

Computational Fluid Dynamics and Vibration Analysis of Hybrid Composite Aircraft Wing

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Abstract

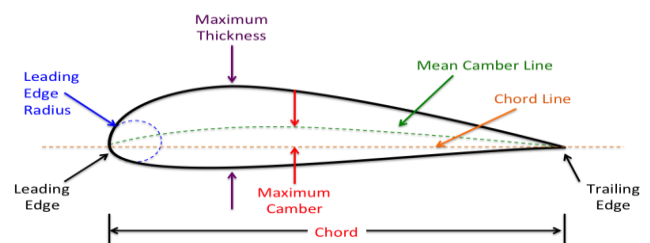
The current trend in aircraft design is to increase the proportion of fiber composites in the structures. Since many primary parts also are constructed using metals, the number of metal-composite structures is increasing. Such structures have traditionally often been avoided as an option because of the lack of methodology to handle the mismatch between the material properties. From the design point of view, it is a challenge to construct a weight optimal hybrid structure with the right material in the right place. With a growing number of hybrid structures, these problems need to be addressed. The purpose of the current research is to assess the strength, durability and thermo mechanical behavior of a hybrid composite aluminum wing structure by testing and analysis. The work performed in this paper focuses on the analysis part of the research and is divided into two parts. In the first part, the theoretical framework and the background are outlined. Significant material properties, aircraft specification aspects and the modeling framework are discussed. In the second part the profile is modeled in detail using the software. Further analysis was done using finite element analysis software and the results are incorporated.

Keywords: Fibre composites structures; metal-composite structures; Carbon Fibre and Aramid Fibre; aluminium - carbon fibre; Aluminium - aramid fibre; Vibration analysis; CFD analysis;

1.Introduction

The aerospace market is one of the largest and arguably the most important to the composites industry. Commercial aircraft, military craft, helicopters, business

jets, general aviation aircraft and space craft all make substantial use of composites, both inside and outside. Aluminium alloys have, for a long time, been the primary materials used in aircraft structural design. Compared to most other metals, aluminium alloys have a high strength-to-weight ratio, which is essential for the aircraft performance and load-carrying capability. Aluminium alloys are, however, susceptible to fatigue and this poses a problem considering that aircraft structures usually are exposed to a large number of cyclic load repetitions during their operational life. Structural parts that are made of both metal and composite materials and that include such interfaces are referred to as hybrid structures. Such mixed solutions have traditionally often been avoided as an alternative, because of the lack of a proper methodology to handle the mismatch of the material properties. But with a growing number of hybrid structures, this problem needs to be addressed. From a design point of view it is a challenge to construct a weight optimal hybrid structure, where the right material is put into the right place. The wing is a framework made up of spars and ribs and covered with metal. Wing structures carry some of the heavier loads found in the aircraft structure. The particular design of a wing depends on many factors, such as the size, weight, speed, rate of climb, and use of the aircraft. Wing is mainly used as a lift producing component in an aircraft.



2. Literature Survey

Mohamed Hamdan et al., [1] were designed and analyzed the ribs and spars of a 150 seated regional aircraft for the stresses and displacements due to the applied loads. The optimum design parameters are suitably selected and then the model was designed. The major wing design parameters were explained in detail and the wing configuration has been described. Different types of loads acting on the aircraft and the wing are determined and the moments, displacements, etc., are also determined. Bret K. Stanford et al., [2] have studied several topology optimization problems conducted within the ribs and spars of a wing box. It is desired to locate the best position of lightening holes, truss/cross-bracing, etc. A variety of aero elastic metrics are isolated for each of these problems: elastic wing compliance under trim loads and taxi loads, stress distribution, and crushing loads. Aileron effectiveness under a constant roll rate is considered as are dynamic metrics natural vibration frequency and flutter.

W.J. Goodey [3] in his articles on the subject of Two-Spar Wing Stress Analysis, has assumed that flexibility of the ribs has no appreciable effect on the distribution of stress in the wing. Using the method of minimum strain energy, this assumption is equivalent to neglecting the strain energy stored in the ribs. Other writers have, in effect, made this same assumption by neglecting change of shape of cross-sections under load. Pritish Chitte et al., [4] studied about preliminary sizing and analysis of a wing box. The main objective is to fix an appropriate structure within the given envelope. Sizing is done by using classical engineering theories and FEA. Skin and web are considered as shell elements.

Flange, spar and stringer are considered as beam elements. The analysis is carried out with iterations such as, with different sections like Rectangular sections, Z-sections and L-sections, Panel breakings and varying skin thicknesses. From the analysis structure has been optimally designed which satisfies the strength and stability criteria, which still has a scope for optimization by redesigning components like Ribs and Spars.

