STRUCTURAL ANALYSIS, FATIGUE ANALYSIS AND OPTIMIZATION OF AIRCRAFT WINGS

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Abstract - *This project addresses multiple objectives in an attempt to apply in the most complete and realistic manner possible, knowledge and skills that were gained throughout the writer's academic programme. The provide background theory familiarizes the reader with the most common types of aircraft failure in terms of material properties and aerodynamics, as well as with thi architecture of wings, and relates them with safety and efficiency. Extensive discussion is made on the loading conditions in which aircraft operate during their service life, and their impact on wing structure.*

Key Words: Fatigue, Finite Element Analysis, Corrosion, Aircraft Optimization, Winglet

I. INTRODUCTION

Aircraft wing is a surface used to produce lift and ensure flight. This geometry of the wing determines its aerodynamic quality and therefore different wing geometries are used for different types of aircraft. Aerodynamic quality is expressed as the lift to drag ratio, and can reach high values, up to 60 for some gliders. This means that a significantly smaller thrust force is necessary to obtain lift.

Failure of an aircraft component can have catastrophic consequences, therefore the study and prediction of aircraft failure can prevent loss of life and property damage. Structural and fatigue analysis are used not just for validating safety but also as a guide for modifications that allow aircraft to operate beyond their original design life, Among all aircraft parts, structural analysis investigates primarily the wings because their performance is critical for the overall aircraft safety. This is because wings account for flight by using aerodynamic forces and thus produce stresses that weaken their structure significantly

II. LITERATURE REVIEW

2.1 AIRCRAFT FAILURE MODES-

The list presented in table 1 compares the modes of aircraft failure with failure from other engineering components. The list shows clearly that fatigue is the most common type o failure accounting for more than 50% of the recorded modes, followed by corrosion and overloading

FAILURE MODES	AIRCRAFT COMPONENTS %	ENGINEERING COMPONENTS %
FATIGUE	55	25
CORROSION	16	29
OVERLOAD	14	11
CORROSION FATIGUE	7	6
WEAR	6	3
HIGH TEMPERATURE CORROSION	2	7
BRITTLE FRACTURE	-	16
CREEP	-	3

Table 1 - Failure Modes of Components (QinetiQ, 2002)

2.2 OVERLOADING

Failure due to overloading can occur gradually with ductile fracture or instantly with brittle fracture. Ductile fracture occurs when a material has been exposed to excessive load at a relatively slow rate to the breaking point. This type of fracture produces plastic deformation in a cup and cone shape as illustrated in figure 1 (left). Brittle fracture,occurs on application of excess load. For this fracture a crack is spread rapidly at constant stress with ittleplastic deformation. Figure 1 (right)

Figure 1 - Ductile and Brittle Fracture

2.3 FATIGUE-

Fatigue can be described as alternating loading or in other words cyclic loading which leads to cyclic stresses and strains developed in the material. Under continuous cyclic loading, at a critical stage the material ultimately fails. The failure starts with a microscope crack which was hardly difficult to find. This crack initiates at a region where the stress concentration was predominantly high such as the surface fuselage, key holes and joints. This continues until thstress reaches the limiting value after which the failure occur in most cases without any prior warning Components that fail form fatigues undergo the following three stages.

- Initiation of fatigue crack' This can be affected by stress concentrations due to material defects or design imperfections
- Propagation of the fatigue crack'
- Sudden failure as eventually the propagating crack reaches a critical size at which the remaining material cannot support the applied loads

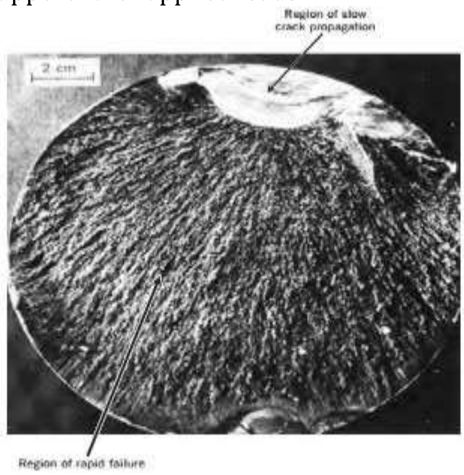

Figure 2- Fatigue Failure

2.4 AERODYNAMIC PRINCIPLES

Aerodynamics deal with the forces that result form pressure difference and friction due to airflow around structures The relationship between pressure and velocity is fundamental for understanding the effect of the aerodynamic force on aircraft wings.

2.5 BERNOULLI'S EQUATION

Bernoulli's equation gives the relationship between pressure and velocity for steady airflows In a closed systems the total energy (TE) is constant and it is given by the sum of potential energy (PE) and kinetic energy (KE).

TE=PE+KE. The compressed air around an airfoil has potential energy because it can do work by exerting force on the surface of the airfoil.

