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Topology Optimization of Aircraft Wing Fuselage Lug Attachment Bracket

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Abstract:- Topology optimization has become an effective tool for light-weight and performance design, especially in the aeronautics and aerospace industry. It has proved to meet the requirement to produce intricate parts that are more robust and lightweight. This technology has proved costeffectiveness, improved payload capacity, and increased fuel economy in the aerospace sector, and enabled structural components to deliver the same or enhanced performance while using less material. Among the aircraft, the fuselage and the wings are important structural components. Wing fuselage lug attachment bracket is the connecting element that connects the wings and the fuselage. Catastrophic failure of the bracket may sometimes lead to the separation of the aircraft structure. This work is focused on modelling, shape optimization, and analysis of an aircraft wing-fuselage lug attachment bracket. The methodology involves modelling and shape optimization of the bracket using different sets of materials. Finite elemental modelling and structural analysis were done to study the stresses and deformation on the bracket. Fatigue damage estimation is carried out to study the behavior of bracket for repeated cyclic loading.

Keywords:- *Topology optimization, wing-fuselage attachment bracket, fatigue damage, static structural, load factor, mass reduction.*

I. INTRODUCTION

An aircraft is a machine capable of flying by gaining support from the air. It has a complex structure comprising of basic components such as fuselage, wing, tail units, and control system. Advancements in aircraft development have been rapid over the years. One of the active areas of technological advancements is to meet the rising environmental concerns dealing with pollution and global warming due to aircraft emissions. This has led to various research for alternative clean energy sources as well as to increase fuel efficiency [1]. Weight is one of the most important factors affecting the efficiency of aircraft and flight endurance. Significant weight reduction can result in improvised efficiency, increased fuel economy thus increasing flight endurance. Reducing the mass of the aircraft has proved to be an effective method in increasing the fuel efficiency as lower mass requires lesser lift force and thrust during flight [2]. Topology optimization has proved to be an effective tool for mass reduction and performance design in the aerospace industry. Topology optimization is an algorithmic method of optimizing the distribution of material within a specified structural domain according to the load cases and boundary conditions to achieve the most efficient design [2,3]. The wings and the fuselage are the most integral structural components of an aircraft. Wings are subjected to a spectrum of flight loads. During every flight, the airplane takes off, flies to certain altitudes which pressurizes the wings and the fuselage, and as a result metal fatigue is created. So in all the operable conditions, the wing and the fuselage must be rigidly attached together and in case of failure might lead to adverse accidents [4]. The lug is a part that connects the wing and the fuselage. Sometimes, the consequences of the failure of the lug can be very severe that it might lead to the separation of the aircraft structure. Thus, it is important to establish damage-tolerant design criteria and analysis methods to ensure high performance and reliability of aircraft lug attachments [4,5,6]. To maintain the load-carrying capacity and performance of the bracket, the lug design must be optimized for a better strength to weight ratio. A detailed study must be carried out on the load cases and the load to which the bracket is subjected must be calculated. Shape optimization must be performed on the structural domain of the lug according to the load path criticality to achieve an optimal design. The structural analysis must be carried out on the shape optimized bracket and comparison must be made between conventional design and topology optimized design in aspects of the factor of safety (FOS) and deformation. Design decisions must be made without compromising on performance and load-carrying capability to arrive at an optimal design. To validate the design for repeated loading conditions, fatigue damage estimation to crack initiation has to be carried out for a typical flight load spectrum [6]. In this current work, an attempt has been made to design and optimize the structure of the wing-fuselage lug attachment bracket for a better strength to weight ratio and estimate the fatigue damage factor for a typical flight load spectrum.

II. METHODOLOGY

This paper is focused on 3D modelling and shape optimization of the bracket. Finite elemental modelling and structural analysis are done to study the stresses and deformation on the bracket. To understand the dynamic characteristics of the bracket under repeated cyclic loading and to validate the safety and reliability of the design, fatigue damage estimation is done to calculate the life to crack initiation.

