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Fatigue Life Prediction on Critical Component for Structure Life Extension of X - Aircraft

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ABSTRACT

Critical aircraft components, such as load-bearing structures, are integral to an aircraft's overall integrity. Factors like fatigue loading, operational conditions, and environmental wear necessitate continuous structural assessment for airworthiness. The Royal Malaysian Air Force (RMAF) employs the Aircraft Structure Integrity Program (ASIP) in tandem with the Safe Life fatigue design concept for ongoing structural integrity monitoring. RMAF's Efforts encompass engineering analyses and task cards, focusing on critical aircraft components. Various Computer-Aided Engineering (CAE) techniques, including fatigue analysis and Low Cycle Fatigue characterization, are applied. Numerical simulations with NX Nastran are used to predict fatigue behavior and failure points, with specific emphasis on the wing root's susceptibility to fatigue failure among six critical areas. Results indicate the wing root's remarkable structural resilience, even with up to a 30% thickness reduction in aluminum components, potentially extending the structural lifespan up to 100 years. This research endeavors to enhance the aircraft's wing structure's operational longevity, underscoring its robust design and commitment to aviation safety through thickness reduction fatigue analysis on the aluminum part of the wing root structure. These findings highlight meticulous engineering analysis and computational methodologies that elevate aircraft safety and compliance with stringent airworthiness standards.

Keywords: Fatigue, critical location, life prediction.

I. INTRODUCTION

Every component of an aircraft's structure holds critical significance, influencing both its performance [1, 2] and structural integrity [3,4]. In the realm of aircraft engineering, fatigue remains a predominant factor contributing to component failures, particularly when considering the complex effects of multiaxial fatigue [5]. Contemporary management approaches address these challenges through a blend of meticulous inspection protocols and strategic early retirement practices aimed at ensuring and preserving structural safety. A series of transformative shifts in the design approach has been implemented, commencing with an initial emphasis on static strength-based design, followed by the integration of redundant load paths within the structure, and ultimately, retiring aircraft prior to an excessive risk of failure. Simultaneously, structural optimization and the utilization of high-strength materials have expanded the number of components or regions that experience high stress levels, rendering them inherently less tolerant to fatigue-induced damage. Among these transformations, one particular aspect has garnered considerable attention from the fatigue research community throughout the years which is the

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susceptibility of fatigue structure to the presence of minute cracks, and, consequently, to surface conditions and manufacturing processes [6].

Global fatigue life assessments are typically conducted using the S-N approach, which involves strain-life and stress-life models. These assessments are supported by experimental data that correlate a comprehensive definition of stress range with the total number of cycles leading to failure. In addition, the traditional nominal stress method was applied to back calculate the S-N curve parameters of the realistic structure details based on full-scale fatigue test data and has been found to have high accuracy in relation to the experimental one [7].

As the expenses associated with aircraft maintenance escalate and the potential to integrate existing fleets with advanced technology at a relatively lower cost becomes apparent, a global trend has emerged in extending the lifespan of critical fatigue-prone aircraft components [8]. The Royal Malaysian Air Force (RMAF) is no exception to this trend, and, recognizing the typically high cost of Aircraft Life Extension Programs offered by Original Equipment Manufacturers (OEMs), has initiated numerous in-house life extension projects [9].

Towards the conclusion of their design service life, operational aircraft witness a progressive decline in reliability, accompanied by the deterioration of parts, equipment, and avionics. As the operational life of these aircraft is extended, the structural integrity of the airframe experiences ongoing degradation, at times exceeding the intended design life, potentially impairing the operational capabilities of these assets. This aging process of aircraft is characterized by the gradual wear and tear endured by airframes and components due to operational usage and environmental influences [10].

