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Stress Analysis of Composite Aircraft Wing using Coupled Fluid-Structural Analysis

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ABSTRACT

Aircraft wings are designed with very low factor of safety to keep the aircraft weight minimum. Thus, for safe design of wings, stress analysis should be carried out under accurately estimated aerodynamic loads and this can be achieved only through coupled fluid-structure analysis. Moreover, modern aircraft wings are made of laminated composite structures and thus the purpose of this study is to employ ANSYS coupled fluid-structure analysis to find the best layup of composite wing of an aircraft that results in higher specific strength and specific stiffness. Firstly, Computational Fluid Dynamics (CFD) analysis has been carried out to find the actual aerodynamic load which is the pressure distribution around a three-dimensional wing. Then, this pressure distribution from CFD was used as a load input for detailed static structural analysis of the wing. Initially, strength and stiffness of an isotropic wing is evaluated and then the material of the wing was changed to composite laminates to achieve better structural performance with higher strength and stiffness to weight ratio. Stress analysis was carried out for different layups to predict the optimum layup that results in high strength and stiffness coupled with the least weight and it was found that the wing made of symmetric cross-ply laminate performs the best.

1. Introduction

Composites are manufactured by combining two or more materials at macroscopic level, either natural or artificial and are not soluble in each other. A fiber reinforced composite laminate is an organized stacking sequence of a uni-directional composite plies that is manufactured to meet some design requirement. Kreja [1] state that a composite layer represents an orthotropic system that have three mutually orthogonal planes of symmetry. Due to the high specific strength and stiffness, composite material has become a growing interest among the researchers during the last three decades.

Modern aircrafts have major components replaced by composite material including the primary structures. Kennedy and Martins [2] made a comparison between metal and composite wing. Based on their study, they prove that composite wing design has reduced the weight of the aircraft about

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34% to 40%. Due to decrement of the weight, it affects the fuel consumption also and they concluded that the fuel can be saved up to 5% to 8% by using composite material. Lastly, changing the metal with composite will reduce take-off gross weight 6% to 11%. Even though the characteristics of the composite aircraft already impressive, still many researchers are keen on optimizing aircraft structural performance by varying various parameters of composite laminates.

Nowadays with many modern tools available such as ANSYS, LS-DYNA, COMSOL. etc. that can handle composite structural analysis, much of the work has been done on the optimization of composite structures. Khandan *et al.,* [3] presented a design optimization of composite plate using Simulated Annealing and Finite Element Method to optimize safety factor by considering not only the effect of Longitudinal and in-plane loading but also the effect of transverse shear force which had been ignored in previous studies. Two Failure Criteria was used which are maximum stress criteria and Tsai-Wu failure criteria. Later, Shabeer and Murtaza [4] done a stress analysis of a well modelled composite wing aircraft to obtain best stacking sequence that produce less deformation and Von Mises stresses using Finite Element Method. In their study Aluminium skin of wing was replaced by Graphite/Epoxy skin, whereas other elements of the wing was maintained as aluminium.

Dillinger *et al.,* [5] has done a study on optimizing mass of the composite wing with the influence of aero elastic constraints and sweep angle of swept forward wings. The result from optimizer shows small variation between balanced and unbalanced laminates and it was concluded that it is possible to reduce the mass of the wing by using the unbalanced laminates.

Hajmohammad *et al.,* [6] use Genetic Algorithm combined with Neural Networks function to optimize buckling load subjected by varying stacking sequence. Zhao *et al.,* [7] also optimized buckling load by varying stacking sequence but by using Permutation Search Algorithm. Sharad and Abhay [8] had done an optimization for maximum stiffness and minimum weight of laminate by using Genetic Algorithm. Maximum failure criteria had been used to determine whether load capacity were exceeded. The optimization had been done by varying fiber orientation, thickness of lamina and stacking sequence.

Wang *et al.,* [9] used the finite element model of the wing with the equivalent strength and stiffness method. They use three-step optimization to improve structural efficiency. Static strength and buckling are used as a constraint in this optimization strategy.

