Investigation of Aluminum and Composite Aircraft Wings Under the Influence of Aerodynamic Forces and their Effects on Environmental Impacts

S. Ebadi[1,*], K. Shahbazi[1], E. Anbarzadeh[2]

[1]School of Mechanical Engineering, Petroleum University of Technology, Ahvaz, Iran.
[2]School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran.
Received: 09 March 2021 - Accepted: 07 June 2021

Abstract

Today, many industries, including the aerospace industry, have been influenced by materials technology development. Aircraft wing structures are generally designed using pure aluminum. Still, in recent years, due to their light weight, composites are used to reduce the overall weight of the structure and lower the consumption of fossil fuels in an aircraft. In this study, the design and analysis of aluminum and composite aircraft wings were done using ANSYS software and are compared. The results show that by using the composite wing instead of the aluminum one, fuel consumption was reduced, bringing positive effects on environmental impacts. According to the results, a 37% reduction in the weight of the composite structure compared to that of aluminum leads to increased aerodynamic efficiency, improved wing performance, reduced fuel consumption and emissions, positive environmental impacts, and reduced construction costs. This is due to the unique properties of composite materials, such as the good power to air ratio and their high flexibility.

Keywords: Aircraft Wing Design, Composite Structure, Aluminum Structure, Aerodynamic Forces, Environmental Impacts.

1. Introduction

Human civilization has been influenced significantly by materials technology, in fact, and most period of technological development have been linked to change in the use of materials (e.g. the stone, bronze, and iron ages). In new generations the driving force for technological changes has led to new family of engineered materials and structures exhibiting multifunctional capabilities which are naturally seen in biological systems, leading to a new era of smart materials. Smart materials and intelligent structures have been a matter of interest since the late 1970s, when the benefits of optical fibers in composite materials were recognized [1]. It has a wide range use in different industries such as, equipment manufacturing, aerial construction and, chemical and military industries. With its wide application in aerospace structure, the advanced composite material is named as "the four main materials of aerospace structure" align with aluminum alloy, titanium alloy, and alloy steel. Smart wings are one of the applications for such intelligent structure that incorporate the use of smart materials. Smart wings are able to generate the forces and moments for maneuvering of aircraft through continuous change of the cross section, in order to overcome defects of conventional flaps [2]. Nowadays, several research studies on smart wings using smart materials have been performed for the delay of flow separation, reduction of wing weight, increase of lift, decrease of drag, and so on. Several research studies have conducted on the use of smart materials in aircraft wing. The critical element of aircraft is the design of the wings. Modern aircraft wings can be designed from different types of materials, depending on the structural function. The wing of aircraft structure is comprised of more different parts, such as skin, spar, and ribs, flight control surfaces, like ailerons and flaps [3]. Each of these parts is supported by different loads and, thus, the right material must be selected. Several factors influence the selection of material of which strength allied to lightness is the most important. Aluminum alloys can be used to manufacture the ribs, while the design of control surfaces of wing skin fabricates by the composite materials. Composite materials are well known for their excellent combination of high structural stiffness, low cost and weight. The advanced composite material has its own prominent features, such as high specific strength, high specific modulus, designable performance and integral forming easily, etc [4]. With the application of the advanced composites, the weight of aircraft structure can be reduced by about 25%~30% compared to the conventional metal structure. Moreover, the aerodynamics and flight performances can be improved to the levels that the conventional materials can hardly achieve. The extensive application of advanced composites is also able to promote some further technology development of structure stealth and intelligent structure design [5].

*Corresponding author
Email address: shirinebadi1998@gmail.com

The aircraft structure performance is significantly dependent on the part and quality of the advanced composites used in aircraft. Because of higher stiffness-to-weight or strength-to-weight ratios compared to isotropic materials, composite laminates are becoming more popular [6]. Composite structures typically consist of laminates stacked from layer with different fiber orientation angles. The layer thickness is normally fixed, and fiber orientation angles are often limited to a discrete set such as 0°, ±30°, ±45°, ±75°, and ±90°. The design and manufacture of aircraft wings require attention to several unique structural demands [7]. High strength and light weight are two primary functional requirements to be considered in selecting materials for the construction of aircraft wing. Traditionally airplanes have been made out of metal like alloys of aluminum. Nowadays the metal matrix composites have replaced the traditional metals, to make an aircraft lighter with added benefits of less maintenance, super fatigue resistance and high fuel efficiency.

These composite materials can provide a much higher strength to weight ratio and stiffness-to-weight ratio than metals.

The necessity to study the performances of aircraft wing against the applied aerodynamics forces to 4 the wing makes sense.

In order to study the structural behavior of a wing the linear static analysis is carried out on an aircraft wing and the stresses and displacements are analyzed [8]. The objective of this study includes structural idealization, finite element modelling using ANSYS, linear static analysis results. The stresses under the equal applied aerodynamics force and deflection of wing will study with considering two different materials of aluminum and composite for aircraft wing. Materials are probably more deep-seated in our culture than most of us realize. Transportation, housing, communication, recreation, and food production virtually every segment of our everyday lives is influenced to one degree or another by materials [9].