P. Murugesan and P. Thirumurugan [5] have mentioned most important aspects in the aircraft design are safety and weight of the structure. Wing is one of the major components of the aircraft. Wing creates the lift required for flight. Spars, ribs and skins are the major structural elements of the wing. Spars are the structural members which run through the wing root at the fuselage to the wing tip. Spars carry the major wing bending loads. Ribs are the structural members which are oriented in the chord wise direction. Ribs carry the shear and compression loads on the wing. Ribs also help the wing to maintain its aerodynamic shape under loaded condition. Current study includes a composite wing configuration consisting of five ribs and two spars. The aerodynamic distributed load on the wing creates shear force, bending moment and torsion moment at wing stations. Static load carrying capability of the wing spar is carried out through a linear static stress analysis. The top skin of the wing box will experience the axial compression during wing bending. The top skin panels between the spar and ribs will be considered for the buckling analysis. These panels will be evaluated for their buckling critical loads through analytical approach.

A. Ramesh Kumar et al., [6] explained Wing structure consists of skin, ribs and spar sections. The spar carries flight loads and the weight of the wings while on the ground. Other structural and forming members such as ribs are attached to the spars, with stressed skin. The wings are the most important lift-producing part of the aircraft. The design of wings may vary according to the type of aircraft and its purpose. Experimental testing of wing structure is more expensive and time consuming process. Then stress analysis of the wing structure is carried out to compute the stresses at wing structure. The stresses are estimated to find out the safety factor of the structure. In a structure like airframe, a fatigue crack may appear at the location of high tensile stress. Life prediction requires a model for fatigue damage accumulation, constant amplitude S-N (stress life) data for various stress ratios and local stress history at the stress concentration. The response of the wing structure will be evaluated. In this study prediction of fatigue life

for crack initiation will be carried out at maximum stress location.

Vikas kumar et. al., [7] stated for designing of wing box it should be noted that the structure should be strong enough to withstand the load forces and exceptional circumstances in which aircraft has to be operate. Wing is essentially a beam which transmits and gathers all the applied loads to the fuselage. Spar, ribs, stringers and skin are the major essential part of the wing. The primary function of wing is to generate a lift. Wing requires longitudinal member to withstand the bending moments which are greatest during flight and landing of aircrafts. Ribs are structural members which maintain the aerodynamic shape of the wing. In this paper we study a wing box; this wing box is subjected to flight loads. Load distribution on wing is also carried out in this paper.

Cindie Giummarra et. al., [8] discussed two aluminium-lithium alloys for aerospace applications, including the relationship between their alloying elements and thermal-mechanical processing, to the alloy's properties. The paper also includes selected properties of these alloys in sheet, plate and extrusion forms. Finally, a trade study conducted between Alcoa and Bombardier using these alloys is discussed which highlights the weight and performance benefits to an aircraft when alloys with optimized properties are selected for specific aircraft applications. William E. Frazier et al [9] studied the design requirements of the next generation of advanced aerospace vehicles and propulsion systems necessitate the development of structural materials with properties vastly superior to those which are currently achievable. Recognizing that each class of materials possesses its own unique set of advantages and disadvantages, the designers of tomorrow's aircraft must choose wisely from the plethora of available alloys. Hashiguchi et al [10] were explained a family of low density - high elastic modulus aluminium-beryllium alloys is under development in order to meet the requirements of advanced aerospace designs. These alloys are aluminium based with 10%-75% beryllium and combine the high specific stiffness of beryllium with the ductility and ease

of fabrication of aluminium. Densities ranging from 2.0 to 2.58 g/cc with excellent strength and ductility have been achieved. The family of AlBeMet alloys under development was manufactured by both powder and ingot metallurgy techniques. Property characterization of extruded bar and rolled sheet included tensile, fatigue and fracture mechanics evaluation. The dependence of microstructure and properties upon composition and fabrication method, as well as upon third element additions is required.

Zlatan Kapid [11] mentioned composite and metal properties differ with respect to thermal expansion, failure mechanisms, plasticity, sensitivity to load type, fatigue accumulation and scatter, impact resistance and residual strength, anisotropy, environmental sensitivity, density etc. Based on these differences, the materials are subject to different design and certification requirements.

The issues that arise in certification of hybrid structures are: thermally induced loads, multiplicity of failure modes, damage tolerance, buckling and permanent deformations, material property scatter, significant load states etc. The purpose of the current research is to assess the strength, durability and thermo mechanical behavior of a hybrid composite-aluminum wing structure by testing and analysis. The influence of the hybrid structure constitution and requirement profiles on the mass, strength, fatigue durability, stability and thermo-mechanical behavior is considered. Based on the conceptual studies, a hybrid concept to be used in the subsequent structural testing is chosen. The second paper focuses on the virtual testing of the wing structure. In particular, the local behavior of hybrid fastener joints is modeled in detail using the finite element method, and the result is then incorporated into a global model using line elements. Damage accumulation and failure behavior of the composite material are given special attention. Computations of progressive fastener failure in the experimental setup are performed. The analysis results indicate the critical features of the hybrid wing structure from static, fatigue, damage tolerance and thermo-mechanical points of view.

