Macro-mechanical Analysis on the Variation of Fibre Orientation in a Composite UAV Landing Gear

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Abstract: Composite materials are increasingly being relied upon for their light weight and high strength to weight ratios and form the backbone of the aerospace industry, which follows a Systems Engineering approach. This paper is an attempt to manifest such an approach at a relatively smaller scale for a composite UAV landing gear. The landing gear acts as a support structure for the fuselage during take-offs and landings and hence needs to be carefully designed, analyzed and manufactured. The strength and weight of a landing gear has to be optimized so as to adhere to the overall aerodynamics and structural integrity of the aerial system. This study is initiated with the design concept of the landing gear and the state of load being acted upon followed by appropriate composite material selection. An approximate number of layers are decided for the composite vacuum layup of the landing gear through iterative experimentation. The fibre orientation of the composite layers is instrumental in gauging the macro-mechanical performance of the composite, thus being the focal point of this study. To execute this, the extensional, coupling and bending stiffness matrices are computed in a mathematical model in MATLAB for different fibre orientations in response to the elastic constants of the fibre and matrix. The global and local strains and curvatures are calculated for a load case and the final combination is down-selected. Corresponding to the down-selected combination, the landing gear is finally fabricated, using Vacuum bag moulding.

Nomenclature:

E1	*=Longitudinal Young's Modulus*
E2	*=Transverse Young's Modulus*
v12	*=Major Poisson's Ratio*
v21	*=Minor Poisson's Ratio*
G12	*=In-plane shear modulus*
[A]	*= Extensional Stiffness Matrix*
[B]	*= Coupling Stiffness Matrix*
[D]	*= Bending Stiffness Matrix*
Nx, Ny	*= Normal force per unit length*
Nxy	*= Shear force per unit length*
Mx, My	*= Bending moments per unit length*
Mxy	*= Twisting moments per unit length*
$\underline{[Q]}$	*= Reduced stiffness matrix*
$\overline{[Q]}$	*=Transformed reduced stiffness matrix*
e_x, e_y, e_{xy}	*= Mid-plane strains*

Kx, Ky, Kxy = *Mid-plane curvatures*
[T] =*Transformation matrix*
[R] = *Reuter matrix*
(1,2) = *Local axes denomination*
(x,y) = *Global axes denomination*

1. Introduction
Systems Engineering, which supplements the design and development of unmanned aerial vehicles follow an inter-disciplinary approach to tackle complex systems such as this one. The landing gear of an unmanned aerial vehicle (UAV) functions as a shock absorber for the fuselage of the UAV, shielding the payload. The dynamic loads acting on the UAV due to sudden gusts and abrupt maneuvers are fully absorbed by the landing gear. It therefore demands a meticulous structural design of the landing gear of the UAV. With the advent of hybrid materials like composites and smart materials, it calls for careful selection of materials and their macro-mechanical analyses of resulting inner fiber and matrix to reach a design with a high technology readiness level.

2. Statement of Objectives
The design objectives for the composite landing gear are bifurcated into high-level and low-level objectives based on their functionality and dependence. The list of objectives in Table 1 presents the objectives kept in mind while approaching the design problem.

Table 1. Statement of objectives for the design of a composite landing gear

S.no	Parameter/Objective	Value/Range
1	Weight	5-7% of UAV weight
2	Static Load on the landing gear	85-90 N
3	Dynamic Load on the landing gear	150-170 N
4	Factor of safety	1.5
5	Strength/Weight %	130-180
6	Material characteristics	CF fabric/Epoxy matrix
7	Technology Readiness Level	5-7

3. Engineering Design
The landing gear is designed to tested for the static load of 85 N and an assumed dynamic load of 150N [1], it may take during the flight along with suitable safety factor, and several materials are qualitatively judged on a number of parameters. Carbon-fibre is finally selected among a list of other metals and composites. Different grades of carbon fibres are tested ranging from 200-400 gsm through a mathematical model and 400 gsm is finally selected.

