Finite Element Analysis of Fatigue and Fracture Behavior in Idealized Airplane Wing Model with Embedded Crack Under Wind Load

Harsha Pandeya*, Dazan Fernandesb, Arpit Khandelwalc, and Dhaneshwar Mishrab,c,*

*BTech. Mechanical Engineering Student, Mechanical Engineering Department, Manipal University Jaipur, Dahmi Kalan, Jaipur 303007, Rajasthan, India
bDepartment of Mechanical Engineering, Manipal University Jaipur, Dahmi Kalan, Jaipur 303007, Rajasthan, India
cMultiscale Simulation Research Center (MSRC), Manipal University Jaipur, Dahmi Kalan, Jaipur 303007, Rajasthan, India

Abstract

Aircraft wings undergo forces like thrust, drag as well as transient loads due to gust. Even though these loads overall help in the stability of an aircraft but over time it can cause growth of defects such as micro cracks or voids due to fatigue. We would like to investigate the fatigue, fracture failure due to wind load during its long operating life of the airplane. Therefore, we have modeled the airplane wing as cantilever beam and applied fluctuating wind load. The airplane wing with embedded crack was modeled in commercial finite element analysis tool, ANSYS. The drag and lift forces acting as pressure on the adjacent faces of the wing with a transient wind load has been simulated to determine the loads on an aero foil working under similar conditions through CFD analysis. The load estimated through the CFD analysis was applied on the wing model to obtain the stress intensity factor and energy release rate. Analysis for fatigue failure was also carried out to predict life of the idealized model under considered loading. The results obtained through this work can be helpful in understanding the fatigue behavior in the transient loading condition such as wind in airplane wing.

Keywords: Airplane wing, cantilever beam model, wind load, fluid structure interaction, crack growth analysis, fatigue life prediction.

*Address for correspondence: dhaneshwar.mishra@jaipur.manipal.edu

1. Introduction

Aircraft have been playing a major role in the transportation sector for both civilian and military purposes. The aircraft is made of five basic parts, namely, the fuselage, empennage, turbines, landing gear and wings. The recent aircrafts are quite advance, still they face many challenges due to extreme weather conditions in which they have to fly. Throwing gusts at high speeds and extreme climate in the path of the aircraft make them vulnerable to accidents. Safety has been an important factor in aircraft design and operation. The wings play an important role in the stability, manoeuvring and producing lift for the aircraft. Wings have to undergo sever wind loads that can generate lift, and drag forces as well as fluctuating outside pressure because of changes over a vast geographical area due to environmental conditions. These extreme loadings can lead to failure because of defects/voids/micro-cracks inherent in the wing materials.

Modelling and analysis of wing structure under various loading conditions can provide appropriate information on the stress distribution, region of stress concentrations that can lead to failure in wing. Finite Element Method is a mathematical modelling tool which provides numerical solutions for the real-life physical problem at hand. There are quite several works available in the literature on finite element modelling, wing design and analysis of various forces and their effects on different components of aircraft structures [1-3]. Most of these works have considered different types of loadings in static analysis environment [4-6] that considers uniform pressure distribution over different surfaces of the wing. It will be useful, if more realistic loading conditions such as wind loads are considered in the analysis that can provide more accurate prediction of the stress distribution in the airplane wing. Therefore, in this work, the wind load on different surfaces of the wing structure has been simulated by conducting computational fluid dynamics (CFD) analysis and mapped to determine the stress distribution, region of stress concentrations, and possible failure zones. The commercial finite element analysis software, ANSYS 16.2 was used to conduct the modelling and analysis work presented here. The analysis also includes micro-crack growth simulation under the considered wind load. The measure of fatigue and fracture behaviour of material such as energy release rate, stress intensity factors, fatigue life have also been estimated using the analysis.

2. Materials and Method
The aim in this work is to study the effect of fluctuating wind load on the various surfaces of the airplane wing structure in terms of defect growth and predict the life cycle under the considered load. Therefore, we have conducted two-fold analysis. In the first analysis, we developed a numerical model of the airplane wing under wind load in computational fluid dynamics (CFD) environment. This analysis helped us to correctly estimate the fluctuating wind load on various surface of the airplane wing. In the second analysis, we mapped the fluctuating wind load on the airplane wing surface and conducted static analysis to estimate the distribution of stresses in different regions and find the region of stress concentration. This analysis was further extended to estimate the energy release rate and stress intensity factor in case of embedded crack in the airplane wing. The analysis also included the fatigue life prediction under the considered wind load in presence of the defect such as crack. The preceding subsections provide the modeling and analysis details in both CFD and static analyses methodologies followed in this work. The commercial finite element analysis tool, ANSYS 16.2 was utilized for the analysis and simulation purposes whereas the modeling of the wing structure was done in SOLIDWORKS, the commercial 3-D modeling software.

