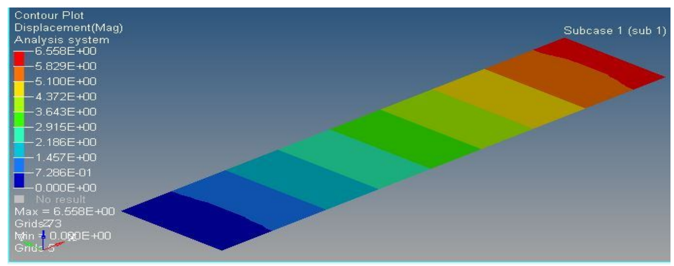

Figure 7. 10 ply laminate results

Uniaxial Loading Optimization Using Hyperstudy:

Then this problem is taken in Hyperstudy where optimization is performed. Ply orientation is taken as discrete variable with values 0°, 45°, -45°, 90°. Genetic algorithm selected as optimization technique. It is seen that displacement is minimum in case of uniaxial fibre laminate when all ply orientation is 0°. For the optimization displacement in laminate is taken as a response and displacement is objective.The analysis results are summarized in Table 6;

TABLE 6 Uniaxial analysis results [6]

SR NO	Force (N)	orientation	Disp. (mm)	Optimized orientation	Optimized solution(mm)
1	9500	(0/45/90)s	11.636	(0/0/0)s	5.651259899
2	3800	(0/-45/45/90) s	8.7377	(0/0/0/0) s	3.78634429
3	8000	(0/45/-45/0/90)s	6.5441	(0/0/0/0/0)s	3.744735956

So, it is concluded that displacement is minimum when all the ply angles are 0°.

VI.UNIAXIAL LOADING EXPERIEMNTAL TESING

FEA results for uniaxial case are validated using experimental work. Three 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 in tension using UTM of 98000N capacity. All specimens were loaded slowly up to failure. For axial loading, the test specimens were clamped with jaws, of which the lower one was fixed during the test, whereas the upper jaw was moved upward by servo hydraulic cylinder.

Figure 8. Uniaxial tensile test machine

Figure 9. Laminate testing

Testing results: As axial load increases gradually, displacement produces in the laminate. The obtained experimental results are provided in figure 10,11 and figure 12 for Test 1, Test 2 and Test 3 specimen respectively.

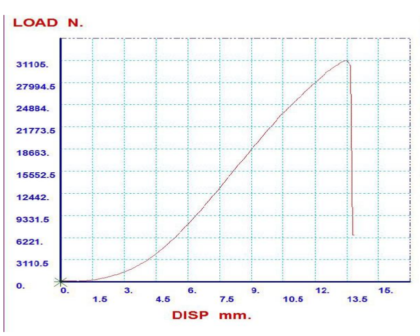

Figure 10. Graph load vs displacement 6 ply specimen

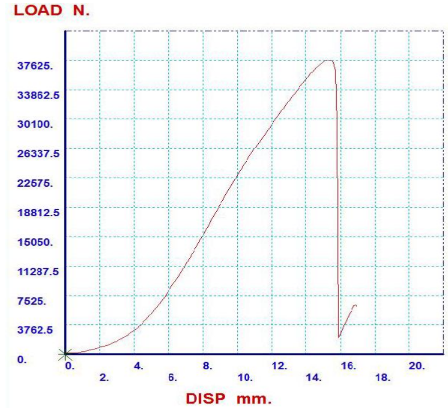

Figure 11. Graph load vs displacement 8 ply laminate

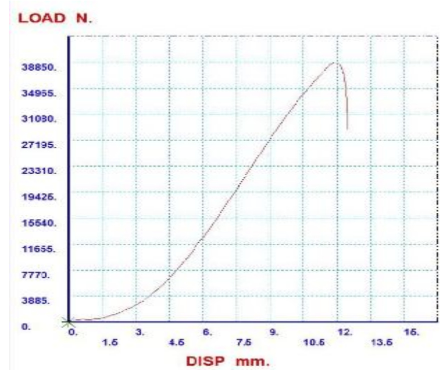

Figure 12. Graph load vs displacement 10 ply specimen

The displacement obtained for 6, 8 and 10 ply specimens are provided in Table 7,

TABLE 7 Uniaxial loading experimental results [7]