P. K Mallick [12] stated the fundamental understanding of fiber reinforcement has not changed, but much new advancement has taken place in the materials area, especially after the discovery of carbon nanotubes. There has also been increasing applications of composite materials, which started mainly in the aerospace industry, but now can be seen in many non aerospace industries, including consumer goods, automotive, power transmission, and biomedical. It is now becoming a part of the “regular” materials vocabulary. Deborah D.L Chung [13] mentioned carbon fiber composites, particularly those with polymeric matrices, have become the dominant advanced composite materials for aerospace, automobile, sporting goods, and other applications due to their high strength, high modulus, low density, and reasonable cost. For applications requiring high temperature resistance, as required by spacecraft, carbon fiber carbon-matrix composites have become dominant. As the price of carbon fibers decreases, their applications have even broadened to the construction industry, which uses carbon fibers to reinforce concrete. An objective of this book is to provide up-to-date information on the whole spectrum of carbon fiber composites, including polymer-matrix, metal-matrix, carbon-matrix, ceramic-matrix, and hybrid composites. Such information pertains to the processing, properties, and applications, and is given in a tutorial fashion, so that no prior knowledge of the field is required. At the end of each chapter, a large number of up-to-date references are included, so the reader can look up further information, if desired. Thus, the book is focused on composites with a variety of matrices but carbon fibers alone as the filler. This focus allows detailed consideration of the fiber-matrix interface and the composite processing for a variety of matrices.

Martin Alberto Masuelli [14] has given brief review of FRP has summarized the very broad range of unusual functionalities that these products bring (Polymers, Aramids, Composites, Carbon FRP, and Glass-FRP). While the chemistry plays an important role in defining the scope of applications for which these materials are suited, it is equally important that the final parts are designed to maximize the value of the inherent

properties of these materials. Clearly exemplify the constant trade-off between functionality and process ability that is an ongoing challenge with these advanced materials. The functionality that allows these materials to perform under extreme conditions has to be balanced against process ability that allows them to be economically shaped into useful forms. The ability of a polymer material to deform is determined by the mobility of its molecules, characterized by specific molecular motions and relaxation mechanisms, which are accelerated by temperature and stress. Since these relaxation mechanisms are material specific and depend on the molecular structure, they are used here to establish the desired link with the intrinsic deformation behavior.

Maria Mrazova [15] said since Orville and Wilbur Wright first decided to power their Flyer with a purpose built, cast aluminum engine to meet the specific requirements for power to weight ratio, new materials have been necessary to improve and advance aviation. This improvement in material properties has helped us to travel quickly and inexpensively around the world, by improving the performance and operations of modern aircraft. In the first part of this study the author introduces the composites materials with their advantages and disadvantages. Airbus and its innovation in composite materials are introduced in the second part of the thesis. Composite technology continues to advance, and the advent of new types such as nano tube forms is certain to accelerate and extend composite usage. This issue is introduced in the last part of this thesis. A continuing trend in material development is the improvement in processing and production of incumbent materials to either improve physical properties or to allow their application in new areas and roles for further usage in the future.

Nikhil V Nayak [16] stated Fiber- reinforced polymer composite materials are fast gaining ground as preferred materials for construction of aircrafts and spacecrafts. In particular, their use as primary structural materials in recent years in several technology demonstrator front-line aerospace projects world-wide has provided

confidence leading to their acceptance as prime materials for aerospace vehicles. Although several applications in the aerospace vector are mentioned, the emphasis of the review is on applications of composites as structural materials where they have seen a significant growth in usage. A brief review of composites usage in aerospace sector is first given. The nature of composite materials behavior and special problems in designing and working with them are then highlighted. The issues discussed relate to the impact damage and damage tolerance in general, environmental degradation and long-term durability.

Fiber Materials

Fibres are the principal constituents in a fibre-reinforced composite material. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Proper selection of the fibre type, fibre volume fraction, fibre length, and fibre orientation is very important. To present the potential of carbon fibre reinforced polymer composites, some important properties of a few metallic materials have been compared. The lowest density of carbon fibre reinforced epoxy composite is 1.55 kg/m³ when compared with 7.87 kg/m³ and 2.7 kg/m³ for SAE 1010 and 6061-T6 Al alloy respectively. Modulus is also competitive with 137.8GPa for composite against 207GPa and 68.9GPa for SAE 1010 and 6061-T6 Al alloy respectively. Further, in the case of tensile strength carbon fibre epoxy composites possess 1550MPa against 365GPa for SAE 1010 and against 310GPa for 6061-T6 Al alloy. Aramid fibres are used mainly in applications where they offer a unique combination of properties, such as high specific strength combined with toughness and creep resistance. The outstanding toughness of paramids is often the reason they are used over cheaper, stiffer or even stronger fibres. Unlike glass and carbon composites, aramid composites loaded in compression, flexure or shear fail in a non-brittle manner, with significant work being required to fail the composite. Their fatigue resistance is also excellent. Aramid fibres are used in numerous applications. Many of these are not as structural composites.

