Additive Manufactured Aircraft Brake Housing Design Assessment Using Finite Element Analysis

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Abstract- The braking action generates a torque which transmits a braking force into the wheel and brake assembly which brings an aircraft to a stop. The aircraft brake housing experiences a large number of fluctuating or cyclic loads during its service life. Therefore, design assessment, optimization and fatigue analysis has been considered in the design process. The present research focuses on three major sections: static structural analysis, high cycle fatigue analysis and tie bolt strength analysis for severe brake operating pressure conditions. Results are correlated using empirical results. Proposed aircraft brake housing design meets the minimum performance standards as specified in the TSO - C135.

Keywords- Aircraft Brake Housing, Additive Manufacturing, Direct Metal Laser Sintering, Brake Operating, Pressure, Fatigue, S-N Method, Goodman Diagram, Tie Bolt.

1. INTRODUCTION

Aircraft Braking System is one of the critical subsystems of an aircraft and is often configured along with the aircraft structure because of its substantial influence on the aircraft structural configuration itself. Braking System and Landing gear detail design is taken up early in the aircraft design cycle due to its long product development cycle time. The need to design these with minimum weight, minimum volume, reduced life cycle cost and development cycle time, poses many challenges to designers and practitioners. These challenges have to be met by employing advanced technologies, materials, analysis methods, processes and product methods. Various design and analysis tools have been developed over the years and new ones are still being developed.

An aircraft braking system is given in Figure 1. As shown, the brake is composed of a stack of rotating brake discs (rotors) which engage the wheel, and stationary brake discs (stators), which engage the torque tube. The torque tube is attached to the brake housing that links to the landing gear through a torque take-out rod. During operation, the brake is activated by the fluid pressure, which compresses the heat stack: the rotors and the stators are squeezed together by fluidic pistons and the brake produces torque by virtue of which aircraft stops.

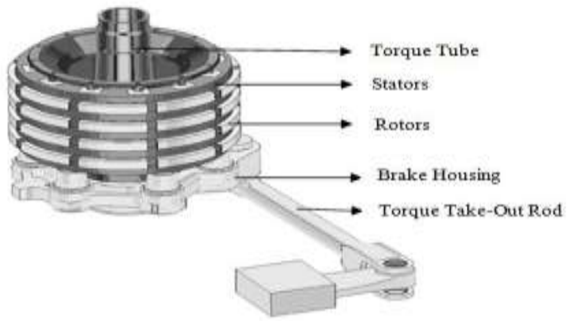


Figure 1: Aircraft Brake System.

Additive manufacturing (AM) is a process of making a three-dimensional solid object of virtually any shape from a digital model. The aerospace industry expects to derive value from additive manufacturing in the aerospace field at the strategic level. The four supposedly critical aspects of AM in the aerospace industry are (1) reduction of lead times, (2) reduction of component weight, (3) reduction of both production and operational costs, and (4) reduction of the negative environmental impacts of production. Numerous additive manufacturing technologies have been developed since the mid-eighties, including stereo lithography (STL) as oldest technology as well as laminated object manufacturing (LOM). In addition, technologies such as direct and indirect laser sintering (LS) have become established. Out of the various processes we have preferred Direct Metal Laser-Sintering process because of its higher accuracy, surface quality and freedom to design.

Direct metal laser-sintering (DMLS) is a production method for creating metal parts. It works by taking 3D geometry data such as a CAD file or scan data, which are sliced into layers by software. From this layer data, laser exposure vectors are calculated for each layer of the build process. In the production machine, very thin (typically between 20 and 60 µm) layers of metal powder are applied onto a powder bed, the surface of which is selectively exposed using a scanned, focused laser beam. The energy of the laser beam melts the powder in the exposed areas, creating a metallic bond to the surrounding exposed material including the previous layer. The process of applying and exposing layers is repeated, thereby creating solid metal parts additively, layer by layer, from the powder material.

