

Dynamic–Fatigue Reliability Analysis of Aircraft Fuselage Structures Using Advanced Composite and Fiber–Metal Laminate Materials

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Abstract

Aircraft fuselage structures are among the most critical load-bearing components in aerospace engineering, as they must safely withstand internal pressurization, aerodynamic forces, vibration, and repeated cyclic loading throughout service life. Traditionally, aircraft fuselages were manufactured using conventional metallic materials, particularly aluminum alloys, because of their favourable strength-to-weight ratio, ease of fabrication, and widespread industrial acceptance. Over time, however, increasing demands for lightweight structures, improved fatigue resistance, and reduced maintenance have driven the aerospace industry toward advanced composite and hybrid materials. Despite the long-standing use of conventional alloys, fuselage structures remain highly susceptible to fatigue damage, stress concentration, and deformation under dynamic operating conditions, which can reduce structural life and compromise safety. Traditional material systems such as aluminum alloy fuselages often exhibit higher cyclic damage accumulation, greater stress levels, and lower long-term durability under fluctuating loads, making them less suitable for next-generation aircraft applications. Hence, there is a growing need to identify and evaluate alternative fuselage materials that offer improved structural efficiency, fatigue performance, and dynamic stability. This study presents a comparative finite element analysis of an aircraft fuselage structure using three different materials: Aluminum Alloy 7075, Carbon Fiber, and GLARE (Glass Laminate Aluminum Reinforced Epoxy). A three-dimensional fuselage model was developed in SolidWorks and imported into ANSYS for

detailed finite element evaluation. Static, fatigue, and transient dynamic analyses were carried out to assess deformation, equivalent stress, hoop stress, longitudinal stress, strain, fatigue damage, and safety factor under varying operating conditions. The proposed system aims to identify the most suitable material for aircraft fuselage applications by comparing structural behavior across all three materials. Results demonstrate that GLARE exhibits lower deformation, reduced stress concentration, lower fatigue damage, and higher safety factor than Aluminum Alloy 7075 and Carbon Fiber. The study establishes GLARE as a superior material for fuselage applications, offering enhanced structural reliability, longer service life, and improved performance for modern aerospace structures.

Keywords: Aircraft fuselage, finite element analysis, Aluminum Alloy 7075, carbon fiber, GLARE, fatigue analysis, transient dynamic analysis, structural deformation, stress analysis.

1. Introduction

Aircraft structural design is one of the most complex and multidisciplinary tasks in aerospace engineering, requiring the integration of aerodynamic efficiency, structural integrity, safety, manufacturability, and operational economy. Among all aircraft components, the fuselage plays a central role as the primary structural body that connects and supports major subsystems such as the wings, empennage, landing gear, propulsion system, crew cabin, and payload section. The design of a fuselage must therefore satisfy multiple and often conflicting requirements, including minimum structural weight, maximum load-carrying capability, resistance to environmental effects, passenger

safety, and long-term service durability. As aircraft technology has advanced, fuselage design has evolved from simple metallic shells into highly optimized structural systems capable of withstanding complex loading environments over extended operational lifespans.



Figure. 1: Aircraft structure

In modern aircraft, the fuselage is subjected to a wide variety of mechanical and environmental loads during service. These include internal cabin pressurization, aerodynamic drag, bending loads, torsional loads, landing impact forces, vibration, and repeated cyclic stresses caused by takeoff, flight, and landing operations. In addition to mechanical loads, fuselage structures must also resist corrosion, temperature variation, lightning strikes, and material degradation caused by long-term exposure to harsh atmospheric conditions, as shown in Figure 1. Because of these demanding service conditions, the fuselage must be designed to provide high stiffness, strength, and fatigue resistance while maintaining low structural weight to improve fuel efficiency and reduce operating cost. The most widely adopted structural configuration for modern aircraft fuselages is the semi-monocoque construction, which offers an efficient balance between strength and weight. In this configuration, the outer skin carries a significant portion of the applied loads and is reinforced internally by structural members such as bulkheads, frames, stringers, and longerons. These stiffening elements improve the load-carrying capability of the fuselage, prevent local buckling, and enhance overall rigidity. Traditionally, semi-monocoque fuselages have been manufactured using

aluminum alloys due to their favorable strength-to-weight ratio and ease of fabrication. However, the increasing demand for lighter, stronger, and more fatigue-resistant aircraft structures has led to the exploration of advanced materials such as carbon fiber composites and hybrid laminates like GLARE for improved fuselage performance.