Historically, the development and advancement of societies have been intimately tied to the members' ability to produce and manipulate materials to fill their needs. In fact, early civilizations have been designated by the level of their materials development (Stone age, Bronze age, and Iron ages). The earliest humans had access to only a very limited number of materials, those that occur naturally: stone, wood, clay, skins, and so on [10].

With time, they discovered techniques for producing materials that had properties superior to those of the natural ones; these new materials included petty and various metals. Furthermore, it was discovered that the properties of a material could be altered by heat treatments and by the addition of other substances [11]. At this point, materials utilization was totally a selection process that involved deciding from a given, rather limits set of materials, the one best suited for an application by virtue of its characteristics. It was not only relatively recent times that scientists came to understand the relationships between the structural elements of materials and their properties [12].

This knowledge, acquired over approximately the past 100 years, has empowered them to fashion, to a large degree, the characteristics of materials.

Thus, tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society, including metals, plastics, glasses, and fibers [13]. The development of many technologies that make our existence so comfortable has been intimately associated with the accessibility of suitable 7 materials. An advancement in the understanding of a material type is often the forerunner to the stepwise progression of a technology. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute [14].

In the contemporary era, sophisticated electronics devices rely on components that are made from what are called semiconducting materials. Aerodynamics, from air plus dynamics, is the study of motion of air, particularly as interaction with a solid object, such as an airplane wing [15].

It is a sub-field of fluid dynamics and gas dynamics, and many aspects of aerodynamics theory are common to these fields. The term aerodynamics is often used synonymously with gas dynamics, the difference being that "gas dynamics" applies to the study of the motion of all gases, and is not limited to air [16]. The rules of aerodynamics explain how an airplane is able to fly. Anything that moves through air is affected by aerodynamics, from a rocket blasting off, to a kite flying. Since they are surrounded by air, even cars are affected by aerodynamics. Most of the early efforts in aerodynamics were directed toward achieving heavier-than-air flight, which was first demonstrated by Otto Lilienthal in 1891 [17]. Since then, the use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations has formed a rational basis for the development of heavier-than-air flight and a number of other technologies. Recent work in aerodynamics has focused on issues related to compressible flow, turbulence, and boundary layers and has become increasingly computational in nature [18]. In this study, after designing the simplistic aircraft wing we go through the analysis as it behaves like a cantilever beam under the concentrated assumed aerodynamics force. At the end, a discussion in terms of environmental effects of changing materials and replacing new green materials like composite which is friendlier with environment is done accordingly.

2. Materials and Methods

In this project we use NACA 2412 co-ordinates for wing skeleton structure.

The NACA airfoils are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). The shape of the NACA airfoils is described using a series of digits following the word "NACA". The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

The NACA four-digit wing sections define the profile by: First digit describing maximum camber as percentage of the chord, Second digit describing the distance of maximum camber from the airfoil leading edge in tenths of the chord, Last two digits describing maximum thickness of the airfoil as percent of the chord. For example, the NACA 2412 airfoil has a maximum camber of 2% located 40% (0.4 chords) from the leading edge with a maximum thickness of 12% of the chord. These are shown in the Fig. 1.

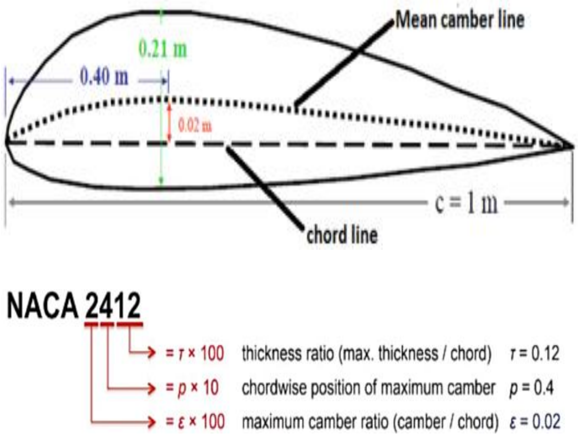


Fig. 1. Numerical properties of NACA2412 airfoil.

In this project, the model wing is designed using the CAD program, SOLIDWOEKS software. By importing the coordinates of NACA2412 airfoil to SOLIDWOEKS through Microsoft excel then the airfoil shape is generated like the Fig. 2.

Fig. 2. Designed NACA2412 airfoil-section in SOLIDWORKS.

The below figures show the complete design of wing skeleton structure design. Three dimensions views of the deigned wing is shown.

The cord lines of airfoil in the root and tip cross sections are selected one mm and five mm respectively.

The length of wing is equal to five mm. Before importing the SOLIDWORKS design file to the ANSYS workbench, the file has to be converted into the STP format.

This is shown in Fig. 3. Prior to the development of Finite Element Analysis (FEA) the only way to validate a design or test a theory was to physically test a part.