2. METHODOLOGY

- Design and numerical modeling of the required Aircraft Braking System parts are modeled in Part Design and then assembled in Assembly workbench of CATIA. This model is now imported to ANSYS, where meshing and Finite Element Analysis is carried out.
- The assembly is subjected to various load conditions such as Maximum brake operated pressure, Proof and burst pressure conditions.
- Static linear finite element analysis is performed to determine the strength margins for design substations.
- Optimization of the design values for Additive Manufacturing.
- High cycle Fatigue analysis is performed to determine the Cumulative Fatigue Damage for Brake housing.
- Tie-Bolts strength assessment is performed.

3. GEOMETRICAL CONFIGURATION OF AIRCRAFT BRAKE HOUSING

3.1 Modeling

The 3D CAD model of Aircraft Brake Housing and Tie-Bolts are developed using CATIA V5 software separately, later assembled for tie bolt strength analysis. The modeled Brake housing and assembly of Brake housing with Tie-Bolts are imported to ANSYS Workbench, where analysis is carried out for various loads and various conditions.

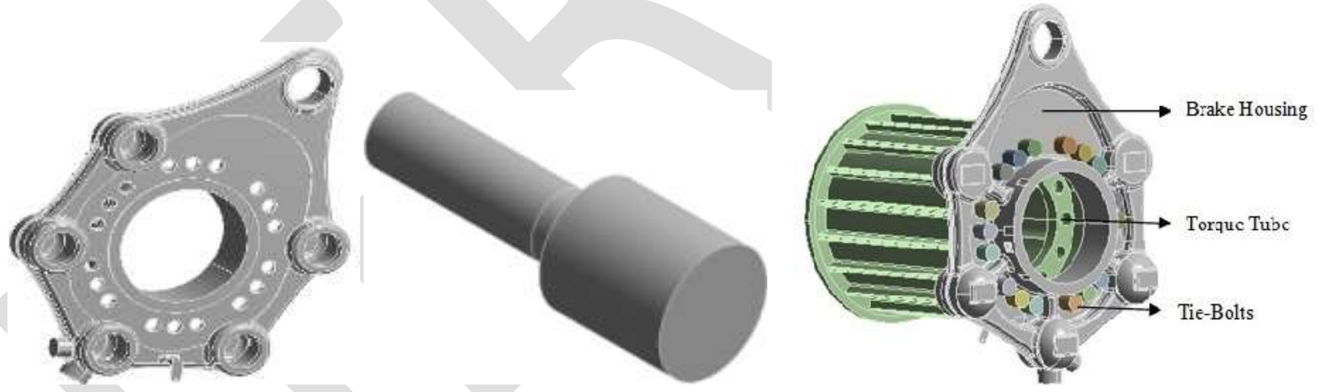


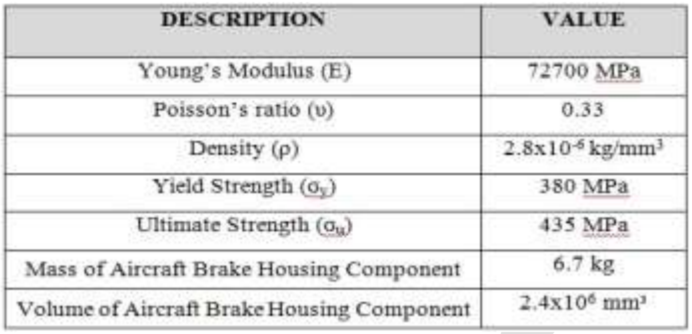
Figure 3.1: CAD models of Brake housing, Tie-Bolt & Assembly.

3.2 Material Properties

Aluminium 2014 T6 is the second most popular of the 2000 series aluminium alloys, after 2024 aluminium alloys. It is commonly extruded and casted. It is easily machined in certain tempers; having high hardness, difficult to weld and mainly this alloy are used for cycling frames and components. Inconel-718 is a high strength, corrosion resistance nickel chromium material, ease and economy. Inconel-718 can be fabricated, combined with good tensile, fatigue, creep and ruptured strength.