2. Literature Review

Vishal Sagar, et al. [1] This paper describes a conceptual design and analysis of fuselage structure for A320 NEO (New Engine Option) aircraft by using Solid works and ANSYS software as a design tool. Specific size, configuration arrangements, weight and performance and some commonality of features with existing A320 aircrafts are need to be considered in the design process. This conceptual design develops the first general size and configuration for a new A320 NEO aircraft fuselage structure. The model of the fuselage structure is then undergoing model analysis, linear buckling and fatigue life. Yung Cheng, et al. [2] The flying-wing is a type of configuration which is a tailless airplane accommodating all of its parts within the outline of a single airfoil. Theoretically, it has the most aerodynamic efficiency. The fuel consumption can be more efficient than the existed conventional airliner. It seems that this configuration can achieve the above mentioned requirements.

Dr.-Ing, et al. [3] Experiences in modeling and development of methods for the nonlinear finite element analysis of the loading behavior of aircraft fuselage panels are presented. Simulations were performed using panels with especially developed aircraft like boundary conditions. Detection of maximum load is influenced by the way the load is applied in connection with appropriate imperfections. M. M. Nadakatti, et al. [4] Catastrophic structural failures in many engineering fields like aircraft, automobile and ships are primarily due to fatigue. Where any structure experiences fluctuating loading during service its load carrying capacity

decreases due to a process known as fatigue. Fatigue damage accumulates during every cycle of loading the structure experiences during its operation. When this accumulated damage reaches a critical value, a fatigue crack appears on the structure under service loading.

Gary L, et al. [5] A design-oriented analysis capability for aircraft fuselage structures that utilizes equivalent plate methodology is described. This new capability is implemented as an addition to the existing wing analysis procedure in the Equivalent Laminated Plate Solution (ELAPS) computer code. The wing and fuselage analyses are combined to model entire airframes. The paper focuses on the fuselage model definition, the associated analytical formulation and the approach used to couple the wing and fuselage analyses. The modeling approach used to minimize the amount of preparation of input data by the user and to facilitate the making of design changes is described. The fuselage analysis is based on ring and shell equations but the procedure is formulated to be analogous to that used for plates in order to take advantage of the existing code in ELAPS. Connector springs are used to couple the wing and fuselage models. Wilhelm Rust, et al. [6] Wider parts of the fuselage of a commercial aircraft are subject to shear and compression loads in such a way that this is relevant for dimensioning. First elastic, later plastic buckling can appear. The ultimate load is reached when a combined buckling of skin and longitudinal reinforcements (stringers) leads to failure of a panel. This behavior is tested physically, but over years CAD-FEM and Airbus Deutschland worked together to simulate the test and analyze further configurations under aircraft-like conditions with ANSYS. The paper describes which difficulties had to be overcome to achieve convergence and obtain reliable ultimate loads. The advantages and disadvantages of different load and solution control features such as force or displacement control, arclength method, different

ways of incrementing are lined out as well as different kinds of imperfections. Furthermore, the use of linear buckling and Eigen value extraction at some stages of non-linear analysis is considered.

