FATIGUE ANALYSIS OF AN ALUMINUM AIRPLANE SPAR STRUCTURE

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ABSTRACT

Airplane is the intercontinentally most widely used mean of passenger transportation. It has a great importance on the actual global economy not only due to passenger and cargo transportation around the world, but also for its remarkable impact on industrial activity, commerce and services. Therefore, the accurate design of airplane components is of prime relevance in the context of the security of its complex operations. Following this reasoning, the spar, which is the principal element of the wing, plays a crucial role in airplane assembly because it supports the greatest part of the external loads. Although some research related to spar structures have been undertaken aiming to find maximum stresses and fatigue life, more studies have to be conducted, showing that the fatigue life prediction of this component still deserve attention. This paper aims to obtain the fatigue life of a non-tapered cantilevered aluminum spar of a single-engine airplane subjected to several point loads (coming from the interface with adjacent wing components) acting on the center of gravity of the distributed loads resultant from these contacts. The mathematical model comprises an I-beam, which one end is cantilevered at wing box (fuselage) and the other is free and almost reaches the airplane wing tip. The spar model is generated using ANSYS® Design Modeler and is computationally assessed using the Finite Element Method (FEM)-based software ANSYS® Mechanical. The results of this analysis show that it is possible to predict fatigue life of a spar under the considerations presented herein. Therefore, the life obtained as a result of this analysis can be used to plan the maintenance of this component, leading to more reliable inspection intervals, which could avoid catastrophic failures under service and operate with a better cost-benefit relation.

Keywords: Fatigue; Airplane; Spar; Structure.

1. INTRODUCTION

There are several distinct definitions to an aircraft. One of the most common is to present by categorization, as made in [1]. Are classified as aircraft all devices capable of flying. Within this concept are found airplanes, helicopters, gliders and vehicles lighter than air. Airplanes represent the majority of aircrafts around the world and, therefore, most researches and publications available are related to them. In literature, there are several subdivisions of an airplane. One of them states that the single-engine airplane main structure, also called airframe, is categorized into six items: power plant structure, fuselage, stabilizers, flight controls, landing gear, and wings. Fig. 1 shows the localization of each structure for a single-engine airplane.

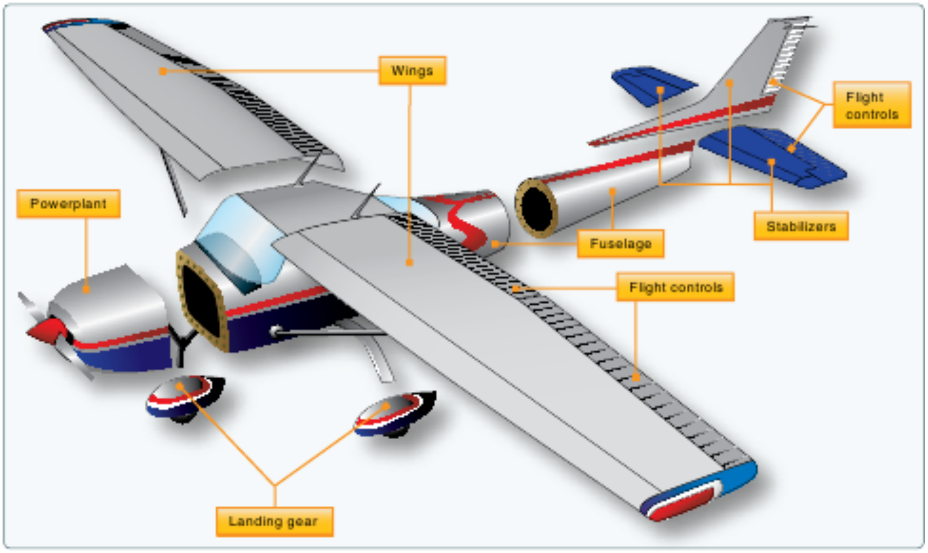


Figure 1 – Main structures in an airplane. [2].

The fuselage, also called airplane body, carries passengers, cargo and interfaces all the other structures. Tail is the stability provider because it houses the stabilizers, which can control yaw and pitch movements. The vertical stabilizer controls yaw movement and the horizontal stabilizer controls pitch movement. Assembled on wings, flight controls are responsible for providing rolling movement, and increase lift and drag loads. The powerplant houses the motor. The landing gear makes the airplane interface with the ground. Attached to the fuselage, wings are airfoils that when moved with a certain speed and position related to the airflow are capable of generating the necessary lift to support the airplane.

The wing structure is subdivided into ribs, stringers, skin, and spars. It can be made from many materials such as wood, polymers, metal alloys and composites. Fig. 2 illustrates the disposition of the main structural wing elements. Internally, spars and stringers run span wise (from wing box to wing tip) and ribs run chord wise (from trailing edge to leading edge). Externally, the skin covers all structural elements, providing the necessary airworthiness.

