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Bend twist coupling effect on the Performance of the Wing of an Unmanned Aerial Vehicle

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Abstract*: Composite materials have intrinsic coupling effects which pave way for the design engineer to stitch them to suit for a given application. In this paper, the wing of an unmanned aerial vehicle is designed using different materials and the performance is evaluated in terms of stiffness and weight. Wing consisting of ribs, spars and skin are modified for weight minimization without reducing the specific strength and stiffness. NACA 4412 profile is adopted for the wing, using which two models are created for the analysis. All parts of the wing are made of same material for isotropic material wing. When modelling composite wing, the ribs are assigned glass-epoxy and spars with carbon-epoxy UD. The stiffness of a composite wing is correlated to the intrinsic bend-twist coupling effects. The modelling of an UAV wing is carried using SOLIDWORKS and analysis is carried out using commercially available ANSYS WORKBENCH ACP software. In order to bring out the comparison, aluminium, balsa wood in the isotropic material category and carbon/epoxy, glass/epoxy in the composite materials category is used. The results have shown that composite materials can be effectively stitched for a wing to bring down the weight without compromising the performance.*

1. Introduction:

Unmanned aerial vehicles are aircrafts that do not require an on-board human crew in order to fly. UAVs can fly fully autonomously or they can be remotely controlled by a human pilot. This makes them a great candidate for missions involving a high degree of risk. In addition to this, their airborne endurance is not limited by the endurance of a pilot. It is known that the flow characteristics over an airfoil can dramatically change the value of lift and drag. In current fixed wings, these changes can be achieved with the use of the control surfaces, which aid in the control and stability of an aircraft [1]. The problem of designing efficient wing internal structure for a high speed civil transport, i.e., of determining the overall arrangement of spars and ribs, is to be considered. Once the arrangement and number of ribs and spars has been determined the design problem reduces to standard sizing structural optimization. However, determining the number of spars and ribs and the overall concept of their arrangement is a topology optimization problem [2]. Structural design and analysis of a composite wing with high aspect ratio is analyzed and the deformation with different heights of the winglet is presented [3]. In aeronautics, the wing of an UAV plays an important role in the generation of lift force and drag force [4], and many researchers have paid attention to its parametric design and optimization [5][6]. If the stiffness of an UAV wing is insufficient during the flight time, the wing will be over-deformed or even destroyed. At the same time, the unstable elastic effect is very dangerous [7], such as divergence, flutter and insufficient torsional rigidity, and they have always been prominent factors in reducing flight performance and stability, especially for wings with large aspect ratio. Eskandary et al. [8] studied the behaviour in terms of the aero-elastic properties of a cantilever wing with double bending and torsional vibrations and with large deflection ability in quasi-steady aerodynamics flows, and the influences of mass ratios and stiffness ratios were both taken into consideration. Duan and Zhang [9] developed a new approach to analyze the aeroelastic stability of a high-aspect-ratio wing based on the transfer function, and it is insentitive to mesh densityand does not require structural modal analysis for aeroelastic stability. Gunasekaran and Mukherjee [10] implemented a novel decambering technique to investigate the influence of wing twist on the induced drag of individual lifting surfaces by means of a vortex lattice approach. With the increase of the length of wings, the shear force and bending moment caused by the aerodynamic force will increase from the tip to the root. As a result, the tip of the wing will have a larger warpage deformation, and the wing will be fatigued and broken easily. A nonlinear method based on the computational fluid dynamic and computational structure dynamics (CFD/CSD) coupled approach was employed to analyze the nonlinear static aeroelastic and flutter characteristics of a composite wing with high aspect ratio, and the vertical and spanwise displacements and torsion angle of wing cross-sections are less than the linear result under the same fligh attitude [11].

The wing of UAV is a typical wing with large aspect ratio. Due to its long wingspan, the structural design problems of this wing are more significant. However, the strength of the wing cannot increase without limit, and excessive strength will lead to excessive conservative margin. This will not only increase the weight of the structure, but also decrease the performance of the aircraft. At the same time, this also explains the reason why the rigid is easy to bend. Only by combining rigidity with flexibility can we find the perfect midpoint between stiffness and structural performance. Therefore, a large number of composite materials are utilized in the wing with high aspect ratio in this paper. The application of composite materials with light weight and high strength can not only reduce the weight of the structure, but also make use of the elasticity of composite materials to realize the complex bending and torsion deformation of the wing, so as to meet the requirements of composite stiffness and strength of the structure [12]. Composite materials are very promising materials as they posses intrinsic coupling effects. These effects are utilized for enhancing the performance of different structures such as marine propellers [14-16].