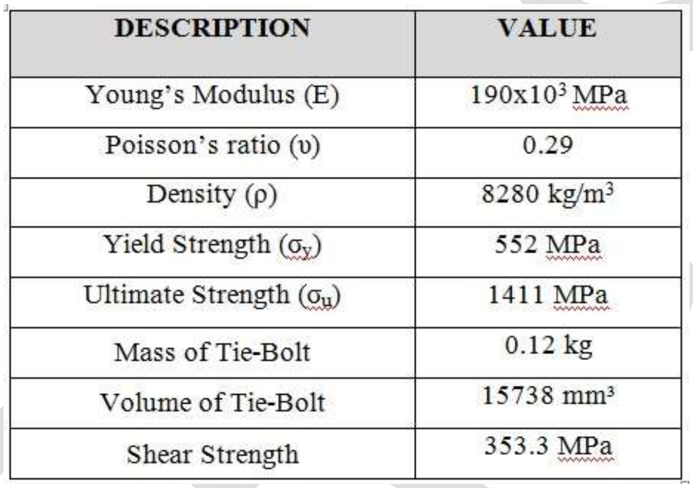
Al 2014-T6 material is used in aircraft brake housing component design and Inconel-718 material is used in tie-bolt design. The material properties of Aluminium and Inconel-718 are listed in Table 3.1 and Table 3.2 respectively as per the tie bolt design consideration.

Table 3.1: Material Properties of Al2014-T6 (Brake Housing)



DESCRIPTION	VALUE
Young's Modulus (E)	72700 MPa
Poisson's ratio (υ)	0.33
Density (ρ)	$2.8x10^{-6}$ kg/mm^3
Yield Strength (σ_y)	380 MPa
Ultimate Strength (σ_u)	435 MPa
Mass of Aircraft Brake Housing Component	6.7 kg
Volume of Aircraft Brake Housing Component	$2.4x10^6$ mm^3

Table 3.2: Material Properties of Inconel-718 (Tie- Bolts).



DESCRIPTION	VALUE
Young's Modulus (E)	$190x10^3$ MPa
Poisson's ratio (υ)	0.29
Density (ρ)	8280 kg/m^3
Yield Strength (σ_y)	552 MPa
Ultimate Strength (σ_u)	1411 MPa
Mass of Tie-Bolt	0.12 kg
Volume of Tie-Bolt	15738 mm^3
Shear Strength	353.3 MPa

3.3 Meshing

The CAD models are imported to ANSYS 16.0 Work bench where the meshing and analysis is carried out. Here carefully, the critical regions are selected for fine mesh such as Passage Hole, Lug Region, Critical fillet Region, Piston Area and Rib region. Brake Housing is meshed with tetra and Tie Bolts with Hex dominant mesh.

