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Comparative Analysis of Aerodynamic and Structural Performance of Aircraft Wings Using Boron Aluminum Metal Matrix Composites and Aluminum Alloys: A CFD and FSI Approach

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Abstract: The aerodynamic and structural performance of aircraft wings constructed from Boron Aluminum Metal Matrix Composites (Boron Al MMC) and conventional aluminum alloys has been comprehensively evaluated through Computational Fluid Dynamics (CFD) and Fluid-Structure Interaction (FSI) studies. The CFD analysis was conducted using ANSYS CFX to investigate the aerodynamic behavior, while the FSI analysis was performed using ANSYS Structural to assess the interaction between fluid flow and structural response under various loading conditions. The findings have demonstrated that wings composed of Boron Al MMC exhibit superior performance in terms of strength, stiffness, and durability when compared to aluminum alloys. Under similar aerodynamic loads, the Boron Al MMC material maintained higher structural integrity, demonstrating a 2.28% reduction in equivalent stress, a 30.1% decrease in induced shear stress, a 69.12% reduction in induced deformation, and a 66.35% lower strain energy relative to the aluminum alloy. These results suggest that Boron Al MMC offers enhanced structural stability at high speeds, especially at speeds exceeding Mach 1, as well as under diverse flight conditions involving high G-forces. The significant reduction in deformation and stress concentrations indicates that Boron Al MMC provides improved resilience against damage under high aerodynamic loads. This analysis underlines the potential of Boron Al MMC as a promising material for aircraft wing construction, capable of delivering improved aerodynamic performance, extended service life, and heightened safety margins. Such properties make it a viable alternative to traditional materials, particularly in advanced aerospace applications where strength, stiffness, and durability are critical. The integration of Boron Al MMC could lead to significant advancements in the development of more efficient and reliable aircraft wings.

Keywords: Fluid-Structure Interaction (FSI) studies, Aircraft; Composites; Aircraft wings; Computational Fluid Dynamics (CFD) analysis; Boron Al Metal Matrix Composites (Boron Al MMC); Aluminum alloy; Aerodynamic characteristics; Structural integrity

1 Introduction

An aircraft wing is an essential structural part of an aircraft, which is most critical to the lift force and stability of the aircraft [1]. Being one of the main sources of lift, the wing structure and its purpose are critical for the performance of the aircraft. Lift is the force that allows an aircraft to stand off the ground and maintain this position, and it is created by the wings. Besides, this interaction can be described in the light of Bernoulli, and it refers to the principle where the speeds of the airflow over and below the wing differ, and this causes the variation in air pressures, which in turn is responsible for the production of the lift [2]. In order to explain the multifaceted nature of wing performance, we need to take into account the forming aerodynamic and structural conditions that the wing has to experience during the flight. At the stage of takeoff, the wing has to produce enough lift to counteract the weight of the aircraft and ensure it gets into the air. This has to make the wing fly at high angles of attack and develop a large amount of lift force. However, during the cruise, the wing design must optimize the lift-to-drag ratio to enable efficiency and the best consumption of fuel and other resources [3]. Lastly, in the landing phase, the wing needs to give a controlled lift and stability to enable it to touch the ground and then accommodate changes in the airflow and load distribution. The lift-to-drag ratio of a wing depends on parameters such as the wing's geometry, dimensions, and the nature of the wing surface [4]. High-lift devices are also utilized to increase aircraft performance, in addition to aerodynamic winglets and variable camber control for varying flight situations. Computer simulations with effective tools such as ANSYS CFX are helpful for airflow and wing flow patterns that can explain pressures acting, flow separation, and other aerodynamic parameters of the wing [5]. This approach is useful in fine-tuning wing shapes and wing configurations to meet certain performance characteristics [6]. At the same time, the wing has to sustain the heavy structural loading that is characteristic of flight. Such loads include forces acting on the wings because of the air pressure, body force due to gravity, and forces that occur due to movements of the aircraft as well as turbulence [7]. The wing structure is one of the most important components of an aircraft and must be designed to have huge structural strength as compared to its weight, with the help of modern strong materials and construction techniques [8]. An advanced dynamic software package like ANSYS Structural is employed in using finite element analysis (FEA) that helps in determining the structures' response to different load cases regarding the wings [9]. This makes it easier to assess the loads that the car is likely to experience, and this result helps the design team to assess the stresses and strains of the car and areas that are possible to fail, thus the design team can make constraints that will make the car safer and more durable. The combination of CFD and FEA analysis provides a full range of aerodynamic and structural performances of the wing, which are crucial to the design of the wing [10]. With these computational solutions, engineers enhance the last design in aspects of aerodynamic performance, structural integrity, and flight reliability. The progress of computational techniques and material science and engineering empowers change in aircraft wing design and in the fabrication of improved, reliable aircraft. Current trends in aircraft wing design have been informed by several new rationales that help in improving the wing's aerodynamics and strength. These experimental methods were directed toward flight control, design configuration, and dynamic modeling of unmanned morphing aircraft by Chu et al. [11]. The changes that they proposed for the wings showed that such a concept can enhance the aerodynamic performance by up to 7%. The study emphasized that shape-shifting wings could be operated flexibly for changing flight situations in the future, which will be useful as a standard for the development of new models. In the work done by Yin [12], FEM was employed in the numerical study of the aircraft wing skin. A review of their findings showed that deformation and pressure distributions on the skin of the wing were low; the maximum skin deformation occurring at the points of maximum pressure is less than 0. Chord thickness: originating from 1% of the chord length. To strengthen the skin material, they put forward solutions allowing for the increase of in-plane stiffness necessary for the construction of the robust wings that can successfully counteract the aerodynamic loads. Monner [13] researched the development of transonic wings for commercial aircraft. The transonic wing design aircraft has fixed geometry that is optimized for altitude, Mach number, and weight of the aircraft. Due to the variation of these aerodynamic characteristics during flight operation, the optimal design of the wing is practically not possible. The possible variation of aircraft wing can be attained by varying chord length and span length of wing camber. The varying camber improves the aerodynamic characteristics of the wing by 3.8%.

Regarding morphing airframes and specifically the wings, Grigorie et al. [14] studied the utilization of smart materials – shape memory alloys - for morphing wings driven by actuators that were incorporated in a fuzzy logic PD controller. Their work focused on aeroelasticity, flight control, and how autostability can be improved by applying adaptive surfaces and composite materials, to show that morphing concepts can improve flight dynamics by seven. A specific improvement of 9% in the lift-to-drag ratio over conventional designs has been achieved. From this study, it was possible to reveal the need for the application of better materials and the possibility of enhancing a control system to achieve more efficient flight of wings. Popov et al. [15] investigated the effects of airfoil geometry changes in reducing the induced drag problem with consideration of the WTEA-TE1 airfoil. They used a single-point control method to control the reattachment point of the laminar to turbulent flow and found a significant reduction of the drag. They underlined that redesigning for enhanced aerodynamic efficiency should be combined with the change of other parameters that define drag, lift, and thrust within certain acceptable boundaries. Popov et al. [16] performed experimental wind tunnel tests on the WTEA airfoil to understand the flow behavior over the flexible composite material mimicking the wing's upper surface. During their testing, varying angles of attack were used, and they gained some knowledge concerning the boundary layer of airflow. Through pressure sensors and memory alloys, the unsteady pressure data were obtained, and thus the phenomenon of aerodynamics can be better explained in relation to the existing conditions.

