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Structural and Stress Analysis of NACA0012 Wing Using SolidWorks

Samara Munaem Naeem

Department of Aeronautical Engineering, College of Engineering, University of Baghdad, Baghdad 10011, Iraq

Corresponding Author Email: samaranaeem@gmail.com

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ABSTRACT

The aircraft wing is a critical component that enables flight and enhances safety and stability. Its design and function are critical considerations in the overall performance and safety of an aircraft. This paper aims to focus on the design of the aircraft wing structure for its importance. SolidWorks-2018 program was used to model the system of the wing parts, which consists of seven ribs and two spars and airfoil NACA 0012 was used and aluminum alloy T7075 as a material for the structure of the aircraft wing and its surface. The generated loads were projected on it obtained using the Vortex Lattice method when dividing it into (8, 16 and 24) panels to extract the amount of stress, strain and deformation to which the wing is exposed. The analyses conducted on the proposed wing showed that the wing structure is acceptable in design because of its lightweight, weighing approximately 5556.98 grams, and safe, as the stress resulting from the numerical analysis under the influence of the aerodynamic force is less than the yield strength of the structural material.

1. INTRODUCTION

The most important part of an aircraft structure that produces lift force is the wings, the design of an aircraft wing structure is a complex process that involves many factors, including lift generation, structural strength, material selection, wing configuration, stability and control, and manufacturing and maintenance considerations. Therefore, all these factors must be carefully studied to ensure a safe, efficient and reliable aircraft. For this purpose, many research takes into account the method used in wing design where a genetic algorithm has been used to verify the design of a composite wing structure by developing a stiffness variable during the optimization process and the results have been verified by Nastran and show that the results meet specified response conditions such as strength and stability in several areas of the wing design [1]. A numerical analysis has been conducted using finite element analysis to obtain pressure, stress and displacement by determining each load acting on the wing structure by describing it with various mathematical integrals to obtain the total load of the profile, the results are represented graphically through the MATLAB environment and showed the effect of loads on the aircraft wing, in addition to the various aircraft variables and operating conditions on the studied system [2]. A structural analysis of a model aircraft wing was conducted via ANSYS 2022 R1 for the purpose of knowing the amount of deformation, stress and strain caused by the wing structure by knowing the natural frequency of the wings to reduce noise and avoid vibrations and to find out the most appropriate material for construction the wings by comparing the results for aluminum alloys and titanium alloys that will be used for the wing of the aircraft and it has been found that stress, strain, and deformation are less by using aluminum alloy, in addition to its light weight, which reduces the weight of the wing and gives it strength [3]. Finite element method used to analyze the structural characteristics of an aircraft wing, taking into account all variables design and the material of the wing structure to reduce cost and increase the efficiency of the aircraft, the results recommended using aluminium in the structure of the aircraft wing [4]. Using the simulation method, the design wing structure has been validated in other research, by using a three-dimensional layout of the aircraft through RDS program, which is placed in a MATLAB simulation environment to verify the wing design. A static stress analysis was performed by the COMSOL finite element software package, and aerodynamic loads were applied to it to ensure the reliability of the wing and it has been proven that the design is good and feasible [5]. An aircraft wing was designed using the CATIA V5R20 program, and estimating the stresses by the finite element method using the ANSYS-12 program package, in order to know the safety factor of the wing structure, the results predicted that the initial fatigue crack was located at the location of maximum stress [6]. While other research relied on comparison between experimental and numerical results to ensure the accuracy of the results obtained such as a wing model with a profile of NACA64A215 was developed using the PROE5 program, and the numerical analysis of the developed model was carried out using the ANSYS WORKBENCH14 program. It was concerned with finding 6 vibration modes with the natural frequency. The experimental results were compared with the numerical analysis of the aircraft wing model and the comparison results were compatible [7]. Other research depends on a comparison between the two types of wings made of the same material when a comparison was made to find the optimal design in terms of mass, stress and displacement for the wing structure of unmanned aircraft (rectangular wing and tapered wing) made of composite materials, where the aerodynamic loads were found through the vortex lattice method and applied onto the wing through the static analysis of the ANSYS 5.4 program, and it was found that the reduction in mass of the tapered wing is more than the rectangular wing when using composite materials [8]. Modeling and analyzing the wing of with a profile of NACA23015 and comparing the materials used in structuring the wing (composite materials, aluminum alloy) to determine the most appropriate material used, external loads were applied to the structure through the SolidWorks 2020 program. The results showed that composite materials are better than alloys, but have a higher cost [9]. The comparison of an aircraft wing structure made of composite materials and aluminium alloy through static analysis of the wing structure consists of 2-spar and 15-ribs via ANSYS software. The results showed that using composite materials is better in the aircraft structure, as it is lighter in weight, less deformation and higher strength [10]. While Sruthi et al. [11] tried to reduce the weight of the wing structure through the material used in its manufacture, the stress analysis of the NACA 4412 aircraft wing was conducted using an aluminum alloy material reinforced with silicon carbide. The results showed the superiority of this material from pure aluminum. Previously, we reviewed the research literature on the design and analysis of the aircraft wing structure, and we see that many researches did not address the internal wing structure and the extent of its effect on the strength and stiffness of the wing, so in this study, we aim to design an aircraft wing structure through simulation of SolidWorks-2018 program to know the ability of the wing to withstand the stresses that were exposed from the aerodynamic loads and the weight of the wing structure together by creating it with the smallest number of spars and ribs, taking into account the material used for the proposed structure to reduce the weight as much as possible.

