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Fatigue Reliability Analysis of Aircraft Wing Mounting Lug

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Abstract

Aircraft is a highly complex flying structure and during its flight, the wings will undergo highest bending moment when the maximum lift is generated. The bending moment will be high at the roots of the wing which causes high stress at this location. Wings are attached to the fuselage structure through wing – fuselage lug attachment. The main objective of this paper is evaluation of fatigue reliability of a wing mounting lug. Fatigue reliability is computed by accounting for the scatter present in the material properties in terms of random design variables. Random design sampling matrix is generated using Monte Carlo sampling method. Fatigue reliability and probability of failure of the lug are predicted using the finite element analysis using the generated sampling matrix. The effect of the random variable variations on the fatigue reliability of the lug is also studied and reported.

The work had been presented *at an* international conference ***Fatigue Durability India 2015****, 28-30th May 2015, JN TATA AUDITORIUM, Indian Institute of Science, Bangalore.*

Introduction

Lugs are the primary structural elements in airframe structure. Failure of lug may lead to the catastrophic failure of the whole structure. Rarely an aircraft will fail due to a static overload during its service life. For the continued airworthiness of an aircraft during its entire economic service life, fatigue and damage tolerance design, analysis, testing and service experience correlation play a pivotal role. During service of lug linked components, the pin bearing load together with fretting between the pin or bolt and the lug hole could endanger the strength of lug under cyclic loading. Since lug failures predominantly occur under fatigue conditions, it is very important to develop reliable computational models/procedures. And it is important to incorporate the fatigue reliability concepts in the design phase and also in analysis methods to ensure the reliable design of aircraft lugs. Consideration of fatigue reliability during the design process can assist in the prevention of failures of structural and mechanical components subject to fluctuating loads in service. Explicit consideration of the reliability of structural and mechanical components provides the means to evaluate alternative designs and to ensure that specified risk levels are met. Probabilistic fatigue analyses may also be applied to life extension of existing structures, and for problem assessment of in-service fatigue failures. Reliability testing is used to discover potential problems with the design as early as possible and, ultimately, provide confidence that the system meets its reliability requirements.

Experimental

The fatigue reliability analysis methodology developed is shown in Fig. 1. The fatigue reliability analysis methodology is established and is validated using plate with multiple stress concentration zones (Benchmark problem). The fatigue analysis is carried out using Altair OptiStruct and Reliability analysis is carried out using Altair HyperStudy. Design sampling matrix for 10000 iterations is generated using Monte Carlo Sampling Technique. The fatigue reliability analysis of aircraft wing mounting lug is explored by taking the fatigue material properties as the reliability parameters with lognormal distribution.