2. Methodology

For the generation of an UAV wing model, the data required for the profile of the wing is taken from the NACA tools. The information available in the form of coordinates is imported to the solid works and the profile is created. The additional features are incorporated into the model to account for ribs, spars and skin as shown in **Fig 1**. The parts thus generated are assembled keeping due connectivity of parts in mind. The whole model of the wing is imported into the Ansys workbench 19.2 as a step file for further analysis. The material properties required for the analysis is imported from the engineering data sources in material library of Ansys Workbench 19.2. The material properties of balsawood, aluminium2024T3, e-glass/epoxy and carbon-epoxy are assigned to the various parts of the wing. the imported geometry is edited in space claim design modular so that only surfaces are activated for physics to build the layer wise composite structure, other parts needed to be suppressed and saved as a space claim document file which can be used for further discretization separately in mechanical modular. Meshing is performed on the skin faces with a fine element size based on the requirement; the meshed file is transferred to ACP Pre module, where the composite skin is generated in ply wise sequence with different orientations. for that number of plies are created by defining the fiber material and thickness of each layer, stack up is built for multi fibers, by defining the rosettes a set of orientation set for layup is prepared, modeling group is created which fully defines the composite structure in terms of number of plies. The space claim document is transferred to mechanical modular where the skin part is suppressed for physics and internal structure consisting of ribs and spars are activated for physics, the discretization of ribs and spars is made using a fine element size of not more than 5mm.

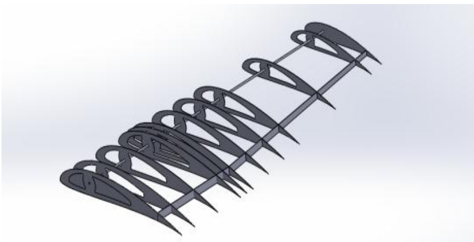

Fig 1. Internal structure of halfwing

2.1. Half wing model

The design of main structural parts such as spars, ribs and skin depend on the selected design parameters. The starting point for the design of a wing box structure is selection of the number of spars. The spars are the main load carrying member of the wing structure. They generally undergo torsional and bending stresses due to aerodynamic loading they are subjected to during the flight. This wing should be consisting of a spar located at 60 % of the chord to support the smart control surfaces which has a chordwise length of 0.4 times the length of the chord. Although, the wing of subject was comparably small only one spar cannot sustain the continuity of the wing, and hence there should be another spar in the wing box structure. The historical design data indicates that for a two-spar wing the front (or main) spar should be located in between 12 % and 17 % of the chord if the rear (or secondary) spar is located at 55 % to 60 % of the chord . The main reason behind this is to make the neutral axis and the shear centers coincide to improve the aero-elastic characteristics of the wing. This combination of spars holds true for the closed cross-section wings. Hence, the dimensions and locations of the spars are selected as shown in **Table1**.

Table 1. Dimensions and chord wise locations of the Spars

S. No	**Parameters**	**Dimensions**
1	Root chord	1000mm
2	Tip chord	760mm
5	Airfoil (Root)	MH114
6	Airfoil (Tip)	MH114
7	Front spar	10mm
8	Rear spar	6x2mm
9	Chord length (c)	1000mm
10	Span length (b)	1800mm
11	Thickness to Chord Ratio, t/c	0.13
12	Planform area S	1.75 m^2
13	Main Spar	25%, Chordwise Location w.r.t. Leading Edge
14	Secondary Spar	60-70%, Chordwise Location w.r.t. Leading Edge

Table 2. The Spanwise Distances of the Rib Segments from the tip Section of the Wing and distance between the ribs

Rib segmental number	Distance between the ribs(mm)	Distance from tip rib (mm)	Thickness of rib (mm)
1	0	0	2
2	100	100	2
3	350	450	2
4	350	800	2
5	150	950	2
6	150	1100	2
7	150	1250	2
8	50	1300	2
9	50	1350	2
10	175	1525	2
11	175	1700	2
12	98	1800	2

The materials for the various parts of the wing are as shown in **Table 3.**

Table 3. Materials for different components

S.No	Part	Material
1	Upper skin	Glass epoxy, 1 mm thick
2	Lower skin	Glass epoxy, 1mm thick
3	Ribs	Glass epoxy, 2mm thick
4	Front spar	Carbon epoxy, 10mm diameter
5	Rear spar	Glass epoxy, 2mm thick

The material properties used in the paper is as shown in Table 4 [13].