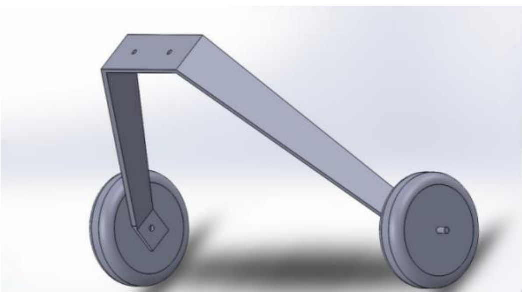

Figure 1. CAD model of the landing gear

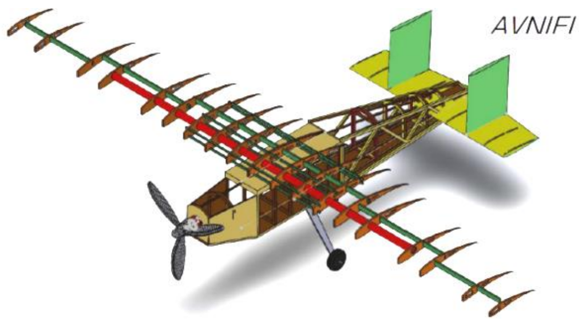

Figure 2. Raw 3D CAD of the UAV

4. Macro-mechanical Analysis

The macro-mechanical analysis of a composite lamina is based on the consideration that the lamina is homogeneous and the average properties of the individual layers are calculated [2]. The stiffness matrices are calculated based on the engineering constants of uni-directional lamina (both fiber and matrix) using a mathematical model.

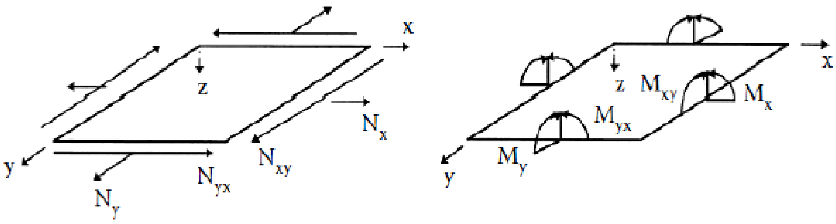

Figure 3. Forces & moments acting on a composite laminate [2]

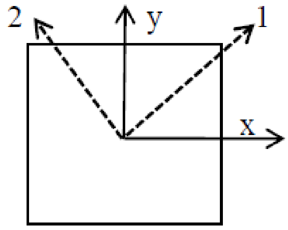

Figure 4. Local & Global axes representation of a lamina [3]

4.1. Mathematical Model.

The mathematical model takes as input, the elastic moduli of the fiber and the matrix of the composite, as specified in [4] to advance to the combined elastic moduli, *E1, E2, ν12* and *G12* to finally calculate the reduced stiffness matrix *[Q]* for each ply of the composite using the following governing equations. (Refer Eq.1 to Eq.4)

$$Q11 = E1 / (1 - \nu12 * \nu21) \quad (1)$$
$$Q12 = E2 * \nu12 / (1 - \nu12 * \nu21) \quad (2)$$
$$Q22 = E2 / (1 - \nu12 * \nu21) \quad (3)$$
$$Q66 = G12 \quad (4)$$

The lamina in consideration is taken as purely orthotropic [5], so the other stiffness coefficients result in value of 0. Based on the reduced stiffness coefficients and restricting the number of plies, the fiber orientation of each ply is arbitrarily taken, considering the ease of fabrication. The number of plies are kept constant at 4, due to restricted weight constraint and the number of test cases are increased to 6 with the following layup.

Layup-1	*Layup-2*	*Layup-3*	*Layup-4*	*Layup-5*
0	0	0	0	0
90	90	45	45	-45
0	90	0	45	45
90	0	45	0	0

Figure 5. Layups with 4 plies each, with their fibre orientations

Each of the layups are separately taken and the transformed reduced stiffness matrix *[Q]* are calculated for each ply. Several assumptions were made in the process, for uniformity in the mathematical model and ease of fabrication.

Assumption 1 : The thickness of the plies were estimated, assuming uniform thickness of matrix(epoxy) and the fibre.

Assumption 2 : The mid-plane of the layup was assumed as origin for calculation of the coordinates of each ply.