2.1 Computational fluid dynamics (CFD) simulation methodology

In this work, we have introduced a cuboidal control volume (Fig. 1) depicting air with the wing made of aluminum alloy. The volume in the shape of the periphery of the wing has been deducted from the control volume with the help of SOLIDWORKS to provide an accurate representation of the pressure due to wind to all the surfaces of the wing structure. The model was imported to ANSYS 16.2 Workbench platform for the analysis purpose. The air density was considered as 1.225 kg/m³, and temperature during the analysis period was considered as 288.16 K. The viscosity of air was considered as $1.79 \times 10^{-5}$ kg-m/s for the analysis purpose. The geometry of the cuboid was discretized by meshing it with 1780840 fluid tetrahedron element with 4 nodes available in ANSYS element library. One of the faces of cuboid closest to the tip of the wing along the leading edge is considered as inlet from where air will enter in our control volume at a speed of 120 m/s and the outlet of air is the face of cuboid opposite to the inlet face where the gauge pressure is zero Pascal. The distribution of air pressure on various surface of the wing structure was obtained from the CFD analysis conducted in this step.

![Figure 1: Control volume of fluid with wing inside.](image)

2.2 Static structural analysis methodology

The pressure distribution obtained in the CFD analysis was mapped for the static structural calculations in ANSYS static structural analysis module. In this module, the wing was considered as idealized cantilever beam (Fig. 2) under fluctuating wind load at various surfaces. The model was fixed at the fuselage and the other end was free as it is the case in the airplane wings. Two simulations were carried out to understand the variation of stresses in both the cases, namely, the model with embedded crack and without crack. An elliptical crack was introduced on the lower surface of the wing in the cracked model. The material properties used for the wing structure model is listed in Table 1 below. The wing structure model was meshed by using 698653 tetrahedron elements available in ANSYS library. In addition to the pressure distribution on the wing surface obtained from the CFD analysis, we have introduced the inertial, drag and lift forces on the surface of the wing. We evaluated the Von Misses stress, fatigue life, J-integral, and the stress intensity factors, which can aid in airplane wing design.
Table 1: Material properties for the wing structure

| S. No. | Property                          | Value     |
|-------|----------------------------------|-----------|
| 1     | Density                          | 2770 kg/m³ |
| 2     | Coefficient of Thermal Expansion | 2.3 x 10⁻⁵ /°C |
| 3     | Reference Temperature            | 22°C      |
| 4     | Young's Modulus                  | 70 GPa    |
| 5     | Poisson's Ratio                  | 0.33      |
| 6     | Bulk Modulus                     | 69.608 GPa|
| 7     | Shear Modulus                    | 26.692 GPa|
| 8     | Tensile Yield Strength           | 280 MPa   |
| 9     | Compressive Yield Strength       | 280 MPa   |
| 10    | Tensile Ultimate Strength        | 310 MPa   |

3. Results and Discussion

In this work, our aim was to study the effect of fluctuating wind load along with the available drag and lift forces acting on the airplane wing surfaces. We were interested to understand the distribution of stresses as well as the failure and fracture due to the wind load on the various wing surfaces. Therefore, the pressure distribution result from the CFD analysis was mapped to conduct the static structural analysis in ANSYS and obtained the variation in Von Mises stress over the surface of the wing. In addition to this, we have also obtained the deformation in different regions of the wing model. The stress intensity factor, the energy release rate, and the fatigue life has also been evaluated for the considered wind load. The detailed results in various analyses are discussed in the sub-sections below.

3.1 Computational fluid flow result

The CFD analysis was carried out to obtain the air pressure distribution on the wing surfaces. The maximum pressure of 7.64 kPa (Fig. 3) was found to be at the tip of the wing away from the fixed end of the wing. The variation in the area of wing along the longitudinal direction can be attributed to the high pressure encountered by the tip of the wing along the leading edge in the region.

3.2 Static Structural results

The aim of conducting static structural analysis was to study the effects of various loadings such as wind, lift and drag forces, etc. on the wing surfaces. The details of the results on stress distribution, the measures of fracture and
failure such as energy release rate, and the stress intensity factors due to the considered loading and their inherent mechanics are discussed below.