Table 4. Material properties used for a wing model

Material	E1(Gpa)	E2(GPa)	V12	G12(GPa)
E-glass	74	74	0.22	30
Carbon	230	230	0.2	10
E-glass/epoxy	38.73	6.59	0.29	2.4
Carbon/epoxy	114.14	6.71	0.28	2.2
Balsa wood	0.9	0.9	0.31	0.3435
Al2024T3	73.1	73.1	0.33	26.6

2.1.1. Modeling groups in ACP for Half wing

2.1.1.1. Skin

Each modeling group consists of four plies of E-glass epoxy UD in different fiber orientations. The composite is built up in layer wise sequence and the thickness of each layer is 0.25mm. Modelling group stacking sequence is [0/45/45/0].

2.1.1.2. Ribs

The thickness of each rib is 2mm and homogeneous E-glass epoxy is used to build the model in mechanical modular, the thickness is assigned to each rib made of 2-D shell element.

2.1.1.3. Spars

The spars are made of 1-D beam elements the diameter of front tubular spar is 8mm over which a thin tube of thickness 2mm made of carbon epoxy is placed to stiffen and to increase the strength properties of spar.

2.1.2. Boundary conditions

Boundary conditions as applied to the half wing model are as shown in Fig 3 and Fig 4.

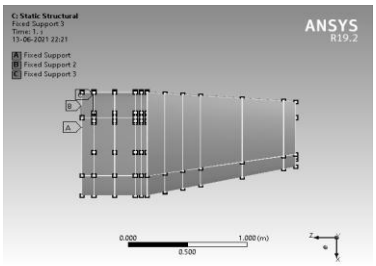

Fig 3. Constrains on the halfwing

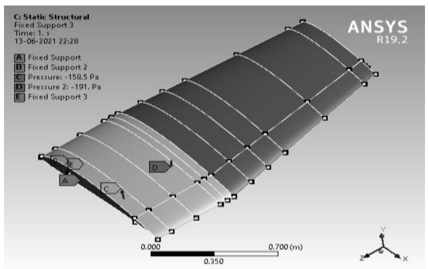

Fig 4. Pressure loads on the halfwing

2.2. Full wing model

2.2.1. Modelling groups in ACP for Full wing

2.2.1.1. Skin

Each modelling group consist of eight plies of composite in different fiber direction orientations. The composite is built up in layer wise sequence and the thickness of each layer is 0.125mm. The stacking sequence adopted for the skin structure is [0/45/45/0]s and [0/30/60/90]s.

2.2.1.2. Ribs

The thickness of each rib is 5mm and homogeneous E-glass epoxy is used to build the model in mechanical modular, the thickness is assigned to each rib made of 2-D shell element.

2.2.1.3. Spars

The spars are made of 1-D beam elements of C-Section and I-Section configuration. The length of spars along the span is 1940mm and height is 6mm (C-section), 8mm (I-section) and thickness is 2mm.

2.2.2. Boundary conditions

Boundary conditions as applied to the half wing model are as shown in fig 5 and fig 6.

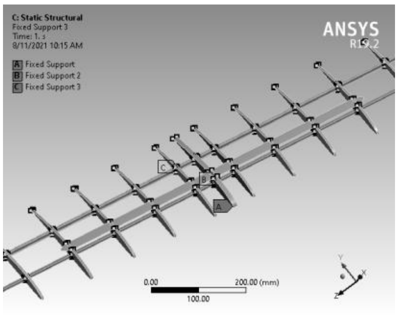

Fig 5. Constrains on the fullwing

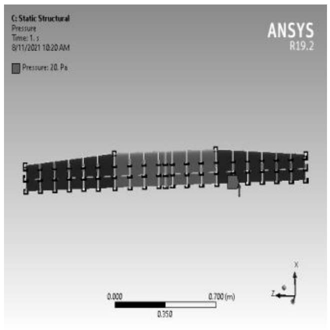

Fig 6. Pressure loads on the fullwing

3. Results and discussion

For validating the methodology adopted in the paper, comparison is made with [ ] available in the literature for the half wing model and the same is as presented in Table [5].