The Royal Malaysian Air Force (RMAF), having operated its X-aircraft fleet for a span exceeding a decade, confronts a formidable challenge in assuring the ongoing structural integrity and airworthiness of its fleet. Over the course of its existence, the most advanced fighter jet within its inventory has demonstrated supermaneuvrability, incorporating cutting-edge technology, including advanced avionics, missiles, and munitions. After close to 12 years of continuous operation, the structural integrity of this aircraft is now at a critical juncture, particularly given the extensive history of high-speed maneuvers, reaching stress levels nearing 13G. Consequently, a comprehensive assessment of the remaining fatigue life of the structure was undertaken, ensuring that it retains the necessary airworthiness standards for continued flight operations. This rigorous evaluation is imperative, considering the demanding operational environment and high-performance expectations associated with such advanced fighter aircraft.

Various methodologies are available for evaluating fatigue life, categorized as either high cycle or low cycle fatigue approaches. Nevertheless, research on fatigue analysis indicates that the progressive and localized structural damage that occurs when materials are subjected to repeated cyclic loading and unloading, often happens at stress levels well below their ultimate tensile strength. This process can lead to the eventual failure of a material, particularly in components exposed to dynamic or cyclic stresses, such as those in aircraft critical structures such as wings, horizontal stabilizer, canards, and many other mechanical systems. This study aims to provide a comprehensive prediction of the fatigue life of the aircraft's critical structure through thickness reduction on the aluminum area of the wing root, encompassing the entire path to fatigue failure. The approach to fatigue life estimation combines computational stress analysis with strain-life techniques. The methods employed here consist of analytical and Finite Element Method (FEM) analyses. The analytical approach is relatively straightforward, whereas FEM analysis is favored for critical locations due to its greater reliability in stress analysis, both in linear and elastic-plastic domains.

II. SETUP AND METHODOLOGY

The investigation will delve into the fundamental requirements for conducting a fatigue analysis with the variation in thickness reduction, elucidated in the fatigue flowchart depicted in Figure 1 for this specific study. The comprehensive methodology encompasses key stages such as CAD modeling, mesh generation, material characterization, loading considerations, and boundary condition establishment, each representing integral facets of the simulation process. The flowchart delineates a systematic procedure for incorporating these critical elements, culminating in the execution of the analysis utilizing the durability module facilitated by NX Nastran.