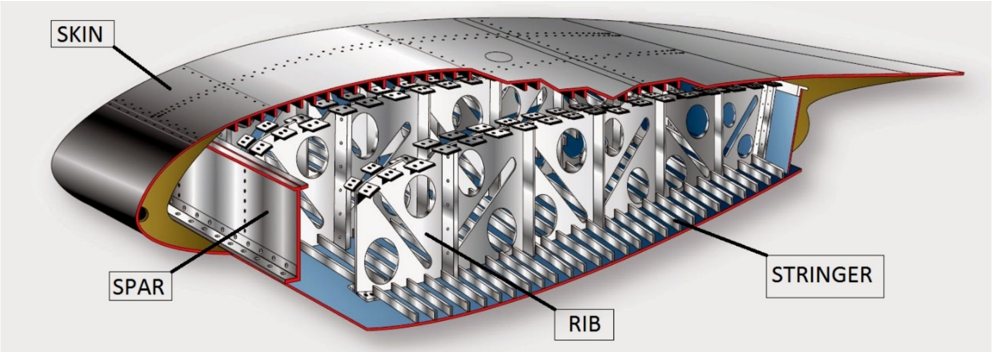


Figure 2 – Principal structural elements of an airplane wing [2].

This paper reports the monospar design, which leads to the concept of a spar that covers almost full wingspan. The most current spar designs are based on an I-beam made of an integral solid extruded aluminum or several aluminum extrusions joined. The spar consists of a beam that runs span wise the wing, from the root (wing box) toward the wing tip, not properly reaching the tip. It is the principal structural element of the wing, having as main function to resist the lift loads (when flying), which are transmitted through the skin and ribs, and support the weight of the wing when the airplane is on the ground. Fig. 3 illustrates some mostly used types of spars.

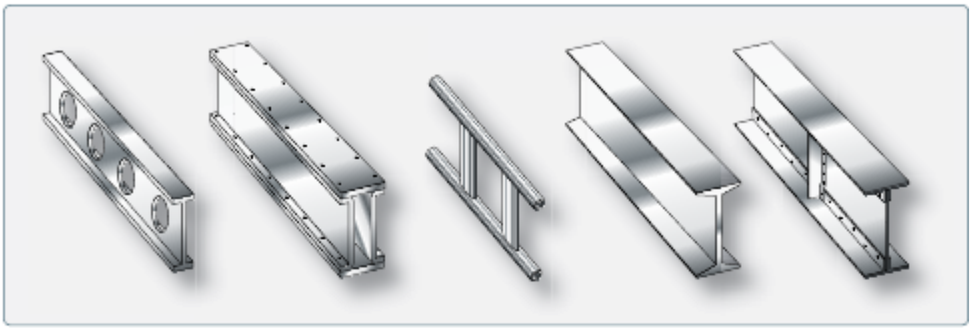


Figure 3 – Several types of spars used in airplane construction [2].

Spars are sometimes used as hinge points to flight controls. During flight, due to the shape of the wing, the airflow produces a lift load (upward load, when the airplane is in its normal position). Therefore, spars are mainly affected by bending loads, which produce compressive stresses on their upper part and tensile stresses on their lower part. Spars support most part of distributed loads and concentrated loads that come from the airflow, landing gears, and fuel tank.

The spar model considered herein is common in single-engine airplanes, which are of great importance to the aircraft context, either for this type of aircraft become the first to be used by those who initiate his or her career as a pilot or for its importance as agricultural pesticide airplane. It is also used for announcements, carrying banners and flags, and for passenger carrying (air taxi service or personal use).

In recent years, research on spar's ability to withstand flight efforts is becoming more widespread, and numerous methods have been developed to analyze the behavior of this component. In an older study [3], point loads were considered for fatigue life analysis of a spar, in which an aluminum model was manufactured and tested by means of a rotary motor that applied the load at the free end of the beam. The results obtained in the laboratory were compared with results generated by software using the FEM. In addition, a crack growth analysis from the fatigue phenomenon was performed.

In a paper published in 2015, a wing with the spar and ribs inside was designed and analyzed, using three models made by S-Glass, Kevlar and Boron Fiber and an original model without the structural elements [4]. The models were designed on PRO-ENGINEER® and performed the analysis on ANSYS®. They also performed a CFD analysis in order to obtain the loads over the wing. They compared the results and concluded that the model with the addition of ribs and spar was the most adequate and S-Glass was most adaptable material to the requirements.

Studies performed in 2016 proposed the simplification of the mathematical model of a spar by a cantilevered beam with one load applied at the free end. There were performed tests on aluminum models, obtaining the response of the beam when subjected to static and dynamic loads, making a comparison with the results obtained through FEM [5].

In another research, softwares were used to obtain the loads under which the spar is submitted. After the loading condition was obtained, the behavior of a cantilevered beam subjected to equivalent loads, but applied in a concentrated manner, was analyzed, thus obtaining an estimate of the spar behavior [6].

In September 2017, a study published in the International Research Journal of Engineering and Technology [7] reported a tapered spar model that was designed and validated for high altitude flight conditions using FEM. In addition, they used a software called Tosca to reduce mass from spar's web, reaching a reduction of 40% of the mass in the web.

