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Aircraft Frames: Dominant Parameters Thresholds, Data Mining for Components Integrity and Pre-Failure Assessment Determination

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Abstract

Concerning airframe fault analysis of aircraft, there is a need for a foundation upon which the knowledge and informed decisions are based. The foundation for this knowledge and informed decisions is data. It is important because it is essential for scientific research serving as the starting point for processes that deliver informed insights of which aircraft fault analysis is not exempt. Data serves as the foundation for understanding phenomenon, testing hypothesis and drawing valid conclusions. For valid conclusions to be drawn in this research, data were mined to judge and validate the results gotten from the analysis of the fault and the proposed maintenance to be carried out in the future. The airframe parts that can develop faults were identified as the aircraft wings, fuselage and landing gears. The materials used for the construction of these parts were investigated and identified as aluminium, titanium, composite materials and steel. The parameters and their standard values under which the aircraft can perform ultimately were harvested through literature review. These parameters and their values characterize the materials identified for airframe construction and were used for pre-failure assessment. These parameters were used on a case study of selected airframes and the results were as follows: wings made of aluminium 7050 having an ultimate stress of 317MPa, maximum deformation of 12%, a factor of safety of 1.5, first bending range of (5–20)Hz, second bending range of (25–60)Hz, torsional range of (20–50)Hz, damping ratio range of (0.02–0.04), and a maximum temperature of 150℃; fuselage made of titanium grade 9 having an ultimate stress of 413MPa, maximum deformation of 25%, a factor of safety of 1.5, first bending range of (10–40)Hz, second bending range of (50–120) Hz, torsional range of (40–100)Hz, damping ratio range of (0.01–0.03), and a maximum temperature of 315℃.

Keywords: *Airframe, Airframe faults, Data Mining, Parameters Required, Materials, Material Characterization, Thresholds*

1. Introduction

The aircraft frame, often termed the airframe constitutes the principal structural backbone of an aircraft. It encompasses critical elements such as the fuselage, wings, empennage (tail assembly), and landing gear attachment structures. Collectively, these components form a robust framework that effectively distributes both aerodynamic and inertial loads encountered throughout various phases of flight. The aircraft frame not only guarantees the physical integrity of the aircraft but also preserves its aerodynamic characteristics, supports pressurization systems, and integrates essential subsystems including avionics, propulsion, and flight control mechanisms [19].

Historically, the evolution of aircraft frames has mirrored the progression of aviation technology. Early iterations of aircraft, exemplified by the Wright Flyer, were constructed from wood and fabric, materials selected for their availability and lightweight properties. Nevertheless, as the demands for enhanced flight performance escalated, so too did the necessity for stronger, more resilient materials. This evolution resulted in the incorporation of high-strength aluminum alloys in the mid-20th century, subsequently followed by the adoption of titanium, steel, and sophisticated fiber-reinforced polymer composites in modern aircraft designs [6, 13].

Contemporary aircraft frames are classified according to their construction methodologies. The truss-type structure, prominently observed in early biplanes, employs a network of struts and braces to effectively manage forces. Monocoque structures depend entirely on the external skin to support loads, while semi-monocoque frames, which are currently the most prevalent, distribute loads between the skin and an

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internal framework comprising longerons, frames, and stringers. This architectural arrangement achieves an optimal equilibrium of weight, strength, and ease of maintenance [14].

The design of the aircraft frame necessitates the capacity to endure a diverse array of loads: static loads resulting from the aircraft's weight, dynamic loads induced by gusts and turbulence, and impact loads experienced during takeoff and landing. These structural requirements are addressed through the utilization of advanced analytical tools such as Finite Element Analysis (FEA), which forecasts the airframe's response under varying conditions. Such simulations facilitate engineers in crafting safer and more efficient aircraft while concurrently minimizing development costs [25].