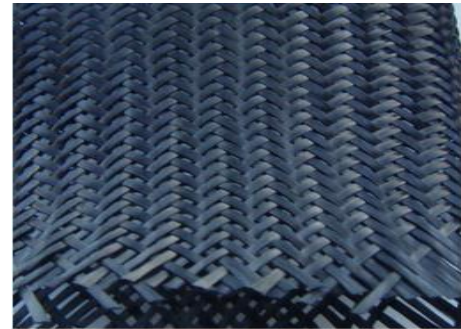
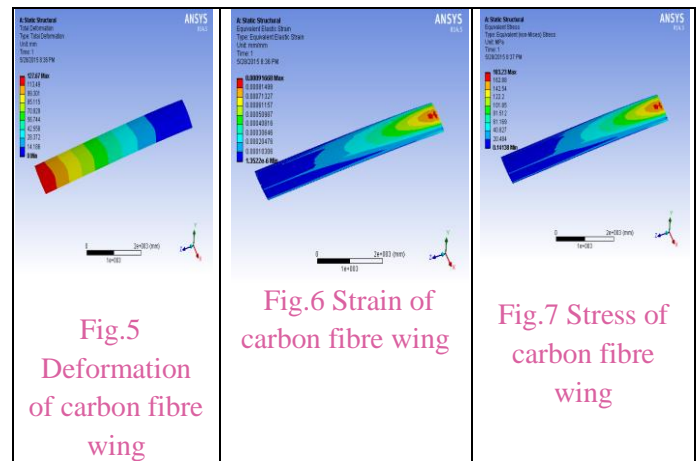


Fig. 1.1 Aramid fibre.

Aramid is short for “aromatic-polyamide”. Aramids are a class of polymers, where self-repeating units contain large phenyl rings, linked together by amide groups. As per US based FTC, aramid fibres are manufactured fibres where “the fibre-forming substance is a long-chain synthetic polyamide in which at least 85% of the amide linkages, (CO-NH) are attached directly to two aromatic rings”.

3. Modeling and Analysis of Composite Wing

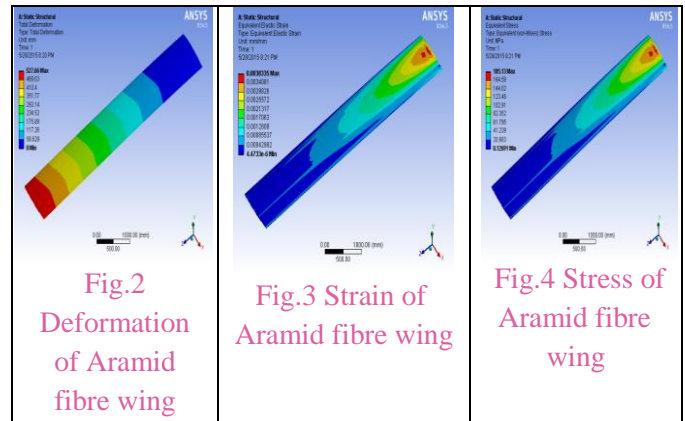
Considering the two fibre materials wings, carbon and aramid which are been used for the study are now being analysed. The structural analysis is being done for both the fibres where the deformation, stress and strain values are calculated and the results are tabulated and compared with the help of graphs. Vibration analysis is done for the wings and the modal values at different frequencies are tabulated and the respective results are compared



with the help of the graphs. CFD analysis is done at different angles of the wing and values of pressure, velocity, lift and drag are calculated and tabulated.