Khairi Yusuf, et al. [7] This paper describes a conceptual design of fuselage structure for very light jet aircraft by using CAD software as the design tool. Specific size and performance, the number of competing designs and the commonality of features with existing light jet aircraft are factors need to be considered in the design process. This conceptual design develops the first general size and configuration for a new light jet aircraft fuselage structure. The model of the fuselage structure is then undergoing engineering simulation programmed which is based on the finite element method. In this analysis, problems with multiple components are modeled by associating the geometry defining each component with the appropriate material model and specifying component interaction. Besides that, the load increments and convergence tolerance are continually adjusted to ensure an accurate solution is obtained. Yii-Mei, Huang et al. [8] tackles the technique of passive sound management systems. Their main objective was to design dynamic dampening absorbers to eliminate fuselage vibrations generated from external influences like propellers etc. They evaluated the appropriate parameters to be chosen in design process of the absorbers, to optimally keep the vibrations and noise generated it a minimum. They primarily constructed mathematical algorithms for the motion, vibrations, interior sound field and the external forces that affect the cylindrical fuselage. These were further used to determine the optimal design and placement of the absorbers. By considering kinetic energy and potential energy of the fuselage and the sound field as objective functions, they concluded that their approach had a major impact in reducing the undesirable noise in the fuselage structure.

ParthaDey, et al. [9] understands the stability of composite skew plates when subjected to loads. The dynamic stability of composite skew plates was analyzed using four-noded shear flexible quadrilateral plate. Finite element equations of the plate were formulated. Gaussian integration rule was used to calculate matrices for elemental mass and linear-geometric stiffness. First and second order dynamic instability boundaries were then identified. The identified principal stability region was four times the secondary instable region. As load amplitude increased, the first and the second order approximations differed. Region of instability increased with the increase in skew angle. The paper lays out the influence skew angle, lay-up and static in plane loads have on dynamic stability. Zhiquan LI, et al. [10] with previous research on tiltrotors as a basis, intended to construct a full-span model tiltrotor followed by its analysis along the parameter of aeroelastic stability in flight. They also established the differences between a semi and a full span model and nailed down the reasons for its instability and monitored the effects of external structures on its aeroelastic stability. After constructing a theoretical model of the tiltrotor, they constructed algorithms to represent various structures and features of the tiltrotor. These equations were used to validate the various parameters, and the results indicated that elastic blades invariably led to more instability than rigid winged aircrafts did, and when these were coupled with fuselage motions, the instability was found to have increased further. Natural laminar flows (NLF) wings are capable of maintaining flow under laminar conditions over relatively large portions of wing surface. But imperfections produced during the manufacturing process (grooves between joints and fixtures) have an adverse effect on aerodynamic performance due to a disruption in air flow over the wing surface. JesúsGaricano-Mena, et al. [11] studied the stability characteristics of NLF wings in the presence of

these indentations. The main objective was to quantify the impact on linear stability under varying degrees of indentation of depth and Mach number. They first established a baseline test under ideal circumstances, and then observed the modifications made to this data when exposed to a perturbation in the surface of the wing structure. They also noted spatial evolution of individual structural elements along the direction of the flow along the amplification factors. They utilized global temporal stability analysis to make these determinations. The results from the test indicated that an increase in groove depth drastically impacted temporal stability which was intensified at higher Mach numbers. They cautioned that these parameters need to be taken into considerations during the design and manufacturing process of NLF wings. Liang QU, et al. [12] studied the stability values for the working parameters (angle of attack and sideslip, yaw, pitch and roll rate) of the aircraft under icing conditions. Apart from increasing the weight of the aircraft, icing also decreases the performance of the aircraft. Stable and unstable equilibrium points for stability of the aircraft were obtained by solving the kinematic equations. The stability region was then obtained by using these equilibrium points in a Jacobi Matrix and solving it. An iced aircraft was in steady state if the angle of attack laid below 25.8 degrees (38.7 degrees for an un-iced vehicle). Time domain simulations carried out validated the stability regions obtained. The stability region provided a working region for the aircraft for safe operation. Marco, et al. [13] performed a buckling analysis for the composite fuselage. Finite element analysis was done on composite fuselage structure. The reduction of weight between the carbon/epoxy composite and the aluminum material is also high, thus encouraging the suitability of carbon/epoxy for fuselage applications.