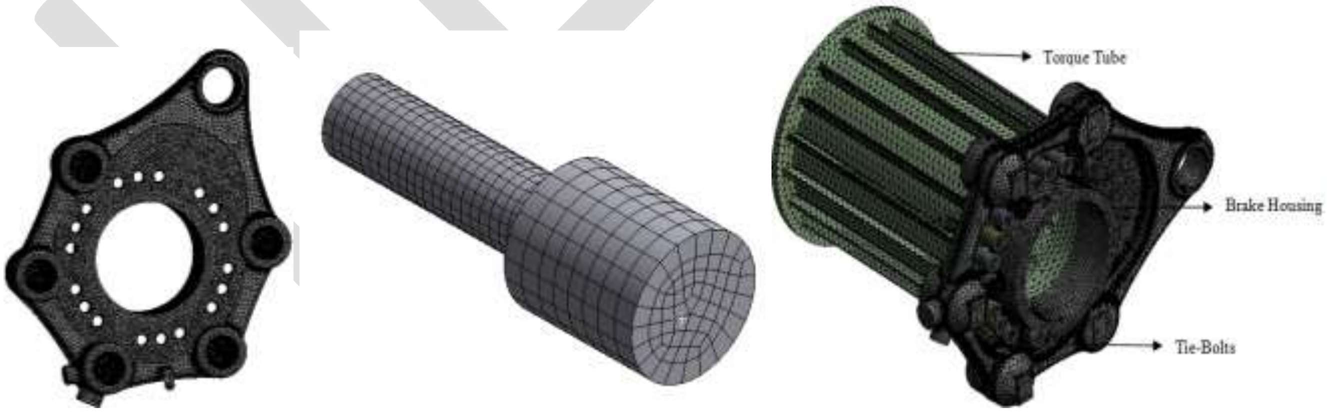


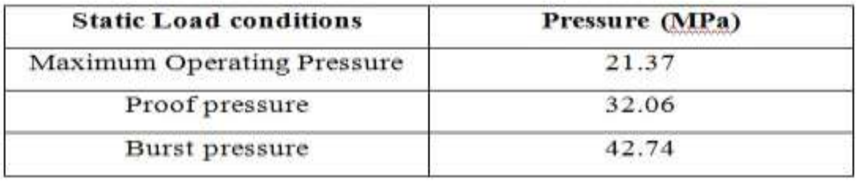
Figure 3.2: Meshed CAD models of Brake housing, Tie-Bolt & Assembly.

4. STRUCTURAL ANALYSIS OF BRAKE HOUSING

As per the TSO - C135 standards, Aircraft brake housing is evaluated for various static loading conditions. The stress observed in the aircraft brake housing must be within the material yield or ultimate strength limit. Static requirements for aircraft brake housing are listed in Table 4.1.

- As per FAR 25.1435: Proof Pressure = 1.5 ×Maximum Operating Pressure
- As per FAR 25.1435: Burst Pressure = 2 ×Maximum Operating Pressure

Table 4.1: Static Load Requirements



Static Load conditions	Pressure (MPa)
Maximum Operating Pressure	21.37
Proof pressure	32.06
Burst pressure	42.74

4.1 Boundary Conditions

The fastener bolts tied between brake housing and torque plate transfers the high torque load from the torque pin and supports the aircraft brake housing. In static structural and fatigue analysis the brake housing part is only considered and bolts analysis is discussed separately. Therefore, tie bolt holes are constrained in all DOF's (Degrees of Freedom) =0.

4.2 Maximum Operating Pressure

The piston-cylinder, piston area and lug regions are considered for loading conditions. The piston end load on piston area in cylinder top, brake pressure in cylinder and maximum structural torque at lug region are considered and applied as per the requirement.

Calculation of Piston End Load and Structural Torque

Maximum Operating Pressure = 21.37 MPa.

Piston Area =1275.29 mm^2.

Maximum Piston End Load = Operating Pressure x Piston Area

= 21.37 x 1275.29 = 27.27 kN.

Maximum Structural Torque = 1.44 x Load x Loaded Radius

= 1.44 x 26310 x 170

= 64407x10^6 N-mm.

(As per ARP5381 for gear with main wheels and brakes)

Piston end load of 27.27 kN is applied on the end face with respect to local coordinate system in negative X-direction and Brake pressure of 21.37 MPa is applied and Torque as shown in Figure 4.1.