Nikbakt *et al.,* [10] presented a detailed review paper on optimization of laminated composites in which the objective functions, design variables, constraints and the algorithms used are highlighted as essential parameters of these optimization approaches. Sachin *et al.,* [11] used multi-objective multi-laminate design optimization of carbon fibre composite wing torsion box using evolutionary algorithm. Recently, Vijayanandh *et al.,* [12] carried out optimization of orientation of carbon fiber reinforced polymer based on structural analysis using finite element analysis. Dillinger *et al.,* [13] very recently improved his previous work on static aeroelastic stiffness optimization of a forward swept composite wing with CFD-corrected aero loads. Very recently, similar parametric study and structural optimization was reported for high-aspect-ratio composite wing [14-16] and composite fuselage [17]. Thus, the optimization of aircraft structures made of composite laminates is still an active field of research. However, there seems to be limited numerical studies on stress analysis of composite wing based on Fluid Structure Interaction (FSI) module of ANSYS. The significance of the analysis based on FSI is that the aircraft structural performance can be analyzed using actual aerodynamic load distribution instead of simplified approximate loads based on analytical methods. Thus, in this study the actual aerodynamic load is evaluated using the CFD and then the loads are used to study the stresses on an aircraft composite wing using FSI module of ANSYS. Finally, various composite laminate sequence was studied to find the optimum layup for minimum deformation and stresses in the composite wing.

2. Methodology

ANSYS provides access for users to couple between two fields of analysis such as fluid flow and Structural Analysis [18]. ANSYS Workbench is one of the common platforms for solving problems that combines different processors such as Design Modeler to design geometry, Static Structural to analyze behavior during static loading and ANSYS (Fluent) to analyze flow.

In FSI analysis, two different solvers were used to solve the equations governing the fluid flow and the structural analysis independently based on numerical solver. FSI approach has one-way or two-way coupling methods based on the extent of coupling, but in both the methods, the information for the solution is shared between the fluid-structure interfaces. In one-way FSI coupling analysis, only the fluid pressure acting on the structure was transferred to the structure solver whereas in two-way FSI approach displacement of the structure was also transferred to the fluid solver simultaneously. For this study, only one-way FSI have been performed considering the large computational costs involved in two-way FSI.

This study was performed numerically using a one-way FSI static run partitioned approach. In this coupling method as shown in Figure 1, for fluid flow ANSYS Fluent module was used and for structural analysis part, ANSYS Mechanical module was used. Firstly, the CFD analysis using ANSYS Fluent was carried out until the desired convergence is reached and then the output of this calculation was interpolated to the structural model at the interface. After that, structural analysis was carried out using ANSYS Mechanical module until convergence was achieved.

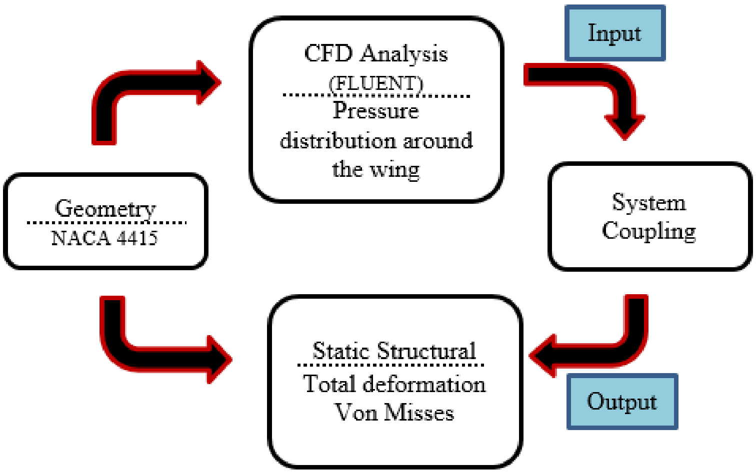

Fig. 1. Flow process on coupled analysis

Initially the geometry of the wing was created using ANSYS Design Modeler. The wing was assumed to be made of NACA 4415 profile and the first spar near the leading edge is placed at the quarter of chord and the second spar is placed at three quarter of chord. The geometry is divided into two, one that will be analyzed in Computational Fluid Dynamics (CFD) and another one will be analyzed in static structural. The control volume around the 3D wing will be used to analyze the flow around the wing. In the modelling of the wing, to make sure that all the surfaces are in contact with each other, Boolean feature was used to combine all ribs and spar to become one integral part. The skin is connected to the frame using joint feature and the wing chord and span is taken to be 1.8m and 4.8m respectively.