Sofia et al. [17] considered the application of shape-memory alloys, piezoelectric actuators, and shape-memory polymers in the wings of aircraft [18]. Their findings showed that there is evidence that the use of such materials could cut the aircraft's weight by 11%. 2% as well, and at the same time, the lift-to-weight ratio was to be preferably not lower than. This study showed the research findings on the importance of using advanced materials to improve the wing's aerodynamics and effectiveness. Song et al. [19] classified hydrogen-electric aircraft designs specifically for the decrease in carbon emissions. The techniques that were employed in their research included the Rayleigh-Ritz method for dynamic analysis of both the composite laminated wing-box structures. The FEM analysis defined the composite wings' structural characteristics under elastic boundary conditions and helped in the design of new-generation green aircraft with enhanced structural characteristics. Shahjahan et al. [20] conducted a numerical analysis of multi-rotor tilt-wing propellers utilizing FEM methods. An analysis of normal cruise, transition, and hover conditions they had for the proprietors revealed that those with small chord lengths are more effective and efficient, with a 5.6% increase in hover power. This study adopted the need for a rotor design that would be efficient under a given set of operations. Ejeh et al. [21] studied the effect of angle of incidence on the aerodynamics of twelve-inch propellers. When they disseminated their findings, this thrust was improved by 14.2% with changing disc angles of attack, and at the same time the electric power consumption also slightly decreased. The specific data produced in this work returned useful information about the connection between thrust force and disc angle of attack that can prove useful regarding the refinement of propellers. Yolcular Karaoglu et al. [22] presented research on the application of composite materials in aircraft. The suitability of any material for aircraft depends upon certain important parameters. These parameters include light weight, thermal resistance, good strength-to-weight ratio, and high creep resistance. The aluminum MMCs are becoming a preferred choice for different sections of aircraft, i.e., fuselage, wings, and other vital support structures. Nevertheless, the existing advancements in these areas reveal rather a significant gap in the complete aerodynamic and structural assessment of aircraft wings through CFD-FSI studies. The previous work is designed mainly in terms of aerodynamic efficiency as well as structural optimization separately, in which aspects of both don't complement each other sufficiently. The use of computational models like ANSYS CFX for CFD and ANSYS Structural for FSI in an integrated manner is not being used to its fullest potential, and there is room for improvement in the generalized wing design. This study hypothesizes that employing the use of CFD and FSI in performing the evaluation will provide a more accurate and complete account of analyzing the performance of the aircraft wing. Using the ANSYS CFX tool for aerodynamics and the ANSYS Structural tool for structural objectives, this research expects to maximize the wing forms as well as increase the efficiency of aerodynamics, and structural durability. The following research questions were given consideration:

1- To what extent does the combination of CFD and FSI analyses enhance the effectiveness of the aerodynamic and structural assessments of the wings of aircraft?

2- What are the most important design parameters related to the aerodynamics and structure of the wing throughout the flight conditions?

3- What are suggestions that can be made from the results of combined CFD and FSI that can enhance the wing design for a better lift-to-drag ratio and extend the wing's useful life?

This study proposes a different concept by using both CFD and FSI analysis to assess the aerodynamics and structures of aircraft wings at the same time. Using various tools like ANSYS CFX and ANSYS Structural, the study tries to fill the gap between the aerodynamic performance and structural integrity of the wing. This concept in synergy represents a novel paradigm for addressing wing design optimization, with an engineering approach beyond the mainstream techniques. Existing approaches towards the assessment of the performance of the wings of airships tend to treat aerodynamics and structural properties as distinct, which results in non-optimal solutions that may fail to account for the actual loads and speeds. The situations apart from that indicate that there is a necessity for the integration of the analysis that can combine CFD and FSI to provide the results for aerodynamics and structural behavior. This research seeks to solve it by using a more comprehensive analytical as well as computational approach to the evaluation of aircraft wing designs as a means of improving their performance and safety. The objective of the current research is to evaluate the aerodynamic characteristics and structural characteristics of aircraft wings using CFD and FSI studies. The CFD analysis of aircraft wings is conducted in ANSYS CFX, and the FSI study is conducted using ANSYS structural.

2 Methodology

The analysis of aircraft wings under Computational Fluid Dynamics and Fluid-Structure Interaction is done in pre-process, solution, and post-process steps [23]. The following sections illustrate the specific means, procedures, and reasons for their application when explaining the process of using the aircraft wing with the NACA 0012 airfoil.

2.1 Preprocessing

2.1.1 Wing modeling

To create the wing of the aircraft, the NACA 0012 airfoil profile is implemented with the help of the ANSYS Design Modeler. This choice of airfoil arises from its optimal aerodynamic characteristics as well as its frequent use as a reference airfoil for calibrating other airfoils in aerodynamic tests [24, 25]. The wing is modeled by drawing the 2D airfoil profile and then extruding it to give it the thickness required for a wing. This modeling approach reduces the possibility of the geometric detailing of the airfoil being distorted. The following Figure 1 shows a CAD model of the wing that is used in aircraft.

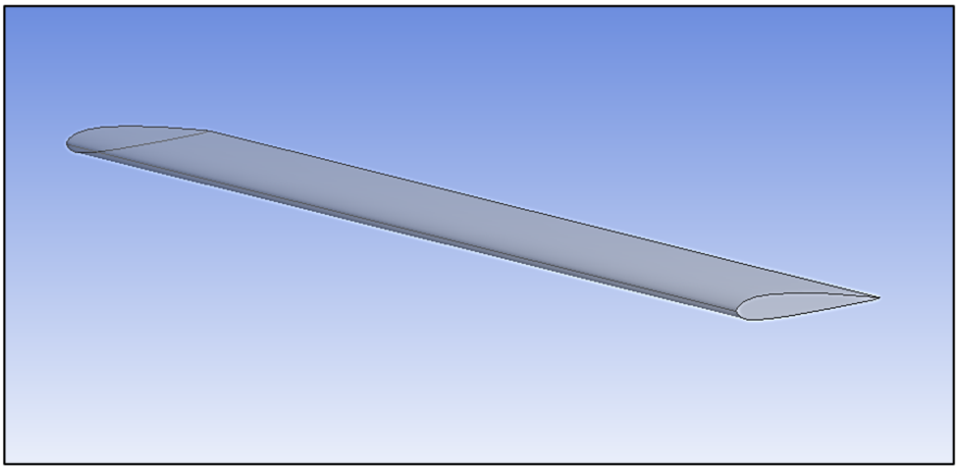

Figure 1. CAD modeling of the aircraft wing

2.1.2 Enclosure modeling

An imaginary bounding around the aircraft wing is employed with a view of outlining the computational domain. The choice as to the size of the model is a measure of 10m×10m×10m, thus allowing sufficient space around the wing whereby undue flow interference from the boundaries of the wind tunnel is eliminated. This size is in accordance with the general procedure for CFD simulation, in which a larger domain reduces the effects of the edges and provides a more realistic flow behavior in the vicinity of the wing. Figure 2 shows the type of enclosure to be used in the model.