Also in 2017, a comparison was made between conventional and optimized methods, in which a commercial spar was used as the object of study. The test consisted in approximating the spar by a cantilevered beam, in which concentrated loads and data were collected. After the test, the computational analysis was performed via FEM. At the end of the study, the data obtained through testing and computation were compared, and the beam was optimized by changing the beam profile and removing material from the core. Such actions produced a reduction of the order of 52.8 kg [8].

In a research also performed in 2017, a U-profile spar consisting of carbon ribbons in the middle of a polyimide matrix was designed and its behavior analyzed when subjected to a 10 kPa pressure acting on the lower flange of the structure [9]. In this experiment, FEM was also performed through ANSYS® simulation. After obtaining the simulation data, the best orientation of the carbon ribbons was selected according to the free-end displacement and the maximum torsion angle.

Given the latest researches, it is possible to observe that several studies implemented the approach of considering the actuating loading in a spar as concentrated. This method has been proven to bring satisfactory results, and, therefore, it can be used in order to get a sense of approximated real spar behavior.

The airplane structure, also known as airframe, is responsible for carrying the loads of thrust, drag, weight, and lift. The loads to which the airframe is subjected are naturally variable due to almost uncontrollable inherent environmental service conditions. These conditions scarcely induce static failure, except in specific situations. During the entire service life of the structural airplane components, the failure is most probable due to fatigue. This paper aims at predicting fatigue life of a non-tapered cantilevered aluminum spar (prismatic I-beam) subjected to point loads (that come from the contact with adjacent components) simulating the condition of cruise flight. It is also concerned with the execution of stress and displacement analysis, obtaining the critical points of the spar considered.

2. MATERIALS AND METHODS

The two main functions of the spars during its entire life are to absorb part of the load and to transmit the other part. The load path initiates from the air flowing through the wing skin, which is attached to the wing structure and partially carries the load. The other part of the load is transferred to the ribs, which in turn absorb a portion of the load and transmits the greatest part of this fraction load to the spars. The latter carries part of the load and transmits the greatest part of the initial load to the wing box connection. It is estimated that about 80% of the total load applied to the wing is supported by the spars [6], and, resulting from the applied loads on the spars, the main stresses are tension, compression, bending, torsion, bearing and shear from bending.

Intrinsically to a natural operation of an airplane, flight parameters are varying permanently. Therefore, since the loads present a variable behavior, further attention has to be deserved in order to perform the operation safely. In this context, fatigue analysis aiming life estimation must be performed on spar, which may assure that this component will not break down catastrophically on service, allowing the maintenance to take the required action in time.

During its estimated life, the spar is subjected to a great variety of situations. For example, when the airplane is parked, under normal environmental conditions, the spar is influenced by the effects of wing weight only, such that bending load is present verifying that the upper external fiber is under tension and its lower external fiber is subjected to compression, besides being affected by a torsion load and shear from bending. When the airplane is taxiing, a low-pressure airflow starts and tends to oppose the wing weight, but in this case, starts to prevail the load from vibrations resultant to the airplane displacement through the ground. Finally, when the machine is flying, the lift load supports its entire weight plus a factor of acceleration of gravity, which causes bending moment (compression at upper fiber and tension at lower fiber), shear from bending and torsional moment.

In this paper, the Computer Aided Design (CAD) model of the spar was constructed on ANSYS® Design Modeler, whereas pre-processing, simulation and post processing were conducted on ANSYS® Mechanical. The computational model of the spar comprises a non-tapered aluminum cantilevered I-beam to which nine concentrated loads of 544.44 lbf are applied (from the contact with adjacent components), as shown in Fig. 4. The left side is cantilevered whereas the free end is the right side. The loads are applied where the contact with adjacent components occurs.