2. PROBLEM CHARACTERIZATION

In this paper, a trapezoidal aircraft wing structure with skin, spars and ribs is considered in the static analysis. The wing structure consists of 7 ribs and 2 spars with skin, front and rear spars having shape as the (I) section beam. Stress analysis evaluated the stress exerted on the wing structure due to the aerodynamic loads and the weight of wing structure. The main objectives are:

• Calculate the lift force generated on the wing surface due to aerodynamic load by vortex lattice method with different numbers of panels (8,16,24) through the MATLAB program to know the effect of subdivisions of the wing in the calculation of the lift force and the reasons for choosing this number of panels are explained in the results section

• Implement the stress analysis of the wing structure to compute the stresses at spars and ribs due to lifting force on the wing section by modelling the wing structure through SolidWorks 2018 package-simulation.

3. MODELING OF WING STRUCTURE

3.1 Selected wing configuration

A typical trapezoidal aircraft wing was selected when the aircraft flight conditions in the subsonic with Mach number =0.25, the wing structure was modelled in SolidWorks 2018 as shown in Figure 1, with the NACA0012 airfoil shown in Figure 2, we chose this airfoil because its symmetry made it a simple analysis and suitable for studying basic aerodynamic principles without camber effects. The aircraft structure consists of 7 ribs and two spars are shown in Figure 3. The wing body configuration data is shown in Table 1.