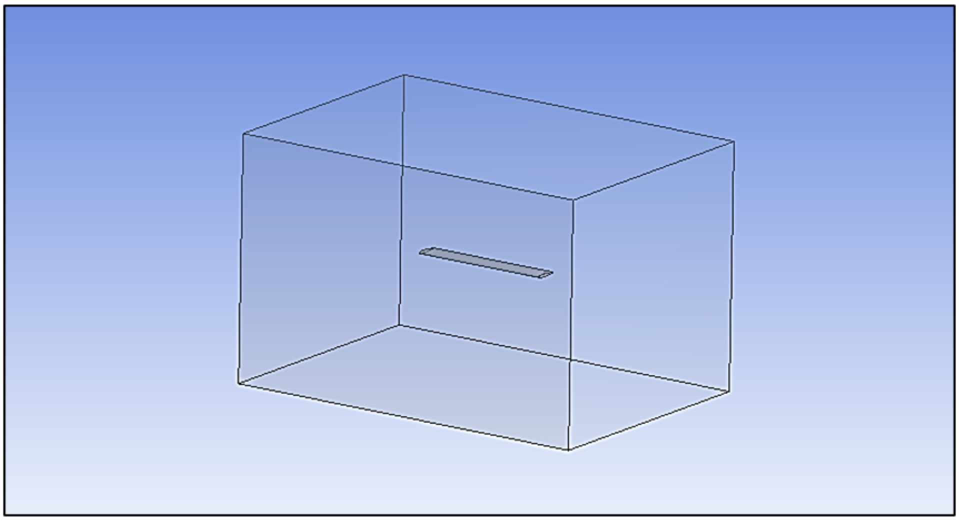

Figure 2. Enclosure modeling of wing

2.1.3 Mesh generation

The computational domain is in the next step discretized into bare tetrahedral because these are relatively unconstrained elements that can model a wide range of geometries [26]. Tetrahedral meshing is quite suitable for accurately capturing the geometry of the wing and the flow field geometry around it. The standard size function of curvature type is used here, and it has been seen that a smaller size of mesh is generated in the region of high curvature like the wing surface. This refinement enhances the level of detail of the aerodynamic predictions since it addresses the boundary layer and, in particular, flow separation. The mesh settings are a relevance center at the medium level, an inflation rate at the normal level, and a and a growth rate of 1.1 to control the range from one to two in order to resolve the conflict between the computer performance and the computational precision. The discretized model in Figure 3 contains 666,465 elements and 156,734 nodes in total. The curvature-based size function was employed, which facilitates finer mesh at the zones of high curvature. Such zones correspond to a location near the leading edge as well as the trailing edge of the wing. The "fine" relevance is set, which enabled enhancement of the mesh density in the vicinity of critical aerodynamic surfaces. This facilitates the capture of boundary layers as well as flow separation. For accurate resolution of boundary layer effects and adequate capturing of near-wall flows, the inflation layers were added. The mesh quality checks were performed, and the meshed model satisfied all the vital parameters. The average skewness of the final mesh attained is 0.22, the aspect ratio was 1.3, the orthogonality was 0.85, and the and the Jacobian ratio was 1.3 with an element quality of 0.88.

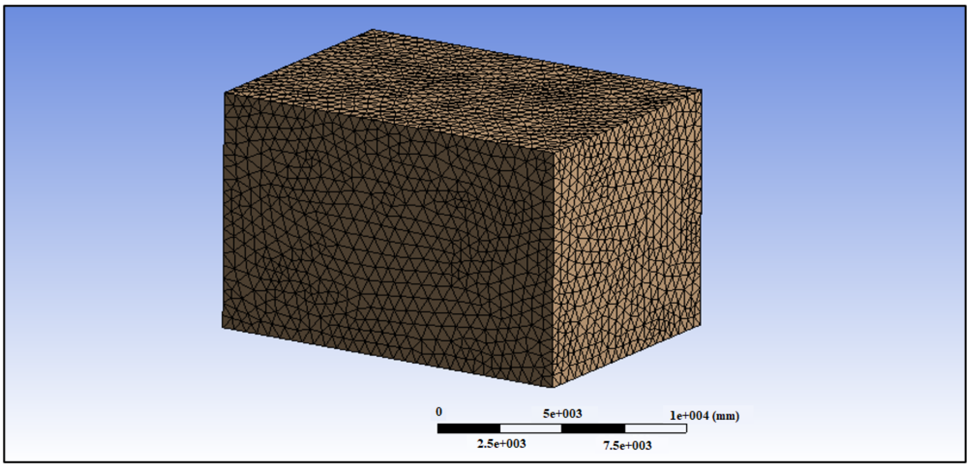

Figure 3. Meshed model of enclosure

2.1.4 Boundary conditions

For the CFD simulation to predict the aerodynamic conditions correctly, the boundary conditions have to be correctly specified. In the air inlet boundary condition, the velocity is kept at 345m/s, which is standard for such flow speed analysis in most flights. A turbulence intensity of 5% is used for interfering turbulence intensity to attain realistic turbulent flow conditions. In this study, the $k - \omega$ turbulence model can be chosen because of the capability of handling the boundary layer and the flow separation [27]. The reference pressure is chosen as 1 atm to match the standard conditions in the atmosphere. The air outlet boundary condition is specified at the relative pressure difference of 0 Pa as for the inlet conditions. The airflow direction is then set orthogonal to the boundary layer in order to model a free stream environment as depicted in Figure 4 and Figure 5.

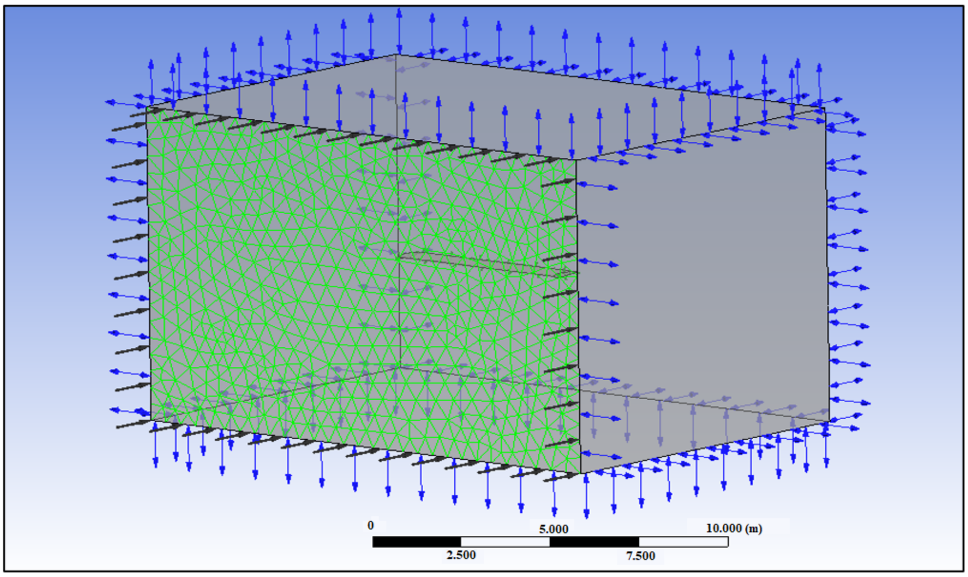

Figure 4. Air inlet boundary condition

2.2 Solver Settings

The CFD simulation is set up with solver parameters to achieve convergence and necessary accuracy levels. Multiple regression analysis is used, and an RMS residual target value of 0.000001 is set to increase the precision of the identified solutions to a great extent. The advection scheme is set to high resolution to increase the order of accuracy of convective flux, which is very important in the resolution of the flow field. The program is continued until the convergence criteria are fulfilled, which helps ensure that the results are accurate for FSI analysis.