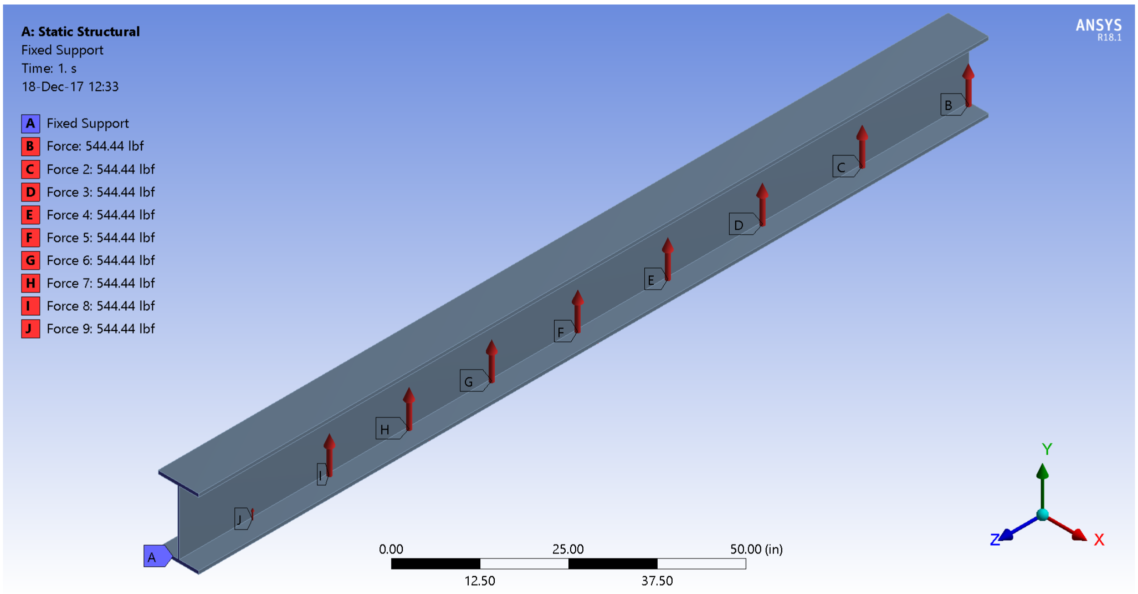


Figure 4 – Computational model used for the spar analysis.

The spar is made of aluminum alloy 2024-T3 (UNS A92024) extruded standardized as ASTM A6 W360 x 79 (mm x kg/m) with 4 meters length, having the following properties:

a) Tension/compression ultimate strength: 70.3 ksi.

b) Tension/compression yield strength: 52.2 ksi.

c) Modulus of elasticity: 10600 ksi.

d) Poisson’s ratio: 0.33.

e) Density: 0.1 lb/in3.

One of the challenges in wing components design is the collection of load spectrum data, because naturally they are rarely available, being a mixture of deterministic, epistemic and random data. The knowledge of uncertainty around load behavior is determinant to assure a bounded reliability, which can guarantee a secure operation at a measured level. As presented in [3], Fig. 5 shows the behavior of load (superposition of two types of loads – deterministic and random) during a cycle Ground-Air-Ground (GAG) used as input data in fatigue tests. This paper makes the assumption of working with cruise flight condition (flight mean line in Fig. 5), establishing the maximum lift load (airplane weight plus a 3 g load effect) and the minimum lift load (airplane weight plus a 1 g load effect).

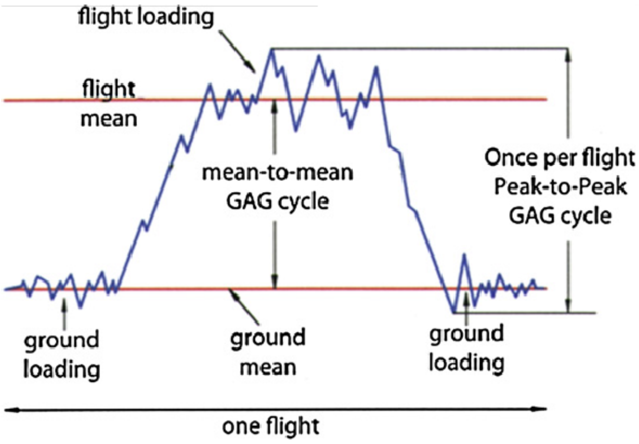


Figure 5 – Cycle Ground-Air-Ground (GAG) [3].

3. RESULTS AND DISCUSSION

The finite element model of the spar, using only tetrahedral elements, after successive mesh refinement, reached 2886228 nodes and 580165 tetrahedral elements, corresponding to maximum tetrahedral face of 0.16 in. The mesh refinement was implemented only in proximities and curvatures. Fig. 6 shows a part of the initial meshed model and Fig. 7 illustrates the final meshed model.

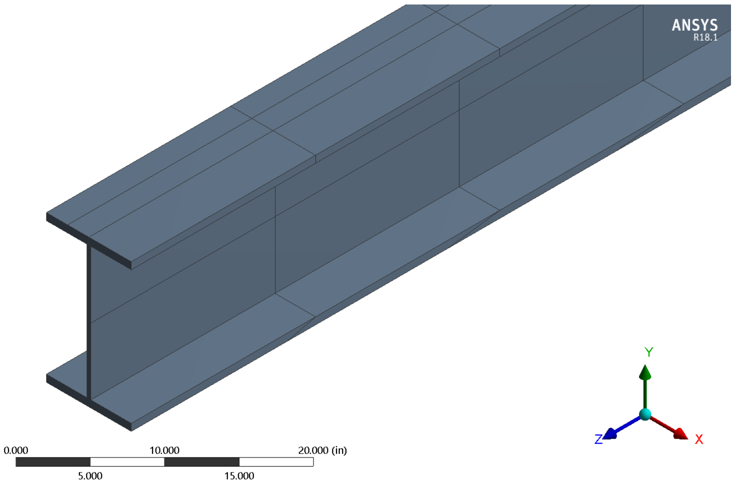


Figure 6 – Initial meshed model (592 nodes and 72 elements).