### 3.2.1 Equivalent stress (Von Mises stress) and total deformation

The equivalent stress in accordance with the distortion energy theory has been calculated for the wing structure with and without the presence of crack on its surface. Equivalent stress on the wing without crack was found to be 47.24 MPa (Fig. 4a) near the tip which can be due to the fact that the wind pressure is maximum in that region as well as due to the pressure applied by drag force. In the case of the model with crack, the maximum equivalent stress was found to be 150.26 MPa (Fig. 4b) at the tip of the crack. We found the stress distribution to be tensile in nature for both cases (the model with and without crack). The total deflection in the wing model was found to be 136.78 mm (Fig. 5) for both the models. The deflection value is consistent with a cantilever beam undergoing transverse loading of the magnitude being observed here due to the wind load.

![Figure 4: Von Misses stress plot (a) without crack (b) with crack](image)

![Figure 5: Total Deformation (a) Without Crack (b) With Crack](image)

### 3.2.2 Stress intensity factor and J-Integral calculations

The fracture toughness is the material characteristic that signifies the material resistance to the defect such as crack growth [7]. The fracture toughness of material is evaluated in terms of the critical energy release rate or critical stress intensity factor [7]. The stress intensity factor (SIF) and the energy release rate were estimated based on the distribution of stresses near the crack–tip using linear elastic fracture mechanics. ANSYS 16.2 has inbuilt facility to model different shapes of the crack as well as to evaluate the SIF and the J-integral, the measure of the energy release rate [8]. Here in our work, we considered an elliptical crack and found the maximum stress intensity factor in mode 3 that depicts the tearing load. The J-Integral value, which is the measure of energy release rate was found to be $1.02 \times 10^3$ J/m$^2$.

### 3.2.3 Fatigue life and Safety factor

We also evaluated the fatigue life using the stress life method using the Goodman diagram for the wing structure for both the cases, namely, the model without crack, and with crack. It is quite natural that material and structure
without defect will have significantly higher life than that of the cracked model. We estimated the minimum life of the wing structure without any fault to be $10^6$ cycles while for the cracked model, it was found to be $2.55 \times 10^6$ cycles (Fig. 7). Similarly, the minimum safety factor which is the ratio of the alternating stress at design life to the alternative equivalent stress at that point [8] was evaluated for wing without crack was found to be 2.216. The wing structure with crack shows minimum factor of safety as 0.763 at the crack-tip. This makes the wing structure vulnerable to failure.

![Figure 6: Life (a) Without crack (b) With Crack](image)

![Figure 7: Safety Factor (a) Without crack (b) With Crack](image)

### 4. Conclusion

We modeled the airplane wing structure and simulated the fluctuating wind load on it’s different surfaces by carrying out computational fluid dynamics (CFD) analysis using ANSYS 16.2. The distribution of the external pressure load due to wind was mapped on different surfaces of the wing. The wing structure was modeled as cantilever beam, fixing at one end of it. The static structural analysis was carried to evaluate the stresses, deflection, the fatigue life, and the factor of safety for both models, namely, the model with crack, and without crack. The stress intensity factor and J-integral, the measure of the energy release rate was also estimated for the considered wind load. The results of these simulations also will be helpful in airplane wing design as it provides better prediction of stresses and other related parameters because it has considered the realistic wind load distribution on the wing surface. Necessary improvements in the model will be done in future works by considering different combination of materials for different sections of the wing.

### 5. References

[1] K. Sureka, R. S. Meher, Int. J. Mech. Eng. & Rob. Res.(IJMERR), 4-2 (2015)124-126.
[2] Y. J. Chen, Z. F. Feng, A. Qi, Y. Huwang, ICEMEE (2018) 4.
[3] Y. E. Pak, D. Mishra, S.-H. Yoo, J. M. Sci. Tech., KSME, 26-11 (2012) 3549-3552.
[4] B. Kozłowiec, ICCMPT, IOP Publishing (2017) 1-8.
[5] A. R. Kumar, S. R. Balakrishnan, S. Balaji, IJERT, 2-5 (2013)1155-1157.
[6] S. Habib, W.B. Yousuf, T. Mairaj, S. Khalid, IBCAST, (2017) 71-75.
[7] T. L. Anderson, Fracture Mechanics fundamentals and applications, fourth ed., CRC press, Boca Raton, 2017.
[8] ANSYS v14.2 WORKBENCH Manual.