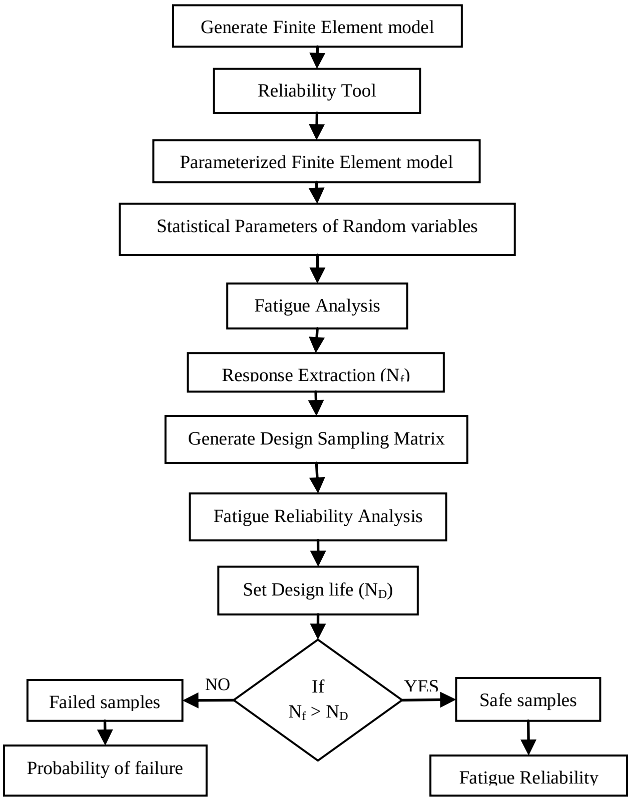

Figure 1: Flowchart illustrating the Fatigue Reliability Analysis methodology

Benchmark Problem

Plate with multiple Stress concentration zones

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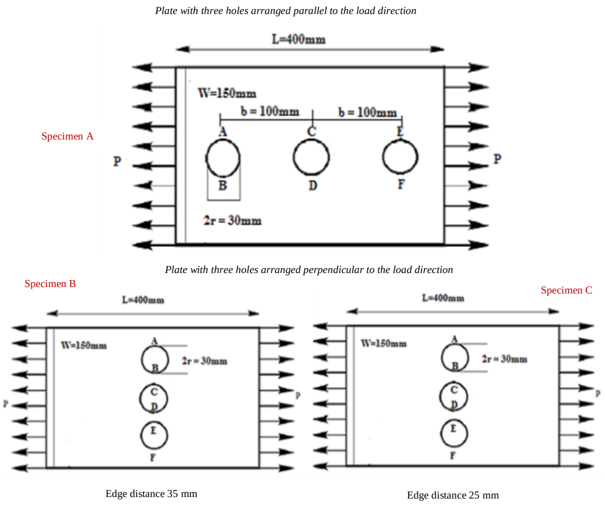

Figure 2: Benchmark Problem Specimens

Deterministic Fatigue Life

The specimens (A, B & C) are made of aluminium with Ultimate Tensile Strength as 477 MPa, Yield Stress as 321 MPa, Young's modulus (E) as 74000 MPa and Poisson's ratio (ν) as 0.33. Using the material properties and the applied load 35 kN, the static analysis of the specimen is carried out using Altair OptiStruct tool. The critical stress location is found out by the static analysis of the specimen which is nothing but the hole boundary location. The fatigue analysis is carried out using the stress results from the static analysis. The fatigue analysis is carried out in Altair OptiStruct by defining fatigue load case using the fatigue properties and the constant amplitude fatigue loading. The fatigue properties of the specimens are Fatigue strength coefficient (S_f) is 1013.53 MPa, Fatigue strength exponent (b) is -0.11 and the endurance limit is 10^8 cycles. Using the stress life approach, fatigue life is calculated for different stress ratios (Tension – tension loading, R = 0.1, pulsating loading R = 0, fully reversed loading R = -1).

Table 1: Deterministic fatigue life of plate multiple with stress concentration zones

Specimen	***Critical Stress Value (MPa)***	***Stress Ratio***	***Deterministic Fatigue Life (cycles) (Present Method)***	***Deterministic Fatigue Life (cycles) (Ref 1)***
A	141.769	R = -1	5.889325×10^{7}	4.43×10^{7}
		R = 0	7.451156×10^{9}	5.33×10^{9}
		R = 0.1	1.654944×10^{10}	1.18×10^{10}
B	217.719	R = -1	1.189742×10^{6}	1.13×10^{6}
		R = 0	6.169892×10^{7}	5.74×10^{7}
		R = 0.1	1.224151×10^{8}	1.14×10^{8}
C	224.458	R = -1	8.950285×10^{5}	8.51×10^{5}
		R = 0	4.259840×10^{7}	3.99×10^{7}
		R = 0.1	8.355128×10^{7}	7.80×10^{7}

Probabilistic Fatigue Life

Probabilistic fatigue life is calculated using Altair HyperStudy tool using random variables for constant amplitude tension-tension loading (R = 0.1). The material parameters like young's modulus, ultimate tensile strength and yield strength will not affect the stress values. In this work, the fatigue life is calculated using the stress value in SN approach and hence those parameters will not affect the fatigue life and are considered as deterministic values. The values which affect the fatigue life are fatigue material properties such as fatigue strength coefficient and fatigue strength exponent and the applied load. Hence, these three parameters are considered as the random variables in this probabilistic study. The lognormal distribution and Monte Carlo sampling technique is used for randomization (sampling). The lognormal distribution is applicable for the positive numbers (R > 0). Among the random variables considered, fatigue strength coefficient is always positive and hence lognormal distribution is suitable. Fatigue strength exponent is always negative. Normal distribution is suitable for variables which have both negative and positive numbers. Hence, in this work, lognormal distribution is used to randomize fatigue strength exponent magnitude value alone (without considering the sign). The load applied is also tension-tension and hence lognormal distribution is used. Fatigue reliability is calculated from the number of samples having fatigue life greater than the design life.