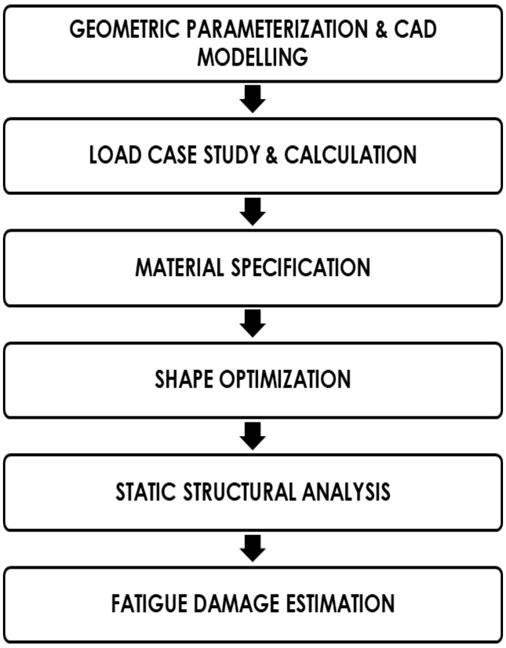

Fig. 1: Workflow

A. *Geometric Parameterization and CAD Modelling*

The wing-fuselage attachment bracket was modelled in Solidworks 2019 and the below figure shows the different configurations of the model. Various structural components of the wing-fuselage lug attachment bracket are:

- Lug: A component with pin holes that connects the wing with the fuselage.
- I-spar: Integral part of wings which carries the weight of the wings and is subjected to flight loads. Wing surfacing is done on the I-spar.
- Rivets: Permanent mechanical fasteners of the cylindrical structure.

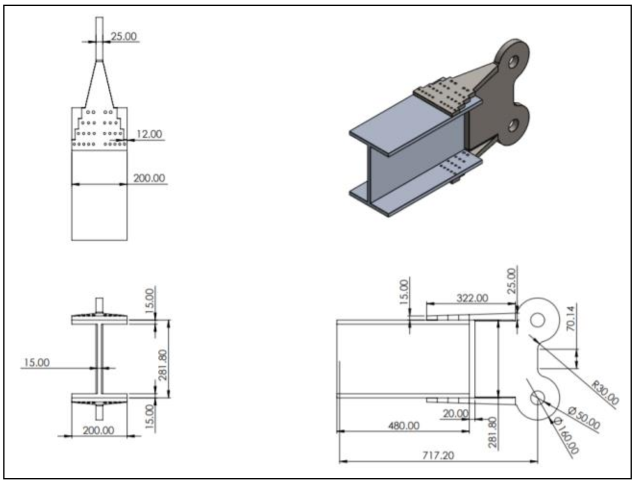

Fig. 2: Geometric configuration of the wing fuselage lug attachment bracket

B. *Load Case Study and Calculations*

Airplane type = medium size aircraft
Weight of Aircraft (MTOW) = 5750 kg = 56350 N
Load factor considered in design = 3g
Limit load on the structure = 169050 N
Factor of safety = 1.5

Ultimate load = 169050×1.5 = 253575 N

Load distribution of on fuselage and wings = 25% and 75%.

Total load acting on the wings = 253575×0.75 = 190181.25 N

Load acting on each of the wings = 190181.25/2 = 95090.625 N

Number of spars in the wing = 3

Load should be shared by each of the spars:
i) spar 1 = 15% ii) spar 2 = 40% iii) spar 3 = 45%
For this analysis, spar 2 is chosen.

Therefore, load acting on it is = 95090.625×0.45 = 42790.78 N

Total load the bracket is subjected to, **W = 42790.78 N**

This load will induce the bending moment acting at the root of the bracket. Thus, it will act as a cantilever beam.

Distance of the root of bracket from the lug node = 727.2 mm

Bending moment created at the root of the bracket = 42790.78 N × 727.2 mm

BM = 31108.89 Nm

C. *Material Specification*

The material chosen for lug is heat-treated Steel alloy AISI 4340 due to its high strength, toughness, and fatigue strength [4,5,6]. For I-spar, the suitable material was decided as aluminum alloy 2024 T351 as it has an excellent strength-to-weight ratio. It also has good machinability and surface finish capability [4,5,6].

Sl. No.	Parameters	Steel Alloy AISI-4340	Aluminium Alloy 2024-T351
1	Young’s Modulus (MPa)	203000	72400
2	Poisson’s ratio	0.32	0.33
3	Ultimate tensile strength (MPa)	1835	483
4	Yield stress,σy (MPa)	1550	345

Table 1: Material property table for chosen materials for lug and I-spar.