Sr. No.	No. of plies	Force (N)	Experimental results (mm)
1	6	9500	6.2
2	8	3800	4.2
3	10	8000	5

The comparison between results from FEA and experimental results are shown in Table 8

TABLE 8 Comparison FEA results and experimental results [8]

Sr. No.	No. of plies	Force (N)	Optimized FEM results (mm)	Experimental results (mm)	% Difference
1	6	9500	5.6512	6.2	8.87
2	8	3800	3.78634429	4.2	10
3	10	8000	3.744735956	4.6	16

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 tensile force displacement results are compared with the results obtained by Daniel [9]. In the reference study. A symmetric laminate consists of 8 plies having square geometry with ply thickness as 0.13 mm. Laminate has central hole of 25.4 mm. Length of side is 400 mm. The force is applied on every side of the specimen. The specimen is made of Graphite epoxy material. For the optimization of laminate thickness and force applied is taken as constant, while fiber ply orientation in each layer is taken as a design variable. The design variables reduced to half due to symmetrical lamination. Force of 4160 N is applied on all sides. Laminate properties are as mentioned in Table 9,

TABLE 9 Properties of Graphite epoxy laminate [9]

Property	Value
E_{11}	151 Gpa
E_{22}	10.6 Gpa
μ_{12}	0.27
G_{12}	6.6 Gpa

Results given by the Daniel are verified in the hypermesh. After that obtained displacement is optimized in the Hyperstudy using the multi-objective Genetic algorithm. Displacement produced in the vertical as well as horizontal directions are verified and optimized. For the optimization Displacement produced in the vertical (y) and horizontal (X) directions are taken as a response, while minimization of displacement in these directions is considered as objective.

TABLE 10 Displacement with FEA compared with displacement from daniel [9] [10]

Sr. No	Component	FEA Displacement (mm)	Displacement From paper (mm)	% error
1	X	0.00416	0.0036	12
2	Y	0.00419	0.0038	10

Geometry and boundary conditions used for simply supported biaxial loading are as shown in below,

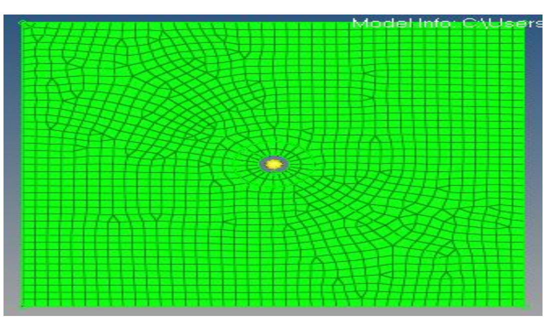

Figure 13. Meshed surface

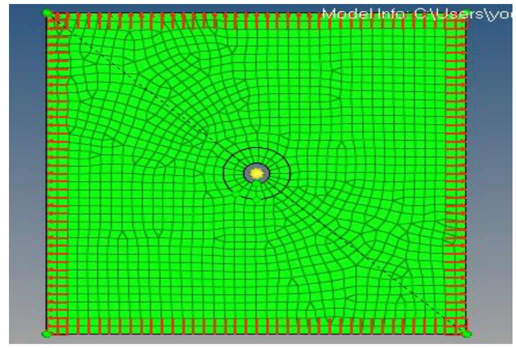

Figure 14. Boundary conditions

Then all this load case is considered in Hyperstudy to check possibility to get optimized displacement. Obtained results from Hypermesh are as follow