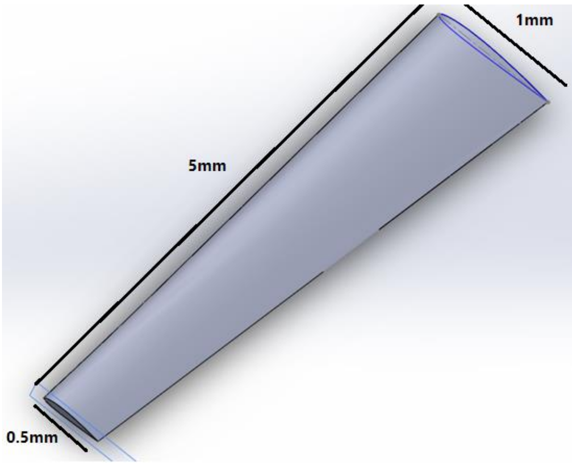


Fig. 3. Side view of a designed wing with dimensional isometric projection.

This was and still is both time consuming and expensive. While FEA will never replace the final physical testing and validation of a design, it can drastically reduce the time and money spent on intermediate stages and concepts. FEA in its infancy was limited to large scale computing platforms but development of powerful personal computers combined with intuitive software package.

Such as ANSYS have brought FEA to the engineer's desktop and has broadened its use and accuracy many fold. Finite Element Analysis is now a vital and irreplaceable tool in many industries such as aerospace, automotive, defense, consumer products, medical, oil and gas, architecture and many others. FEA is performed in three stages, pre-processing, solving and post processing and other are outlined below.

In this simulating, pure aluminum (aluminum, commercial purity, 1-0, wrought) and carbon fiber reinforced (carbon matrix, carbon fiber reinforced (Vf: 50%, 0°,+90°,0°,-90°), composite (Exel C AC-250-B10-2000) materials with the specific physical and mechanical properties are assigned to every element in the aircraft wing model. Data compiled by Granta Design team at ANSYS, incorporating various sources including JAHM and MagWeb.

The physical and mechanical properties of pure aluminum and carbon fiber reinforcement plymer are given in the Table. 1.

Table. 1. Physical and mechanical properties of pure Al and CFRP[6]

Property	Pure Aluminum	CFRP
ρ - Density (kg/m^3)	2700	1700
E - Young's modulus (Gpa)	69	$\mathbf{E_{12}.E_{21}}$ 94.87
ν - Poisson's ratio	0.34	$\boldsymbol{\nu_{12}}$ 0.3198
Tensile yield strength (Mpa)	24.98	$x_t.y_t$503.4
Tensile ultimate strength (Mpa)	57.92	$x_c.y_c$600
In plane shear modulus (Gpa)	25	5

In the following results of each under the same applied time independent force are excluded. The stress analysis of the wing structure is carried out using the finite element analysis approach. The wing structure of an aircraft is connected to the fuselage through keel beam. So the wing structure is act as a cantilever beam connected with fuselage. One end of the wing structure can be fixed and taken as the boundary conditions of the model. This was satisfied by fixing all six degrees of freedom on the nodes corresponding the fixing point. The static analysis was conducted by using the CAE ANSYS software, workbench package program. After material assignment, mesh generation is defined. The following figure illustrates the mesh structure, which is used to be mechanical preference, program controlled element order with slow transition and fine span angle center. 225913 number of nodes and 160124 number of elements are generated through the wing surface. This is shown in Fig. 4.

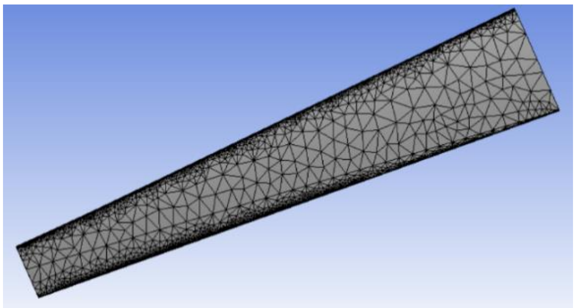


Fig. 4. Meshed wing (Meshed by ANSYS Static Structure).

3. Results and Discussions

Fixing one end of wing (wing root), the pressure 100 pa is applied on the top of the wing to find out some structural parameters like total deformation, equivalent stress, equivalent strain, max principle stress, max shear stress, stress intensity and also volume and weight. Following pictures illustrate the amount of mentioned parameters for two assigned materials.

Total deformation analysis is shown in Fig. 5. As it shows clearly the amount of deformation go up slightly from the root of the wing to the tip. The amount of maximum total deformation is much less in CFR than Al. Less deformation can cause less vibrations in the wing structure, which is one of remarkable issues in the design procedure.