D. *Topology Optimization*

Topology optimization is an algorithmic method of optimizing the distribution of material within a specified structural domain according to the load cases and boundary conditions to achieve the most efficient design [1,2,3]. Topology optimization of the bracket was carried out in Autodesk Fusion 360. The optimization process is as follows: Initially, the shape optimization target needs to be set. In our case, the lug part of the wingfuselage attachment bracket is set as the optimization target. Under the material study feature, respective materials for lug (steel alloy AISI 4340) and I-spar (aluminum alloy 2024 T351) was applied. A model-based size mesh is generated for the bracket with 26348 nodes and 105260 elements. Under optimization settings, target mass is set as below or equal to 60% with maximizing stiffness as the goal objective. The entire I-spar region is set as a preserved region as we aim to optimize the lug part of the bracket. And a 40 mm offset from both the lug holes is set as a preserved region considering safety aspects. The load case needs to be specified for the model. Both the lug holes of the bracket are structurally constrained with all six degrees of freedom. A vertical load of 42791 N is applied at one end of the I-spar acting upwards which creates the required bending moment. Contacts type is set as bonded contact.

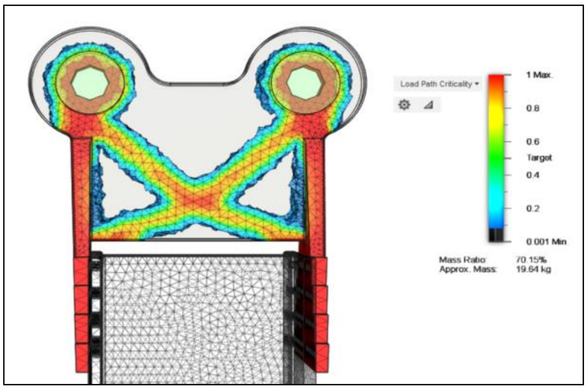

Fig. 3: Optimal topology design for the lug portion of the bracket

A significant mass reduction of nearly 30% was achieved. Mass of the lug was reduced from 27.99 kg to 19.64 kg after shape optimization. The above figure shows the load path criticality of the lug for the applied load case.

Name	Value
Mass before	27.999 kg
Mass after	19.640 kg
Mass Ratio	70.15%

Table 2: Topology Optimization Summary

E. Finite Elemental Modelling

The finite element modelling (FEM) is a discretization technique in structural mechanics. It uses a numerical method to approximate the solution of boundary and/or initial value problems characterized by partial differential equations (PDEs) [7]. A finite elemental model of the topology optimized bracket was carried out in ANSYS Workbench 19.0. Meshing is the process where the structural domain is subdivided into smaller domains or elements known as meshes. The entire structural domain was meshed with tetrahedron type meshing. The fine mesh was accomplished in high-stress gradient domains and the coarse mesh was accomplished in low-stress gradient domains. As a result of meshing 1666570 nodes and 826297 elements were developed.

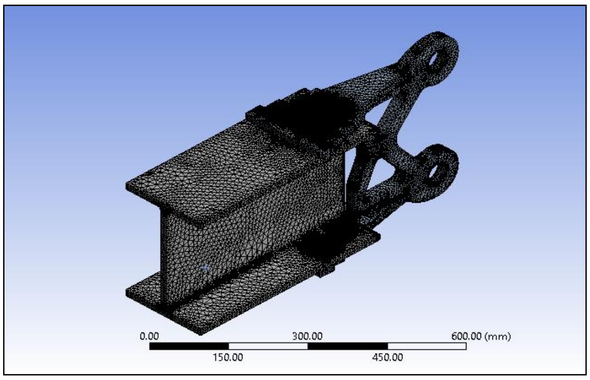

Fig. 4: Finite elemental model of the bracket

III. RESULTS AND DISCUSSIONS

A. Static Structural Analysis Load and Boundary Conditions

The below figure shows the load and boundary conditions applied on the topology optimized bracket. Both the nodes of the lug section of the bracket are structurally constrained with all six degrees of freedom. A vertical load of 42791 N is applied at one end of the I-spar acting upwards (Y-direction) which creates the required bending moment [6,8].