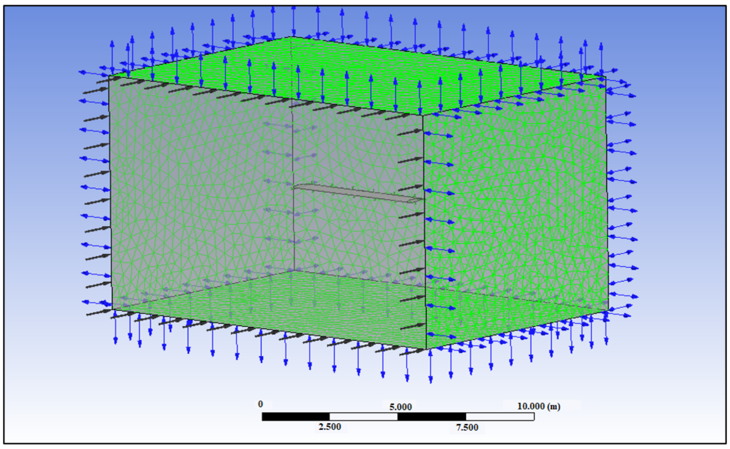

Figure 5. Air outlet boundary condition

2.3 FSI Analysis

After passing through the CFD analysis, the FSI analysis is conducted with the purpose of evaluating the structures' reactions to the loads exerted on the wings. The pressure distribution drawn from CFD simulation at critical locations is then brought onto the wing surface to assess the produced aerodynamic loads. This mapping is very important to know how pressure must be processed by each structure of the wing due to aerodynamics, as illustrated in Figure 6 below.

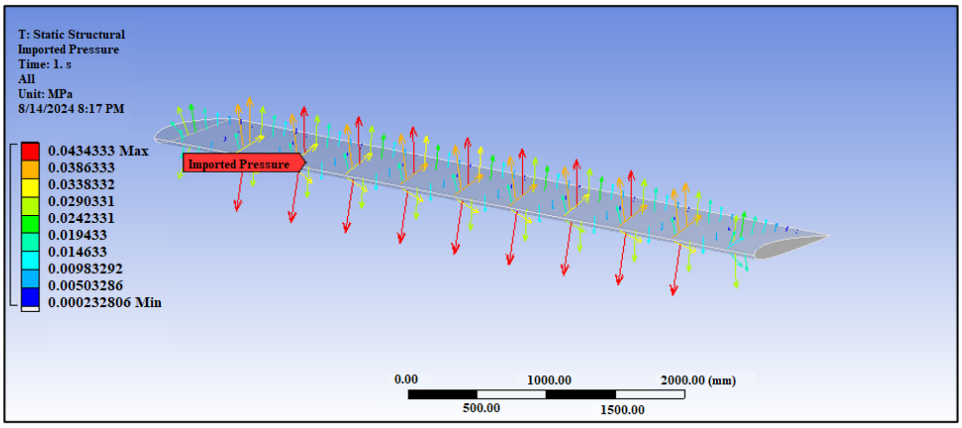

Figure 6. Mapped pressure on an aircraft wing

2.3.1 Wing discretization for FSI

For FSI analysis, the wing is modeled with mesh, which is used for structural analysis to define points of interaction and forces. Fine mesh relevance setting, growth rate of 1.4, and normal inflation settings enhance the setting representation of structural surfaces and precise distribution of stress. The mapped mesh technique that has been accomplished provided the model with 128765 elements and 28763 nodes as depicted in Figure 7 helps in determining the structural response of the model under aerodynamic loading.

2.3.2 Structural boundary conditions

Boundary conditions include structural constraints and support on the left side of the wing in the form of a fixed condition to represent the wing's connection to the fuselage. The fixed support is crucial to correctly predict the aerodynamic loads to which the wing can be subjected and evaluate the structural condition of this structure. The boundary conditions are shown in Figure 8 below.

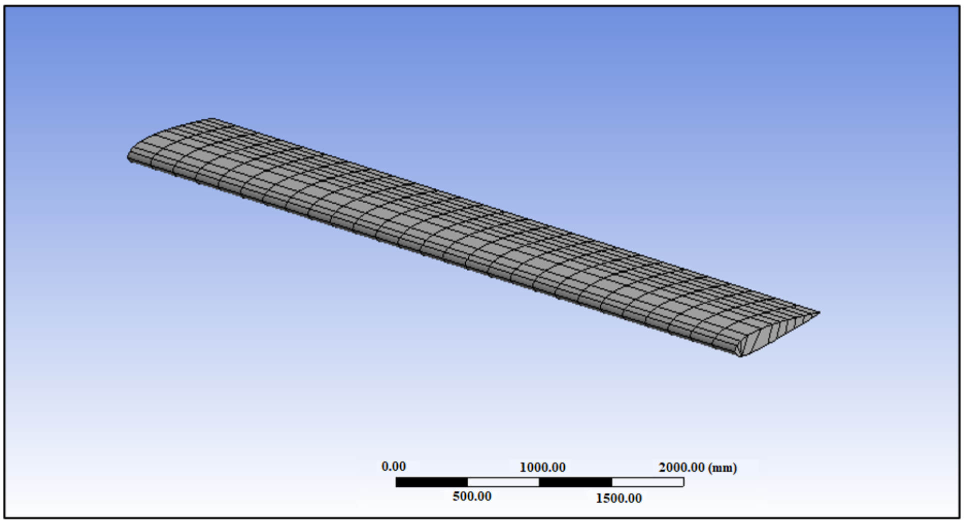

Figure 7. Discretization of aircraft wing

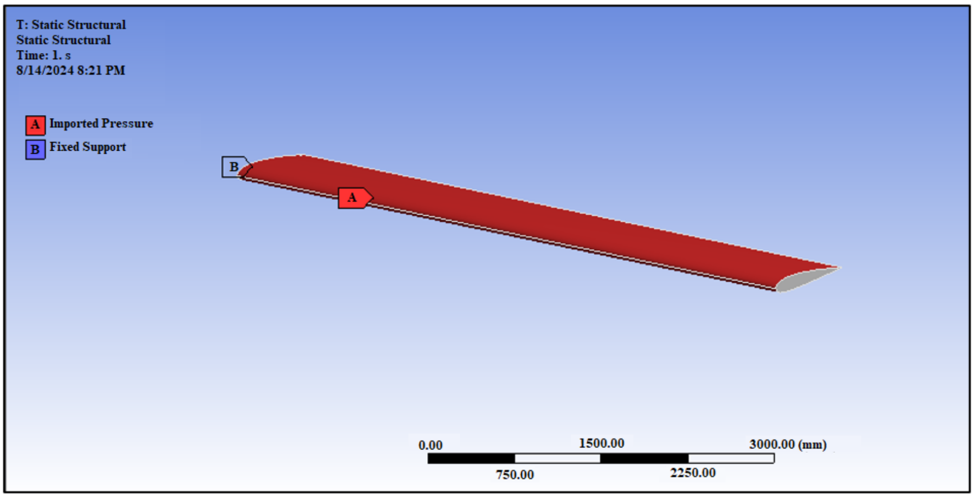

Figure 8. Structural boundary conditions for FSI studies

2.4 Material Properties

Two materials are analyzed in the FSI study: conventional aluminum alloy (2024-T3) and MMC. The material properties are presented in Table 1:

Table 1. Material properties [28]

Material Name	**Modulus of Elasticity**	**Density** $(\mathrm{g/cm^3})$
Aluminum Alloy 2024-T3	72.4 GPa	2.78
Boron Al MMC	235 GPa	2.7

These materials are selected in order to evaluate the structural response of the wing depending on the specific material properties and the influence on the design of the wing.

2.5 Post-Processing

Analysis of the flow field and structure response of the wing through the numerical simulations and then extracting more details from the CFD and FSI simulations are part of post-processing. Optimum parameters of the design, such as lift coefficients, drag coefficients, and structural stresses, that contribute to the efficiency and endurance of the wing design are measured and assessed by software.