Table 2: Probabilistic fatigue life for plate with three holes arranged parallel to load direction (Specimen A)

Random Variables	***Deterministic Fatigue Life (cycles)***	***Probabilistic Fatigue Life***			
		Standard Deviation	***Design Life (cycles)***	***Reliability***	***Probability of Failure***
S_f	1.64×10^{10}	5 %	1×10^{9}	1.0000	0.0000
		10 %	1×10^{9}	0.9983	0.0017
		15 %	1×10^{9}	0.9758	0.0242
b	1.64×10^{10}	5 %	1×10^{9}	0.9954	0.0046
		10 %	1×10^{9}	0.9098	0.0902
		15 %	1×10^{9}	0.8174	0.1826
Applied Load	1.64×10^{10}	5 %	1×10^{9}	1.0000	0.0000
		10 %	1×10^{9}	0.9949	0.0051
		15 %	1×10^{9}	0.9610	0.0390

Table 3: Probabilistic fatigue life for plate with three holes arranged perpendicular to load direction

Random Variables	***Deterministic Fatigue Life (cycles)***	***Probabilistic Fatigue Life***			
		Standard Deviation	***Design Life (cycles)***	***Reliability***	***Probability of Failure***
Specimen B					
S_f	1.22×10^{8}	5 %	1×10^{7}	1.0000	0.0000
		10 %	1×10^{7}	0.9958	0.0042
		15 %	1×10^{7}	0.9601	0.0399
b	1.22×10^{8}	5 %	1×10^{7}	0.9986	0.0014
		10 %	1×10^{7}	0.9335	0.0665
		15 %	1×10^{7}	0.8481	0.1519
Applied Load	1.22×10^{8}	5 %	1×10^{7}	1.0000	0.0000
		10 %	1×10^{7}	0.9798	0.0202
		15 %	1×10^{7}	0.9189	0.0811
Specimen C					
S_f	8.36×10^{7}	5 %	1×10^{7}	1.0000	0.0000
		10 %	1×10^{7}	0.9877	0.0123
		15 %	1×10^{7}	0.9307	0.0693
b	8.36×10^{7}	5 %	1×10^{7}	0.9948	0.0052
		10 %	1×10^{7}	0.9056	0.0944
		15 %	1×10^{7}	0.8105	0.1895
Applied Load	8.36×10^{7}	5 %	1×10^{7}	0.9996	0.0004
		10 %	1×10^{7}	0.9584	0.0416
		15 %	1×10^{7}	0.8834	0.1166

From the above results table, it is clear that the 5% standard deviation is not making any failed samples while using random variables S_f and load. But when the percentage of deviation increases the fatigue reliability starts to decrease. In this case also, fatigue strength exponent (b) is playing the critical role in fatigue life. The fatigue reliability value decreases as the standard deviation increases. As the random variables values deviating from the mean value, many samples are failing. This results in the decrease in the fatigue reliability value and increase in the probability of failure value.

Aircraft Wing Mounting Lug

Principal Structural Elements (PSE) are those elements of primary structure which contribute significantly to carry flight, ground, and pressurization loads, and whose failure could result in catastrophic failure of the airplane. Engineering design and damage evaluation – repair criteria for aircraft structures are location dependent, and are depending on whether the structure is considered as either Primary, Secondary or as a PSE. Areas classified as PSE's must be designed (by regulations) with a level of Damage Tolerance that maintains residual strength, fail safe ability, limits damage growth rates and resists a catastrophic failure due to the effect of manufacturing defects or typical damage scenarios. Examples of Principal Structural Elements typically include Control surfaces, primary fittings, spar caps, door frames, pressure bulkhead, landing gear and attachments, engine mounts etc. Lug is the main component used for mounting the engine and mounting the wing to fuselage. Hence, here we have taken Wing mounting lug for this fatigue reliability analysis.

Wing & Fuselage Front Pick-Up Lug

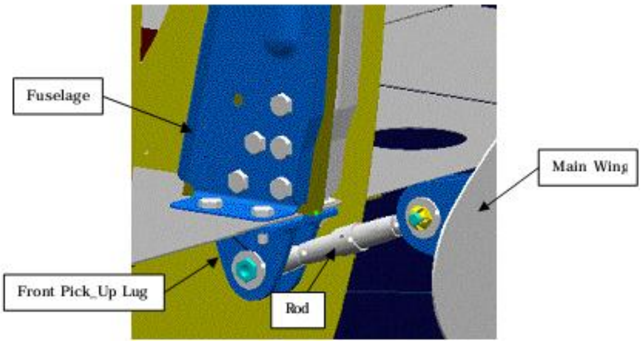

Figure 3: Front Pick-Up Lug shape connected Main Wing and Fuselage by a rod [2]

Fitting Lugs are subjected to concentrated load converted from distributed load according to variable load condition of aircraft. After that, it delivers the concentrated load to adjacent structure. So, high load was applied to these Fitting Lugs. One example is Front Pick-up Lug connected wing as shown in Fig. 3. The geometry, material properties and loading are taken from literature [2]. The finite element model and stress distribution of lug are shown in Fig. 4. The critical stress location is at one of the fastener hole.