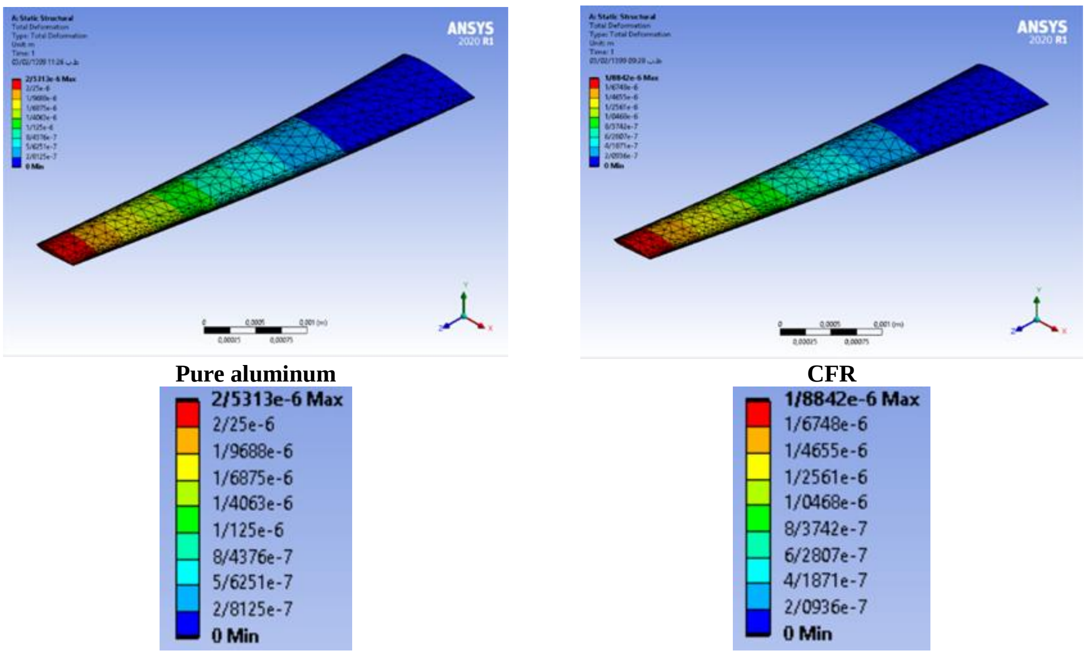


Fig. 5. Total deformation distribution of pure aluminum and CFR wing (Run by ANSYS Static Structural)

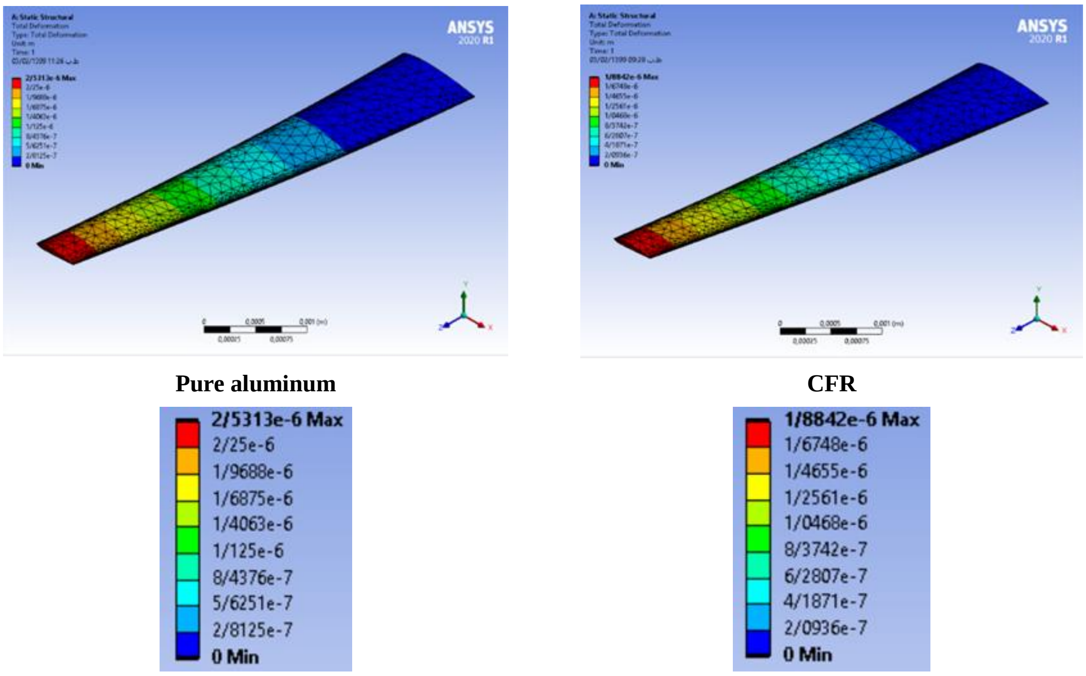


Fig. 6. Equivalent Stress distribution of pure aluminum and CFR wing (Run by ANSYS Static Structural).