The product is verified by calculation based on the theoretical data and the study data to enhance the reliability of the simulation results. The given process of validation helps make sure that the computational models as well as the boundary conditions chosen are appropriate for the given application. The general procedure for the CFD and FSI computation of aircraft wings presented here outlines a general methodology. This process enables one to apply all or any of the aspects of modeling that involve detail, mesh generation and refinement, setting of boundary conditions and contact, and material analysis and characterization to arrive at the most accurate or real solution possible. After applying structural boundary conditions, the simulation process is run. During the simulation process, a sparse matrix solver is selected, which has fast computation and higher reliability of nodal results. The first FSI analysis is conducted using conventional aluminum alloy material, and the second FSI analysis is conducted using metal matrix composite. By using complex types of simulations, it is possible to evaluate such aspects of design as aerodynamics and structure to come up with better wings and their performance.

3 Results

The CFD analysis of the wing of an aircraft proved to ascertain the aerodynamics of the aircraft, including induced pressure, pressure distribution, and velocity fields. All these results provided the foundation for the subsequent FSI study. The convergence of the CFD results was verified with the help of the grid independence test to obtain accurate information for the further stages of the research.

3.1 Pressure Distribution

The pressure distribution on the aircraft wing [4] is illustrated in Figure 9, and it can be observed that pressure concentrations are high near the wing tip, where compressive pressure is 97530 Pa and tensile pressure is 161100 Pa, as depicted in Figure 9. The present results are in very good agreement with published work. This distribution is quite important in determining how the structure is loaded when the plane is flying, and whether there are areas where the force is concentrated. The results obtained are in agreement with the literature [29], which validates our research findings.

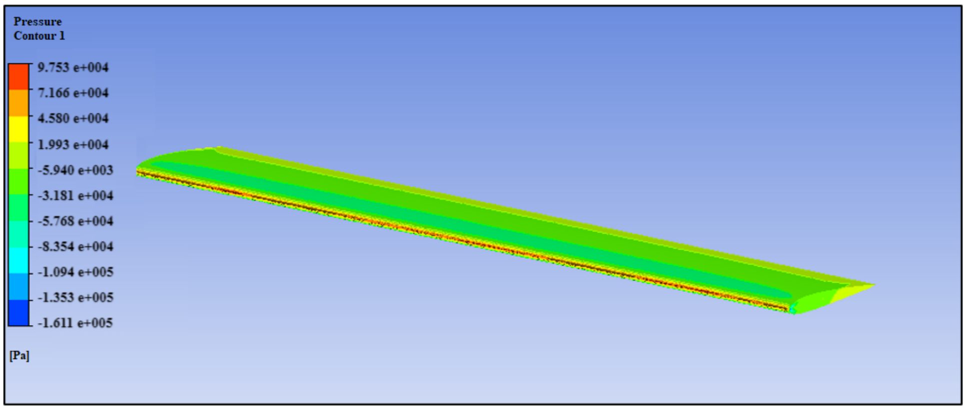

Figure 9. Pressure distribution plot on wing at 0^0 AOA (Angle of Attack)

3.1.1 Pressure field analysis

The distribution of pressure field across a mid-sectional plane is shown in Figure 10 where the pressure variation reached a maximum of 32860 Pa in the leading edge of the wing tip and reduced towards the upper and rear parts of the wing, reaching almost similar pressure at the trailing edge. Such distribution is in harmony with the behavior that is foreseen over the wing for airflow pressure, where there is a variation of pressure between the upper and lower part to form lift. The pressure field distribution for NACA 0012 shows similar distributions as in the literature [30].

3.2 Velocity Field Analysis

The velocity field along the mid-sectional plane is depicted in Figure 11. The maximum velocity of flow was observed at the top of the wing and was equated to 443 m/s; however, at the bottom, the velocity was only 425 m/s. These changes in velocity between the upper and lower surfaces of the wing are a result of the application of Bernoulli's principle and lift production. The velocity distribution also corresponds to the smooth flow over the wing as far as the objective is to maintain aerodynamic efficiency. The velocity field shows a higher magnitude at the top of the wing as represented by the red-colored zone, while the velocity at the bottom zone of the aircraft wing is represented by the yellow-colored zone.

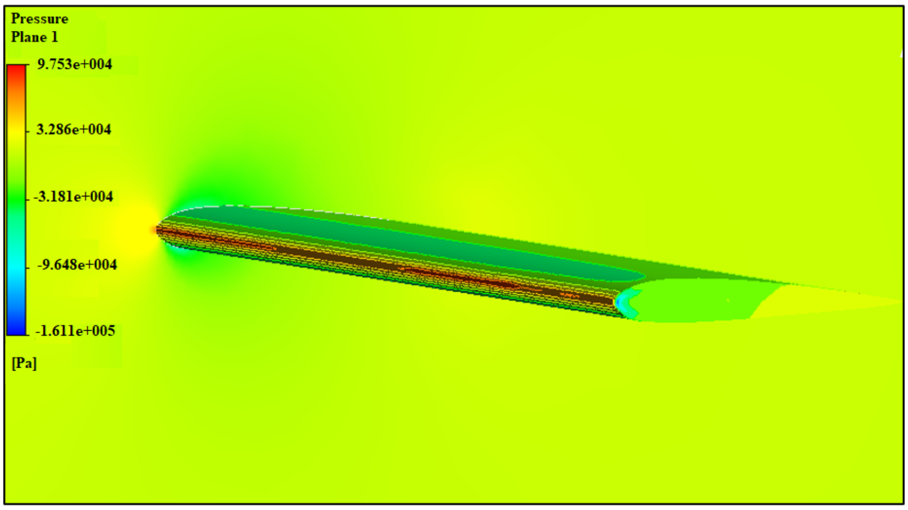

Figure 10. Pressure field across cross-sectional plane 0^0 AOA

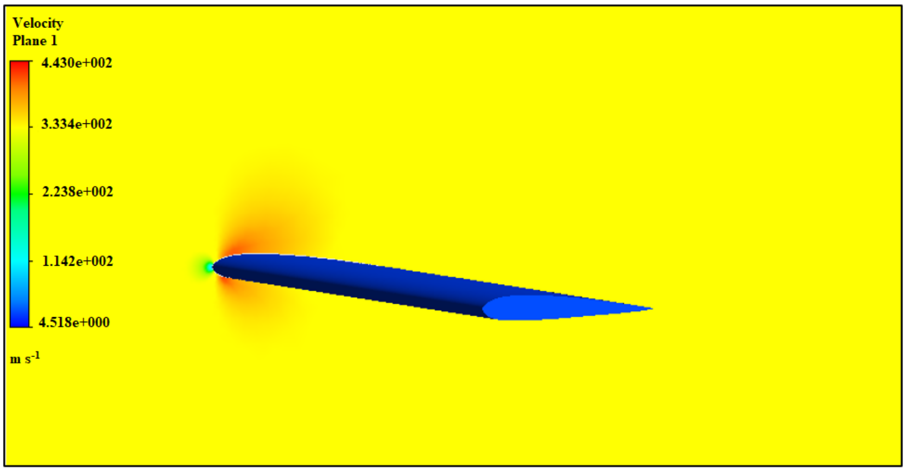

Figure 11. Velocity field across cross-sectional plane 0^0 AOA

3.3 Grid Independence Assessment

A grid independence test was conducted to confirm that the results obtained were not influenced by the grid used in the simulations. As we can also see from the test results, the number of elements increases, the calculated pressure values tend to become stable, and the specific data is given in Table 2. In particular, the pressure was constant at about 97,530 Pa, which corroborates the fact that the adopted mesh was highly accurate in solving the flow physics issues without including extra computational expenses. This step is important so that the rest of the analysis is done as efficiently, and as accurately as possible.