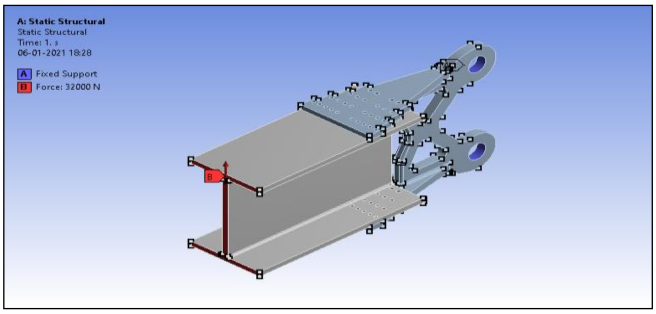

Fig. 5: Load and boundary conditions applied on the bracket

B. Analysis Readings

The maximum deformation was found to be 0.46 mm and it occurred on the edge of the I-spar region. The below figure shows the total deformation contour of the bracket when subjected to a bending load of 42791 N. The observed displacement (0.46 mm) lies within 1.3% of the total length of the bracket. This is permissible according to the aircraft industry standards [5].

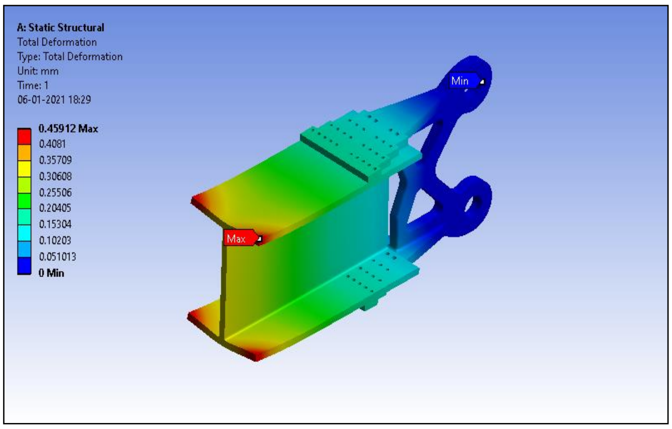

Fig. 6: Total deformation contour of the bracket

The maximum equivalent stress value was observed to be 137 MPa occurring at the flange portion of the lug. The below figure shows the stress contour of the bracket when subjected to a bending load of 42791 N.

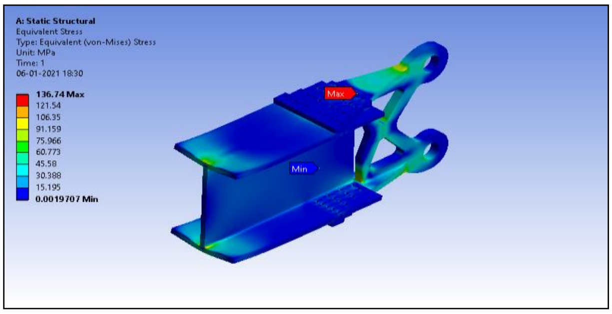

Fig. 7: Stress contour of the bracket

The minimum factor of safety (FOS) for the optimal topology design was found to be 1.82. Thus, we can conclude that our design is safe.

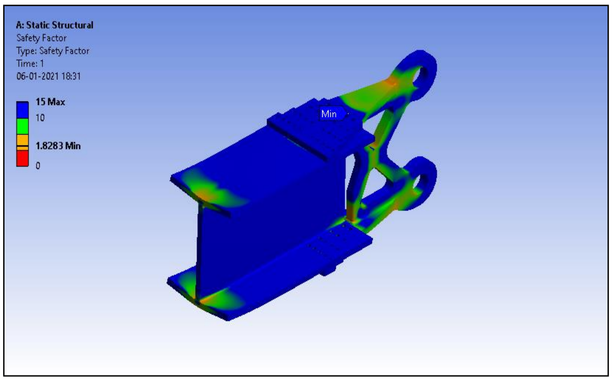

Fig. 8: The factor of safety [FOS] of the bracket

C. COMPARISON BETWEEN CONVENTIONAL AND TOPOLOGY OPTIMIZED DESIGN

Conventional Design		**Topology Optimized Design**	
Factor of safety [FOS]	1.81	Factor of safety [FOS]	1.82
Total deformation	0.46 mm	Total deformation	0.46 mm
Maximum stress (MPa)	138	Maximum stress (MPa)	137