B. Deformation, Strain and Stresses of Aramid fibre wing

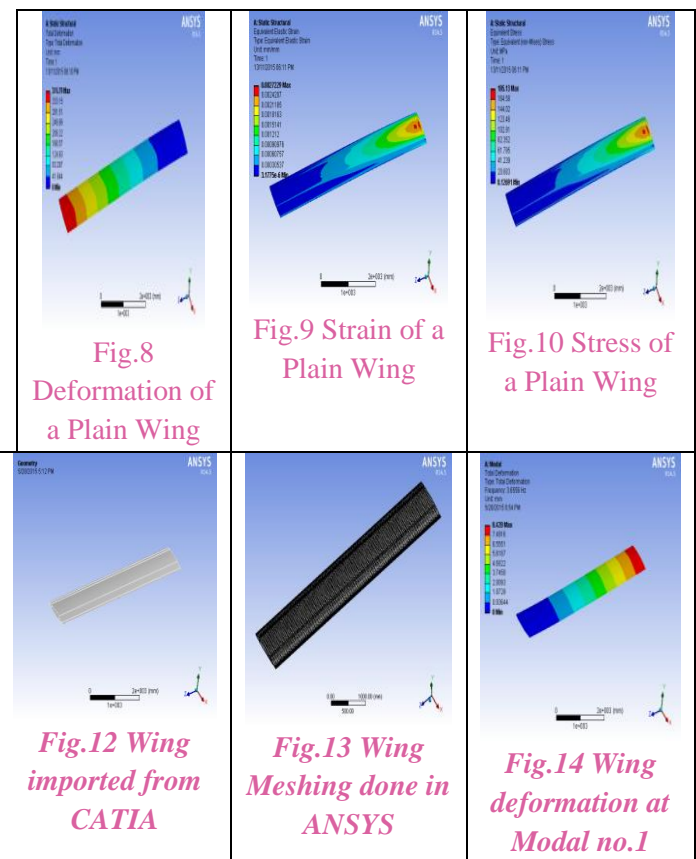
From the contour plot (Fig.2), wing minimum deformation at one end is 0mm and a uniform gradual increase is noticed to 527.66mm at other end. According to the contour plot (Fig.3), the minimum change of the length at bottom end of wing is $4.4733e-6$ while the maximum change of the length on top of the surface is 0.0038335. Based upon the contour plot (Fig.4), the minimum stress at the bottom end of wing is 0.12691N/mm² and the maximum stress on top of the surface is 185.13N/mm².



C. Structural Analysis of Carbon Fibre Wing

- Density : 1.75 g/cc
- Young's modulus : 85 GPa
- Poisson's ratio : 0.20

The contour plot (Fig.5) specifies that the wing minimum deformation initially is 0mm and is increased periodically to 127.67mm at other end. According to the contour plot (Fig.6), the minimum change of the length at bottom end of wing is $1.3522e-6$ while the maximum change of the length on top of the surface is 0.0009168. From the contour plot (Fig.7), the minimum stress at the bottom end of wing is 0.14138N/mm² and the maximum stress on top of the surface is 183.23 N/mm².



Based on the contour plot (Fig.8), wing minimum deformation at one end is 0mm and gradually increased to 374.79mm at other end. According to the contour plot (Fig.9), the minimum change of the length at bottom end of wing is $3.1775e-6$ mm while the maximum change of the length on top of the surface is 0.0027229mm. According to the contour plot (Fig.10), the minimum stress at the bottom end of wing is 0.12691N/mm² and the maximum stress on top of the surface is 185.13 N/mm².

Structural analysis of the three different wings i.e. plain or regular wing, carbon fibre wing and aramid fibre wing are calculated in ANSYS and the deformation, strain and stress values are being tabulated and represented graphically.