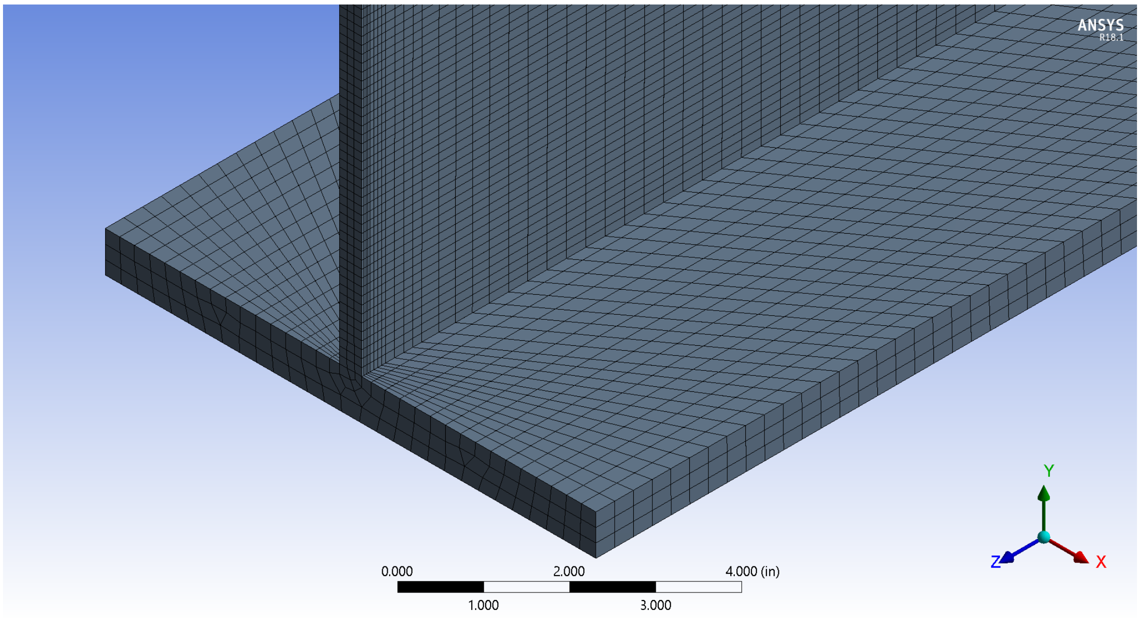


Figure 7 – Final meshed model (2886228 nodes and 580165 elements).

Comparing these meshed models, it was necessary to reduce the maximum tetrahedral face of element from 20 in to 0.16 in, which increased the number of nodes from 592 to 2886228 and the number of elements from 72 to 580165. This is necessary to obtain an error lower than 1.69% when the criteria is von Mises stress and an error lower than 5.79% cycles when the criteria is fatigue life.

Fig. 8 and Fig. 9 represent von Mises stress plot related to the most refined mesh. Both figures have scale in inches and von Mises stress in psi. The cross section shown in Fig. 8 is the cantilevered end, which is located at left side in Fig. 9. Considering the conditions imposed to the spar and the maximum von Mises stress (10733 psi), stress plot shows that the distribution of stresses is in accordance with what was expected for a cantilevered beam with concentrated loads applied, presenting its maximum stress at the outermost fiber of the cantilevered cross section and its minimum at the free end. In addition, it is possible to observe that the stress distribution at the cantilevered cross section goes from maximum compression to the maximum tension, passing through the neutral axis, which stress is almost null.