3. Proposed Methodology

The proposed methodology establishes a structured computational framework for

evaluating the structural performance of an aircraft fuselage under varying loading conditions using finite element analysis. The analytical workflow begins with geometric modelling of the fuselage structure, followed by material assignment, finite element discretization, and simulation under different loading environments. A three-dimensional fuselage model is first developed in a computer-aided design environment and then transferred to a numerical simulation platform for structural evaluation. The computational framework investigates the mechanical response of the fuselage under static, fatigue, and dynamic loading conditions to understand the influence of material behaviour on structural integrity. Three aerospace-grade materials are considered in the analysis, namely Aluminum Alloy 7075, Carbon Fiber, and GLARE, to enable a comparative assessment of conventional, composite, and hybrid structural systems, as shown in figure 2. The finite element framework is designed to capture critical structural responses such as deformation, equivalent stress, hoop stress, longitudinal stress, strain, fatigue damage, and safety factor. The analysis begins with static structural evaluation to determine the immediate elastic response of the fuselage under constant loading. This is followed by fatigue assessment to estimate the effect of cyclic loading on damage accumulation and structural durability.



Figure. 2: System architecture.

CAD Modelling Environment

- The structural workflow begins with the development of a three-dimensional

fuselage geometry in a computer-aided design environment.

- The model includes essential structural components such as the outer shell, bulkheads, and stringers to represent the actual fuselage configuration.
- The geometry is created with suitable dimensions and structural proportions required for finite element simulation.
- The completed model serves as the primary geometric input for numerical analysis.

Material Definition Module

- The material definition stage assigns the required engineering properties to the fuselage model.
- Three materials are considered for structural comparison: Aluminum Alloy 7075, Carbon Fiber, and GLARE.
- Each material is defined using its mechanical properties such as density, Young's modulus, Poisson's ratio, and strength characteristics.
- This module enables the structural solver to evaluate the influence of material behavior on fuselage performance.

ANSYS Simulation Environment

- The ANSYS simulation environment acts as the central numerical analysis platform.
- It receives the imported fuselage geometry and performs structural evaluation using finite element techniques.
- The environment manages preprocessing, solution execution, and result generation for all analysis stages.
- It serves as the primary computational platform for static, fatigue, and transient structural simulations.

Finite Element Mesh Generation

- The fuselage geometry is discretized into a finite number of smaller elements through meshing.

- This process converts the continuous structural model into solvable finite elements for numerical computation.
- Mesh generation improves the accuracy of stress and deformation prediction across the fuselage body.
- The discretized model forms the computational basis for finite element analysis.

Boundary Condition and Load Application

- Structural constraints and external loads are applied to simulate realistic aircraft operating conditions.
- Fixed supports are assigned at appropriate structural locations to restrict unnecessary degrees of freedom.
- Mechanical loads and pressure conditions are applied to represent operational forces acting on the fuselage.
- This stage ensures that the numerical model replicates actual service conditions during analysis.

Static Structural Analysis

- Static structural analysis is performed to determine the response of the fuselage under constant loading conditions.
- The analysis evaluates deformation, equivalent stress, hoop stress, longitudinal stress, and strain.
- It provides an understanding of the immediate load-bearing capacity and stiffness of each material configuration.
- The static response forms the baseline for structural comparison.

Fatigue Assessment Module

- Fatigue analysis is carried out to evaluate the durability of the fuselage under repeated cyclic loading.
- The analysis estimates fatigue life, cumulative damage, and structural safety factor.
- This module determines the long-term resistance of each material to crack initiation and fatigue failure.

- It provides insight into structural reliability during repeated service cycles.