2.6 AERODYNAMIC FORCES

There are four forces during a steady level flight, thrust, drag, lifts and weight' Thrust is a force produced by the engines

Theoretical and experimental results show that lift and drag can be expressed as the product of air density a at the altitude of flight, airspeed v, wing surface area S and a coefficient representing the shape and orientation of the airfoil C_L and C_D respectively. The equations for lift and drag are:

Lift, L = ½ $\rho V^2 S C_l$ Drag, D = ½ $\rho V^2 S C_d$

2.8 SOME RESEARCH STUDY RELATED TO FATIGUE AND STRUCTUAL ANALYSIS

Immanuel – Arulselvan:- "Stress Analysis and Weigh Optimization of a Wing Box Structure Subjected to Flight Loads by In this paper FEA is conducted to validate the structural integrity of a wing box. *Pritish Chitte*:-"Static and dynamic analysis of typical wing structure of aircraft using Nastran" investigates not just the static but also the dynamic performance of wings using Nastran FEA software.
Makandar – Kusugal: -"Stress Analysis of Wing Root Fitting-Box and Its Fatigue Life Estimation for Crack Initiation Due To Fluctuating Wing Loads" The paper addresses static strength and calculation of fatigue life is determined using Miner's rule.

Kumar – Balakrishnan:- "Design of an Aircraft Wing Structure for Static Analysis and Fatigue Life Prediction" This paper investigates the static and fatigue strength of a full wing model using FEA, and validates the results with hand calculations.

III. RESULTS AND DISCUSSION-

3.1 STRUCTURAL ANALYSIS

Taken form the aircraft's manual, the following specifications apply:
Wing Span: 15.50 m
Semi Span: 7.75 m
Aircraft Maximum Weight: 9,752 kg
Using dimensions form the official drawings of the aircraft3, Exposed Single Wing Span = 5.9m
Root chord length = 2.6m
Tip chord length = 1.1m

The airfoils are selected according to the Airfoil Guide (Lednicer, 2010).

As the Bombardier Learjet C70 is not included in this list, the airfoil of the Gulfstream G280 - a very similar aircraft - is selected.
Root Airfoil - NACA 0012
Tip Airfoil - NACA 64008A
Front Spar is located at 20% of the chord length
Rear Spar is located at 65% of the chord length

3.2 FEA MODEL

Using the given dimensions and pressure load, and by applying a fixed constraint for the wing root, the model is produced and FEA was conducted giving the results shown in figures 3 and 4.

Maximum Von Misses stress at the bottom root is 256.9MPa

Maximum Deflection at the tip is 239.4mm

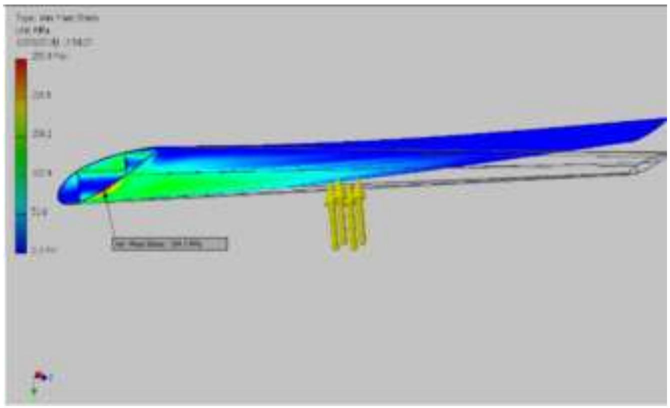

Figure 3 - FEA Von Misses Stress

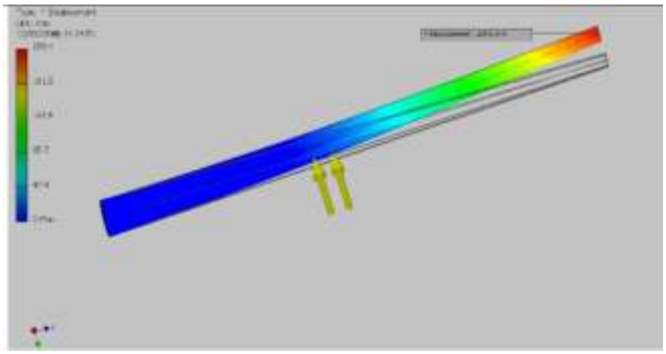

Figure 4 - FEA Displacement

3.3 FATIGUE ANALYSIS

Generally aircraft wing experiences variable spectrum loading during the flight. A bombardier aircraft flight load spectrum is considered for the fatigue analysis of the wing structure. Calculation of fatigue life is carried out by using Miner's Rule. For the fatigue calculation the variable spectrum loading is simplified as block loading. Each block consists of load cycles corresponding to 100 flights. Damage calculation is carried out for the complete service life of the aircraft. The load factor "g" is defined as the ratio of the lift of an aircraft to its weight and represents a global measure of the load to which the structure of the aircraft is subjected.