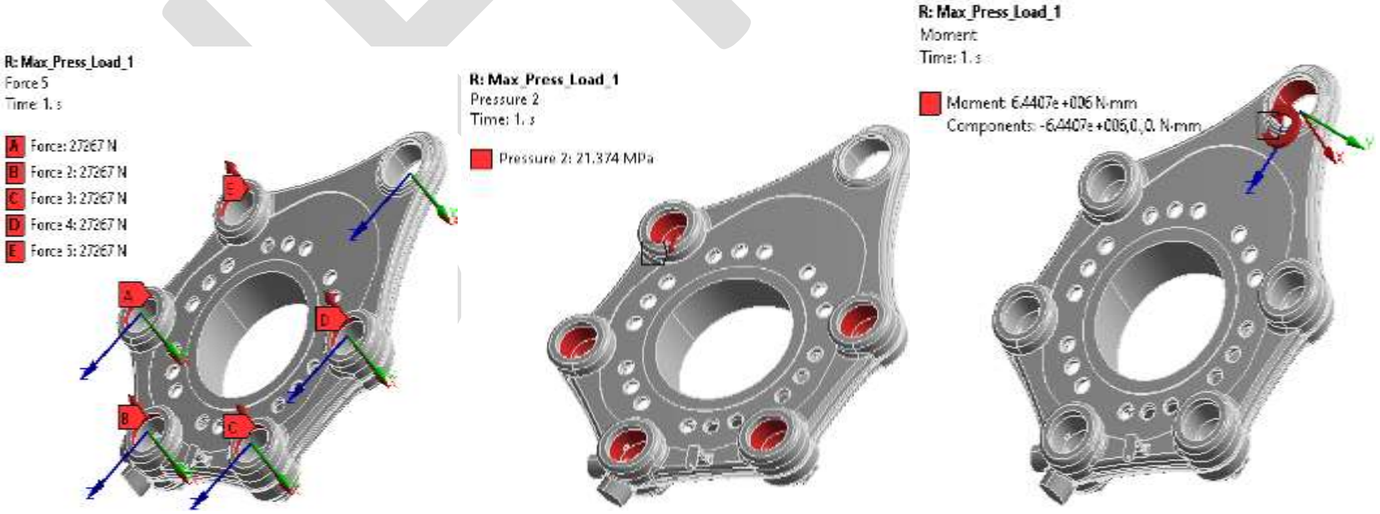


Figure 4.1: Application of load and torque.

4.3 Proof Pressure

Same model and boundary condition has been used in Proof pressure analysis as maximum operating pressure analysis. However, there is no torque load applied in this condition. The piston end load of 40.8 kN and brake pressure of 32.06 MPa is applied.

4.4 Burst Pressure

Same model and boundary condition has been used in Burst pressure analysis as maximum operating pressure analysis. However, there is no torque load applied in this condition. The piston end load of 54.5 kN and brake pressure of 42.74 MPa is applied.

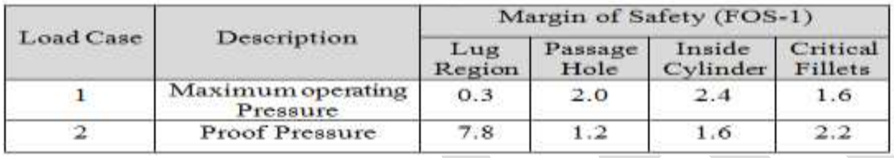
4.5 Results

Total deformation plot and Equivalent Von-Mises Stress Plot is taken at all the critical parts in all the pressure requirement cases and values are tabulated as shown in below table.

Table 4.2 (i) (ii) Results of Maximum operating and Proof Pressure condition

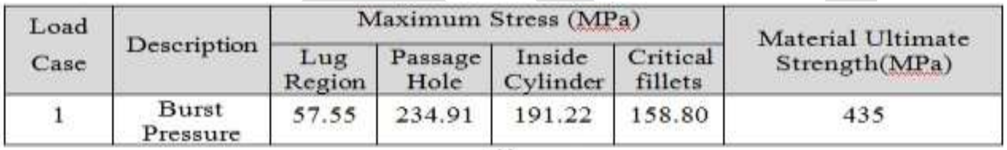
Load Case	Description	Maximum Stress (MPa)				Material Yield Strength(MPa)
		Lug Region	Passage Hole	Inside Cylinder	Critical fillets	
1	Maximum operating Pressure	291.95	126.88	112.12	144.78	380
2	Proof Pressure	43.16	176.18	143.41	119.10	380

(i)



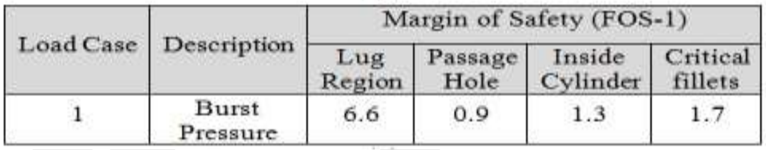
Load Case	Description	Margin of Safety (FOS-1)			
		Lug Region	Passage Hole	Inside Cylinder	Critical Fillets
1	Maximum operating Pressure	0.3	2.0	2.4	1.6
2	Proof Pressure	7.8	1.2	1.6	2.2

Table 4.3 (i) (ii) Results of Burst Pressure condition.