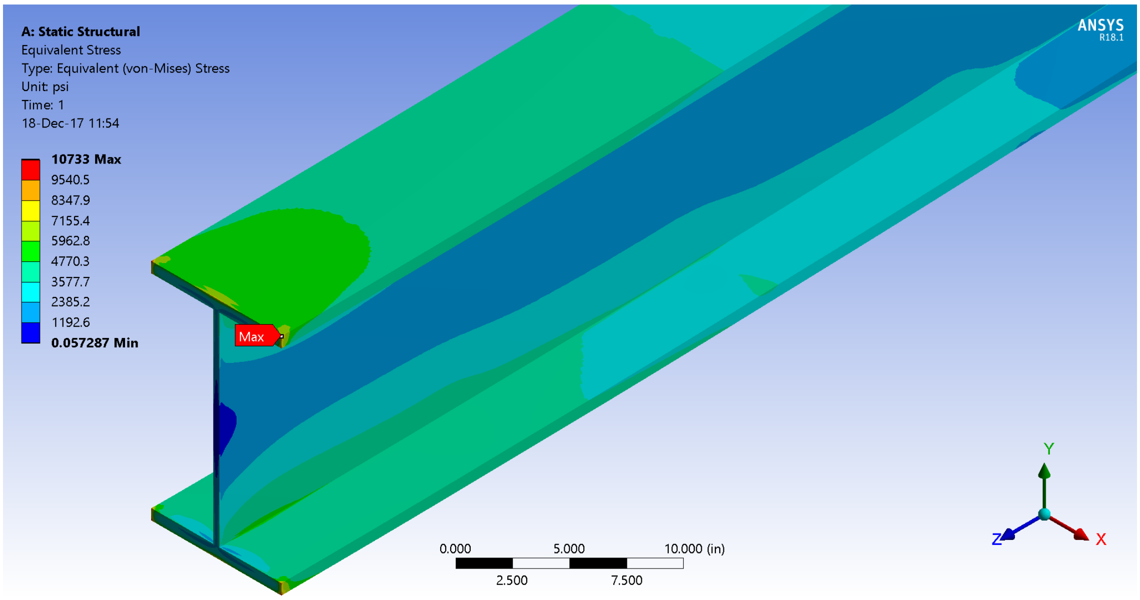
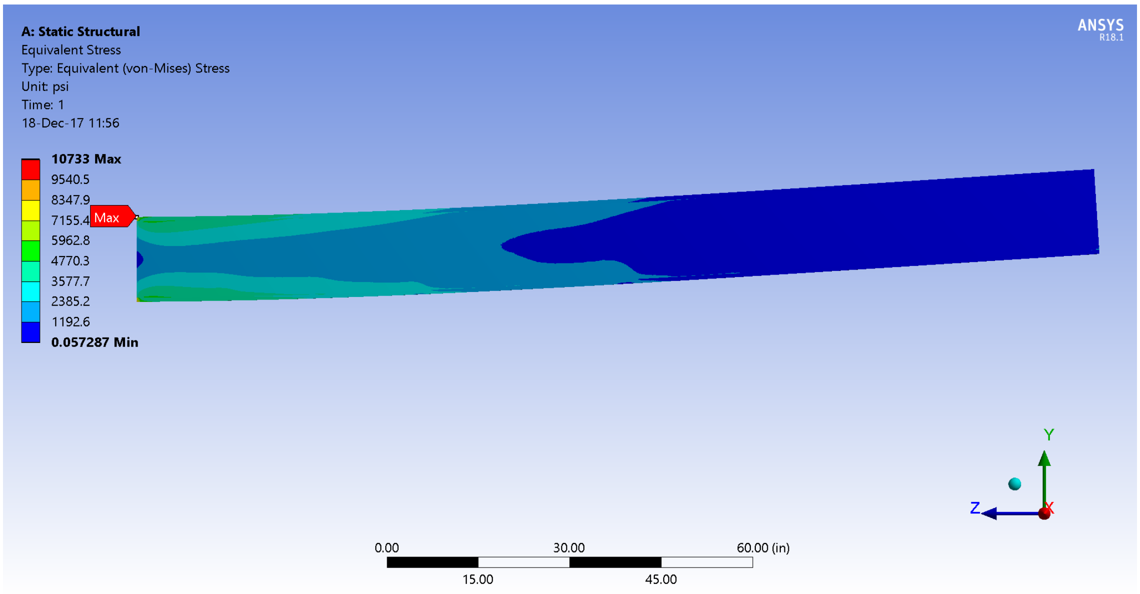


Figure 8 – Von Mises stress plot showing the cantilevered end.

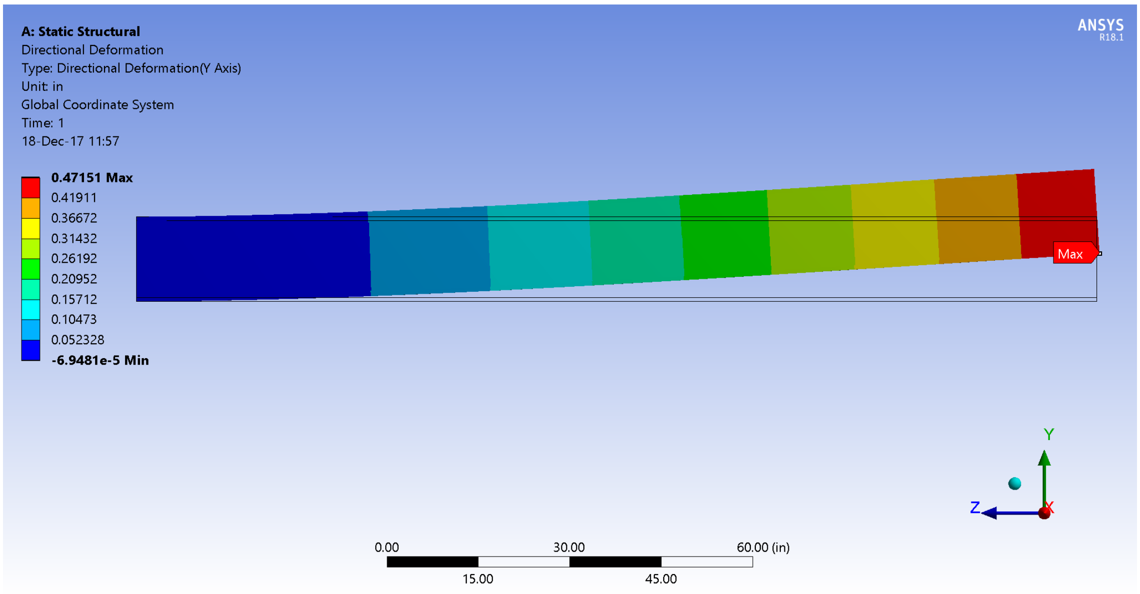


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
18-Dec-17 11:56

10733 Max
9540.5
8347.9
7155.4
5962.8
4770.3
3577.7
2385.2
1192.6
0.057287 Min

Figure 9 – Von Mises stress plot showing the longitudinal axis.