Table 2 –Bombardier Learjet 70 Loading Spectrum *(Makandar, Kusugal, 2015)*

LOADING CONDITION	LOADING RANGE	CYCLES
1	0.5G-0.75G	1000
2	0.75G-1G	200
3	1G-1.25G	40
4	1.25G-1.5G	25
5	0G-1.75G	30
6	0G-3.5G	5
7	-0.5G—1.5G	25

The maximum stress value of 256.9MPa that was obtained form the stress analysis, corresponds to 3.5 g including the FOS, and so the stress for 1G of loading is 256.9/3.5=73.4MPa.
Thus the stress values of the given load spectrum table 3 is produced.

Table 3 - Stress Limits

LOADING CONDITION	LOADING RANGE G	STRESS MIN MPa	STRESS MAX MPa
1	0.5 - 0.75	36.7	55.05
2	0.75 - 1	55.05	73.4
3	1 - 1.25	73.4	91.75
4	1.25 - 1.5	91.75	110.1
5	0 - 1.75	0	128.45
6	0 - 3.5	0	256.9
7	-0.5 - 1.5	-36.7	110.1

For the sinusoidal stress for each of thi above loading conditions the Alternating and the Mean Stress, are given by'
Alternating Stress: $\sigma = \sigma max - \sigma min / 2$
And Mean Stress: $\sigma m = \sigma max + \sigma min / 2$

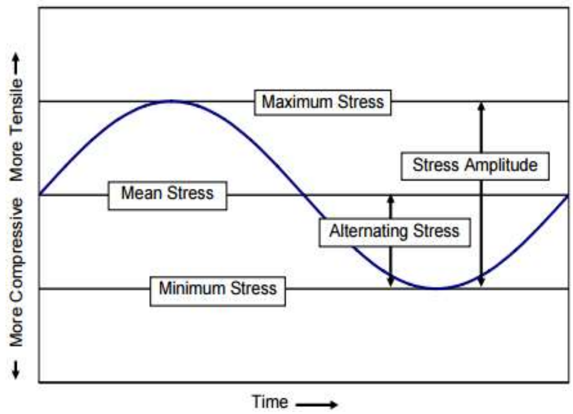

Figure 5 Representation of Characteristic cyclic Stress Values

A correction factor accounting for surface roughnessanddesignreliability is considered.Thiscorrection factor is defined as the product of the corresponding correction factors of these two characteristics (Makandar, Kusugal 2015)
Correction Factor= Surface Roughness CF x Design Reliability CF

For the aircraft wing the following values apply:

Surface Roughness CF= 0.8
Design Reliability CF=0.897

And hence, Correction Factor=0.8x0.897=0.7176

For Cu-Mg Aluminum Alloys like AA2024-T351, the S-N chart form figure 27 applies. The chart is in logarithmic scale, and it was produced form measurements on the wings of 250 different aircraft

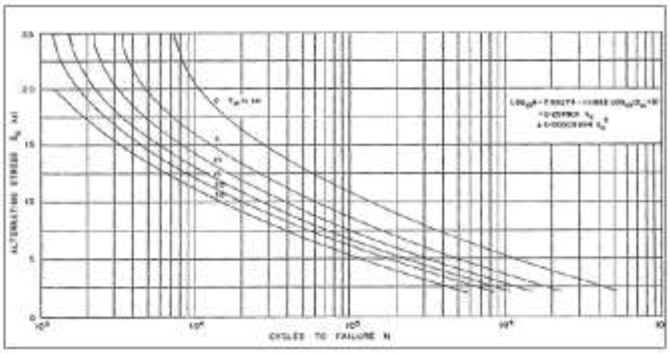

Figure 6 - S-N Chart for Al-Cu-Mg Alloy Wings (Han Gartner, 1974)

The simplest and most practical technique for predicting fatigue performance is the Palmgre-Miner hypothesis. The hypothesis contends that fatigue damage incurred at a given stress level is proportional to the number of cycles applied at that stress level divided by the total number of cycles required to cause failure at the same level. If the repeated loads are continued at the same level unit failure occurs, the cycles ratio will be equal to one.Total accumulated damage

From Miner's equation (Jadav etal., 2012), $\Sigma\ N_i/N_f = C$
Where, Ni= Applied number of cycles
N_f = number of cycles to failure
Table 4 shows damage D, accumulated on each range of load condition.