Load Case	Description	Maximum Stress (MPa)				Material Ultimate Strength(MPa)
		Lug Region	Passage Hole	Inside Cylinder	Critical fillets	
1	Burst Pressure	57.55	234.91	191.22	158.80	435

(i)



Load Case	Description	Margin of Safety (FOS-1)			
		Lug Region	Passage Hole	Inside Cylinder	Critical fillets
1	Burst Pressure	6.6	0.9	1.3	1.7

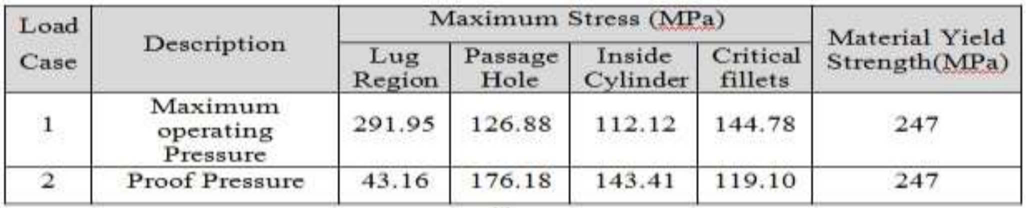
From the above table it is clear that, the maximum stresses observed in all critical regions of the aircraft brake housing component are less than the material allowable yield and ultimate strength and thereby having a positive design margin. Hence Design is Safe.

4.6 Optimizing Design values for Additive Manufacturing.

According to the Engineering Laboratory, Material standard for Additive Manufacturing, National Institute for standards and Technology, when properly processed, the static mechanical properties of Additive Manufactured metallic materials are comparable to conventionally fabricated metallic components. The relatively high cooling rates achieved reduce partitioning and favour reduced grain sizes. The yield strength of the components decrease by 9% and upon controlled cooling it will further decrease by 26%. Hence there will be a total decrease of 35% in yield strength. According to this, Yield strength of Al2014-T6 will be 247 MPa (35% of 380 MPa).

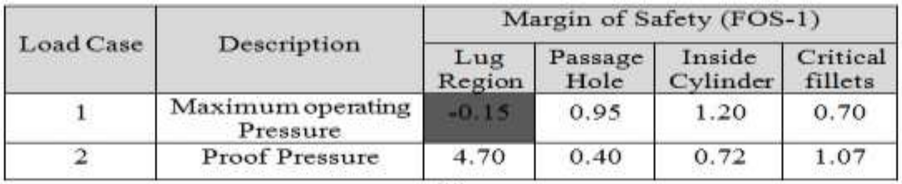
Design values from result summary:

Table 4.4 (i) (ii) Results of Maximum operating and Proof Pressure condition.



Load Case	Description	Maximum Stress (MPa)				Material Yield Strength(MPa)
		Lug Region	Passage Hole	Inside Cylinder	Critical fillets	
1	Maximum operating Pressure	291.95	126.88	112.12	144.78	247
2	Proof Pressure	43.16	176.18	143.41	119.10	247

(i)



Load Case	Description	Margin of Safety (FOS-1)			
		Lug Region	Passage Hole	Inside Cylinder	Critical fillets
1	Maximum operating Pressure	-0.15	0.95	1.20	0.70
2	Proof Pressure	4.70	0.40	0.72	1.07

From the above Table, For Maximum operating Pressure condition at Lug region Margin of safety is negative, which is not acceptable. Hence it is to be redesigned by adding material locally at the lug region.

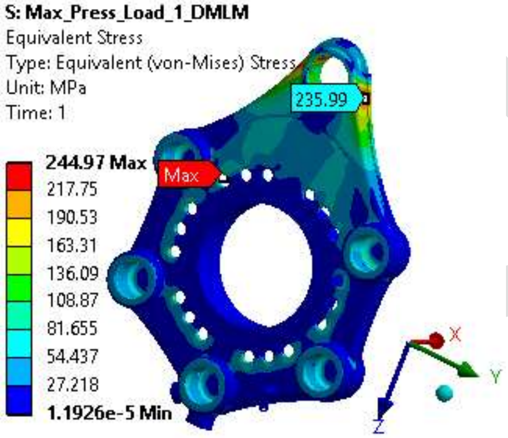


Figure 4.2 Equivalent Von-Mises stress.