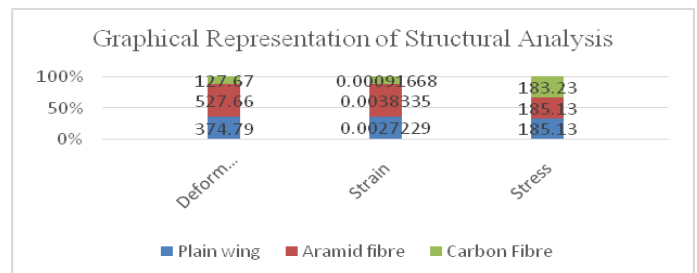


Fig.11 Graphical Representation of Structural Analysis for different wings

D. Vibration Analysis of Aramid fibre Wing

Density : 1.52 g/cc
 Young's modulus : 4.83Mpa
 Poisson's ratio : 0.36

E. Modal values of Aramid Fibre Wing

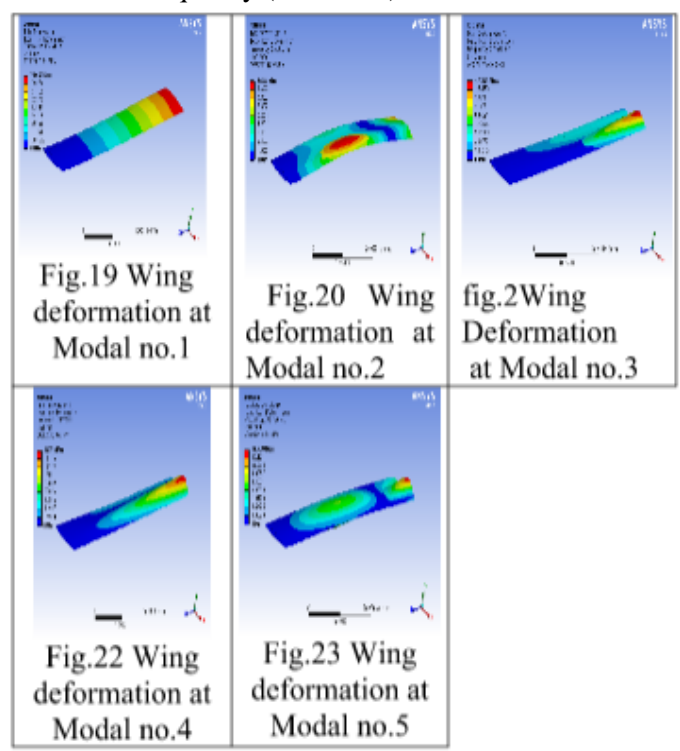
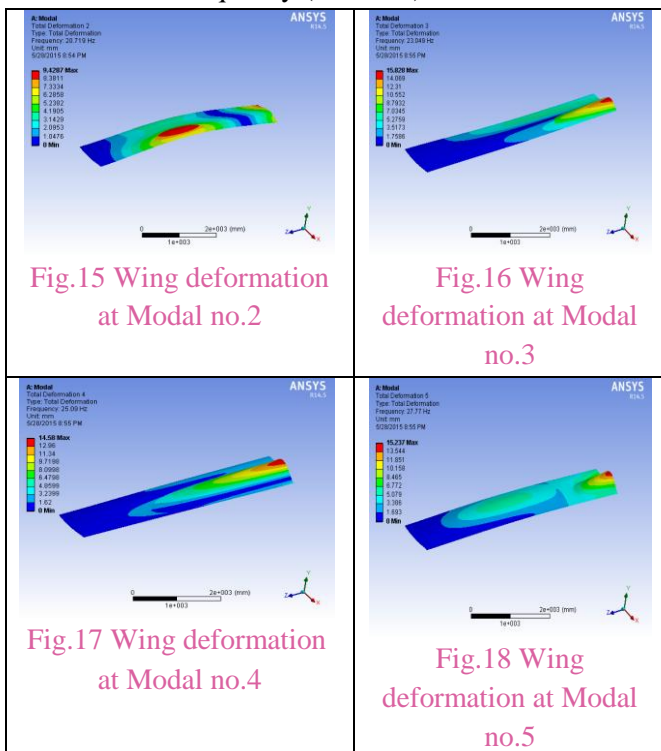
According to the contour plot, wing minimum deformation at one end is 0mm and is gradually increased to 8.428mm which is maximum towards the other end because of frequency (3.6556Hz). According to the contour plot, wing minimum deformation is towards bottom and 3/4th end on the top surface is 0mm and increases at middle of the wing to 9.4287mm because of frequency (20.719Hz). According to the contour plot, wing minimum deformation is towards bottom end 0mm and increases to the top end of the wing surface 15.828mm because of frequency (23.049Hz). According to the contour plot, wing minimum deformation is towards bottom end 0mm and increases to top end of the wing surface 14.58 mm because of frequency (25.09Hz). According to the contour plot, wing minimum deformation is towards bottom end is 0mm and increases to top end of the wing surface 15.237 mm because of frequency (27.77Hz)

F. Vibration Analysis of Carbon Fibre Wing

Density : 1.75 g/cc
 Young's modulus : 85GPa
 Poisson's ratio : 0.20

G. Modal values of Carbon Fibre Wing

According to the contour plot, wing minimum deformation at one end is 0mm and gradually increased to 7.8563mm which is maximum towards the other end because of frequency (4.5161Hz). According to the contour plot, wing minimum deformation is towards bottom and 3/4th end on the top surface is 0mm and increases at middle of the wing to 9.453mm because of frequency (25.608Hz). According to the contour plot, wing minimum deformation is towards bottom end 0mm and increases to the top end of the wing surface 17.384mm because of frequency (27.693Hz). According to the contour plot, wing minimum deformation is towards bottom end 0mm and increases to top end of the wing surface 14.372 mm because of frequency (29.219Hz). According to the contour plot, wing minimum deformation is towards bottom end is 0mm and increases to top end of the wing surface 14.739 mm because of frequency (32.734Hz)



4. Vibration Analysis of a Plain Wing Modal values of Plain Fibre Wing

According to the contour plot, wing minimum deformation at one end is 0mm and gradually increased to 6.3353mm which is maximum towards the other end because of frequency (3.2605Hz). According to the contour plot, wing minimum deformation is towards bottom and 3/4th end on the top surface is 0mm and increases at middle of the wing to 7.0876mm because of frequency (18.48Hz). According to the contour plot, wing minimum deformation is towards bottom and 3/4th end on the top surface is 0mm and increases at middle of the wing to 11.898mm because of frequency (20.558Hz). According to the contour plot, wing minimum deformation is towards bottom end 0mm and increases to top end of the wing surface 10.96 mm because of frequency (22.378Hz). According to the contour plot, wing minimum deformation is towards bottom end is 0mm and increases to top end of the wing surface 11.454 mm because of frequency (24.768Hz).