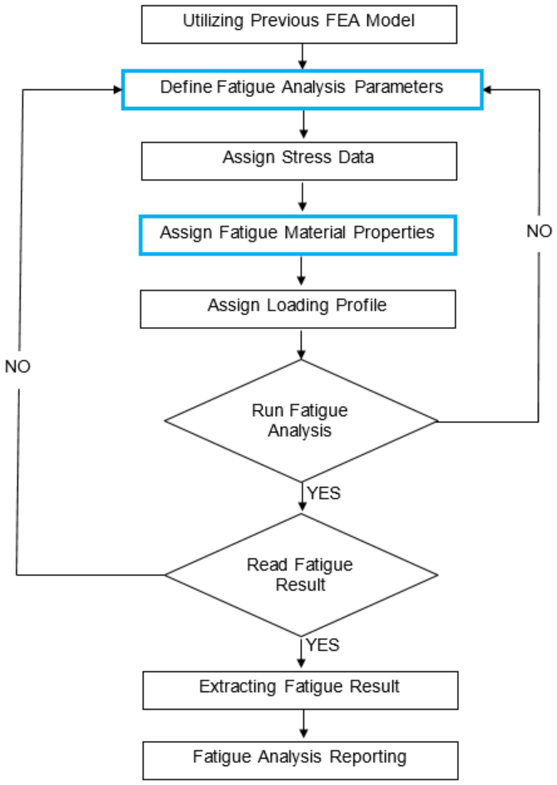

Figure 1 Fatigue analysis flowchart

2.1 CAD Wing Root Development

The wing root joint exhibits intricate geometric complexity, encompassing various components with distinct material parameters. In accordance with the research presented by [11], it is posited that it is feasible to develop a simplified model that accurately represents the comprehensive model, without compromising the fidelity of finite element (FE) simulations. The approach proposed in this paper involves deconstructing the intricate CAD modeling component into a simplified model, offering a pragmatic means to address the complexities inherent in the structural analysis of the wing root joint. The development of Computer-Aided Design (CAD) commenced with the creation of the CAD model for the wing root. The dimensional and design attributes of this model were acquired through the application of 3D scanning methodology. The initial 3D CAD model was generated based on the output of the 3D scanning procedure. Subsequently, the scanned 3D CAD model underwent a refinement process, focusing on delineating the key features, such as spars, longerons, frames, and bulkheads, rendering it suitable for Computer-Aided Engineering (CAE) Analysis. The refinement process encompasses the elimination of extraneous elements and error-inducing lines, surfaces, and solids, as well as the enhancement of the scanned data. This refinement process is an iterative one, involving the successive stages of cleaning, meshing, and solving the CAD data. In instances of errors, the CAD data was revisited at the specific error location, and the sources of the errors were rectified.

Initially, the CAD data did not encompass the internal structures. Regrettably, the process of scanning the entire aircraft, though not detailed here, solely provided information on the external structure without internal details. Moreover, the dimensions for a significant portion of the internal structures remained unknown. Addressing this challenge, a dimension procurement effort was undertaken, involving manual dimension measurements taken from an actual aircraft and a comparative analysis with maintenance manual diagrams. These obtained dimensions were subsequently integrated into the NX. Nastran software. The wing root CAD model is presented in Figure 2 for reference.

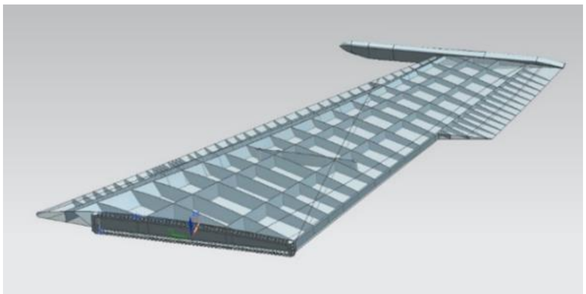

Figure 2 CAD Wing root development

Subsequent to acquiring the CAD model, a partial remodelling of the wing root was carried out, as illustrated in Figure 3. This remodelling was essential to align with the specific design prerequisites stipulated by the N.X. software applications.

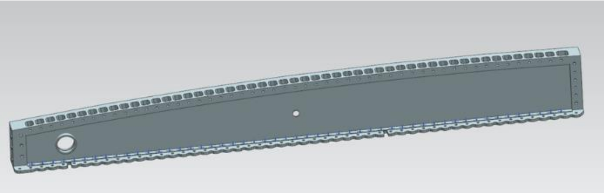

Figure 3 Remodelled Wing Root for Fatigue Analysis

2.2 Model Weight Validation

The Nastran weight check analysis serves as the initial gauge of the CAD quality after the Nastran solver has completed its calculations. Preceding this stage, checks pertaining to the quality of geometry and shape have generally been satisfactorily addressed. The manufacturer's specified empty weight (MEW) for the X-aircraft is 18400 kg. MEW encompasses the combined mass of the aircraft's structure, power plant, furnishings, installations, systems, and various other equipment components. This information has been sourced from the manufacturer's manual and includes the mass of components apart from the internal structures.

Upon careful computation, the cumulative mass values, reflecting the contributions of various aircraft components and systems, converge at a total of 9376 kg from GRDPNT and 8510 kg from the Manufacturer's Data, culminating in an aggregate mass of 17886 kg. This computed figure, when contrasted with the Manufacturer's Empty Weight (MEW) specification of 18400 kg, reveals a remarkable degree of correspondence, amounting to 97.2%. In quantitative terms, this signifies a mere 2.8% deviation, underscoring the meticulousness and precision of the CAD modelling and associated data.

The implications of this calculation extend beyond numerical accuracy. They provide valuable insights into the integrity and reliability of the CAD data, particularly in relation to the physical mass distribution within the aircraft structure. The congruence between the calculated mass and the established MEW benchmarks serves as an affirmative validation of the CAD data's fidelity and its alignment with the expected weight characteristics.