Using the stiffness coefficients $[Q_{ij}]$ and the location of each ply, the extensional *[A]* , coupling *[B]* and bending *[D]* stiffness matrices are calculated [1], (Refer Eq.5 to Eq.7)

$$A_{ij} = \Sigma[\overline{Q_{ij}}]_k * (h_k - h_{k-1}) \text{ where } i=1,2,6 \text{ ; } j=1,2,6 \text{ ; } h_k = \text{coordinate of kth ply} \quad (5)$$
$$B_{ij} = \Sigma[\overline{Q_{ij}}]_k * (h_k^2 - h_{k-1}^2) \quad (6)$$
$$D_{ij} = \Sigma[\overline{Q_{ij}}]_k * (h_k^3 - h_{k-1}^3) \quad (7)$$

Corresponding to the obtained matrices *[A]*, *[B]* and *[D]*, the required forces and moments are applied to the final configuration of the layup and the mid-plane strains and curvatures are found by solving 6 simultaneous equations.(Refer to Eq.8)

$$\begin{bmatrix} Nx \\ Ny \\ Nxy \\ Mx \\ My \\ Mxy \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} e\,x \\ e\,y \\ e\,xy \\ Kx \\ Ky \\ Kxy \end{bmatrix} \quad (8)$$

The local and global strains are also evaluated using the transformation operator $[R][T][R]^{-1}$. Finally, 6 variables are calculated through the mathematical model, 3 each for midplane strains and mid-plane curvatures.

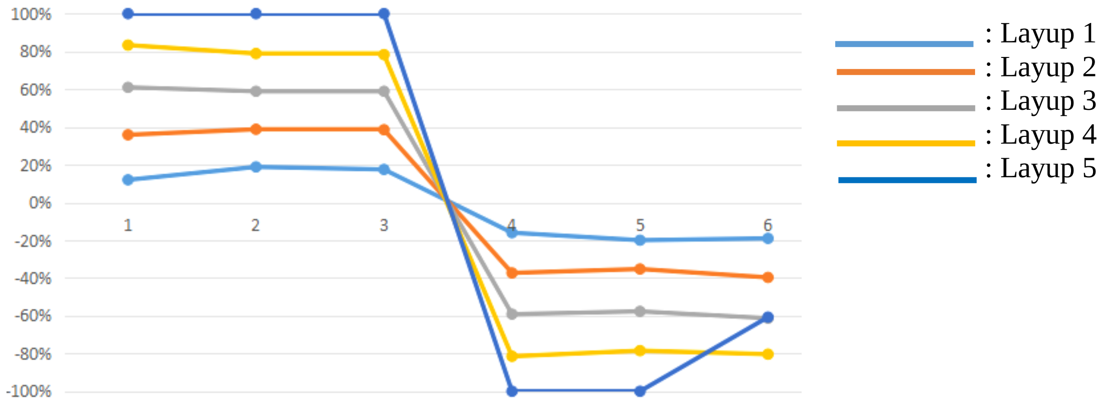

Figure 6. Percentage variation of the values of 6 variables for 5 layups in the mathematical model

4.2. Finite Element Method.

To analyze the accuracy of the results obtained from the mathematical model, a finite element simulation is performed for the composite landing gear with identical material properties and configurations. The finite element method simulation is performed on ABAQUS CAE, in which appropriate material properties of cross-weaved Carbon fibre of 400 gsm is stored, followed by layer selection, input of fibre orientation data and finally load application [6].

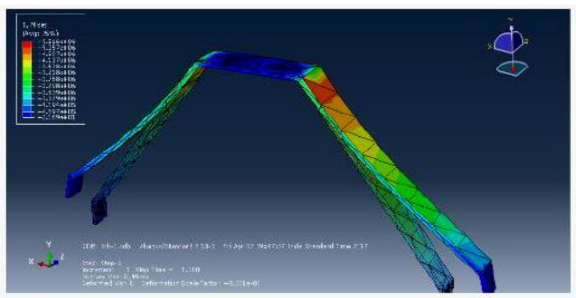

Figure 7. Strain energy contours on landing gear

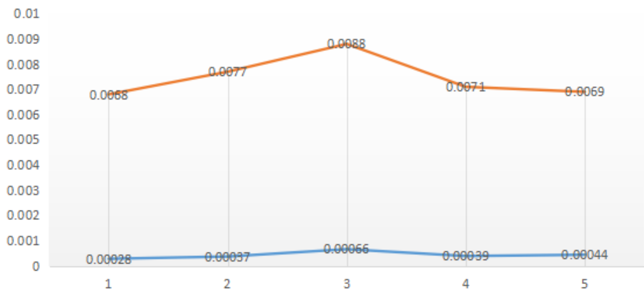

Figure 8. Variations in strains & curvature (FEM)

The results obtained from the finite element model are found to be in close proximity of the results obtained from the mathematical model.