Fig. 10 (in inches) represents the transversal (y axis) displacement of the spar, which maximum value of 0.47151 in. occurs at its free end, and minimum displacement occurs at the cantilevered cross section, which behavior is coherent with what was expected from it, and its non-displaced form.



A: Static Structural
Directional Deformation
Type: Directional Deformation(Y Axis)
Unit: in
Global Coordinate System
Time: 1
18-Dec-17 11:57

0.47151 Max
0.41911
0.36672
0.31432
0.26192
0.20952
0.15712
0.10473
0.052328
-6.9481e-5 Min

Figure 10 – Displacement plot of the spar.

Fig. 11 and Fig. 12 illustrate the behavior of fatigue life x number of nodes and versus number of elements, respectively. These figures show the convergence of fatigue life cycles as the number of nodes and elements increase.

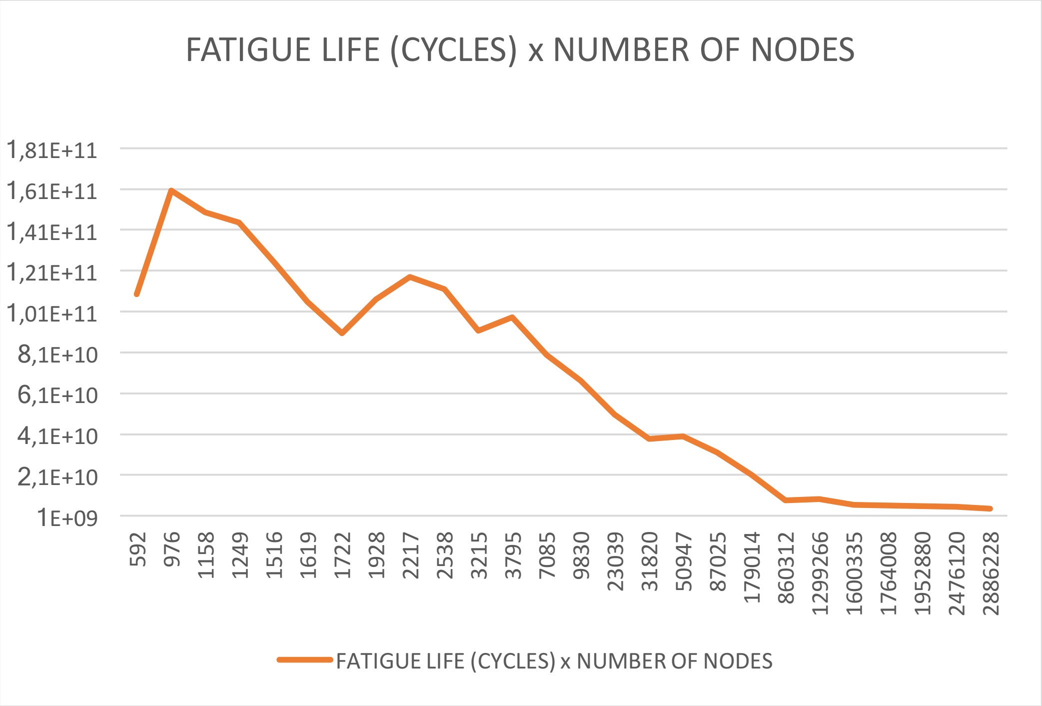


Figure 11 – Convergence of fatigue life related to number of nodes.