2.3 Structure Material Properties

The Science and Technology Research Institute for Defense (STRIDE), conducted the initial material identification, utilizing STRIDE's advanced material scanning capabilities. Additionally, supplementary material properties were gleaned from authoritative sources, including the Metallic Materials Properties Development and Standardization (MMPDS) handbook [12] and the Titanium Alloy Russian Aircraft and Aerospace Application [13].

The specific material identified through this collaborative effort is the VT20 Titanium alloy, with material properties referenced from the work of S. Ya. Yarema [14]. Table 1 provides a comprehensive overview of the primary material properties. Subsequently, for the wing root, the VT20 titanium alloy, equivalent to the Ti-8Al-1Mo-1V titanium alloy in Western standards, and the V95 aluminum alloy, corresponding to the AL7075 aluminum alloy in Western specifications, were chosen based on their suitability and specific properties for meeting the structural requirements of the wing root.

An alternative validation method involves an examination of the structure's center of gravity (CoG). This entails utilizing the known CoG values and aligning them with the corresponding values derived from the constructed CAD model. While CoG data are typically supplied by the Original Equipment Manufacturer (OEM), alternative methodologies such as photogrammetry as proposed by [15] and modelled using multibody techniques [16], offer additional avenues for determining the CoG of the aircraft or structure.

Table 1 Basic Material Data for VT20 and V95

No	Property	Value
AL7075		
1.	Young's Modulus	71.02 GPa
2.	Poisson Ratio	0.33
3.	Yield Strength	413.69 Mpa
4.	Ultimate Tensile Strength	468.84 Mpa
VT20		
1.	Young's Modulus	121 GPa
2.	Poisson Ratio	0.34
3.	Yield Strength	805 Mpa
4.	Ultimate Tensile Strength	845 Mpa

2.4 Development of the Finite Element Model

As illustrated in Figure 4, the Finite Element Models depict the segment of the wing root structure in consideration, with HEX and TET elements assigned for analysis. In the aircraft's configuration, the wing root structure is directly affixed to the center wing, and the outer wing is attached to the wing root using bolts that pass through pre-existing holes. The finite element model was meshed with elements no larger than 2mm in size, ensuring a detailed representation of the structure and to accommodate the design requirement by the finite element software NX Nastran. This comprehensive approach and the mesh integrity study done has enabled a thorough examination of the behavior and structural integrity of the wing root structure, particularly in relation to potential high stress areas.

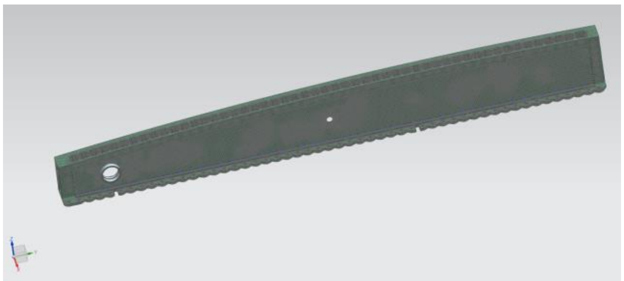

Figure 4 Wing root finite element model.

A mapped stress area was obtained from the complete aircraft static stress analysis. The model was used as an initial load input of the structure. An initial load value was placed on the wing root structure model using these location-based input loads. Figure 5 shows the mapped force used as a load input for the fatigue analysis.

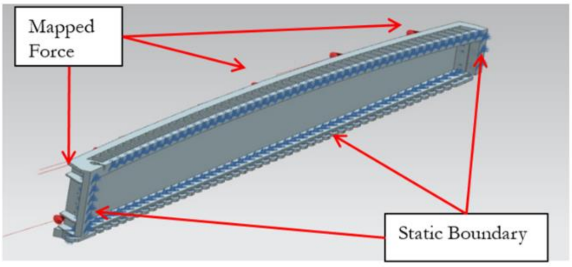

Figure 5 Wing root finite element model load and boundary condition

The upper attachment wing surface pocket, a significant component in the intricate design of an aircraft's wing root structure, is subjected to a meticulous and deliberate engineering process. This process involves a gradual reduction in thickness, transitioning from the initial dimension of 1mm to a final measurement of 4mm. The thickness reduction is systematically executed along the surfaces of both the floor and the walls of the pocket, as thoughtfully depicted in Figure 6.