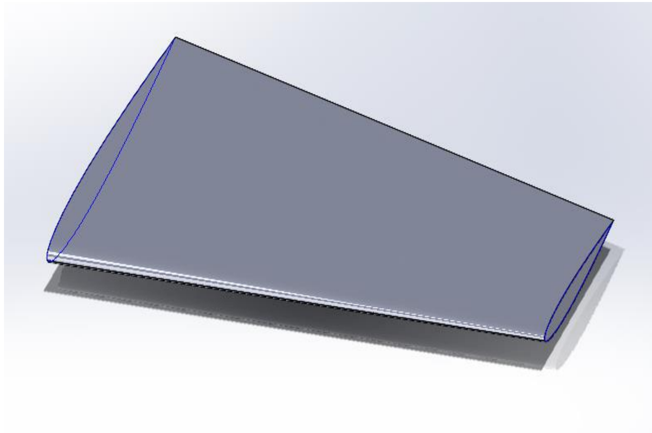


Figure 1. The wing design using SolidWorks-2018

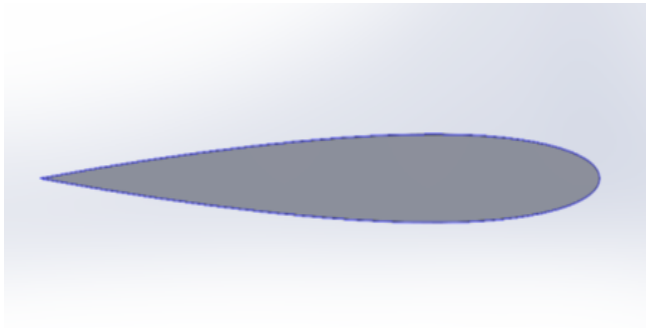


Figure 2. NACA0012 an airfoil wing section

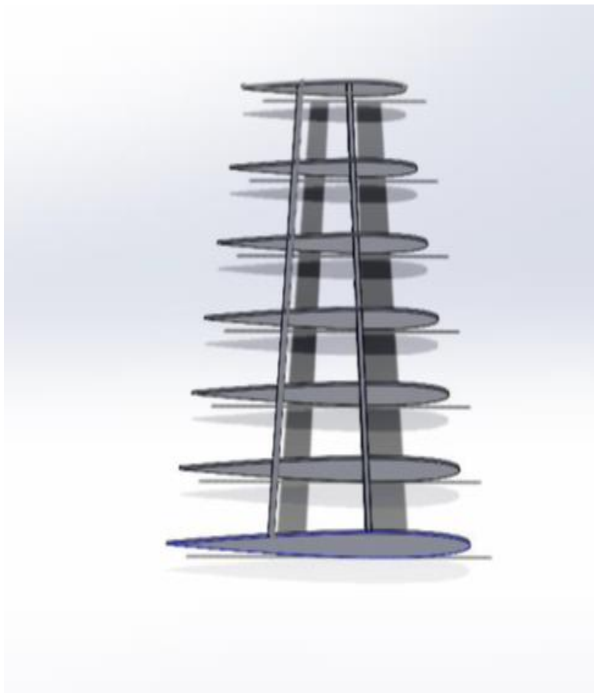


Figure 3. The wing structure

Table 1. The wing body configuration

Wing Span (mm)	3050
Wing Area (mm²)	$1.4*10^6$
Taper Ratio	0.5
Root Chord (mm)	600
Tip Chord (mm)	320
Mean Aerodynamic Chord (mm)	460
Sweep Angle Along Leading Edge	6°
Wing Section Airfoil	NACA0012

3.2 Material used in the wing structure

Different aluminium alloys have been used in many researches [3, 5, 9-11] due to their lightweight nature and cost-effectiveness in the manufacture of aircraft wings. The structure of the wing in this study was made of AL-7075-T6, the properties of the isotropic material that used in modelling the components of the wing are shown in Table 2. The total weight of the wing was equal to 5556.98 grams includes the weight of the skin, spars and ribs.

Table 2. Properties of isotropic material

Material	Young Modulus (N/m²)	Yield Stress (N/m²)	Poisson Ratio	Density (kg/m³)
[AL] 7075-T6	71E+9	470E+6	0.33	2800

4. FINITE ELEMENT ANALYSIS

The Finite Element Method (FEM) is the numerical technique used to solve many engineering problems related to structure and stress analysis for instance a wing structure. Various software programs have been used for this in many researches [2-4, 9-10]. This method describes the behaviour of a component or assembly under specific conditions using static structural analysis and numerical design of an aircraft wing structure [12, 13]. In this paper, this method has been used to find the distribution loads along the span of the wing resulting from the aerodynamic loads that affected on the surface of the wing through using the (VLM) in order to calculate the total lift force and added this effect on the wing in addition to its weight, so the numerical analysis results of the SolidWorks 2018 package that simulates practical results and shows the amount of stress and strain that wing is exposed.