Table 5. Validation of results with literature.

Parameter	Simulation values	Reference values[ ]	location
Total deformation	6.52mm	8.6mm	Wing tip
Max equivalent stress	14.14Mpa	11.9MPa	Ribs

Having validated the halfwing model with the literature, fullwing model is analyzed on similar lines. The results of which are as presented below.

3.1. Deformation patterns on fullwing

The analysis is carried out on a glass epoxy and carbon epoxy material with the two stacking sequences. This is done to see the effect of bend-twist coupling on the deformation performance of a composite wing. Two pressures are applied to the wing at 20Pa and 135Pa. The results of the same are shown in Fig.7 to Fig.18.

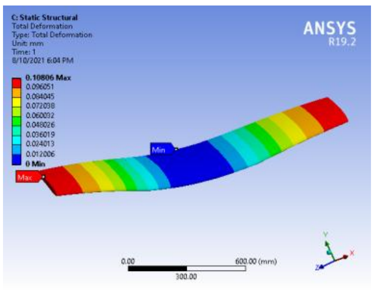

Fig.7. Maximum deformation of 0.108mm at 20Pa, in (0/30/45/60)s Glass/epoxy wing

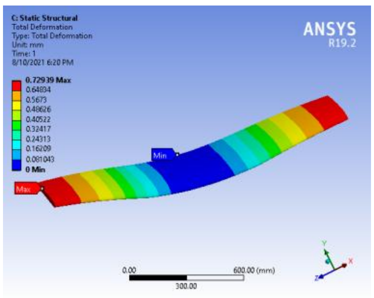

Fig.8. Maximum deformation of 0.73mm at 135Pa, in (0/30/45/60)s Glass/epoxy wing

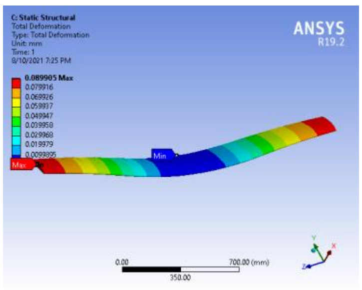

Fig.9. Maximum deformation of 0.09mm at 20Pa, in (0/30/60/90)s Glass/epoxy wing

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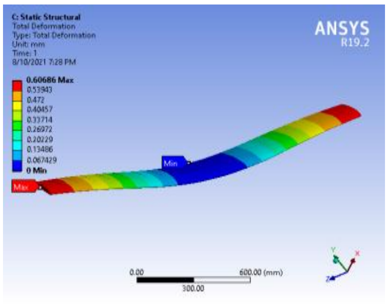

Fig.10. Maximum deformation of 0.6mm at 135Pa, in (0/30/60/90)s Glass/epoxy wing

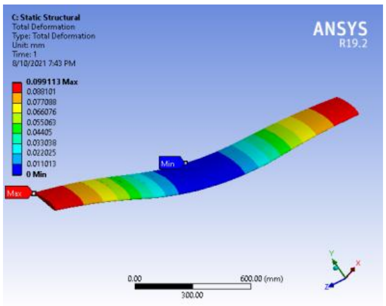

Fig.11. Maximum deformation of 0.1mm at 20Pa, in (0/30/45/60)s Carbon/epoxy wing

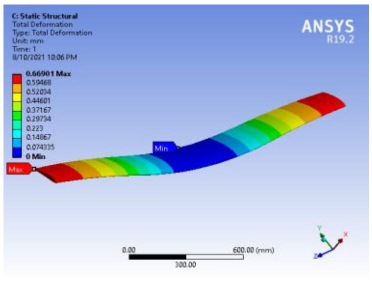

Fig.12. Maximum deformation of 0.66mm at 135Pa, in (0/30/45/60)s Carbon/epoxy wing

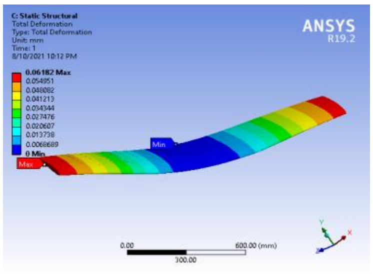

Fig.13. Maximum deformation of 0.061mm at 20Pa, in (0/30/60/90)s Carbon/epoxy wing