CFD Analysis of Flow parameters and Forces at Angle 2

According to the counter plot, the pressure will be minimum, middle portion of the wing is - 2.89e+04N/mm² and pressure will be maximum at both ends 2.03e+04N/mm². According to the counter plot, the Velocity will be maximum, middle portion of the wing is 2.82e+02N/mm² and pressure will be maximum at both 1.41e+01N/mm²

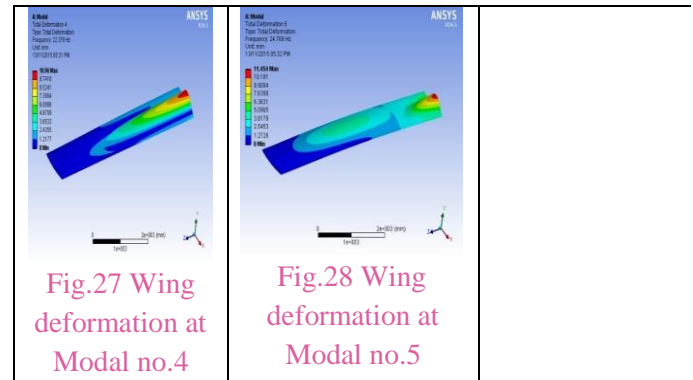


Fig.27 Wing deformation at Modal no.4

Fig.28 Wing deformation at Modal no.5

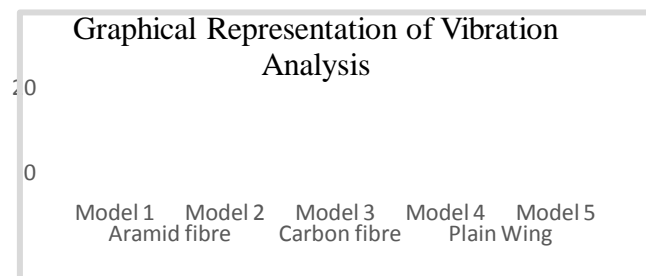


Fig.29 Graphical Representation of Vibration Analysis of different wings.

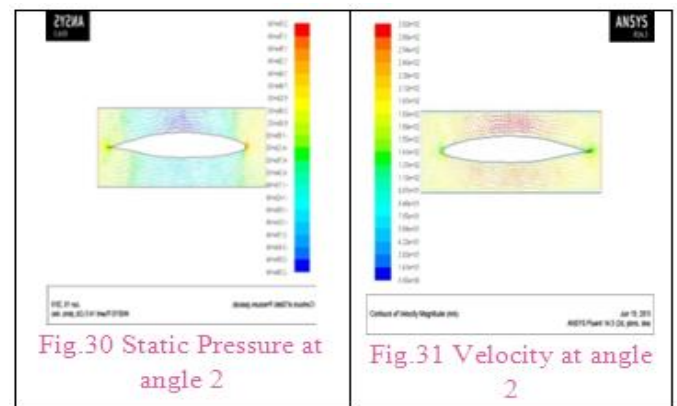


Fig.30 Static Pressure at angle 2

Fig.31 Velocity at angle 2

Flow parameters and Forces at Angle 4

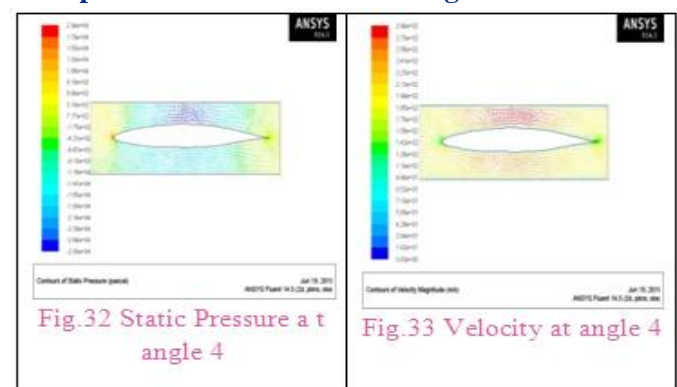


Fig.32 Static Pressure at angle 4

Fig.33 Velocity at angle 4

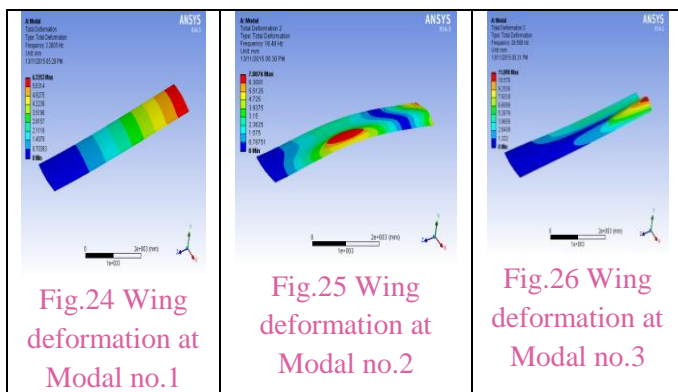
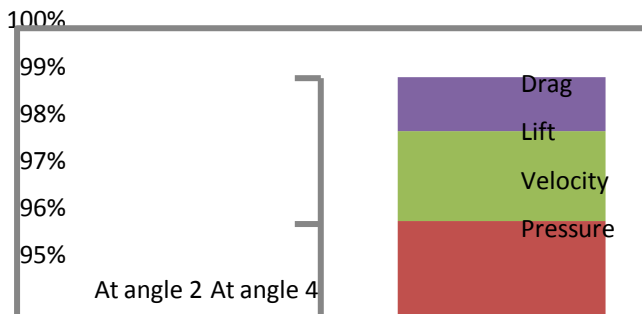