4.1 Aerodynamic loads on the wing structure

To analysis and design a wing structure and determine its stresses, it is necessary determine the total loads that cause the wing structure bend or shear, so the main source of these loads is generated by aerodynamic loads that refer to the forces and pressures on an aircraft wing surface as a result of the air flowing around it during flight. These loads are caused by changes in speed, direction and density of the air surrounding the aircraft during flight, and can cause problems if not handled properly, so the magnitude of these loads is determined by the vortex lattice method that is a numerical technique used in aerodynamics to model and analyze the flow around wings and other lifting surfaces, there are many of researches were used this technique [14-17]. In this paper the lift force was analyzed by dividing the wing surface into several panels (8), (16) and (24) to find a numerical solution of the flow around the wing surface plane was termed the (VLM) that programmed in MATLAB package to produce the load distribution along the semi-span of the right and left-wing and then calculate the total lift force that wing exposed, for each case of dividing the total lift force was calculated in order to know the effect of dividing of wing panels on the resulting of the total lift force, the airfoil of the wing section was assumed to have only one airfoil shape along the span which is NACA0012, the lift force against number of panels is shown in Figure 4, there are many different method to find lift force such as in the study of some researchers [6, 18-21].

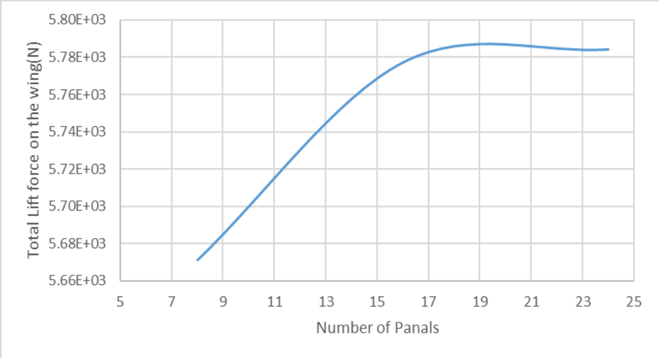


Figure 4. Lift force with different number of panels curve

4.2 The finite element analysis

The geometry of the wing is constructed using SolidWorks-2018 to build the finite element model and diving these elements the material properties as shown in Table 2, setting the boundary condition by fixed the root side of the wing and the aerodynamic loads will be applied on the wing surface and after connecting the elements, the complete model was meshed using free tetrahedral elements for analysis with:

Total of No. of nodes = 40932
No. of elements = 20122
No. of DOF = 243306

The finite element mesh of the wing structure is shown in Figure 5.

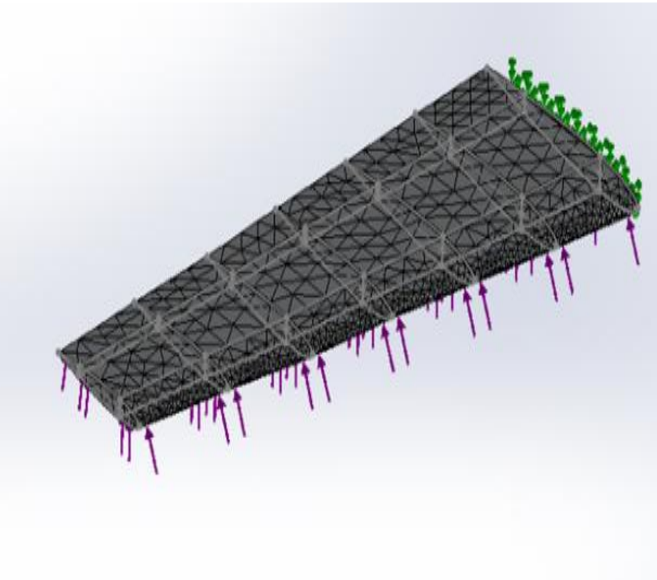


Figure 5. The mesh of the wing structure in the SolidWorks

5. RESULTS AND DISCUSSION

5.1 Results

Modeling the wing through SolidWorks-2018 program considered that it is fixed at the root end so it was be similar to the mathematical model of the cantilever beam. This means that the linear and rotational motion is zero at the root of the wing and free motion at the tip of the wing. The normal force represented the (lift force) was applied to the lower face of the skin of the wing and the mesh parameters was curvature -based, this parameter can improved represent the geometry of the wing, which is important for accurate simulation results, particularly in applications of stress concentrations are influenced by curvature.