The geometry was meshed first before the solution and the edge sizing was used to mesh for the flow around the wing. The properties of the flow and solid were selected and defined in setup section with Reynold's Number (Re) of 135.54 x 10^6 was used based on the properties at an altitude of 6000m above sea level and with a velocity of aircraft at 100m/s. Thus, the flow in this analysis is considered as turbulent and hence k-epsilon turbulence model has been selected. Boundary condition for this problem is the velocity along x direction was taken as 100m/s and the iteration had been carried out by ANSYS until the solution converged.

After the CFD part is completed, ANSYS Composite PrepPost (ACP) set up was intiated. The layup of the composite, angle orientation and each lamina thickness were defined here. It next linked to static structural module so that the wing can be meshed for static structural analysis. The input file has been setup by using system coupling so that the pressure distribution from CFD is directly linked as the input for static structural analysis. For static structural analysis, the wing surface that is attached to the fuselage was set as fixed support resulting in a cantilever wing. Finally, the above coupled analysis will result in total deformation and Von Mises stresses of the wing. Manual optimization was then carried out by changing the stacking sequence in ACP tool for to find the best layup that results in high strength and stiffness to weight ratio.

3. Results

3.1 CFD Analysis

The purpose of carrying out CFD analysis is to obtain actual pressure distribution around the wing so that this pressure distribution obtained from CFD solution can be directly used as an aerodynamic load to analyze structural performance of wing under Static Structural Analysis. To start with, CFD analysis was carried out and the solution is obtained once the iteration stopped with a message showing that the solution is successfully converged. Since the data is directly linked and applied to the static structural analysis, there is no need to record the numerical data. The output of the CFD solution, the pressure distribution is depicted in Figure 2 for the entire wing and the pressure profile around the airfoil of the wing is presented in Figure 3 at an angle of attack of 10˚.

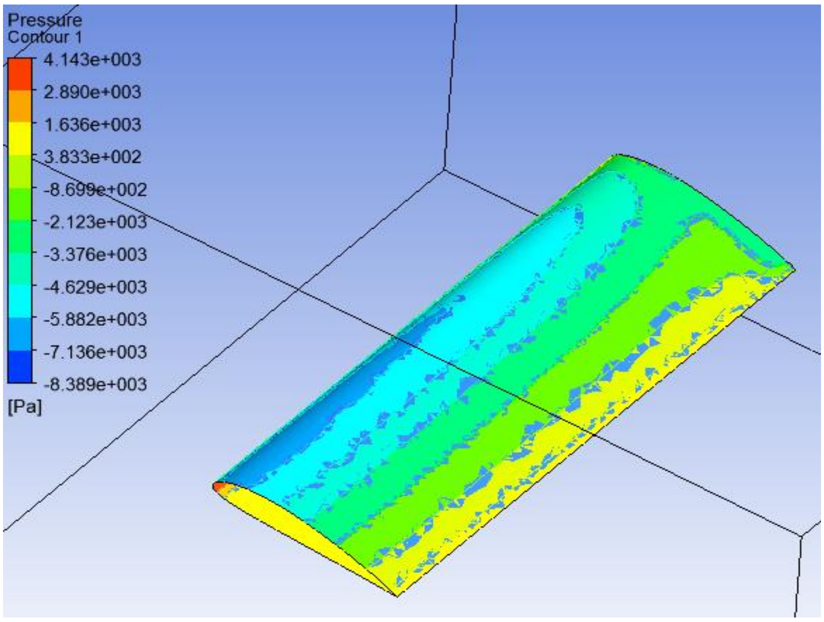

Fig. 2. Pressure distribution on wing

From Figure 3 it can be seen that positive pressure at the bottom and negative pressure at the top of the airfoil will result in the aerodynamic loads, lift and drag. As the angle of attack increases, the pressure distribution changes such that the pressure builds at the bottom of airfoil thus leading to increase in lift and drag which may be result in increase in the deformation and stresses in the wing. With increase in angle of attack, the load steadily increases until it reaches the stalling angle of attack and then the load starts decreasing with the separation of flow. Thus, the maximum load and hence the maximum deformation and stresses will occur corresponding to the stalling angle of attack which is around 18° for the NACA 4415 airfoil considered in this study.