Fig.24 Wing deformation at Modal no.1

Fig.25 Wing deformation at Modal no.2

Fig.26 Wing deformation at Modal no.3

CFD Analysis of Plain Wing



IV Conclusions

In this paper, an aircraft wing is designed and modelled in 3D modelling software. The materials used for aircraft wings are hybrid composite aluminum alloys and specifically the composite materials preferred are Carbon Fibre and Aramid Fibre. Further, Structural analysis is done using analysis software, in which Static analysis is done on the wing by applying air pressure for two materials aluminium - carbon fibre and aluminium - aramid fibre. By observing the analysis results, the deformation and stress are less for Carbon Fibre than Aramid Fibre. Vibration analysis is also done on the aircraft wing for the similar two materials to determine the frequencies. By observing the results, the frequencies are more for Carbon Fibre than Aramid Fibre, so the vibrations are more when Carbon Fibre is used.

CFD analysis is done on the wing to determine the lift and drag forces by changing angle of attacks. The angle of attack taken is 20 and 40. By observing the results, the drag force is less for 20 angle of attack. It is better if the drag force is reduced. So it can be concluded that by decreasing the angle of attack, the drag force is reduced. By observing both the results, the stress produced when Aramid fibre is used are slightly more than that of carbon fibre, but by vibration analysis, Aramid fibre is better.

However considerably the hybrid composite – aluminium wing produce fine results when analysed under pressure and frequencies when compared to a basic aluminium wing which is used today. Considering an example of two unlike natured fibre this is being

analysed that where a normal aluminium alloy wing performance would comparably less effective than a hybrid composite wing.

References

- [1] Design and Structural Analysis of the Ribs and Spars of Swept Back Wing by Mohamed Hamdan A, Nithiyakalyani, International Journal of Emerging Technology and Advanced Engineering, Vol.4, Issue 12, Dec2014
- [2] Optimal Topology of Aircraft Rib and Spar Structures Under Aeroelastic Loads by Bret K. Stanford, Peter D. Dunning, Journal of Aircraft
- [3] Two- Spar Wing Stress Analysis: An Investigation into the Effect of Flexibility of Ribs by W.J. Goodey, M.A., A.F.R. Ae.S, Aircraft Engineering and Aerospace Technology,
- [4] Statistic and Dynamic Analysis of Typical Wing Structure of Aircraft using Nastran by Mr.PritishChitte, Mr. P. K. Jadhav, Mr. S. S. Bansode, International Journal of Application or Innovation in Engineering & Management (IJAIEM), Volume 2, Issue 7, July 2013
- [5] Analytical and Numerical Investigation of Critical Buckling Analysis of Composite Wing by P. Murugesan and P. Thirumurugan, International Journal Of Modern Engineering Research (IJMER)
- [6] Design of An Aircraft Wing Structure For Static Analysis And Fatigue Life Prediction by A.Ramesh Kumar, S. R. Balakrishnan, S. Balaji, International Journal of Engineering Research & Technology, Volume/Issue: Vol.2 - Issue 5 (May - 2013).
- [7] Preliminary Design Approach of the Wing Box by Vikaskumar, Pushpraj, Harpreet Singh, International Journal of Aerospace and Mechanical Engineering Volume 1 – No.1, September 2014.
- [8] New aluminium lithium alloys for aerospace applications by CindieGiummarra, Bruce Thomas and Roberto J. Riojam, Researchgate
- [9] Advanced lightweight alloys for aerospace applications by William E. Frazier Eui W. Lee Mary E. Donnellan M.S., James J. Thompson B.S, JOM, May 1989, Volume 41, Issue 5, pp 22-26.



- [10] Aluminium-beryllium alloys for aerospace applications by D. Hashiguchi, A.N.Ashurst, F. C. Gensing, J.M. Marder
- [11] Strength analysis and modelling of hybrid composite- aluminium aircraft structures.
- [12] ZlatanKapidžić.
- [13] Fibre-reinforced compositesmaterials, manufacturing, and design, Third edition. P.K Mallick.
- [14] Carbon fibre composites Deborah D.L Chung.
- [15] Introduction of Fibre-Reinforced Polymers – Polymers and Composites: Concepts, Properties and Processes. Martin Alberto Masuelli
- [16] Advanced composite materials of the future in aerospace industry by Maria Mrazova.
- [17] Composite Materials in Aerospace Applications by Nikhil V Nayak.
- [18] Composite Materials for Aircraft Structures by Baker, Alan A. Bake, Stuart Dutton, Donald Kenny.