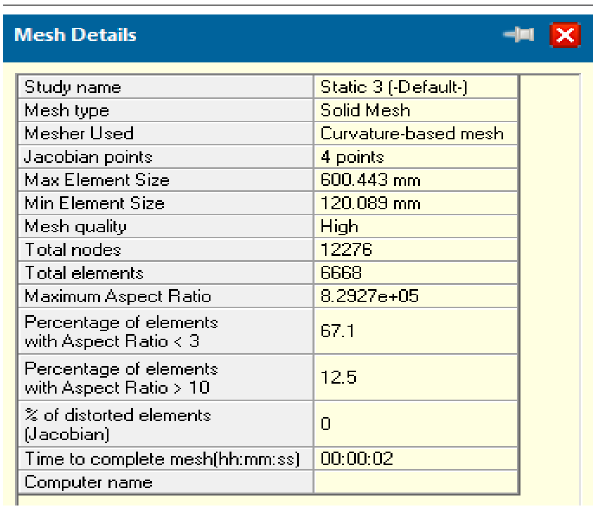
mesh with max. element size=600.44mm

min element size=120.08mm

element size growth ratio=1.6

The mesh details can be shown in Figure 6.

After meshing the wing structure, the stress distribution of the applied aerodynamic loads in addition to weight of the wing has been observed and that exposes the stress was distributed uniformly and we can show that the maximum stress occurred near the root of the wing section .The simulation results in the SolidWorks-2018program showed the amount of von mises stresses and strains as well as the displacement for each of the three divisions (8 panel, 16 panel and 24 panel) on the basis of which the aerodynamic loads imposed on the wing were found, we chose a specific number of panels because the geometry of the proposed wing is simple and does not have a sharp leading edge, requiring more panels. Also, the flow conditions were at low speeds around the aircraft (subsonic), so it required a small number of panels compared to the high speed. Finally, we need a specific time for the simulation, the analysis was carried out and the simulation results are shown in the Table 3.



Mesh Details

Study name	Static 3 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Curvature-based mesh
Jacobian points	4 points
Max Element Size	600.443 mm
Min Element Size	120.089 mm
Mesh quality	High
Total nodes	12276
Total elements	6668
Maximum Aspect Ratio	8.2927e+05
Percentage of elements with Aspect Ratio < 3	67.1
Percentage of elements with Aspect Ratio > 10	12.5
% of distorted elements (Jacobian)	0
Time to complete mesh(hh:mm:ss)	00:00:02
Computer name	

Figure 6. Mesh details

Table 3. The simulation results for different number of panels

No. of Panel	Von Mises Stress (N/m^2)	Strain	Displacement (mm)
8	6.03E+05	3.663E-06	5.656E-01
16	6.14E+05	3.732E-06	5.761E-01
24	6.155E+05	3.736E-06	5.768E-01

The highest von mises stress was obtained from the 24 panels, as it exerted the highest lift force compared to another division of the wing sections when the stress of (24) panel is higher than (16) panel with a rate 0.25% and higher than (8) panel with a higher rate equal to 2% as shown in Figure 7.

We can consider the structure of the wing was safe and stand the stresses that were exposed where the magnitude of the max. Von mises stress obtained from the static analysis is less than the yield strength of the structural material. The strain of the wing structure and its displacement can be shown in Figures 8 and 9.