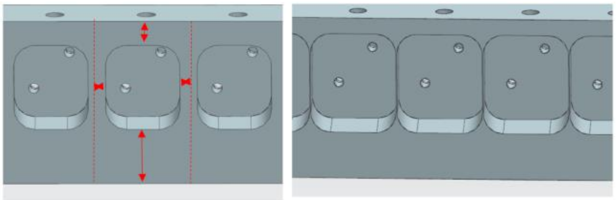

Figure 6 Thickness reduction on the FE model

It is important to underscore that this procedure is not an isolated event; rather, it is an essential aspect of a comprehensive strategy due to the underlying problem of pitting corrosion [17]. Each and every pocket within the wing root structure is slated to undergo this transformative thickness reduction. The overarching objective is to enhance the understanding of the wing root structure's ability to withstand load at different values of sanding.

III. RESULTS AND DISCUSSION

The results data obtained from the VLM simulations on the BWB-X are tabulated and plotted to give graphical representations of all aerodynamics forces and moments. The lift, drag, roll moment, pitch m

3.1 Static Analysis Result with Thickness Reductions

The composition of the X-aircraft's wing root is a matter of critical significance, primarily featuring two distinct materials: the VT20 Titanium alloy and the comparably less robust V95 aluminium alloy [18]. The VT20 wing root structure has been extensively analysed, revealing that even under the considerable load of approximately 9G multiplied by the maximum force exerted on the structure, the stress level remains comfortably below the maximum yield strength [19]. This is a testament to the impressive toughness and resilience of the VT20 material.

In light of these findings, there arises a compelling rationale for conducting an in-depth study of the V95 aluminium alloy, which, in direct comparison, emerges as the relatively weaker of the two materials constituting the wing root structure. Understanding the limitations and potential stress thresholds of the aluminium alloy is of paramount importance, as it plays a pivotal role in shaping the overall structural integrity and performance of the aircraft.

Additionally, referencing the valuable insights from [19], it becomes evident that the aluminium alloy, in contrast to the titanium alloy, exhibits a greater susceptibility to corrosion. This corrosion susceptibility underscores the need for rigorous study and mitigation strategies such as surface sanding analysis, as the long-term durability and airworthiness of the wing root structure depend on our ability to manage the potentially detrimental effects of corrosion.

Furthermore, Table 2 presents the results of the finite element static analysis conducted on the wing root structure, incorporating a comprehensive thickness reduction study on the V95 section. This analysis reveals that, following a 40% reduction in thickness, there is a notable and concerning increase in stress levels within the V95 structure. These findings underscore the critical importance of evaluating the structural implications of material alterations and the necessity for diligent management of such changes.

Table 2 Maximum Stress at V95 wing root structure with thickness reduction

Thickness Reduction (mm)	**0**	**1**	**2**	**3**	**4**
Stress (MPa)	3.08	3.78	4.38	11.32	23.09
Percentage stress increase	0	22%	42%	267%	650%

3.2 Fatigue Analysis Result with Thickness Reductions

Figure 7 serves as an illustrative representation encapsulating the outcomes emanating from the static test conducted on the aluminium wing root, wherein no thickness reduction has been applied. This visual exposition provides a holistic depiction, offering insights into the structural response under static loading conditions. Of particular note is the discernment that the maximum stress observed in this particular scenario registers at 3.08 MPa, a value appreciably beneath the material's established yield stress.

The consequential implications of this static test outcome are of paramount importance in substantiating the inherent structural robustness of the aluminium wing root. The meticulous evaluation of stress levels, as meticulously delineated in the figure, not only underscores the material's adeptness in withstanding static loads but also accentuates a noteworthy margin of safety, with the stress levels comfortably residing below the material's yield stress.