After adding material at Lug region, the maximum Von-Mises stress at Lug region is found to be 235.99 MPa. Since the maximum Von-Mises stress at Lug region is less than the yield strength of 247 MPa. Hence design is safe.

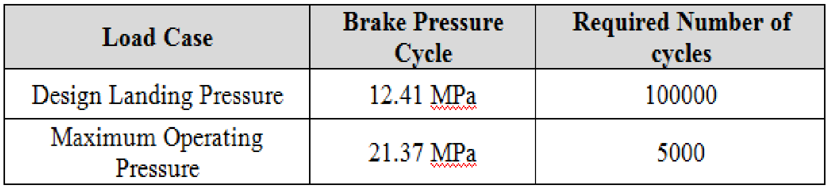
$$\text{Margin of Safety (MOS)} = 247/235.99 - 1$$
$$= 0.04$$

Takeaway: The maximum stresses observed in all critical regions of the aircraft brake housing component are less than the material allowable yield limit of 247 MPa and thereby having a positive design margin.

5. FATIGUE ANALYSIS

As per the TSO - C135, fatigue requirements for aircraft brake housing are listed in Table 5.1. Ref. ARP 5381. The BRPDL "brake rated pressure for the design landing" is determined from the normal of the peak brake pressures from the 100 normal stop tests. The BRPDL pressure used is 12.41 MPa, from brake performance data.

Table 5.1 Fatigue Life Requirements.



Load Case	Brake Pressure Cycle	Required Number of cycles
Design Landing Pressure	12.41 MPa	100000
Maximum Operating Pressure	21.37 MPa	5000

5.1 Design Landing Pressure

Piston end load of 15.83 kN is applied on the end face with respect to local coordinate system in positive X – direction and brake pressure of 12.41 MPa is applied in the pressure cavity include passage hole region.

5.2 Maximum Operating Pressure

Same model and boundary condition has been used in maximum pressure fatigue analysis as design landing pressure condition. However, brake pressure of 21.37 MPa and piston end load of 27.27 kN is applied.

5.3 Results

5.3.1 Design Landing Pressure

The maximum displacement of 0.12 mm is observed at fluid inlet region. It is more than the displacement value of design landing pressure condition and it is less than the displacement observed in static structural analysis. The maximum von-Mises stress of 68.2 MPa is observed in passage hole fillet region and it is less than the material allowable yield limit of 380 MPa.

Fatigue Estimation Based on SN Method

S-N diagram plots nominal amplitude stress versus cycles to failure. S-N method does not function admirably in low cycle applications.

Goodman diagram can be used to estimate a failure condition. It plots stress amplitude against mean stress with the fatigue limit and the ultimate strength of the material as two extremes.

S-N Curve and Goodman Diagram for the maximum stress are shown in Figure 5.1(i) (ii). Maximum stress is observed in passage hole fillet region and empirical results are shown for corresponding maximum value.

i. σ_{max} = 68.2 MPa.

ii. σ_{min} = 0 MPa. (Because of Repetitive loading)

iii. $\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma max - \sigma min}{2}$ = 34.1MPa.

iv. $\sigma_m = \frac{\sigma max + \sigma min}{2}$ = 34.1MPa.

v. Corrected Alternating Stress (σ_{ac}) to make $\sigma_m = 0$.

$\sigma_{ac} = \sigma_a/(1-\sigma_m/\sigma_u)$ = 34.1/(1-34.1/435) = 37 MPa.

vi. Fatigue Strength Margin = Endurance Factor of Saftey-1

$$= \frac{Endurance\ Stength}{FE\ stess} - 1$$

$$= \frac{193}{37} - 1$$

$$= 4$$

Since Fatigue Strength Margin > 1, Hence Design is safe.

vii. Fatigue Damage at Passage Hole = Required Cycles / Actual Cycles

= (1e5) / (1.4e13)

= 0

Since Fatigue Damage < 1, Hence Design is safe.

viii. The Fatigue Damage effect is extremely weak and negligible on aircraft brake system for1e5 cycles.