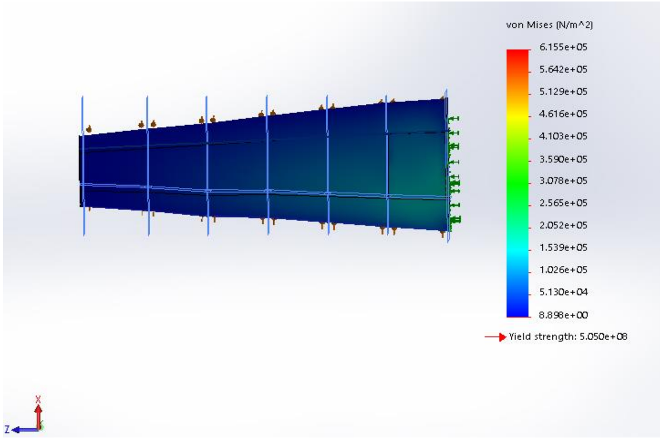


Figure 7. The von mises stress for (24 panels) of wing section

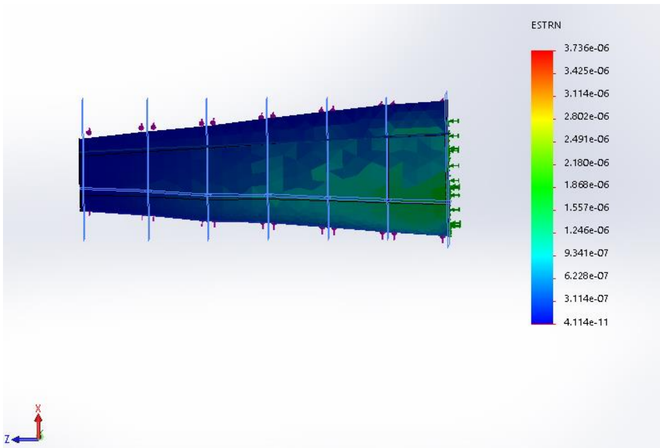


Figure 8. The strain of wing structure

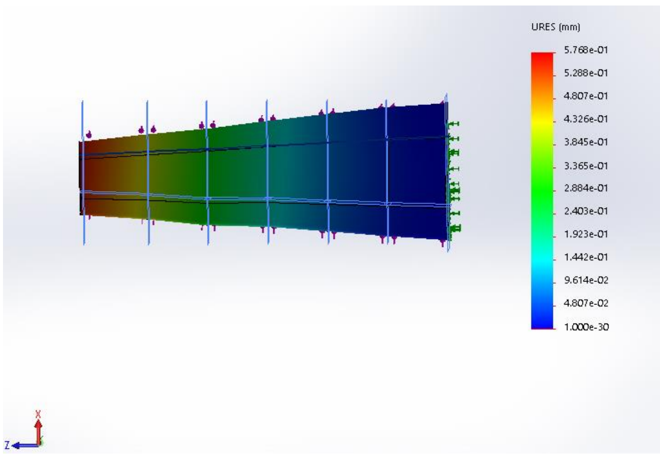


Figure 9. The displacement of wing structure

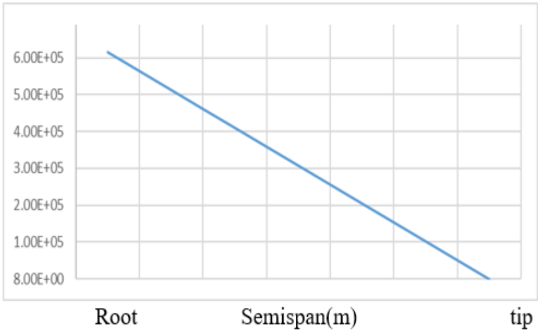


Figure 10. Distribution of Von-mises stresses in (N/m^2) along the wing semi-span

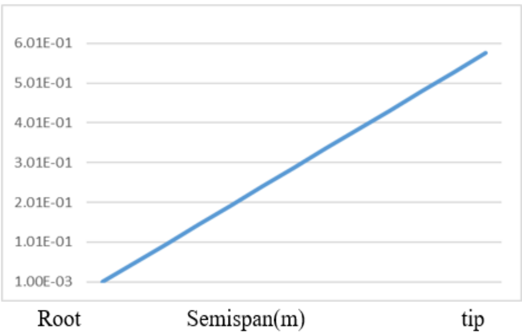


Figure 11. The displacement of the wing semi-span

The stress distribution along the wing semi-span notes the higher stresses occurred near the root of the wing compared to the tip this reason of concentrated of bending moment in this region and to resist this excess stress at the wing root, Therefore, increasing the thickness of the material in this region increases the wing's ability to resist stresses resulting from moments and forces as shown in Figure 10.

While the displacement at the tip of the wing was higher than at its root because of the aerodynamic forces acting on an aircraft wing certainly caused bending deformation, which was a direct result of bending moments also that the wingtip was tapered, which means it had a smaller cross-sectional area compared to the root. This tapering can result in greater deformation at the tip for a given load. as shown in Figure 11.

From the results, we can see that the wing structure design was successful and safe, according to the linear static analysis.