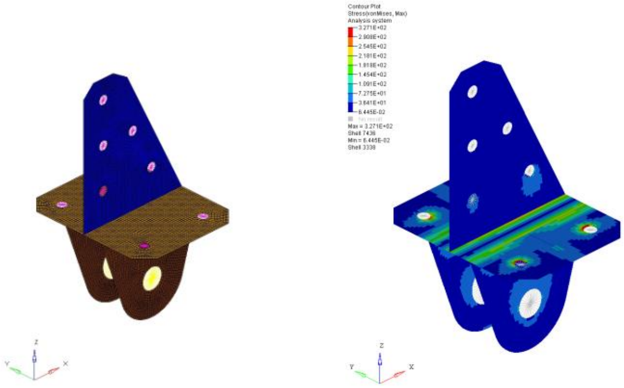

Figure 4: FE model and stress distribution of Front Pick-Up Lug

Deterministic Fatigue Life

Fatigue analysis is performed using Altair OptiStruct by taking the properties and the load spectrum given in [2]. The fatigue log life contour is shown in Fig.5. Fatigue life is critical at the fastener hole location with the value of 5,21,977 Flight hours and is in good agreement with the reference paper [2] value 5,39,470 Flight Hours.

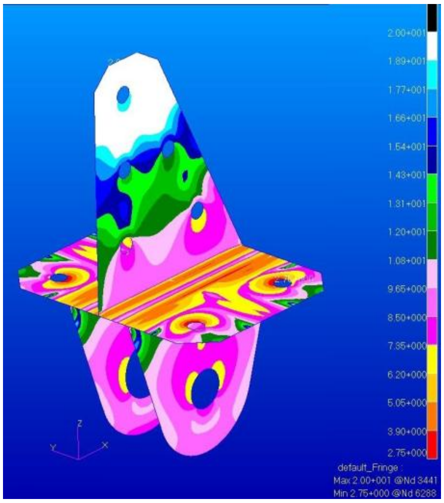

Figure 5: Fatigue Life contour of Front Pick-Up Lug

Fatigue Reliability Analysis of Front Pick-Up Lug

Fatigue Reliability analysis is carried out in Altair HyperStudy by randomising the fatigue material properties S_f, b1 and b2 using lognormal distribution for 10000 Monte Carlo Samples and the results are tabulated in Table 4. Design life is taken as 5,00,000 Flight Hours for this Reliability study. There is no variation of b2 for the design life considered and hence 5,21,000 Flight Hours is taken as design life to study the effect of scatter.

Table 4: Fatigue Reliability analysis results

Random variable	Design Life (Flight hours)	Probabilistic Fatigue Life		
		Standard Deviation	Reliability	Probability of Failure
S_f	5,00,000	1%	0.7376	0.2624
		3%	0.5810	0.4190
		5%	0.5444	0.4556
b1	5,00,000	1%	0.6241	0.3759
		3%	0.5474	0.4526
		5%	0.5338	0.4662
b2	5,21,000	1%	1.0000	0.0000
		3%	0.9957	0.0043
		5%	0.9443	0.00557

From the above results, it is clear that the reliability is significantly affected by the scatter value of parameters considered. It is noticed that increase in the scatter value decreases the fatigue reliability and the effect of fatigue strength exponent (b1) is very high when compared to the other two parameters.

Conclusions

Fatigue reliability analysis methodology is developed using Altair OptiStruct and Altair HyperStudy and is validated using plate with multiple stress concentration zone specimens subjected to constant amplitude loading by incorporating the uncertainties present in fatigue property and loading using lognormal distribution. Fatigue reliability analysis of Wing & Fuselage Front Pick-Up lug is carried out using the developed methodology. Fatigue material properties are taken as the random variables and the effect of the variation of those variables in the fatigue reliability is studied and reported. Fatigue Strength Exponent (first slope of the SN curve) is the critical property which highly affects the fatigue reliability.

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