Transient Dynamic Analysis

- Transient dynamic analysis is performed to study the time-dependent structural response of the fuselage.
- The fuselage response is evaluated under varying loading conditions at different time intervals.
- The analysis measures deformation, stress variation, and strain response over time.
- This stage captures the dynamic stability and vibration behaviour of the selected materials.

Result Evaluation and Comparative Analysis

- The outputs obtained from static, fatigue, and dynamic analyses are systematically compared.
- Parameters such as deformation, stress, fatigue damage, and safety factor are used for comparison.
- The comparative analysis identifies the material with superior structural performance.
- This stage establishes the most suitable material for aircraft fuselage applications based on numerical evidence.

Output Visualization and Performance Interpretation

- The final structural responses are presented through contour plots, tables, and comparative graphs.
- Visualization enables clear interpretation of deformation and stress distribution across the fuselage.
- Performance trends across materials are analysed to support engineering conclusions.
- This final stage assists in selecting the most efficient and reliable fuselage material configuration.

4. Results And Discussion

This section presents the analytical results obtained from the structural evaluation of the aircraft fuselage under static, fatigue, and dynamic loading conditions. The numerical outcomes are used to compare the mechanical performance of Aluminum Alloy 7075, Carbon Fiber, and GLARE based on key structural parameters. The obtained results are discussed in terms of deformation, stress distribution, fatigue damage, safety factor, and transient response. A comparative interpretation is carried out to examine the influence of material properties on structural behavior and durability. Graphical and tabulated representations are used to provide a clear understanding of performance variations among the selected materials. The discussion highlights the structural advantages and limitations of each material under different loading environments. Based on the observed responses, the most suitable material for fuselage applications is identified through detailed performance comparison.

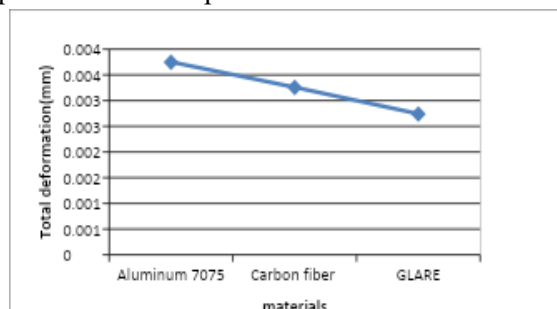


Figure. 3: Materials vs Total Deformation

Figure 3 illustrates the variation in total deformation of the fuselage structure for different material configurations under identical loading conditions. The graphical results indicate that Aluminum 7075 exhibits the highest total deformation, followed by Carbon Fiber, while GLARE demonstrates the lowest deformation among the selected materials. This progressive reduction in deformation highlights the improved stiffness and load-carrying capability of advanced material systems. The observed trend clearly shows that GLARE provides superior resistance to structural displacement when

compared with conventional metallic and composite alternatives. The reduced deformation response of GLARE indicates enhanced structural rigidity and improved dimensional stability, making it a more suitable material for fuselage applications where minimal deformation is essential for maintaining structural integrity and operational reliability.

Figure 4 depicts the variation in equivalent stress developed in the fuselage structure for different material configurations under the same loading conditions. The results show that Aluminum 7075 experiences the highest equivalent stress, followed by Carbon Fiber, whereas GLARE exhibits the lowest stress among the selected materials. This gradual decrease in equivalent stress indicates that GLARE distributes the applied load more effectively and experiences lower stress concentration compared to the other materials. The reduced stress response observed in GLARE reflects its improved structural strength and enhanced resistance to mechanical loading. The overall trend demonstrates that GLARE provides superior stress-handling capability, making it a more reliable material for fuselage structures requiring improved strength, durability, and structural safety.