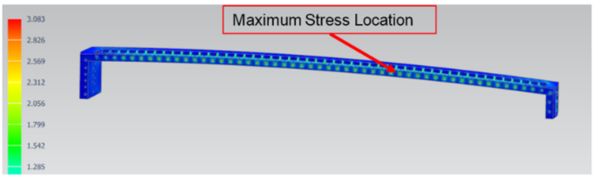

Figure 7 Stress results for upper attachment wing surface without thickness reduction

In the absence of any thickness reduction, this static test assumes the role of a fundamental baseline assessment. The provided insights into structural behavior and stress distribution across the aluminium wing root lay a foundational understanding that is invaluable for subsequent analyses. These findings not only contribute pivotal data for further assessments but also establish a solid groundwork for comprehensive evaluations within the broader domain of aircraft structural performance.

Table 3 Fatigue damage and life on the V95 wing root structure with thickness reduction

Thickness Reduction (mm)	0	1	2	3	4
Fatigue Damage	0	0	0	1.48e-16	1.82e -12
Fatigue Life	1.0e36	1.0e36	1.0e36	6.75e15	3.65e11

Building on the static analysis, a comprehensive fatigue analysis was also conducted, employing a methodology similar to that used in the static analysis. Specifically, this analysis focused on the V95 wing root structure. The outcomes of this fatigue analysis, as presented in Table 3, mirror the observations from the static analysis, demonstrating a significant increase in fatigue damage following a 40% reduction in thickness of the V95 structure. These findings further accentuate the importance of material and structural integrity considerations in the context of aircraft design and maintenance.

Figure 8 serves as an insightful depiction of the fatigue outcomes, revealing an absence of any discernible fatigue damage on the wing root structure. This noteworthy observation stands validated through the meticulous analysis of the (S/N) curve, as meticulously outlined in the scholarly work by [12]. According to this empirical curve, the onset of any perceptible fatigue life or damage is contingent upon the stress level reaching the critical threshold of 110 MPa.

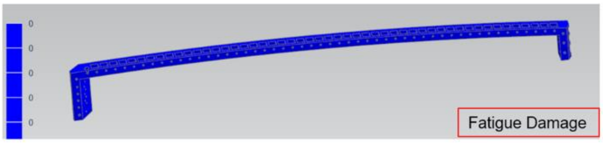

Figure 8 Fatigue results for upper attachment wing surface without thickness reduction

Upon closer scrutiny of the provided data, it becomes apparent that even under the influence of a gravitational cyclic loading of 13G, the stress value peaks at a modest 39 MPa. This measured stress level remains notably below the stipulated threshold of 110 MPa, affirming a substantial margin of safety against the initiation of initial fatigue damage.

However, it is imperative to note that as the process of thickness reduction commences, there is a discernible increase in stress levels, surpassing the critical threshold of 110 MPa. This escalation in stress levels heralds the initiation of fatigue damage, concurrently leading to a reduction in the overall fatigue life of the wing root structure.

3.3 Validation of Fatigue Analysis

Within the context of references [12] and [18], and with the elucidation derived from Figure 9 obtained from [12], a compelling correlation comes into focus. This correlation pertains to the interplay between gravitational forces experienced by the X-aircraft and the consequential stress results, specifically in relation to the initiation of potential fatigue damage. The critical determinant in this scenario is the extent of thickness reduction, a significant factor. Figure 9 stands as an essential visual representation of this phenomenon. It reveals the dynamic relationship between the gravitational forces acting upon the aircraft, the corresponding stress levels, and the pivotal threshold at which the initiation of fatigue damage occurs. This juncture becomes apparent when the thickness reduction reaches 3mm, coupled with the initial stress data of 11.32 MPa during nominal 1G conditions and the peak stress data of 147.16 MPa experienced during high stress 13G maneuvers.