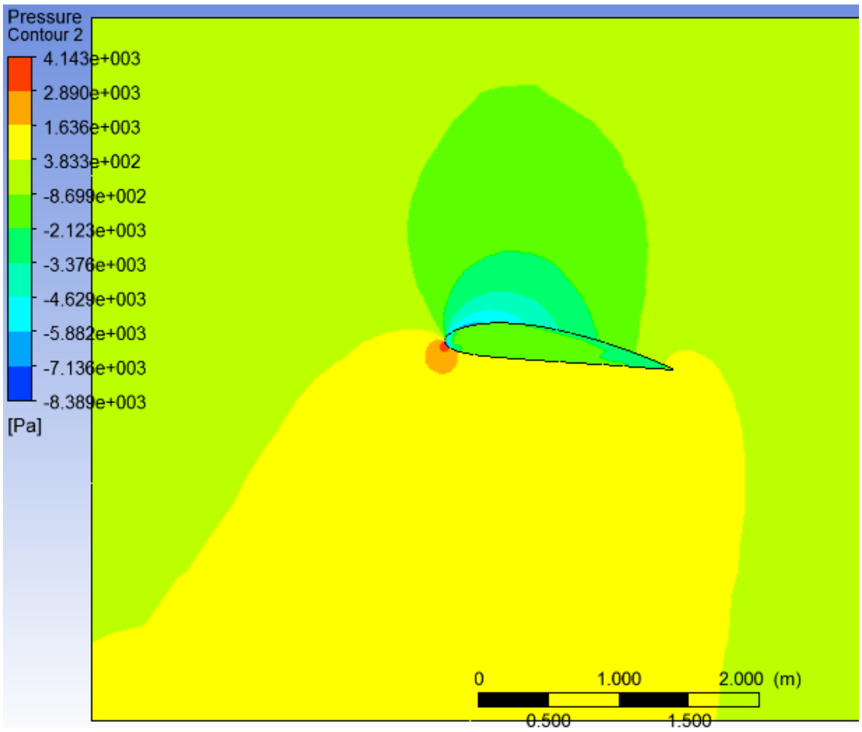

Fig. 3. Pressure profile around the airfoil

3.2 Static Structural Analysis

As elaborated in methodology, coupled field analysis was carried out on a wing geometry to analyze the total deformation and stresses on the wing made of Aluminium first and then the skin material was replaced by composite material. Then later the best stacking sequence for highest specific strength and specific stiffness is evaluated. For structural analysis the following properties for Aluminium alloy and Graphite/ Epoxy lamina were used as given in Table 1 and Table 2 respectively [19,20].

Table 1
Properties of Aluminium alloy

Property	Value
Density (r)	2800 kg/m^3
Ultimate Strength (s_{UT})	572 MPa
Modulus of Elasticity (E)	71.7 GPa
Shear Modulus (G)	26.9 GPa
Poisson‘s ratio (n)	0.33

Table 2
Properties of Graphite/Epoxy lamina

Property*	Value
r	1600 kg/m^3
s_{1UT}	1500 MPa
s_{2UT}	1500 MPa
E_1	181 GPa
E_2	10.3 GPa
E_3	10.3 GPa
n_{12}	0.28
n_{13}	0.28
n_{23}	0.6
G_{12}	7.17 GPa
G_{23}	3.00 GPa
G_{13}	7.17 GPa

*subscript 1 is the direction parallel to the fibre
subscript 2 and 3 is the direction perpendicular to the fibres

The process of transferring data from FLUENT to Static Structural was done using Fluid-Structure system coupling. Using the pressure distribution generated from CFD analysis on the wing, static structural analysis was carried out to obtain the total deformation and Von Mises stress on the wing made of Aluminium material as shown in Figure 4 and Figure 5 respectively. Then similar coupled analysis was carried out with the Aluminium skin replaced by Graphite/Epoxy laminate and the resulting deformation and the Von-Mises stresses were compared with the Aluminium based wing.