Table 2. Grid independence test

Number of Elements	Pressure (Pa)
126238	97124
127320	97424
127564	97489
128698	97529

3.4 FSI Analysis Results

The FSI studies, obtained through the integration of CFD results with structural analysis, offered quite valuable data regarding stress, deformation, and strain energy distribution. The subsequent step is to conduct FSI studies by coupling the CFX solver with ANSYS structural. From the FSI studies, the output parameters evaluated are equivalent stress, shear stress, total deformation, and strain energy.

3.4.1 Equivalent stress distribution

The distribution of the equivalent stress for the aluminum alloy wing indicated the highest stress around the fuselage-wing intersection, as shown in Figure 12, about 67.9 MPa. The higher stress induced on the left side of the wing near the fuselage is also evident in the literature [31]. It reduces moving away from the fuselage towards the wing-free end, as represented by the dark blue-colored zone. It pointed out that although stress increased toward the middle of the wing, it progressively reduced towards the wing's free end. This distribution of stress around the fuselage region is anticipated because the boundary condition at that particular location is fixed and due to the loading that is exerted on the wing. In the same manner, the stress analysis of the Boron Al MMC wing (Figure 13) exhibited slightly lower stress values with a maximum value of 66.37 MPa, which showed its better load-carrying capacity.

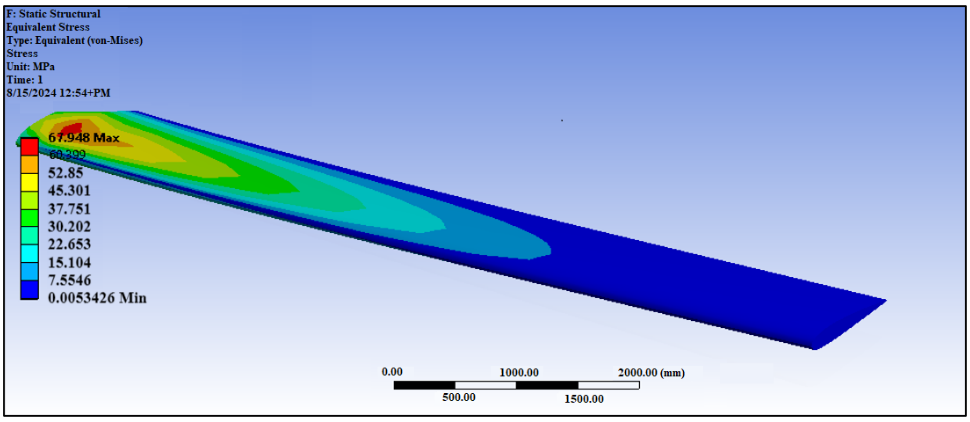

Figure 12. Equivalent stress using aluminum alloy material

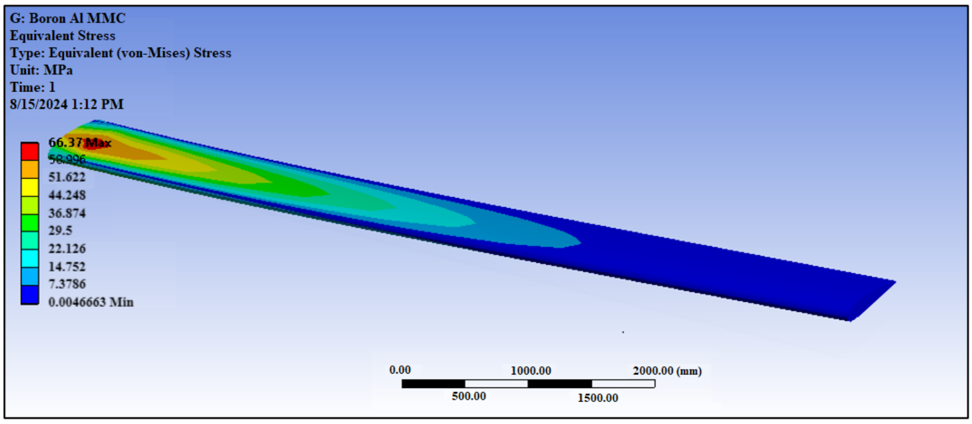

Figure 13. Equivalent stress using Boron Al MMC

3.4.2 Shear stress distribution

The shear stress analysis of both the wing designs is depicted in Figure 14 and Figure 15. It was observed that in both cases the shear stresses were more near the fuselage region, but overall shear stresses were comparatively less in the Boron Al MMC wing, indicating 30.1% less than in the case of the aluminum alloy. This reduction is meaningful in order to avoid the damages due to shear forces, which represent one of the major failure causes of aircraft wings. The shear stress distribution plot is obtained for the entire wing span, as shown in Figure 14. The shear stress distribution plot shows a higher magnitude of shear stress near the fuselage region, with a magnitude of 1.8574 MPa in tensile and 2.2527 MPa in compressive.

The shear stress distribution plot is obtained for the entire wing span using Boron Al MMC material as shown in Figure 15. The shear stress distribution plot shows a higher magnitude of shear stress near the fuselage region, with a magnitude of 1.1709 MPa in tensile and 1.555 MPa in compressive.

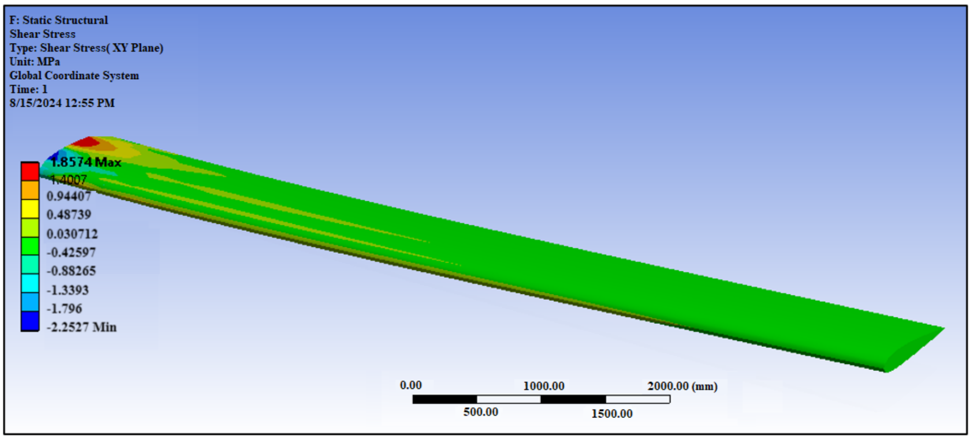

Figure 14. Shear stress using aluminum alloy material

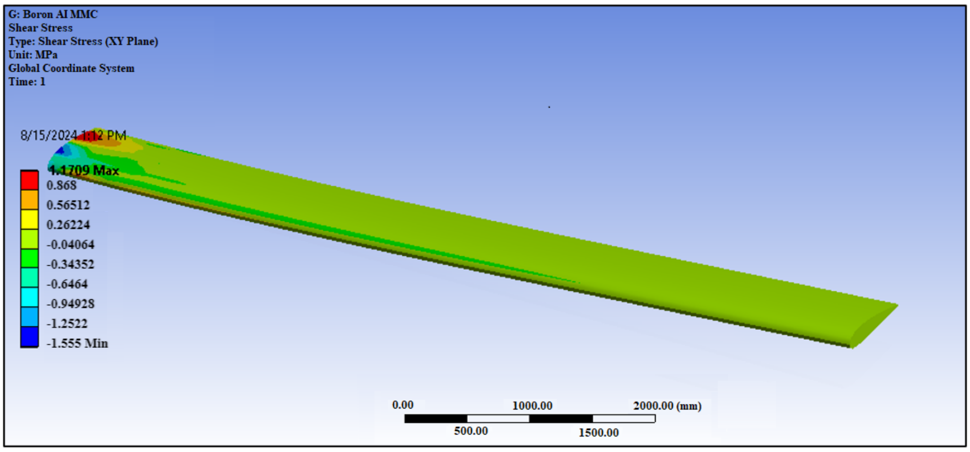

Figure 15. Shear stress using Boron Al MMC

3.4.3 Deformation and strain energy

The total deformation results summed up in Figure 16 and Figure 17 revealed the dissimilarity of behavior between the two types of materials. The total deformation distribution plot is obtained for the entire wing span as shown in Figure 16. The deformation is lower at the fuselage region, which increases successively towards the free end of the wing. The deformation near the fuselage region is nearly 37.4 mm, whereas the deformation at the free end of the wing is 112.47 mm.