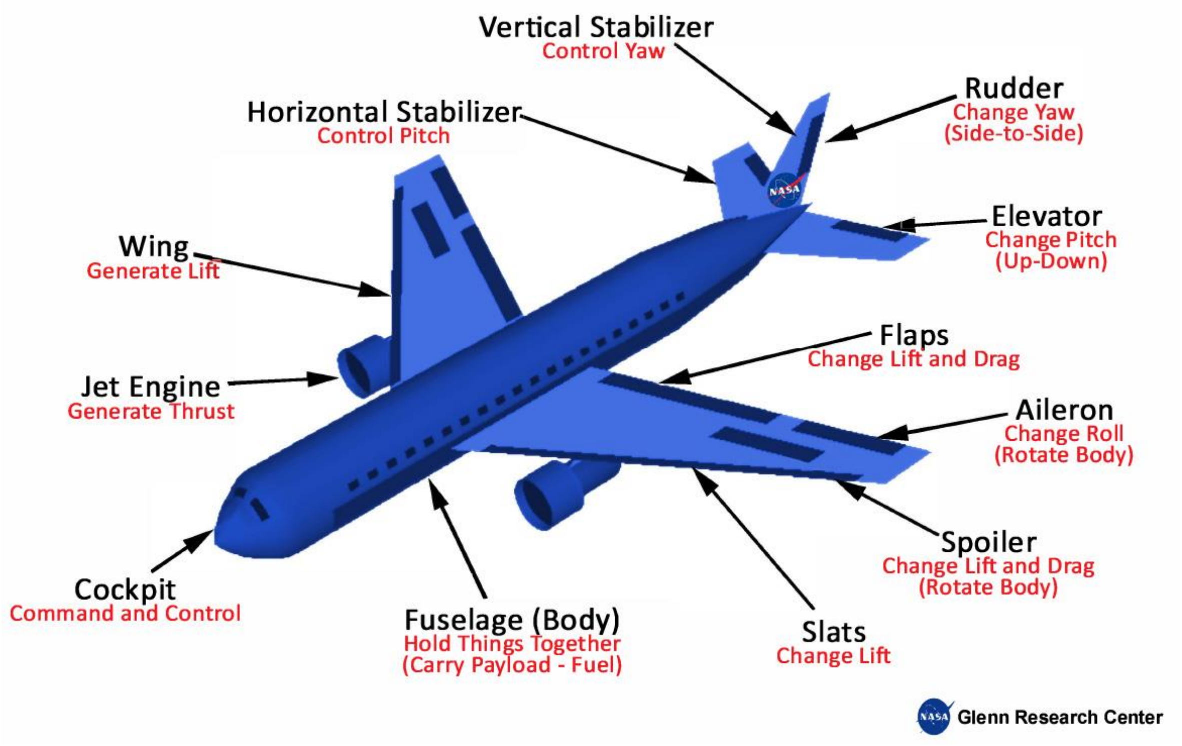

Figure 1. Picture showing components of an airframe [6]

Ultimately, the aircraft frame transcends its role as a mere structural component—it serves as the foundational basis upon which safety, efficiency, and performance are established. A thorough comprehension of its design, evolution, and function within contemporary aviation is imperative for engineers, operators, and regulators alike.

Aircraft structural integrity is a critical factor in aviation safety, as undetected faults can lead to catastrophic failures. Traditional maintenance strategies often rely on scheduled inspections, which may fail to detect early-stage damage, leading to unexpected failures and increased operational costs [9]. The demand for more efficient and cost-effective maintenance solutions has driven research into predictive maintenance strategies that integrate real-time monitoring with computational modeling [15].

The airframe is the structural core of an aircraft, comprised of several key components that work together to maintain stability, provide lift, and ensure safety during all phases of flight [19]. The three principal components of the airframe include:

i. Fuselage: The fuselage is the central body of the aircraft. It houses the cockpit, passenger or cargo compartments, fuel storage, and connects all other structural components like the wings, tail assembly, and landing gear. It also provides the main-loading structure and must resist internal pressure in the pressurized cabins [14]. The materials used in the construction of the fuselage are mainly aluminum alloys (such as 2024-T3 and 7075-T6) for their strength and weight efficiency, and composite materials to reduce weight and improve corrosion resistance [13].

ii. Wings: Wings generate lift and serve as mounting pairs for engines (in most configurations), landing ger, and control surfaces like ailerons and flaps. They must withstand aerodynamic loads and bending stresses during flight [19]. The materials mainly used in the construction of wings include aluminum-lithium alloys for improved weight efficiency, carbon fiber composites for high strength and fatigue resistance, and titanium alloys in high-temperature or high-load areas [1, 3].

iii. Landing Gear: The landing gear supports the aircraft during taxiing, takeoff, and landing, and absorbs and distributes impact loads from the ground [23]. The materials mostly used in the construction of landing gear are high-strength steels (such as 300M alloy) for superior load-carrying capacity, with titanium and forged aluminum used to reduce weight in certain aircraft designs.