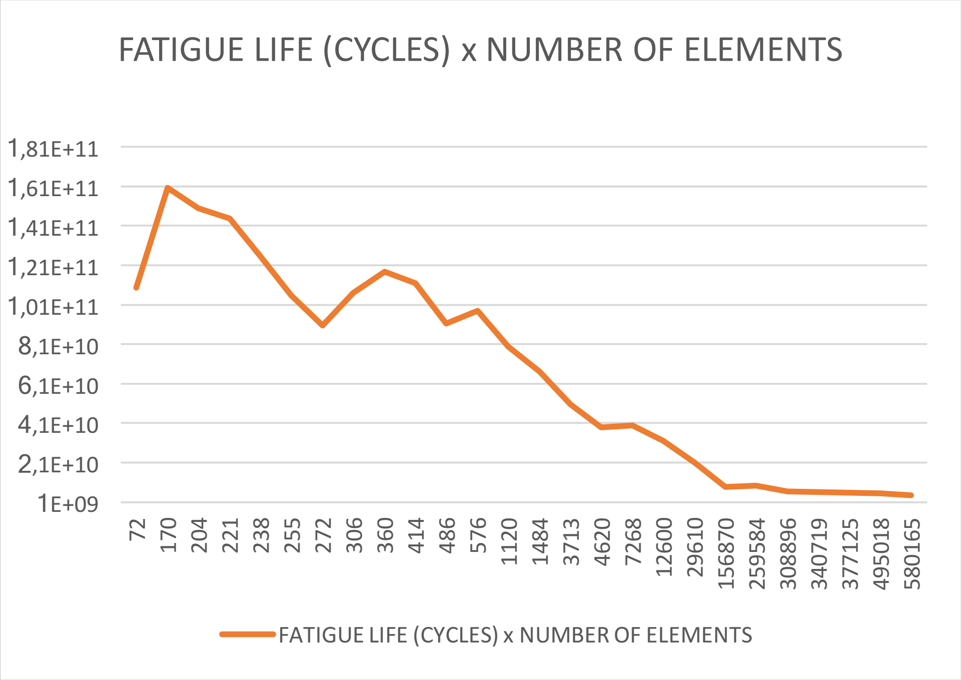


Figure 12 – Convergence of fatigue life related to number of elements.

Fig. 13 shows the component mapping related to fatigue life (cycles). It presents its limiting point at the cantilevered beam, probably indicating that a crack may initiate exactly at this point or at a point located at the cantilevered cross section, which is plausible considering the conditions imposed herein. It is emphasized that the minimum fatigue life is 9.2379 x 109 cycles and, based on this value, the inspections intervals can be planned, proceeding with processes of repair, replacement, or even no action required to assure the airplane airworthiness.

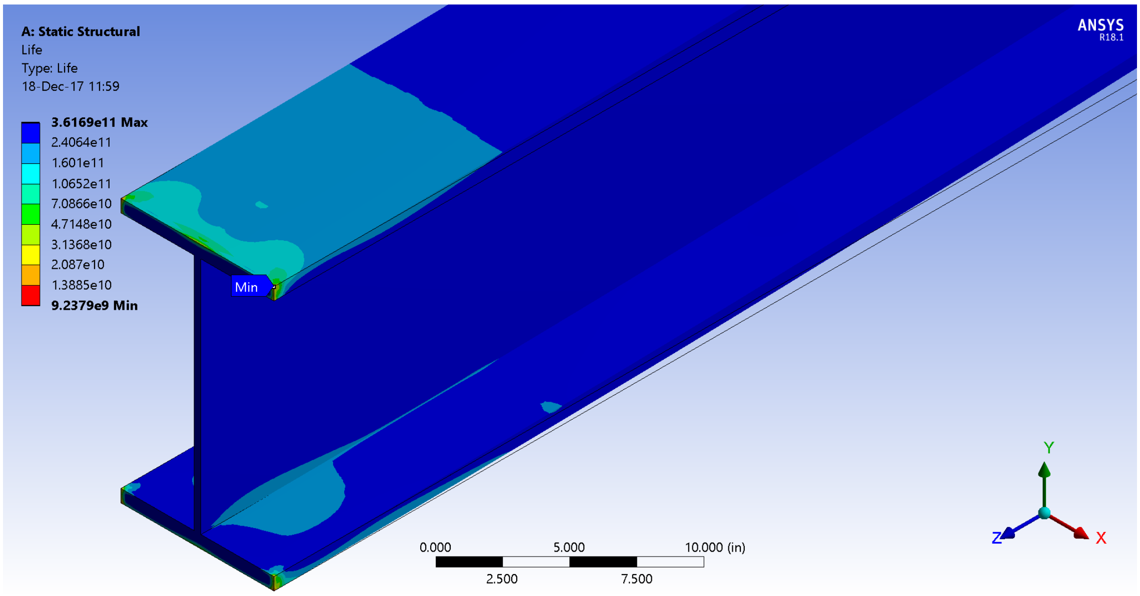


Figure 13 – Fatigue life mapping (in cycles).

Observing the results presented herein, as expected, the limiting parameter to a wing component is its fatigue life. Due to the operating characteristics of an airplane, the nature of the loads acting on the wing is variable. Therefore, in order to design a spar, a study of life estimation by fatigue analysis must be conducted. It is emphasized that this analysis considered the specific condition of cruise flight, which is only one load case of occurrence. In more advanced spar designs, additional conditions have to be observed to guarantee a certain level of trustworthiness.

4. CONCLUSIONS

In accordance with what was presented in this paper, due to its intrinsic characteristic of operation, airplane design must consider a spectrum of loads applied instead of a static load (even when modified by a dynamic amplification factor) because this is the procedure to account for fatigue failure, the limiting design. In addition, although this paper has adopted one load condition to predict service life, there are several load spectra from innumerous flight conditions to be considered in order to deliver a trustworthiness design and a reliable product.

The Finite Element Analysis aiming to obtain the fatigue life of the spar component has proved successful under the conditions stated herein because after some refinements, the number of cycles has turned out to a value with stabilization tendency. The information collected from the results can be used to predict the component maintenance, allowing engineers and technician to inspect, repair, test, and replace it just in time, maximizing its cost-benefit relation without disregarding the security aspects at any time.

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