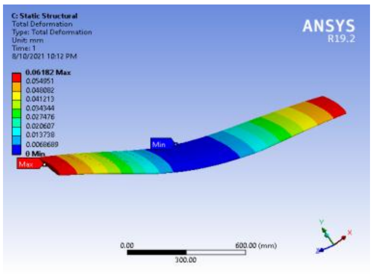

Fig.14. Maximum deformation of 0.417mm at 135Pa, in (0/30/60/90)s Carbon/epoxy wing

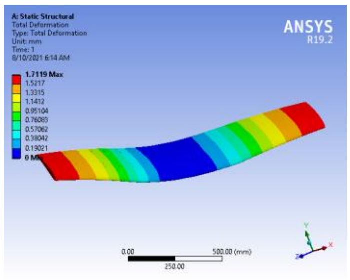

Fig.15. Maximum deformation of 1.71mm at 20Pa, in Balsa wing

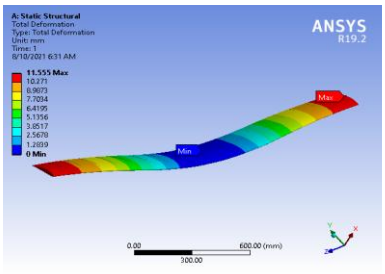

Fig.16. Maximum deformation of 11.55mm at 135Pa, in Balsa wing

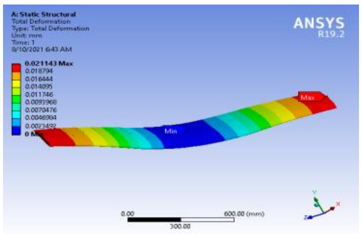

Fig.17. Maximum deformation of 0.021mm at 20Pa, in Aluminium2024T3 wing

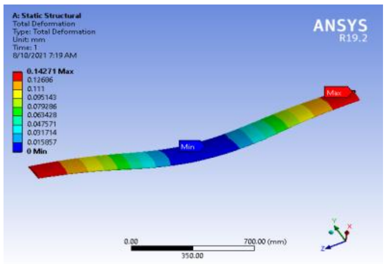

Fig.18. Maximum deformation of 0.142mm at 135Pa, in Aluminium2024T3 wing

The layup sequence adopted for the fullwing skin is symmetric which results in coupling matrix B=0. The bend-twist coupling coefficients D_{16} and D_{26} are as are as presented in Table [6].

Table 6. Bend-twist coupling coefficients with stacking sequences.

Sequence & materials	Applied Pressure load[Pa]	Maximum deformation(mm)	D_{16} [(GPa-mm^3)]	D_{26} [(GPa-mm^3)]	Weight (gm)
Glass-epoxy (0/30/45/60)s	20	0.108mm	0.34060	0.17568	3056.03
Glass-epoxy	135	0.73mm	0.34060	0.17568	3056.03

(0/30/45/60)s					
Carbon-epoxy (0/30/45/60)s	20	0.1mm	0.11306	0.57831	2276.74
Carbon-epoxy (0/30/45/60)s	135	0.66mm	0.11306	0.57831	2276.74
Glass-epoxy (0/30/60/90)s	20	0.09mm	0.29397	0.18402	3056.03
Glass-epoxy (0/30/60/90)s	135	0.6mm	0.29397	0.18402	3056.03
Carbon-epoxy (0/30/60/90)s	20	0.061mm	0.97516	0.60698	2276.74
Carbon-epoxy (0/30/60/90)s	135	0.417mm	0.97516	0.60698	2276.74
Balsa wood	20	1.71mm	0	0	343.80
Balsa wood	135	11.55mm	0	0	343.80
Aluminium 2024T3	20	0.021mm	0	0	4232.60
Aluminium 2024T3	135	0.142mm	0	0	4232.60

From Table 6 it is evidenced that the stacking sequence of the composite materials plays a vital role in the deformation patterns of a wing. The composite materials can be stitched according to the needs of the application as they have shape adoptable nature inherently. Based on the above study, the following conclusions are derived.

4. Conclusions

In this paper, the fullwing of an unmanned aerial vehicle is analyzed at two operating conditions, i.e., at 20Pa and 135 Pa representing the range of operation of UAV. The bend-twist coupling coefficients have considerable effect on the deformation pattern produced in UAV which will affect the performance of the same.. The various parameters and their effect on the deformation pattern of UAV full wing made of balsawood, Aluminium2024T3, glass-epoxy and carbon-epoxy are studied.

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