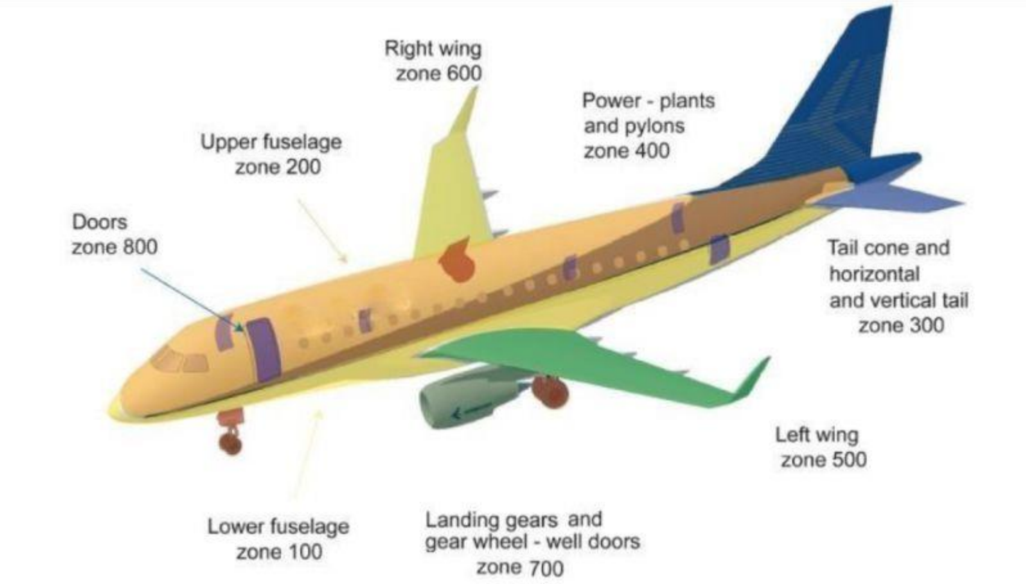

Figure 2. Image showing the fuselage of an aircraft [1]

Figure 3. Image showing the Wings of an aircraft [3]

Figure 4. Image showing the landing gear of an aircraft [8]

A key challenge in airframe maintenance is the variation in material properties, as different aircraft components experience unique stress loads and environmental conditions [22]. Aluminum alloys, titanium, and composites each exhibit different failure mechanisms, requiring tailored fault detection techniques [18]. The ability to incorporate material-specific parameters into predictive models is essential for improving fault detection accuracy [28].

This study focuses on major ways for collecting the required data for airframe component performance judgment before failure.

2. Methodology

Literature was fully reviewed and the parameters that are dominant to airframe were sought through variety of media including print materials like books and newspapers as well as electronic sources like website and databases.

Analysis of the media: The variety of media which were consulted can be classified into the following:

a) Print media: Through this, books such as newspapers, journals and magazines were well studied.
b) Electronic sources: Concerning this study, websites, databases and audiovisual contents were thoroughly gone through.
c) Other sources: Human sources, institutional sources, grey literature (unpublished or informally published materials) and library literature were all gone through.

Structural parameters such as stress, strain, deformation, temperature, vibration frequencies, damping ratios, and factor of safety are essential for determining the health performance of airframe components. These values are obtained from various sources which were classified as; primary, secondary and tertiary sources.

i. Primary sources: This is the original data usually obtained through direct measurement, experimentation or sensor-based monitoring on actual aircraft systems or during controlled simulations. These sources are considered the most accurate and are typically used in certification, damage tolerance analysis and fault detection systems.
ii. Secondary sources: This has to do with interpreting, analyzing or repurposing of primary data. They are often compiled by researchers, analysts or engineers for comparative studies, validation or model training.
iii. Tertiary sources: This involves information that summarizes or abstracts data from both primary and secondary sources. These sources include documents from FAA and EASA, and textbooks.