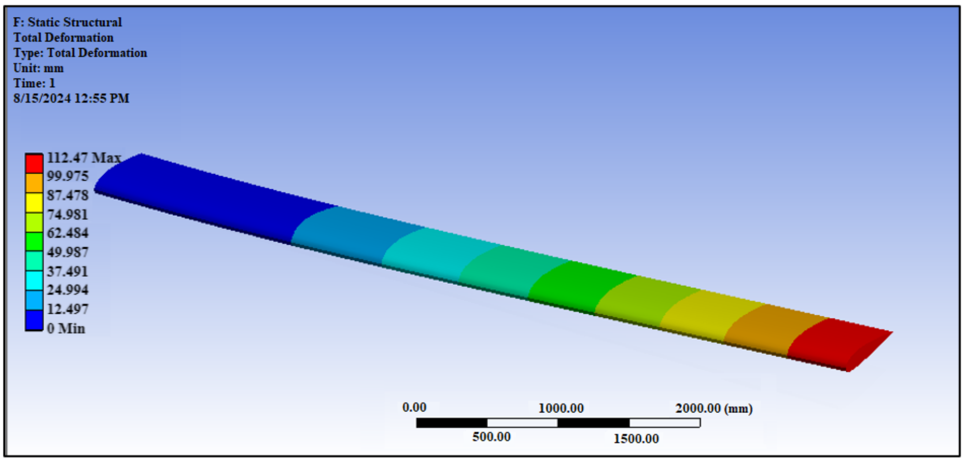

Figure 16. Total deformation using aluminum alloy material

The total deformation distribution plot is obtained for the entire wing span using Boron Al MMC material as shown in Figure 17. The deformation is lower at the fuselage region, which increases successively towards the free end of the wing. The deformation near the fuselage region is nearly 3.83 mm, whereas the deformation at the free end of the wing is 34.47 mm.

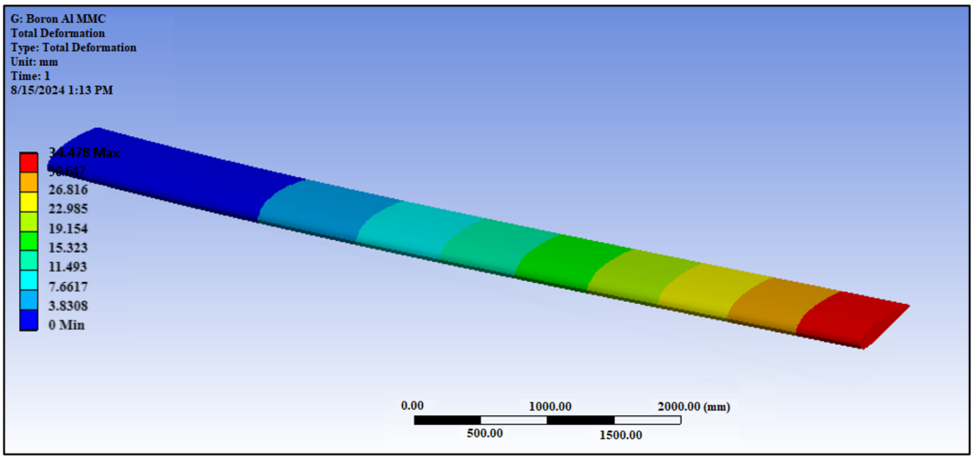

Figure 17. Total deformation using Boron Al MMC

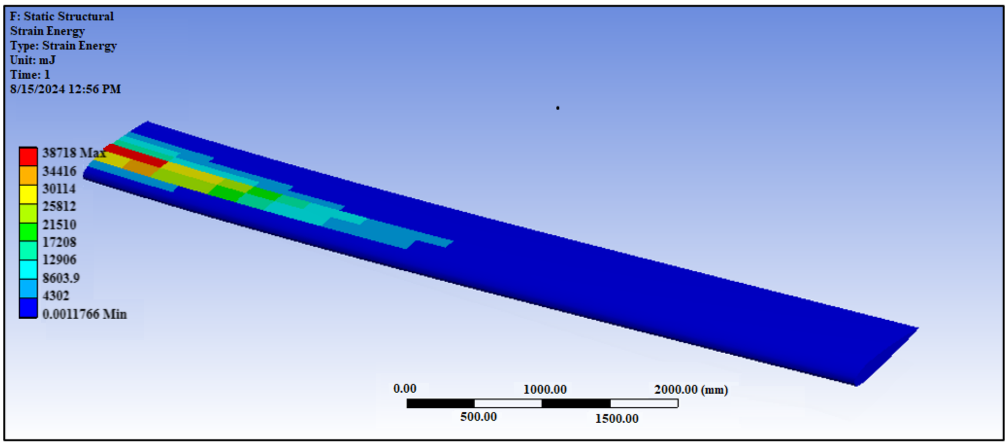

Figure 18. Strain energy using aluminum alloy material

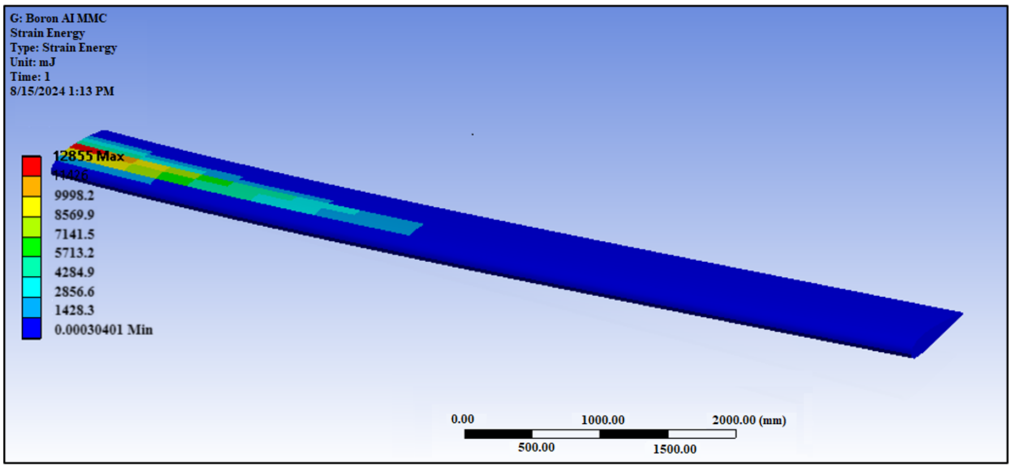

Figure 19. Strain energy using Boron Al MMC

Analysis of the strain energy (Figure 18 and Figure 19) also proved in favor of Boron Al MMC. The total strain energy computed in the aluminum alloy wing was 38,718 mJ, while in the Boron Al MMC wing it was only 12,855 mJ, which is 66% less energy-storing capability, 35% reduction. Lower strain energy means decreased internal energy storage to harm the material under flights, and cyclic loading conditions improve the wing's useful life. As per Figure 18, the higher strain energy is observed near the zone of the wing attached to the fuselage. The maximum strain energy obtained from the analysis is represented in the red and yellow colored zones.