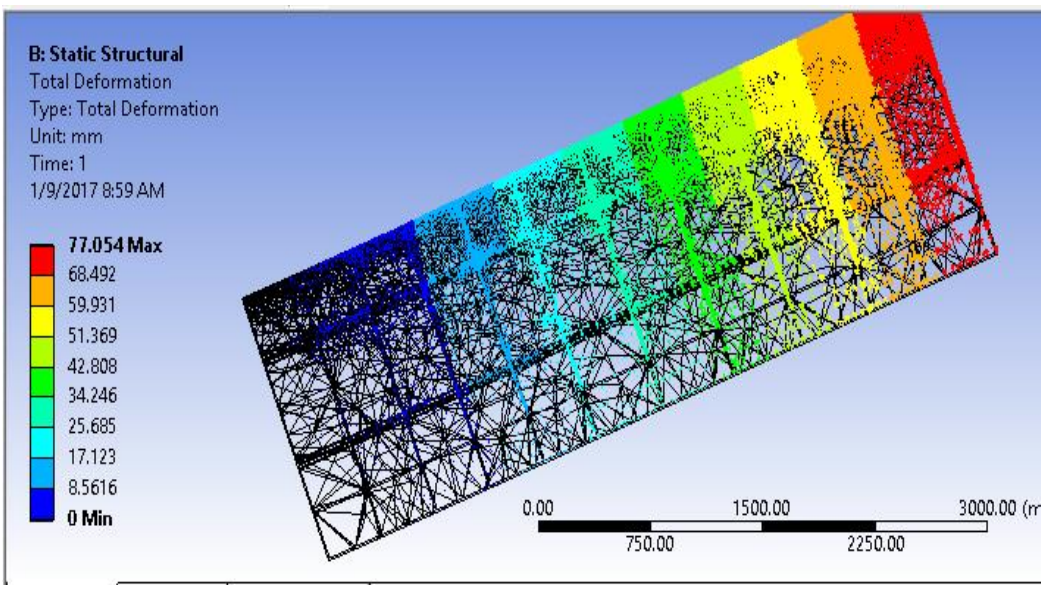

Fig. 4. Total deformation of the wing

To find the best stacking sequence that have the best combination of high specific strength and specific stiffness, optimization was done manually by varying fibre orientation of each lamina, both symmetric crossply and angle ply laminate with different layup scheme were tried to arrive at the best layup. Table 3 below summarizes results obtained for each set of stacking sequence for the aerodynamic load at an angle of attack of 10°.