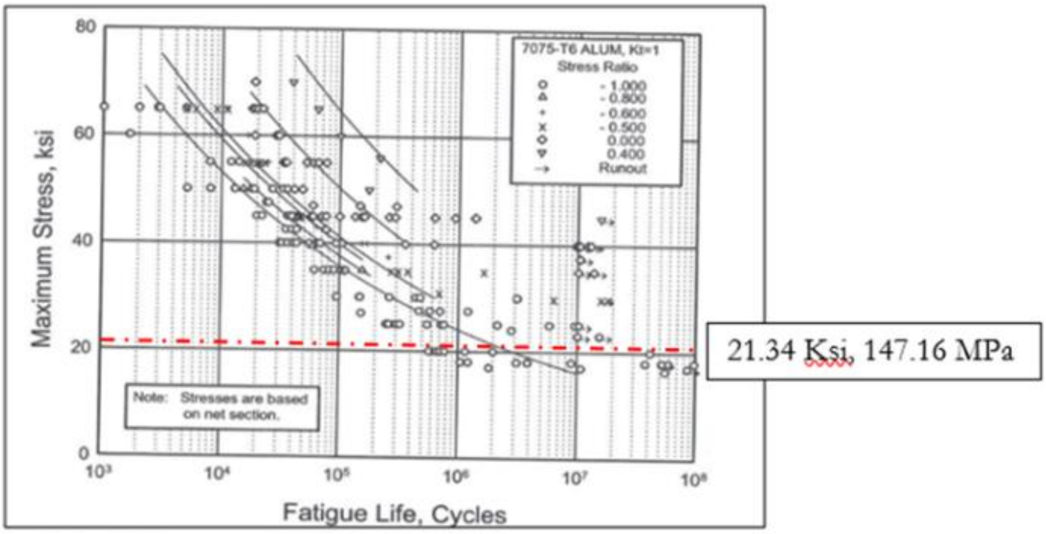

Figure 9 S/N Curve validation for AL7075-T6 fatigue data [12]

IV. CONCLUSIONS

In summary, our analysis of the X-faircraft's wing root structure has shed light on critical considerations in the field of aerospace engineering. The study has highlighted the robustness of the VT20 Titanium alloy and the relative weakness of the V95 aluminium alloy, emphasizing the need for a nuanced understanding of their properties and structural implications.

The finite element static analysis, in conjunction with the thickness reduction study, has revealed significant implications for the structural integrity of the V95 structure, underscoring the necessity for meticulous material and structural management. Moreover, the findings have emphasized the importance of proactive corrosion management strategies, especially for the more corrosion-prone aluminium alloy, ensuring the long-term durability and airworthiness of the wing root structure.

Based on the comprehensive analysis of the obtained results, a nuanced understanding of the wing root's structural behavior emerges. Initially, the wing root exhibits remarkable resilience and strength in the absence of imperfections. However, as the thickness undergoes a reduction of up to 40%, a discernible increase in stress levels becomes evident. This rise in stress has cascading effects, notably escalating fatigue damage and, consequently, exerting a tangible impact on the overall fatigue life of the wing root structure.

An insightful exploration of relevant literature, particularly the study referenced in [19], unveils a compelling narrative. The VT20 material demonstrates a notably superior fatigue life, contrasting with the discernible reduction in fatigue life observed in aluminium. This stark divergence prompts a call for further in-depth investigation into the structural strength of the wing root, unravelling intricate material dynamics.

Moreover, considerations extend to the susceptibility of aluminium, as highlighted in [17], towards corrosion. This introduces a vital dimension necessitating corrosion treatments, such as sanding. Consequently, a meticulous analysis of thickness reduction becomes imperative, intertwining with corrosion management strategies.

Conclusively, these considerations are instrumental in achieving the highest standards of safety and performance in aviation. The fatigue analysis, investigating the progressive structural damage under cyclic loading, is an integral component of ensuring the durability and reliability of aircraft critical structures. The study combines computational stress analysis with strain-life techniques, utilizing both analytical and Finite Element Method (FEM) analyses. The reliability of FEM analysis in critical locations, particularly in linear and elastic-plastic domains, makes it a preferred choice for structural stress analysis.

In essence, our comprehensive examination has illuminated the multifaceted nature of aerospace engineering, where each component's structure and integrity play pivotal roles in maintaining the highest standards of safety and performance in the demanding operational conditions of aviation.

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