Data Collection and Preprocessing: Data for this study is obtained from FEA simulations and SHM sensor outputs from aircraft components. Key parameters collected include stress, deformation, factor of safety, first and second bending frequencies, torsional frequency, damping ratio, and temperature [2, 29]. These parameters influence the structural behavior of the aircraft significantly:

i. **Stress:** Stress is the internal force per unit area within a material that arises due to externally applied loads [16]. In aircraft structures, stress can result from aerodynamic forces, engine thrust, weight distribution, or pressurization. High stress concentrations can lead to fatigue cracks and material failure [12].
ii. **Deformation**: Deformation refers to the change in the shape or size of a body due to applied forces or thermal effects [13]. Excessive deformation compromises aerodynamic efficiency and flight stability[12].
iii. **Factor of Safety**: The Factor of Safety is the ratio of a material’s allowable stress (yield or ultimate strength) to the expected operational stress, used to account for uncertainties in material behavior and loading [8]. A reduced factor of safety indicates higher risks of structural failure, necessitating immediate maintenance action [32].
iv. **Bending Frequencies:** Bending frequency is a structure’s natural frequency of vibration in its flexural mode, where the shape changes in curvature without twisting [23]. Changes in these frequencies can indicate structural degradation, leading to potential resonance issues that affect aircraft stability [20].
v. **Torsional Frequencies**: Torsional frequency is the natural frequency at which a component oscillates about its longitudinal axis in a twisting motion [16]. Changes in these frequencies can indicate structural degradation, leading to potential resonance issues that affect aircraft stability [20].
vi. **Damping Ratio**: The damping ratio quantifies how quickly oscillations decrease in amplitude in a dynamic system and is expressed as a fraction of critical damping [13]. A lower damping ratio suggests higher susceptibility to oscillatory failure, increasing the likelihood of structural vibrations that may propagate cracks [17].

vii. **Temperature**: Temperature is a measure of thermal energy, which affects material properties such as elasticity, strength, and thermal expansion [1]. Variations in operating temperature affect material expansion, contraction, and stress distribution, impacting fatigue life [7].

Preprocessing steps include noise reduction, normalization, and feature extraction to improve data quality and model performance [4, 27, 30, 31]. Further statistical techniques such as principal component analysis (PCA) are applied to refine the dataset and remove redundancies, ensuring more accurate predictions.

3. Results and Discussions

Based on the methods used which are generally classified as primary, secondary and tertiary sources, the following were reported;

a) Materials used for airframe construction and their grades
b) Parameters for evaluating faults and threshold of parameters

These are all shown in the table below.

Table 1. Aircraft components, materials used, their parameters and thresholds harvested

S/N	Airframe Component	Material Used	Grade	Parameters	Thresholds
1	Wings and Landing Gear	Titanium	Grade 5	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	587 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 400 [5, 10, 24]
2	Wings and Fuselage	Aluminium	2024	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	230 15 1.5 (5–20) (25–60) (20-50) (0.02–0.05) 150 [21, 25]
3	Wings and Fuselage	Aluminium	6061	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	184 16 1.5 (5–20) (25–60) (20-50) (0.02–0.04) 120 [25]
4	Wings, Landing Gear and Fuselage	Aluminium	7075	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	335 12 1.5 (5–20) (25–70) (20-60) (0.02–0.04) 150 [25]
5	Wings and Fuselage	Aluminium	7050	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz)	337 12 1.5 (5–20) (25–60) (20-50)

S/N	Airframe Component	Material Used	Grade	Parameters	Thresholds
				Damping ratio Temperature (℃)	(0.02–0.04) 150 [25]
6	Wings and Fuselage	Aluminium	2090	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	293 15 1.5 (5–20) (25–60) (20-50) (0.02–0.04) 150 [11]
7	Wings and Fuselage	Aluminium	7475	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	313 14 1.5 (5–25) (25–70) (20-60) (0.02–0.05) 150 [25]
8	Wings and Fuselage	Aluminium	2124	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	313 13 1.5 (5–20) (25–60) (20-50) (0.02–0.04) 150 [11]
9	Wings and Fuselage	Aluminium	7055	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	393 11 1.5 (5–25) (25–70) (20-60) (0.02–0.04) 150 [25]
10	Wings and Fuselage	Composite Materials	Carbon Fiber Reinforced Polymer (CFRP)	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	533 2 1.5 (20–150) (100–350) (50-250) (0.05–0.10) 150 [24]
11	Wings	Composite Materials	Boron Fiber Reinforced Polymer (BFRP)	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1333 25 1.5 (30–200) (150–500) (80-350) (0.01–0.02) 200 [24]