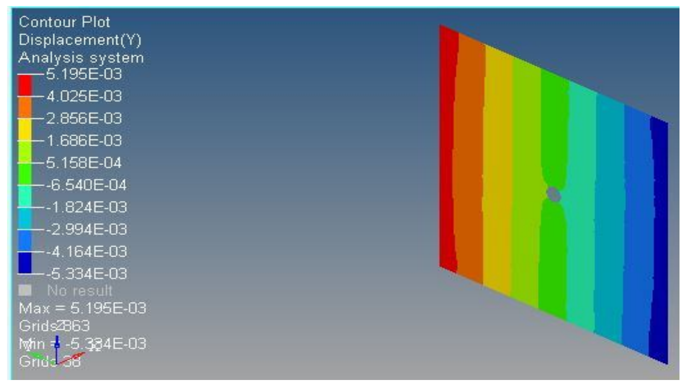

Figure 15. Displacement results in horizontal direction

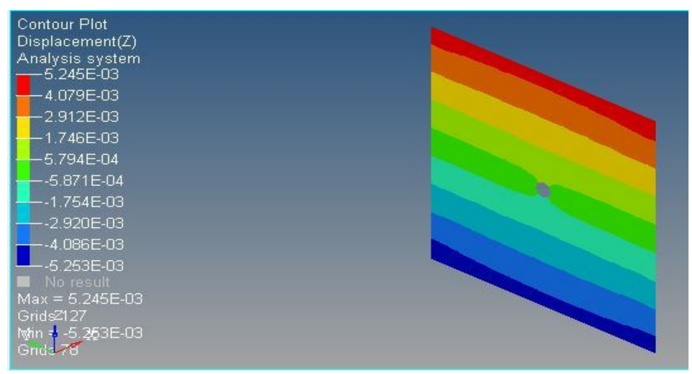

Figure 16. Displacement result in vertical direction

After Hypermesh analysis. Case is then optimized in the Hyperstudy. Here, ply thickness is taken as constant and ply orientation is variable.

TABLE 11 optimization results for bidirectional force [11]

Sr. No.	Component	Optimized stacking sequence	Optimized displacement
1	X	$(45/45/45/45)_2$	0.001136204
2	Y	$(45/45/45/45)_2$	0.00157749

From the above results, it can be concluded that when biaxial forces are acting on the laminate, equal to 45^0 orientation plies give maximum stiffness and minimum displacement

VII.CONCLUSION

In the present article, Stiffness maximization by minimizing the displacement in composite laminate is carried out using genetic algorithm for uniaxial as well as biaxial load conditions. The optimized displacement results obtain for uniaxial load condition from the Hyperstudy are validated by the experimental means. Then the similar methodology is used for biaxial load condition provided by Daniel [9]. It is observed that, by changing the stacking sequence of the laminate displacement can be reduced. Hence, stiffness can be maximized.

REFERENCES

[1] Zeaid Hasan, Feras Darwish, Suhayb Al-Absi Failure Stress Analysis of Fiber Reinforced of Composite Laminates under Uniaxial/BiaxialLoading

[2] Mohammed A Torabizadeh, tensile compressive and shear properties of unidirectional glass epoxy composite subjected to mechanical loading and low temperature service, Vol 20, August 2013, pp, 299-309

[3] C. S. Verma, Stiffness and strength analysis of four layered bamboo composite at microscopic scale,

[4] P. D. Soden, M. J. Hinton, A. S. Kaddou, Lamina Properties, Lay-Up Configurations And Loading Conditions For A Range Of Fibre-Reinforced Composite Laminates, Composites Science and Technology 58 (1998) 1011-1022

[5] R. E. Rowlands, I. M. Daniel and J. B. Whiteside, Stress and Failure Analysis of a Glass-Epoxy Composite Plate with a Circular Hole.

[6] Abdolhossein Fereidoon, Mohammad Amin Torabizadeh Progressive Failure Analysis of Glass/Epoxy Composites at Low Temperatures, http://dx.doi.org/10.5772/55093

[7] Hisao Fukunaga And Tsu-Wei Chou, Probabilistic Failure Strength Analysesof Graphite/Epoxy Cross-Ply Laminates

[8] P.D. Soden, M.J. Hinton, A.S. Kaddourc, Biaxial test results for strength and deformation of a range of E-glass and carbon fibre reinforced composite laminates: failure exercise benchmark data, Composites Science and Technology 62 (2002) 1489–1514

[9] Isaac M. Daniel, Behavior of Graphite/Epoxy Plates with Holes under Biaxial Loading.

[10] DV Hemelrijck, AMakris, C Ramault, E Lamkanfi, WV Paepegem and D Lecompte, Biaxial testing of fibre-reinforced composite laminates.

[11] M. J. Hinton, Strength of Composite Laminates under Biaxial Loads, Applied Composite Materials 3: 151-162, 1996.

[12] Irina M.M.W., A.I. Azmi1, Tan C.L., Lee C.C. and A.N.M Khalil, “Evaluation of Mechanical Properties of Hybrid Fiber Reinforced Polymer Composites and Their Architecture,” Procedia Manufacturing 2, pp. 236–240, 2015

[13] Book of Fiber-Reinforced Composites by P.K. Malik