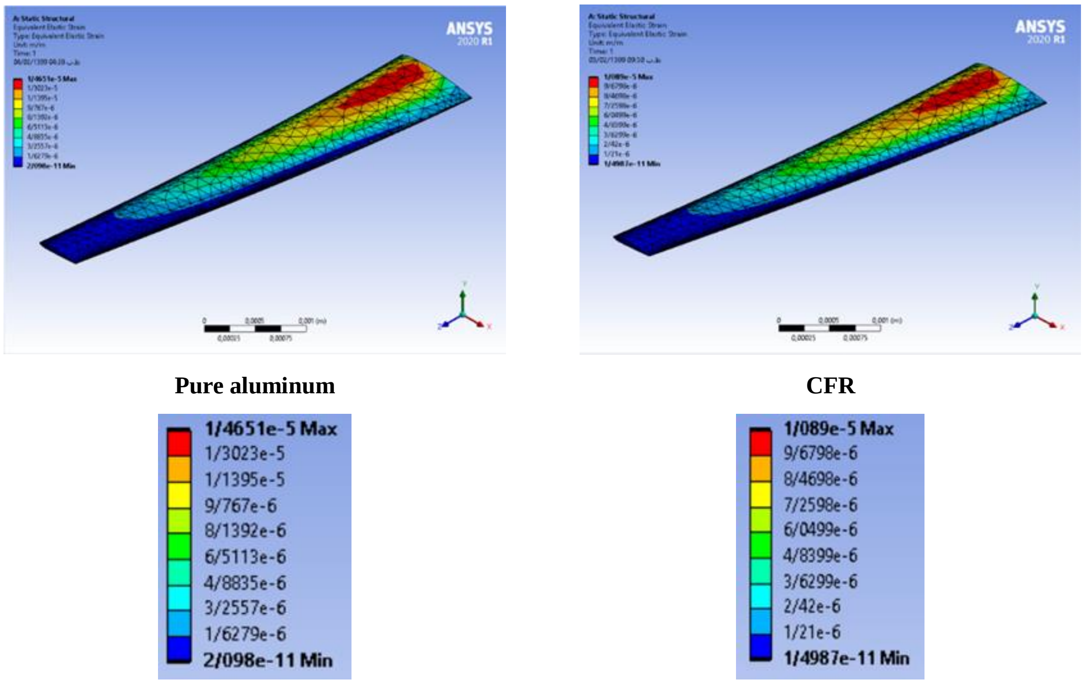


Fig. 7. Equivalent elastic strain distribution of pure aluminum and CFR wing (Run by ANSYS Static Structural)

Equivalent Stress analysis is shown in Fig. 6. Equivalent or von misses stress of the wing is maximum at the end of tip for both materials and as it desfined it consists of the principle normal stresses when the shear stress equals zero. The final results show that this kind of stress is much less for CFR in comparison with pure Al.

Equivalent Elastic Strain distribution is shown in Fig. 7. As it shows the amount of equivalent elastic strain is maximum in the place of applying force then it becomes weaker at the free end for both materials. As it shows clearly, the maximum amount of equivalent elastic strain in CFR is considerably less in comparison with pure Al.

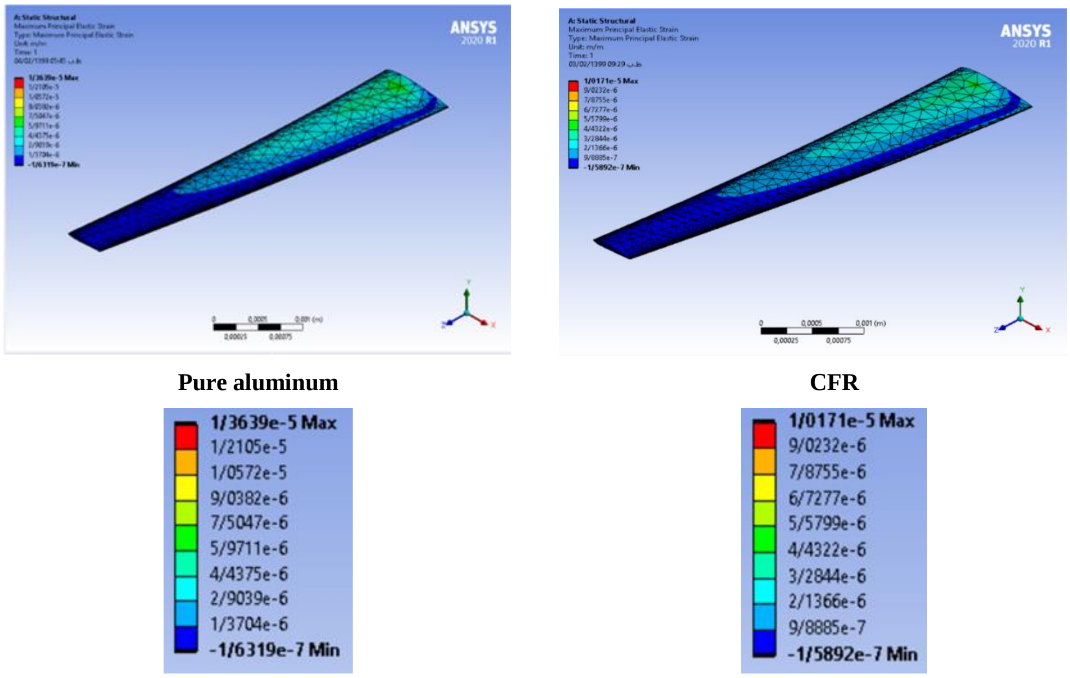


Fig. 8. Maximum principle elastic strain distribution of pure aluminum and CFR wing (Run by ANSYS Static Structural).