The strain energy distribution plot is obtained for a wing made of Boron-Al alloy material, as shown in Figure 19. The strain energy quantifies the energy stored in the wing when it is subjected to aerodynamic loads. The higher strain energy is observed near the zone of the wing attached to the fuselage. The maximum strain energy obtained from the analysis is represented in the red- and yellow-colored zones.

4 Discussion

It is worth noting that the outcomes observed from CFD work as well as the FSI study correlate with prior theoretical outcomes and studies. The results of engineering analysis for Boron Al MMC material in comparison with conventional aluminum alloy confirmed that it had less stress, deformation, and strain energy and a slight reduction in mass, also making Boron Al MMC a suitable material for aircraft wings with improved mechanical strength and stability without much penalization of weight. Table 3 shows the comparative analysis based on the results obtained.

Table 3. Comparison chart for both materials

Material Type	Eq. Stress (MPa)	Shear Stress (MPa)	Total Deformation (mm)	Strain Energy (mJ)	Mass (Kg)
Aluminum Alloy	67.94	2.25	112.47	38718	1394.5
Boron Al MMC	66.37	1.555	34.47	12855	1359.3

From the comparison chart shown in Table 3, the Boron Al MMC material exhibits 2.28% lower equivalent stress as compared to conventional aluminum alloy material. The induced shear stress on the Boron Al MMC aircraft wing is 30.1% lower than the conventional aluminum alloy aircraft wing, which makes it less susceptible to damages incurred due to high shear stresses. This is vital to prevent material damage to aircraft wings. The induced deformation on the Boron Al MMC aircraft wing is 69.12% lower than conventional aluminum alloy, which signifies higher stiffness for aircraft wings made of Boron Al material. The lower deformation is highly beneficial to maintaining the aerodynamic profile as well as the structural integrity of the aircraft wing. The induced strain energy on the Boron Al MMC aircraft wing is 66.35% lower than that of a conventional aluminum alloy aircraft wing. The lower strain energy of Boron Al MMC signifies better structural resistance to damage and thus ensures a longer life span under cyclic loading conditions. The boron Al MMC wing has a 2.52% lower mass as compared to aluminum alloy wings. The observed results, especially the lower deformation and strain energy, are quite expected due to the higher modulus of elasticity and strength of the Boron Al MMC material. These outcomes can corroborate the hypothesis in relation to the assumption that the choice of complex material such as Boron Al MMC can enhance the efficiency of aircraft wings' structural and aerodynamic characteristics under conditions of flight. Therefore, it can be concluded from the present investigation that the use of Boron Al MMC material is advantageous over conventional aluminum base alloys, especially in suppressing deformation and improving the life of the material. These enhancements are anticipated to enhance the increase of safety and efficiency of airplanes, hence validating the use of high-end composite material in present and evolving aerospace engineering. The higher strength-to-weight ratio of Boron Al MMC provides superior strength as compared to aluminum alloys. The light weight of Boron Al MMC enables the design of lighter aircraft structures. The lightweight aircraft structure signifies higher payload capacity and lower fuel consumption. The even stress distribution on Boron Al MMC offers higher fatigue resistance, which is vital for aircraft wings undergoing repetitive cyclic loads. Besides the boron, Al MMC has other advantages, such as reduced wing deflection of aircraft due to higher stiffness and maintaining optimal shapes. This benefits in improving lift-to-drag ratios of aircraft and ultimately improvement in overall flight efficiency. The Boron Al MMC has good thermal stability, which ensures that the aircraft maintains structural integrity during different flight conditions, specifically at supersonic speeds. As aircraft are meant to operate in harsh environmental conditions, the higher corrosion resistance is vital to reducing the likelihood of corrosion-induced degradation.

The Boron Al MMC has better noise and vibration damping, which can provide better noise and vibration damping properties, which is crucial to having quieter and more comfortable cabins. The boron Al MMC has a higher cost as compared to conventional aluminum alloys, which can be attributed to the high cost of boron fibers. This is a major barrier for commercial aircraft manufacturers to use MMC, which is highly cost-sensitive. In order to justify the use of MMC for aircraft, a detailed cost-benefit analysis can be done. The Boron Al MMC has another limitation pertaining to its manufacturability. The manufacturing process of MMC involves various complicated procedures, including powder metallurgy, diffusion bonding, and fiber replacement bonding. The machining and joining of MMCs is challenging and requires advanced machining techniques such as EDM and laser cutting. The joining of MMCs is also complex and can be attained using special techniques such as adhesive bonding. The use of innovative manufacturing techniques like advanced powder metallurgy, additive manufacturing, and automated fiber replacement is suggested. These methods of manufacturing can mitigate the existing challenges by reducing costs and simplifying the maintenance process.

5 Conclusions

In this work, the CFD & FSI analysis for the aerodynamic and structural of aircraft wings were examined with special reference to aluminum alloy and Boron Al MMC. Therefore, the research hypothesis that postulated that Boron Al MMC would enhance the structural characteristics of the wings of aircraft has been supported by the results attained. The research has centered on the main research questions on the use of Boron Al MMC in the wing structure, stress, deformation, and durability of the aircraft wing structure under aerodynamic loading. This research elucidates that the CFD is a useful technique in determining the aerodynamics of the aerofoil wings of aircraft. The research findings have shown that aircraft made of Boron Al MMC exhibited superior performance with respect to strength, stiffness, and durability. Under similar loading conditions, the Boron Al MMC maintained higher structural integrity as compared to the aluminum alloy. The enhanced structural integrity using Boron Al MMC signifies stable aerodynamic characteristics at higher speeds. The Boron Al MMC material exhibits 2.28% lower equivalent stress, 30.1% lower induced shear stress, 69.12% lower induced deformation, and 66.35% lower strain energy as compared to aluminum alloy. The boron Al MMC wing has a 2.52% lower mass as compared to aluminum alloy wings. These research findings are indicative of the superior properties of Boron Al MMC in enhancing the structural integrity, stiffness, and durability of the aircraft wing. This makes aircraft wings less prone to damage at high aerodynamic loads (especially over Mach 1 speed) and also at different flight operating conditions (high G forces). Overall, Boron Al MMC is a promising material to be used in aircraft wings, which can offer longevity and improved performance. These outcomes evidence that Boron Al MMC provides the highest strength and stiff and durable nature, which make Boron Al MMC more suitable for usage in aircraft wings. Optimization of the microstructure of Boron Al MMC makes it possible to provide a stable flight with minimal changes in aerodynamics, increasing speed, and flight conditions. This places Boron Al MMC as a competent material that can be used in place of conventional materials in aerospace applications. However, some limitations of this study were identified as follows: It is important to note that these simulations were carried out on perfect conditions, and the effects of manufacturing tolerances, environmental effects, fatigue, etc. were not considered exhaustively. Further research can be dedicated to the study of the aforementioned aspects as well as to extending the research to other types of high-performance composites. Expanded studies should be directed at the description of such characteristics that define the performance of the vehicle, such as lift-to-drag ratios, stress distribution, and deformation at different conditions. A parametric study for variation in flight details and wing designs will enhance the generalization of the results. Furthermore, researching the possibility of diminishing manufacturing costs and the complexity of structures using new-generation manufacturing methodologies and evaluating the lifecycle of structures in terms of performance will add to the application of Boron Al MMC in aerospace engineering.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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