5. Results

The results tabulated below are obtained through the mathematical model developed in MATLAB which represents the mid-plane strains and mid-plane curvatures for each of the 5 composite layups. Layup 1 [0/90/0/90] was found to be the optimal orientation of the fibres in the composite.

Table 2. Mid-plane strains and curvatures for the 5 layups through the mathematical model

Layup	e_x	e_y	e_{xy}	Kx [m]	Ky [m]	Kxy [m]
1	0.000112	0.000188	0.000295	-0.003096	-0.006721	-0.00715
2	0.000223	0.000199	0.000355	-0.004112	-0.005133	-0.00777
3	0.000235	0.000201	0.000344	-0.004215	-0.007541	-0.00812
4	0.000209	0.0002	0.000327	-0.004311	-0.007001	-0.00716
5	0.000156	0.000211	0.000367	-0.003577	-0.00723	0.00738

The results obtained by performing the finite element simulation on the composite landing gear to calculate the mechanical variables are shown in Table 3.

Table 3. Mechanical variables from the finite element simulation

Layup	Max principal stress [Mpa]	Max Strain Energy [J]	Max Equivalent strain	Mean curvature [m]
1	85.7	8.22e9	0.00028	0.0068
2	89.5	8.81e9	0.00067	0.0087
3	80.7	8.34e9	0.00034	0.0077
4	91.7	8.93e9	0.00073	0.0091
5	89.7	8.82e9	0.0070	0.0088

The absolute mean errors obtained for the values of mid-plane strains and curvatures from the 2 methods in Layup 1-5 are approximately 5%, 9%, 7.5%, 12% and 11% respectively.

6. Fabrication

The laminates are fabricated using Vacuum Bagging technique [7] in which the composite material layers are stacked on top of each other using the matrix (Epoxy with a 1:10 ratio of resin and hardener) and then vacuum is created using a sealed plastic bag connected to a vacuum pump. The temperature during the process needs to be increased to accelerate the curing time of the whole layup. This technique is dependent on season temperature, wherein the curing time varies by a large margin in summers compared to winters [7].

Figure 9. Composite layup using carbon fibre

Figure 10. Sealed vacuum layup

The laminates fabricated are then used for physical testing through a 3 point flexural test, before fabricating the actual model. The landing gear, initially designed and followed for a static load of 85N and a dynamic load of 150N behaved structurally well beyond the specified limits, giving a margin of safety of 1.7.

7. Conclusion

The conducted research presents an outline for the engineering analysis of composites in a UAV landing gear. The results of the formulated mathematical model are in close agreement with the Finite Element simulation performed on ABAQUS CAE for 5 different composite layups considered for the landing gear. Fabrication of the small scale laminates for 5 layups followed by a 3 point flexural test validates the design of the composite landing gear. Vacuum Bagging technique has been utilized in the fabrication process of the laminates as well as the actual model. Finally, for a UAV weight of 7.7 kilograms, the landing gear was fabricated with a total weight of 400 grams and reaching a strength/weight percentage of 160%. The technical readiness level of the developed system is observed to be 5.

References

[1] Sadraey M., *Aircraft Design: A Systems Engineering Approach, 2012, Wiley Publications*
[2] Autar K. Kaw: *Mechanics of composite materials*, *2nd Edition*,2006 by Taylor & Francis Group, LLC
[3] https://www.asminternational.org/documents/10192/1849770/05287G_Sample_Chapter.pdf
[4] https://snebulos.mit.edu/projects/reference/MIL-STD/MIL-HDBK-17-2F.pdf
[5] Chen, C.H. and Cheng, S. (1967). *Mechanical Properties of Fibre Reinforced Composites*, Journal of Composite Material, 1(1): 30–40.
[6] Klaus Jurgen Bathe: *Finite Element Procedures, 1996 by Prentice Hall, Inc.*
[7]https://www.amtcomposites.co.za/sites/default/files/media/howto/Intro%20to%20Vacuum%20Bagging.pdf