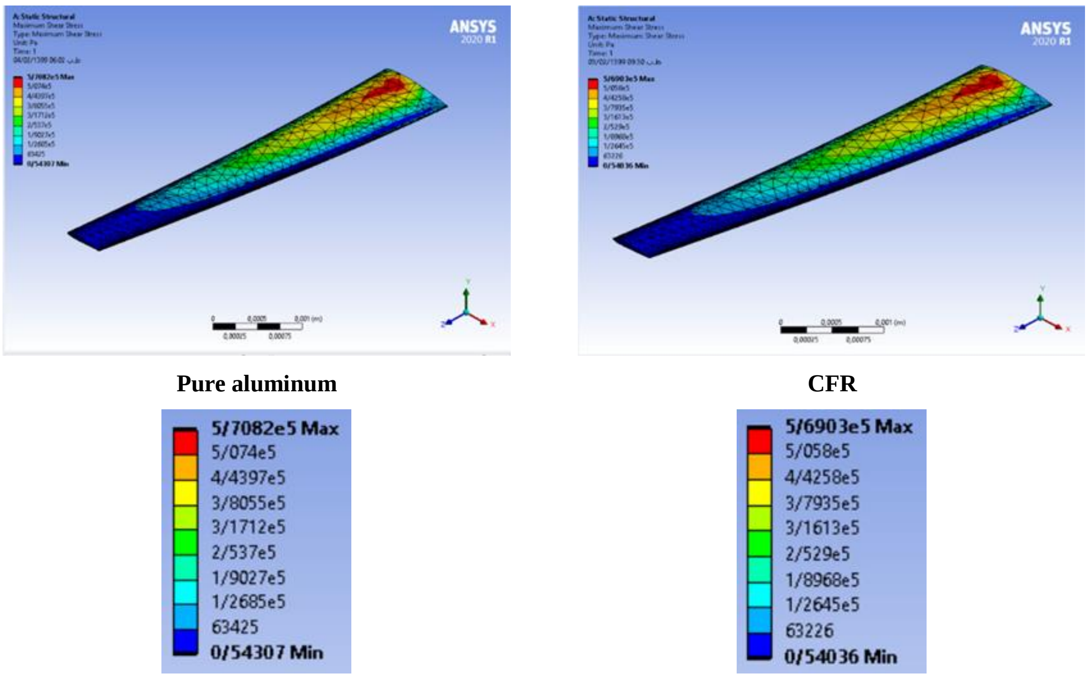
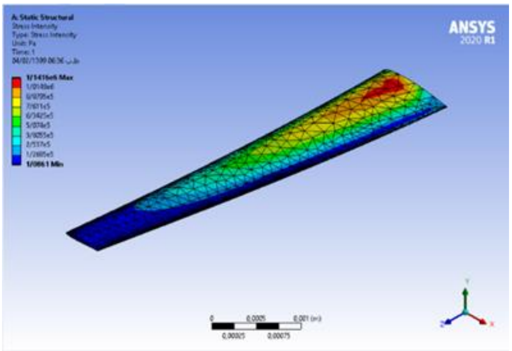
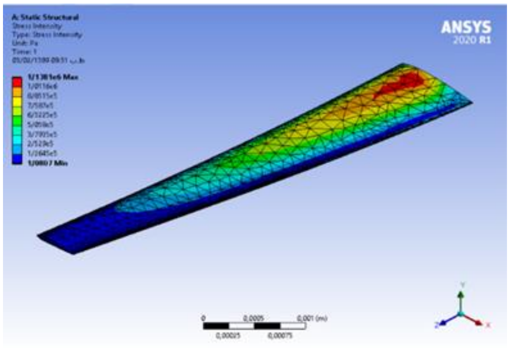


Fig. 9. Maximum shear stress distribution of pure aluminum and CFR wing (Run by ANSYS static Structural).

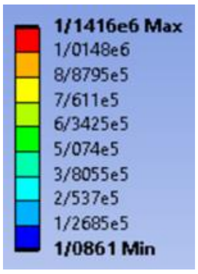
Maximum Principle Elastic Strain is shown in Fig. 8. The elastic strain amount fir CFR is noticeably less than pure Al which can cause less deformation in the wing structure. As the results show obviously, the distribution of principle elastic strain is maximum at the place of applying force and then it becomes weaker in other surrounding points.

Maximum Shear Stress is shown in Fig. 9. As illustrated the shear distribution is nearly similar for both materials and it has the maximum value in the place of applying force and then it becomes weaker at the other points. In terms of shear stress there is not a significant difference cause the results show equal amounts. Stress Intensity distribution is show in Fig. 10. The maximum amount of stress intensity in the place of force applying, and as we go farer it becomes less. As the output data shows clearly, there is not much diffrences in terms of stress intensity. So for both materials the distribution of stress intensity is the same aming the their elements.The Volume distribution of each element is shown in the Fig. 11. As it shows for both pure Al and CFR the volume elements are similar. It should be mentioned