Table 3: Design comparison

D. Fatigue Damage Estimation

From the results of static structural analysis of wing-fuselage lug attachment bracket, it is observed that the maximum stress occurs at the lug part whose material is steel AlSl 4340. Fatigue damage estimation of the bracket to crack initiation was carried out in accordance with a typical flight load spectrum [6,9]. A damage-tolerant design criterion and stress-life approach has been followed for carrying out fatigue damage estimation [6,10]. Fatigue failure primarily occurs in three stages, i.e. crack initiation, crack propagation, and final rupture. Calculation of fatigue life to crack initiation is carried out by using Palmgren-Miner's Rule. According to Miner's rule,

$$D = \sum (N_i/N_f) = C$$

Where D = damage accumulate factor; N_i = applied number of cycles; N_f = number of cycles to failure; C = constant equal to 1.

Cycles applied (N_i)	**Range of Load factor g**	**Stresses in lug portion (MPa)**	
		Minimum stress	**Maximum stress**
1000000	0.5g - 1.0g	20	73
712740	1.0g - 1.5g	30	109
156850	1.5g - 2.0g	39	145
69534	2.0g - 2.5g	49	181
35619	2.5g - 3.0g	60	218
20234	3.0g - 3.5g	70	254
12798	3.5g - 4.0g	80	290
8680	4.0g - 4.5g	90	326
6268	4.5g - 5.0g	100	363
4668	5.0g - 5.5g	109	399
3568	5.5g - 6.0g	120	435

Table 4: Stress values in the lug for flight load spectrum

The total damage accumulate (D) was calculated for different load factors in the flight load spectrum and the total damage accumulate factor is found to be 2.030959e-1 < 1. According to Palmgren-Miner's rule, the design is safe if the damage accumulation factor happens to be less than unity [6,10]. The result obtained is much lesser than unity and thus we can validate that our design is safe and reliable. So, under all the flight load spectrum the wing-fuselage lug attachment bracket is safe and no crack initiation happens.

Failure no. cycles N_f	**Amplitude stress (MPa)**	**Mean stress (MPa)**	**Stress ratio R**	**Damage accumulate D**
>10^7	26.50	46.50	0.27	0.1000000
>10^7	39.50	69.50	0.28	0.0712740
>10^7	53.00	92.00	0.27	0.0156850
>10^7	66.00	115.00	0.27	0.0069534
>10^7	79.00	139.00	0.28	0.0035619
>10^7	92.00	162.00	0.28	0.0020234
>10^7	105.00	185.00	0.28	0.0012798
>10^7	118.00	208.00	0.28	0.0008680
>10^7	131.50	231.50	0.28	0.0006268
>10^7	145.00	254.00	0.27	0.0004668
			∑D	**0.2030959**

Table 5: Fatigue damage accumulate factor under typical flight load spectrum

IV. CONCLUSION

Mass reduction is of major interest in improving aircraft performance. In this work, we have designed and optimized the structure of the aircraft wing-fuselage bracket with topology optimization tools by studying the load paths and validated the design by estimating the fatigue damage for repeated cyclic loading. A significant mass reduction in the lug part of nearly 30% (27.99 kg to 19.64 kg) was achieved by the topology optimization technique. Maximum deformation of 0.46 mm, maximum equivalent stress of 137 MPa was observed and the minimum factor of safety of 1.82 was achieved from the static structural analysis. From the static structural analysis, the maximum stresses observed was much lower than the yield strength, so the optimized bracket design is safe and reliable under all operable conditions [5,6,12]. Fatigue damage estimation to crack initiation is carried out for the bracket. For the considered typical flight load spectrum, the damage accumulate factor is much less than unity, i.e. 0.2030959 < 1. So for all the load spectrum, the design is safe and no crack initiation happens.

V. IMPLICATIONS AND INFLUENCES

Multi-body dynamic simulation of the bracket can be performed to study its behavior under dynamic conditions. Fatigue crack growth analysis can be performed on the bracket to calculate its life from crack initiation to the fracture stage. Modal analysis can be performed on the bracket to study its performance under varied frequency ranges. The use of composite material may result in improvised strength to weight ratio. Structural testing of the bracket can be carried to validate the theoretical calculation and software analysis results.

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