S/N	Airframe Component	Material Used	Grade	Parameters	Thresholds
12	Wings, Landing Gear and Fuselage	Composite Materials	Hybrid Metal Matrix Composites	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	400 5 1.5 (30–250) (150–500) (70-350) (0.02–0.03) 250 [24]
13	Fuselage	Titanium	Grade 9	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	413 25 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 315 [5]
14	Fuselage	Aluminium	2219	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	217 15 1.5 (5–25) (25–70) (20-60) (0.02–0.04) 150 [21]
15	Fuselage	Composite Materials	Aluminium Honeycomb Core Composite	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	200 10 1.5 (10–40) (50–120) (40-100) (0.01–0.02) 120 [24]
16	Fuselage	Composite Materials	Aramid Fiber Reinforced Polymer (AFRP)	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1500 3 1.5 (20–150) (100–350) (50-250) (0.05–0.10) 200 [24, 26]
17	Landing Gear	Steel	4130	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	290 25 1.5 (10–40) (50–120) (40-100) (0.02–0.03) 315 [25]
18	Landing Gear	Steel	4140	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz)	437 18 1.5 (10–40)

S/N	Airframe Component	Material Used	Grade	Parameters	Thresholds
				Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	(50–120) (40-100) (0.02–0.03) 315 [25]
19	Landing Gear	Steel	17-4 PH	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	687 12 1.5 (10–50) (60–170) (50-140) (0.01–0.02) 315 [25]
20	Landing Gear	Steel	9310	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	597 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 315 [10]
21	Landing Gear	Steel	Aermet 100	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1197 15 1.5 (10–50) (60–170) (50-140) (0.01–0.02) 300 [10]
22	Landing Gear	Steel	Maraging Steel	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1400 12 1.5 (10–50) (60–170) (50-140) (0.01–0.02) 300 [25]
23	Landing Gear	Steel	300M	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1193 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 315 [25]
24	Landing Gear	Steel	52100	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	1000 12 1.5 (10–40) (50–120) (40-100) (0.01–0.02) 300

S/N	Airframe Component	Material Used	Grade	Parameters	Thresholds
					[5]
25	Landing Gear	Steel	4340	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	496 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 315 [25]
26	Landing Gear	Titanium	Grade 23	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	530 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 400 [5]
27	Landing Gear	Titanium	Beta C	Stress (MPa) Deformation (%) Factor of safety First bending freq. (Hz) Second bending freq. (Hz) Torsional freq. (Hz) Damping ratio Temperature (℃)	800 15 1.5 (10–40) (50–120) (40-100) (0.01–0.03) 315 [10]

Table 2. Summary of thresholds for the parameters of the materials used

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Bending Range (Hz)	Torsional Range (Hz)	Damping Ratio	Temperature Range (°C)	Factor of Safety
Aluminum Alloys	340-572	470-638	10-15	5-70	20-60	0.02-0.05	-50 to 150	1.5-2.0
Titanium Alloys	827-950	880-1280	8-15	10-120	40-100	0.01-0.03	-200 to 400	1.5-2.0
Composites	400-1000	800-3000	1-4	10-500	40-350	0.05-0.10	-50 to 200	2.0-3.0
Steel Alloys	350-2100	560-2250	5-15	10-170	40-140	0.03-0.07	-50 to 315	1.5-2.0

These thresholds stated in Table 1 as related to each parameter will be used as judgement values to access the components to prove its level of integrity before failure.

Summary of Material Properties: The properties of the materials used in aircraft airframes were also gotten. These properties serve as the threshold which the data gotten from the FEA and SHM will be based off to identify faults to the airframe of the aircraft by the model developed using Python.

4. Conclusions

The results gotten proved this study's aim achieved. Methods used were successful. Materials and grades of materials used for airframe component construction were identified as well as the threshold of their parameters used to evaluate their performance under their dominant character template. This is a death – knell for airframe integrity assessment and pre-failure.

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