Pure aluminum



CFR

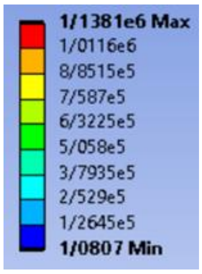
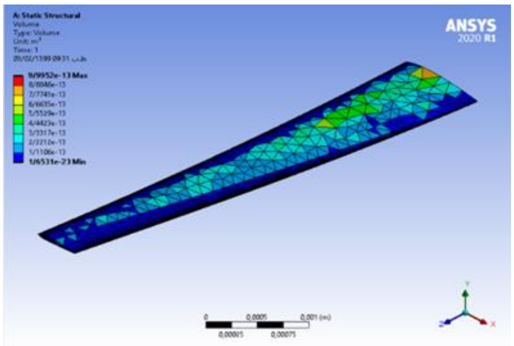
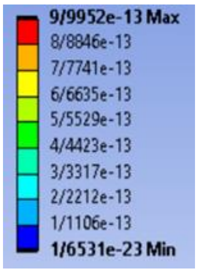


Fig. 10. Stress intensity distribution of pure aluminum and CFR win (Run by ANSYS Static Structural).





Pure aluminum and CFR **CFR**

Fig. 11. Volume distribution of pure aluminum and CFR wing (Run by ANSYS Static Structural).

Table. 2. Total volume and overall weight of pure aluminum and CFR wing.

property	Pure Aluminum	CFR
Total Volume (m^3)	2.2654×10^{-10}	2.2654×10^{-10}
Density (kg/m^3)	2700	1700
Overall weight (kg)	6.11658×10^{-7}	3.85118×10^{-7}

Table. 3. Mechanical behavior of pure aluminum and CFR under the same applied force with the advantages of using CFR.

property	Pure Aluminum	CFR	CFR advantages
Max total deformation (m)	2.5313×10^{-6}	1.8842×10^{-6}	35% less deformation
Max equivalent stress (pa)	1.0298×10^{6}	1.0312×10^{6}	0.1% more (nearly equal) equivalent stress generation
Max equivalent elastic strain (m/m)	1.4651×10^{-5}	1.089×10^{-5}	25% less equivalent elastic strain generation
Max principle elastic strain (m/m)	1.3639×10^{-5}	1.0171×10^{-5}	25% less principle elastic strain generation
Max shear stress (pa)	5.7082×10^{5}	5.6903×10^{5}	0.3% less (nearly equal) shear stress generation
Max stress intensity (pa)	1.1416×10^{6}	1.1381×10^{6}	0.3% less (nearly equal) stress intensity
Overall weight (kg)	6.11658×10^{-7}	3.85118×10^{-7}	37% less weight

that the scale of design was too small in comparison with the real scale, but the proportions are the same. Then the total volume and weight then is extracted from software.
In Table. 2. the physical final properties of pure aluminum and carbon fiber reinforcement polymer which has been used is shown. An analysis by varying the parameters was performed in ANSYS software and obtained the results. As the stored energy in the structure increases, the generated deflection and stress are increase too. As it's clear in the above pictures, the maximum amount of applied stress is in the root of wing. By moving away from the wing root, the amount of applied stress decreases gradually. So that the structure has the minimum amount of stress in the tip of the wing. It should be mentioned that, the principle stress means the Von-Mises stress. In Table. 3. the final results of replacing CFRP material to pure aluminum is compared and the advantages of it are shown. From the comparison of above noted data of two materials, the differences between the values of deformation, max equivalent stress, max equivalent elastic strain, max principle elastic strain, max shear stress, max stress intensity and overall weight are noticeable. The CFR material can be used instead of pure aluminum or even aluminum alloy in order to give more strength to structure. The effect of pressure during take-off condition is more for aluminum and less for CFR which is strongest and light weight, and also reduces the weight of the wing. It can be concluded that at the above assumed loading conditions and constraints flight wing structure will not fail due to material properties. So the CFR composite wing with its great advantages can be replaced with pure aluminum and even aluminum alloy and gives the better mechanical properties and performance than pure aluminum. Results show that the Von-Mises stress distribution in the case of wing is less towards the wings leading and trailing edges and decreases towards the wing tip. The variation in fiber orientation at the same skin thickness will produce the variation in the Von-Mises stress (increase or decrease). Maximum values of Von-Mises stress were observed at the support position of the combined wing. The largest magnitude of displacement was obtained at the free end of the combined wing.

4. Conclusion

This paper focused on the design and analysis of a smart composite wing. A conceptual design of a general aviation airplane wing was introduced in the first section. The conceptual design provided a general shape of the aircraft wing. The relative results are as follow:

1. The structural integrity of the composite wing against the applied aerodynamics load was analyzed using the commercial finite element software ANSYS. The stress values were extracted from the FEM analysis.
2. The replacement of pure aluminum by CFRP reduces total weight of aircraft wing by 37%.
3. By comparing the stress and displacement in the previous table, it is concluded that the CFRP is seen to have better performance.
4. The lower weight results in lower fuel consumption and emissions, enhanced aerodynamics efficiencies, improved the performances and lower manufacturing costs.
5. Thus it is desirable to adopt the CFRP material for composite aircraft wings in comparison with the conventional pure aluminum considered in the present study.
6. Reducing the harmful effects of the environment today is one of the concerns of engineers in the field of equipment design. One of the effective factors in reducing the fuel consumption of aircraft is to reduce the weight of these structures. As a result of this 37% reduction in the weight of the aircraft wing structure, the application of composite wings instead of aluminum wings will reduce fuel consumption, which in turn will reduce the harmful environmental effects.
7. Extensive researches can be done on the deeply discovering and broadly using of green composites in the aerospace industry to improve aircraft performance and manufacture the new area of airplanes which have less harmful effects on the environement. Future work will focus on implementing and manufacturing a prototype of a smart composite wing in order to observe their production feasibility.