5.2 Discussion

The purpose of this paper is to focus on designing a wing structure with a specific number of ribs and spars and testing its ability to withstand stress taking into account the total weight of the wing and the effect of the aerodynamic loads on it. This procedure was done through finding the effect of different numbers of panels on the results of the total lift force that wing exposed in terms of dividing the surface of the wing into (8, 16 and 24) panels in order to study the effect on the total lift that results and analysis the stress on the wing and conclude the ability of the wing design to withstanding. The von- Mises stresses are deducted for a wing structure to identify the maximum stress accrues before failure and help designers develop the wings of the aircraft. From the results obtained, observed that the high stress was at the root of the wing, the highest amount of stress near the wing's root was caused by a combination of bending loads and wing geometry. Also, we analyze the strain and displacement results to assess the structural integrity of the wing and to ensure that the materials and designs can withstand these stresses without compromising flight safety. even though the stress that occurs in this region still can be characterized as a safety component because the maximum stress that occurs does not permit the yield strength of the material. The present study gives a comprehensive investigation effect on the functioning of the wing structure, in this paper the results of basic simulation tasks are compared to literature values from the past data when they used the (aluminum alloy) as shown in Table 4.

Table 4. The comparison of properties of the current study with different studies

Property	Current Study	Other Studies
Max. Stress(N/m^2)	6.155E+05	318 E+06 [5] 6.180E+08 [9] 16.034 E+06 [10] 4.9898 E+06 [11]
Strain	3.736 E-06	6.606 E-03 [9] 2.2722 E-04 [10]
Displacement (mm)	5.768 E-01	62 [5] 4.99 E+03 [9] 6.7377 [10] 8.112 [11]

It was noted that the Von-Mises stress for wing structure in the study conducted by Atmeh et al. [5] was greater than the stress in the current study this is due to the airfoil that used in that study was NACA23012 and it was created higher stress on the wing structure cause of the high aerodynamic loads generated on it due to camber effects, the stress [10-11] also greater than current study due to the same reason when he used NACA 64A215 and NACA 4415 for the wing airfoil also we noted that the Von-Mises stress for wing structure in the study of Krishna and Priyatham [9] was higher than the Von-Mises stress generated in the current study, because of the applied pressure load on the unit area equivalent to 400,000pa, the load pressure was added without reference to the basis of that addition, in the current study we were applied the loads according to the aerodynamic effect and weight of the wing structure , the distribution of the loads was compatible with the airfoil of the wing and the load will be distributed over all of the wing surface areas with value 5.784 E+03 N, so the different of airfoil and geometry of both studies will cause the different in the results even though the structures were made of the same material. We also note that the displacement generated as a result of these loads is acceptable compared to previous studies, especially since the wing length is approximately 1.5 meters and the generated displacement is 3.736e-01mm.

6. CONCLUSION

(1) The simulation results of the model through SolidWorks -2018 of the current study are compared with other studies as shown in Table 4 and showed the influence of airfoil selected on the stress analysis results where the current study taking into account the effect of aerodynamic loads and wing structure weight together in order to asset the results also, we can note the impact of geometry of the wing structure on the results.

(2) The model aircraft wing was safe. It withstanding with a structure containing 2-spar, 8-ribs and made of aluminium

alloy without the need to increase structural components, so we worked on reducing the weight and cost of the wing design.

(3) In the current study, the distribution of loads to which the wing is exposed during subsonic flight was improved when the Vortex Lattice method was taken into account and the extent of the effect of the number of panels on the distribution of loads on the wing. The structural weight of the wing was added during the analysis, which helps in designing the wing structure properly to better ensure its ability to withstand the stress and loads associated with flight.

(4) The SolidWorks model can successively assist in studying the aircraft wing, which can further support improving the design when the optimization technique can be used to improve wing geometry and optimize the shape and structure of the wing, so that the maximum possible performance is achieved while using the least amount of material.

(5) Future work should extend these findings by dynamic analysis requirements to be carried out along with static analysis validation for a comprehensive investigation such as fatigue life of aircraft wing.

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NOMENCLATURE

NACA	National Advisory Committee for Aeronautics
VLM	Vortex Lattice Method
DOF	Degree of Freedom