Table 4 - Accumulated Damage

Loading condition "g"	Load cycles "N_i"	Actual mean Stress (MPA)	Cycles to failureN_f	Accum.Damage D_i/N_f
0.50 – 0.75	1000	63.91	∞	0
0.75 – 1.00	200	89.49	∞	0
1.00 – 1.25	40	115.1	∞	0
1.25 – 1.50	25	140.6	∞	0
0.00 – 1.75	30	89.49	1.16×10^4	25.90×10^4
0.00 – 3.00	5	179.2	0.094×10^4	55.30×10^4
-0.50 – 1.50	25	51.15	1.05×10^4	23.80×10^4

ΣD= (25.9+53.3+23.8) x10-4=0.0103

The total damage accumulated is less than 1 and therefore a crack will not initiate immediately for the given loading conditions.

3.4 AIRCRAFT OPTIMIZATION

This section introduces the different metals used in aircraft manufacturing and investigates optimization with alternative materials like composites and sandwich structures. Aerodynamic optimization is also looked into with the use of winglets and shape changing wings.

3.5 COMPOSITE MATERIALS IN THE AIRCRAFT INDUSTRY

Aircraft designers are increasingly turning to composites for lighter structures and improved efficiency. Composites are usually built up with laminates where unidirectional fabric layers embedded within a resin matrix are stacked on top of each other at different orientations for maximum stiffness.

3.6 AERODYNAMIC OPTIMIZATION

There are several new concepts under development having to do with innovative wing shapes and materials with a focus on reduction of drag and noise and increase of fuel efficiency. It is estimated that 1% reduction of drag for a large commercial aircraft, can save up to 400,000 liters of fuel and reduce carbon emissions by 5,000 kg.

3.7 WINGLETS

The high pressure on the lower surface of the wing creates airflow form the bottom of the airfoil outward form the fuselage around the tips. At the tip, due to relatively lower air pressure above the wing, air tends to spill over and swirl around it forming a vortex that creates additional drag and thereby reducing the aerodynamic efficiency of the wing. A well designed winglet rises vertically and is swept back by approximately 25' such that it significantly reduces the size of the wingtip vortex and the induced drag.

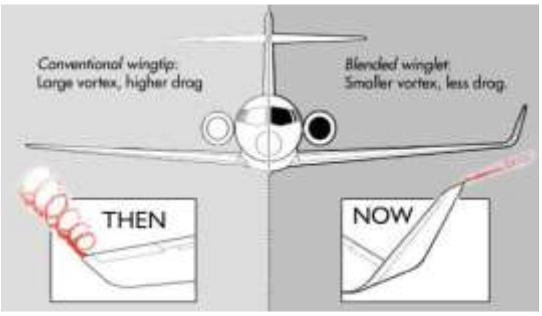

Figure 7 - Differences between flat wing tips and Winglets

Winglets bring several additional advantages due to the increased lift to drag ratio which results in better take-off performance and rate-of-climb.

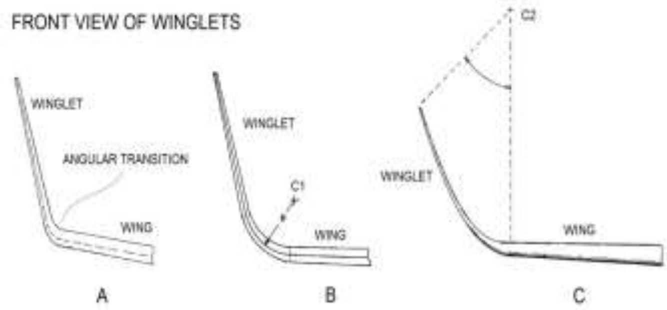

Figure 8 - Different winglet shapes

IV. CONCLUSIONS

Investigating failure contributes significantly to aircraft safety' The identification of the primary causes of failure and analysis enable recommendations for corrective action that will prevent similar failures form occurring in the future. Stress analysis of the wing structure is carried out and maximum stress is identified at near wing root which is found out to be lower than yield strength of the material. Normally the fatigue crack initiates in a structure where there is maximum tensile stress is located. The fatigue calculation is carried out for the prediction of the structural life of wing structure. Since the damage accumulated is less than the critical damage in the wing structure is safe form fatigue considerations.

The cyclic pattern of loading calculated based on blocks of loading cycles that result to a certain number of flight hours at which inspection must be carried out. In this project structural analysis and fatigue analysis were carried out on a reference aircraft wing. Von Misses stress and the modal natural frequencies of the wing were obtained with FEA and were validated with hand calculations. Calculations for fatigue life were also carried out and the fatigue safe life of the aircraft was obtained

In aircraft manufacturing, the fields of design, materials, fabrication and maintenance all work hand in hand to ensure safety. Metal fatigue and cracks corrosions excessive loadings bad design and faulty maintenance are sources of problems and an oversight in any of these areas can cause catastrophic failure. Service bulletins and airworthiness directives, constantly add new knowledge and information that combined with previous experience ensure building and maintaining safer aircraft'

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BIOGRAPHIES

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