References

[1] M. Rayatpour and Z. Lalegani, Thermal Analysis and Microstructural Evaluation of Inconel 738LC Superalloy Gas Turbine Blade. J. Environ. Friendly Mater.,4(2), (2020), 31.
[2] Z. Hasan, H. Hammoudeh and G. Design and Analysis of a Smart Composite Wing. Atmeh, In ASME Int. Mech. Eng. Cong. and Expo., 5489, 1 Jan 1, (2011), 213.
[3] C. S. Ananda, H. M. Nanjundaswamy and B.Ashok Adv. Fighter Aircraft Dev. Int. J. Res. Eng. Technol., Feb;6(3): (2018), 53.
[4] M. E. Adamy, M. A. Ghofur, A. Infantono and Y. T. Purwantiningsih, Optimasi Desain Dan Dnalisis Kekuatan Struktur Sayap Komposit Dengan Variasi Material, Thickness, Arah Serat Dan Kondisi Batas Menggunakan MSC Patran Nastran (Studi Kasus Pesawat UAV CH-4). In Conf. SENATIK STT Adisutjipto Yogyakarta, Dec 9, 6 (2020), 81.
[5] S. H. Song, H. Lee, J. G. Lee, J. Y. Lee, M. Ch and, S. H. Ahn, Des. Analys. Smart Soft Compos. Struct. for Various Modes of Actuation. Compos. Part B: Eng., Jun 15;95:155-65, (2016).

[6] K. Yu, W. Yin, S. Sun, Y. Liu and J. Leng, Design and Analysis of Morphing Wing Based on SMP Composite. In Ind. Comm. Appl. Smart Struct. Technol. Int. Soc. for Optics Photonics., Mar 31 , (7290), (2009), 72900S.
[7] F. Kopsaftopoulos, R. Nardari, Y. H. Li and F. K. Chang, Experimental Identification of Structural Dynamics and Aeroelastic Properties of a Self-sensing smart composite wing. In Proceedings of the 10th International Workshop on Structural Health Monitoring, Sep 2, (2015).
[8] R. J. Wood, Design, Fabrication and Analysis of a 3DOF, 3cm Flapping-Wing MAV. In IEEE/RSJ Int. Conf. on Intell. Robots and Sys. IEEE., Oct 29, (2007), 1576.
[9] A. Y. Sofla, S. A. Meguid,K. T. Tan and W. K. Yeo, Shape Morphing of Aircraft Wing: Status and Challenges. Mater. Des., Mar 1;31(3), (2010), 1284.
[10] S. M. Lim, S. Lee, H. C. Park, K. J. Yoon and N. S. Goo, Design and Demonstration of a Biomimetic Wing Section Using a Lightweight Piezo-Compos. Actuator (LIPCA). Smart Mater. and Struct., May 4;14(4), (2005), 496.
[11] K. J. Narayana and R. G. Burela, A Rev. of Recent Res. on Multifunctional Compos. Mater. and Struct. With their Appl. Mater. Today: Proc., Jan 1;5(2), (2018), 5580.
[12] R. Elhajjar, V. La Saponara and A. Muliana, Editors. Smart Compos.: Mech. and Des. CRC Press, Dec 14, (2013).
[13] C. Thill, J. A. Etches, I. P. Bond, K. D. Potter and P. M. Weaver, Compos. Corrugated Struct. for Morphing Wing Skin Appl. Smart Mater. Struct., Nov 11;19(12), (2010), 124009.
[14] L. Butt, S. Day, J. Weaver, C. Sossi, A. Wolek, O. Bilgen, W. Mason and D. Inman, Wing Morphing Design Utilizing Macro Fiber Compos. Smart Mater. SAWE Paper., May 23,3515-S, (2010), 1.
[15] W. Yu, V. V. Volovoi, D. H. Hodges and X. Hong, Validation of the Variational Asymptotic Beam Sectional Analys. AIAA J., Oct;40(10), (2002), 2105.
[16] J. Aboudi, S. M. Arnold and B. A. Bednarcyk, Micromech. of Compos. Mater.: a Generalized Multiscale Analys. App. Butterworth-Heinemann, (2013).
[17] P. K. Mahato and D. K. Maiti,. Aeroelastic Analysis of Smart Composite Structures in Hygro-Thermal Environ.. Compos. Struct., Mar 1;92(4), (2010), 1027.
[18] M. J. Patil and D. H. Hodges, Flight dynamics of Highly Flexible Flying Wings. J. of Aircraft. Nov;43(6), (2006), 1790.