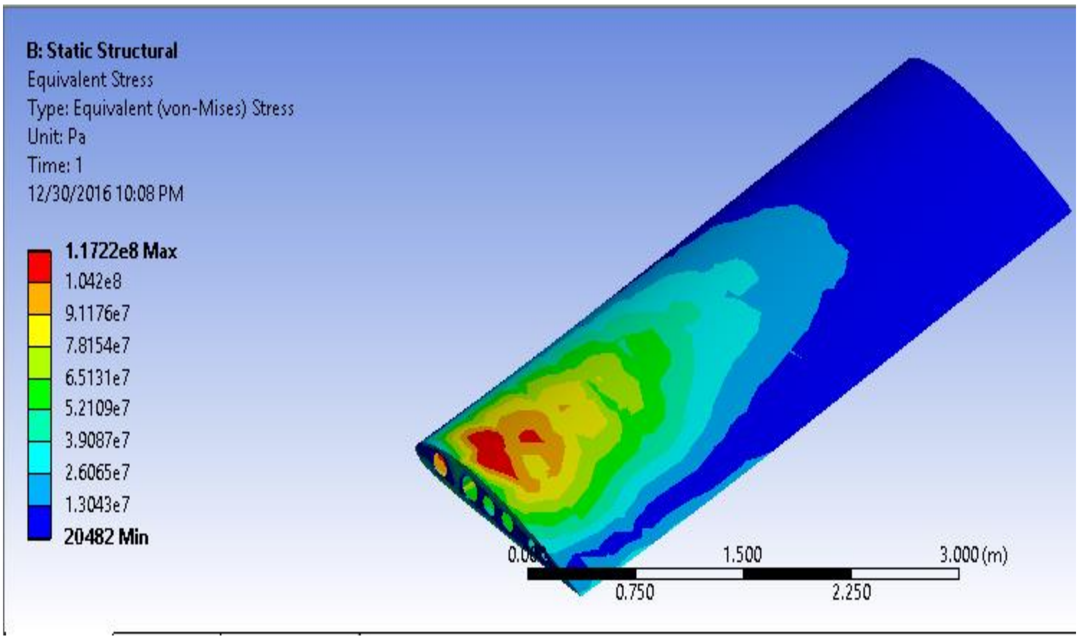

Fig. 5. Von Mises stresses on the wing

Table 3
Effect of Composite layups on static structural behaviour of wing

Stacking sequence	Total Deformation (mm)	Von Mises Stresses (MPa)	Mass (kg)
Aluminium	77.054	117.22	288.76
$[0/0/0/0/0]_S$	19.956	216.46	165.00
$[0/45/-45/45/90]_S$	31.361	175.93	165.00
$[45/-45/45/-45/45]_S$	21.682	125.72	165.00
$[0/90/0/90/0]_S$	11.422	120.39	165.00
$[0/30/-30/-30/30]_S$	17.762	196.22	165.00
$[45/-45/90/-45/-30]_S$	11.974	132.26	165.00
$[0/30/45/-45/-30]_S$	18.964	205.89	165.00
$[45/-30/-45/30/0]_S$	18.964	205.89	165.00
$[90/45/-45/30/-30]_S$	12.086	133.46	165.00
$[30/-30/45/0/90]_S$	12.950	141.22	165.00

It can be seen from the table that the wing skin made of Graphite/Epoxy material with symmetric crossply layup of $[0/90/0/90/0]_S$ has the best combination of least deformation and least Von Mises among others. From this analysis, we can also calculate the weight reduction caused by replacing Aluminium with Graphite/Epoxy on the wing skin and thus 42.86% of weight reduction was achieved using this composite layup. Thus, it can be concluded that this cross-ply layup is the best stacking sequence for the wing skin with highest strength to weight ratio and stiffness to weight ratio. Moreover next to this cross ply layup, the angle ply layup $[45/-45/90/-45/-30]_S$ has the best combination of least deformation and Von Mises stresses with same reduction in weight as cross-ply.

3.3 Safety Factor

To assess the safety of the new design of aircraft wing with composite material and to ensure the structural integrity of the composite wing, a safety factor (*SF*) can be defined as follows

$$SF = \sigma_{\mathrm{ULT}} / \sigma_{\mathrm{V}M} \quad (1)$$

where $\sigma_{\mathrm{V}M}$ is the Von Mises stresses reported in Table 3 and σ_{ULT} is the ultimate strength (as given in the Table 1 and Table 2) of the material for the wing. The stresses experienced by the composite wing must be less than the ultimate strength σ_{ULT} of the material for the wing to perform under the given flying conditions without compromising its structural integrity. Safety factor greater than one means the stresses in the structure are below the ultimate stress and hence the structure is safe. From the Table 3 it can be noted that the safety factor for the best crossply layup of $[0/90/0/90/0]_s$ made of Graphite/Epoxy is 12.46 whereas for the Aluminium, the safety factor is just 4.9, thus replacement of the Aluminium wing with the composite wing is advantageous both in terms of its strength as well as wieght.

Moreover as discussed earlier that at an angle of attack equal to 17˚ which is close to the stalling angle of attack of the selected NACA 4415 airfoil, the pressure difference is the highest and that leads to the maximum lift load attained at that speed. As expected, the deflection and stresses at this angle of attack will be very high and the corresponding Von Mises stresses and deflection for the wing with $[0/90/0/90/0]_s$ laminate made of Graphite/Epoxy is 190.41 MPa and 30.70 mm respectively, resulting in a safety factor of 7.88. Thus for the given geometry and material, even for the case of highest load, it can be noted that the stresses in the composite wing are still well below the ultimate stress and thus the composite wing perform efficiently without compromising its structural integrity.

4. Conclusions

Coupled field analysis in ANSYS have been used to find the stresses and deformation on a wing made of laminated composites. The coupled field analysis of CFD and Static Structural analysis has been used to get the accurate aerodynamic load on the wing and hence the accurate deformation and stresses. The comparison between isotropic Aluminium wing and laminated composite wing has been carried out to bring out the advantages of using composites. Fiber orientation and stacking sequence becomes the important variable in this analysis and it can be seen from the results that composite wing has better structural performance than isotropic wing. It can also be noted from the results, the skin made of Graphite/Epoxy, symmetric crossply layup of $[0/90/0/90/0]_s$ and angle ply layup $[45/-45/90/-45/-30]_s$ has the highest specific strength and specific stiffness. This work can be further extended by using the ANSYS Optimization tool optiSLang for multi-objective optimization.

Acknowledgement

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