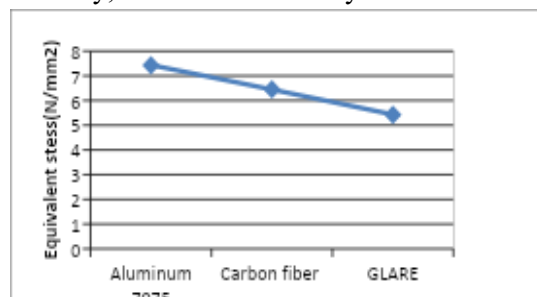


Figure. 4: Materials vs Equivalent Stress

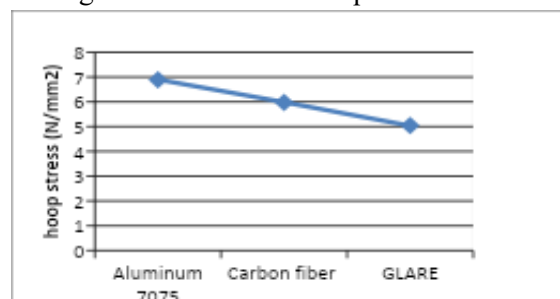


Figure. 5: Materials vs Hoop Stress

Figure 5 illustrates the variation in hoop stress developed in the fuselage structure for different material configurations under identical loading conditions. The graph shows that Aluminum 7075 produces the highest hoop stress, followed by Carbon Fiber, while GLARE exhibits the lowest hoop stress among the selected materials. This decreasing trend indicates that GLARE offers improved resistance to circumferential stress generated due to internal and external loading on the fuselage shell. The lower hoop stress observed in GLARE suggests better load distribution and enhanced structural stability compared with the conventional metallic and composite alternatives. The results clearly demonstrate that GLARE provides superior circumferential stress resistance, making it a more effective material for improving fuselage strength, durability, and operational safety.

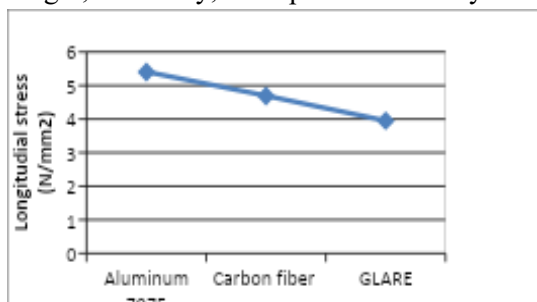


Figure. 6: Materials vs Longitudinal Stress

Figure 6 depicts the variation in longitudinal stress developed in the fuselage structure for different material configurations under the same loading conditions. The results indicate that Aluminum 7075 experiences the highest longitudinal stress, followed by Carbon Fiber, while GLARE exhibits the lowest longitudinal stress among the selected materials. This consistent reduction in longitudinal stress demonstrates the improved ability of GLARE to withstand axial loading along the length of the fuselage. The lower stress values observed in GLARE indicate better resistance to axial deformation and enhanced structural efficiency under longitudinal loading conditions. The overall trend confirms that GLARE offers

superior axial load-bearing performance, making it a more suitable material for improving fuselage strength, structural stability, and service reliability.

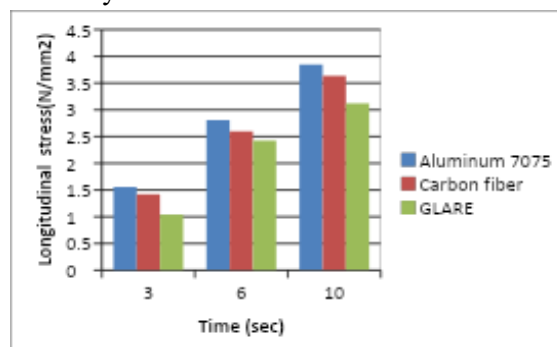


Figure. 7: Materials and Time vs Longitudinal Stress

Figure 7 illustrates the variation in longitudinal stress of the fuselage structure with respect to time for different material configurations under dynamic loading conditions. The results show that longitudinal stress increases progressively for all three materials as the loading duration increases from 3 sec to 10 sec. Aluminum 7075 exhibits the highest longitudinal stress at each time interval, followed by Carbon Fiber, while GLARE consistently records the lowest stress values throughout the analysis. This trend indicates that GLARE offers better resistance to time-dependent axial loading and experiences lower stress accumulation under dynamic conditions. The reduced longitudinal stress response of GLARE demonstrates improved structural stability and superior load-handling capability, making it the most effective material for sustaining longitudinal loads during dynamic operation.

The table 1 presented in this section describe the time-dependent structural response of the fuselage for Aluminum Alloy 7075, Carbon Fiber, and GLARE under transient loading conditions. The comparative evaluation is carried out at three different time intervals, namely 3 sec, 6 sec, and 10 sec, to examine the variation in deformation, equivalent stress, hoop stress, longitudinal stress, and strain with respect to

time. The obtained results show that all three materials experience an increase in stress and strain as the loading duration increases, indicating progressive structural response under dynamic conditions. Aluminum 7075 consistently exhibits the highest stress values at all time intervals, followed by Carbon Fiber, whereas GLARE demonstrates comparatively lower stress levels throughout the analysis. A similar trend is observed in hoop stress and longitudinal stress, where GLARE maintains reduced stress accumulation under time-varying loads. The deformation values also indicate

improved dimensional stability for GLARE when compared with the conventional material system. These observations highlight the influence of material properties on the transient structural behavior of the fuselage. The lower stress and deformation response of GLARE indicates improved resistance to dynamic loading and enhanced structural stability. The results provide a clear basis for comparing the dynamic performance of the selected materials and identifying the most reliable material for fuselage applications under variable operating conditions.

Table. 1: Dynamic analysis results

Materials	Time (sec)	Deformation (mm)	Stress (N/mm ²)	Hoop stress (N/mm ²)	Longitudinal Stress (N/mm ²)	Strain
Aluminum 7075	3	0.0016079	1.8701	1.5005	1.5565	5.74e-6
	6	0.00037544	3.3661	2.701	2.8054	1.7243e-5
	10	0.0006613	4.6728	3.701	3.8445	2.361e-5
Carbon fiber	3	0.00014305	1.7039	1.3672	1.42	5.109e-6
	6	0.0004469	2.41403	2.5009	2.597	1.56e-05
	10	0.00062503	4.3635	3.5012	3.636	2.23e-5
GLARE	3	0.0001788	1.2467	1.003	1.039	6.386e-6
	6	0.0004171	2.909	2.3342	2.4244	1.4901e-5
	10	0.0005362	3.7401	3.0011	3.1171	1.91e-5

5. Conclusion

The study presented a detailed finite element evaluation of an aircraft fuselage structure under static, fatigue, and dynamic loading conditions using Aluminum Alloy 7075, Carbon Fiber, and GLARE. A comparative structural assessment was carried out to examine deformation,

equivalent stress, hoop stress, longitudinal stress, strain, fatigue damage, and safety factor for all selected materials. The analytical results showed that GLARE consistently exhibited lower deformation and reduced stress concentration under static loading when compared with Aluminum Alloy 7075 and Carbon Fiber. In fatigue assessment, GLARE demonstrated the

lowest damage accumulation and the highest safety factor, indicating superior durability under repeated cyclic loading. Under transient dynamic conditions, GLARE also maintained lower equivalent, hoop, and longitudinal stress values with improved structural stability over time. These results confirm that the hybrid laminate structure offers better load distribution and higher resistance to both static and time-dependent mechanical loading. Carbon Fiber showed improved performance over Aluminum Alloy 7075, but its structural response remained less efficient than GLARE in overall comparison. Aluminum Alloy 7075 exhibited the highest deformation and stress values, making it comparatively less favorable for long-term fuselage applications. The analysis confirms that GLARE provides improved structural efficiency, enhanced fatigue resistance, better dynamic stability, and longer service life. Therefore, GLARE is identified as the most suitable material for fuselage applications requiring lightweight construction, improved strength, and superior operational reliability.

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