Aircraft brake housing passage hole fillet region is having a corrected alternating stress of 37 MPa and it is less than the material endurance strength of 193 MPa and there by having an infinite design life of more than 1e6 cycles.

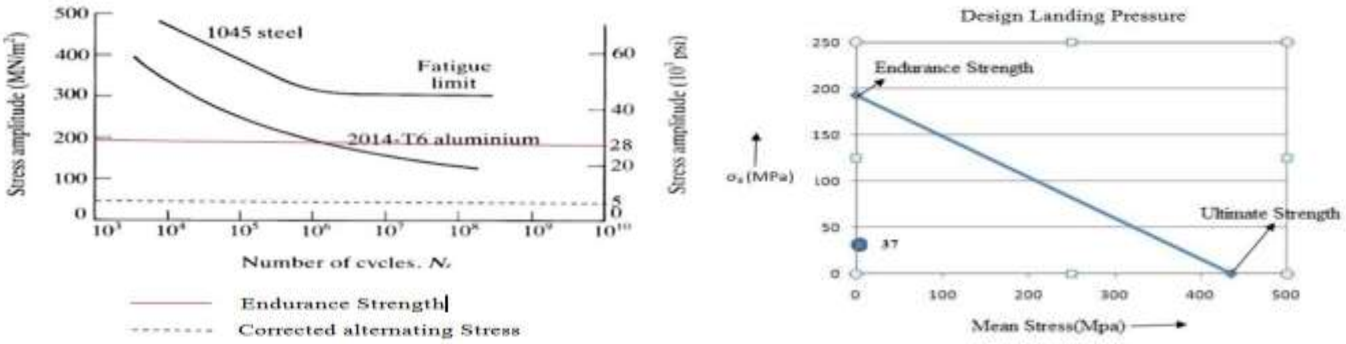


Figure5.1(i) (ii) Graphs Showing SN curve and Infinite Design Life Curve.

From the above graph it's clear that, the corrected stress value lies below the Infinite life curve hence the design is safe.

5.3.2 Maximum Operating Pressure

The maximum displacement of 0.2 mm is observed at fluid inlet region. It is more than the displacement value of design landing pressure condition and it is less than the displacement observed in static structural analysis. The maximum von-Mises stress of 117.45 MPa is observed in passage hole fillet region and it is less than the material allowable yield limit of 380 MPa.

Fatigue Estimation Based on SN Method

S-N Curve and Goodman Diagram for the maximum stress are shown in Figure 5.2(i) (ii). Maximum stress is observed in passage hole fillet region and empirical results are shown for corresponding maximum value.

i. σ_{max} = 117.45 MPa.

ii. σ_{min} = 0 MPa. (Because of Repetitive loading)

iii. $\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma max - \sigma min}{2}$ = 58.73MPa.

iv. $\sigma_m = \frac{\sigma max + \sigma min}{2}$ = 58.73MPa.

v. Corrected Alternating Stress (σ_{ac}) to make $\sigma_m = 0$.

$\sigma_{ac} = \sigma_a/(1-\sigma_m/\sigma_u)$ = 58.73/(1-58.73/435) = 67.9 MPa.

vi. Fatigue Strength Margin = Endurance Factor of Saftey-1

$$= \frac{Endurance\ Stength}{FE\ stess} - 1$$

$$= \frac{193}{67.9} - 1$$

$$= 1.8$$

Since Fatigue Strength Margin > 1, Hence Design is safe.

vii. Actual number of cycles at 67.9 MPa for Maximum Stress Location: >1e6 Cycles

viii. Fatigue Damage at Passage Hole = Required Cycles / Actual Cycles

= (5000) / (3e10)

≈ 0

Since Fatigue Damage < 1, Hence Design is safe.

ix. The Fatigue Damage effect is extremely weak and negligible on aircraft brake system for1e5 cycles.

Aircraft brake housing passage hole fillet region is having a corrected alternating stress of 67.9 MPa and it is less than the material endurance strength of 193 MPa and there by having an infinite design life of more than 1e6 cycles.

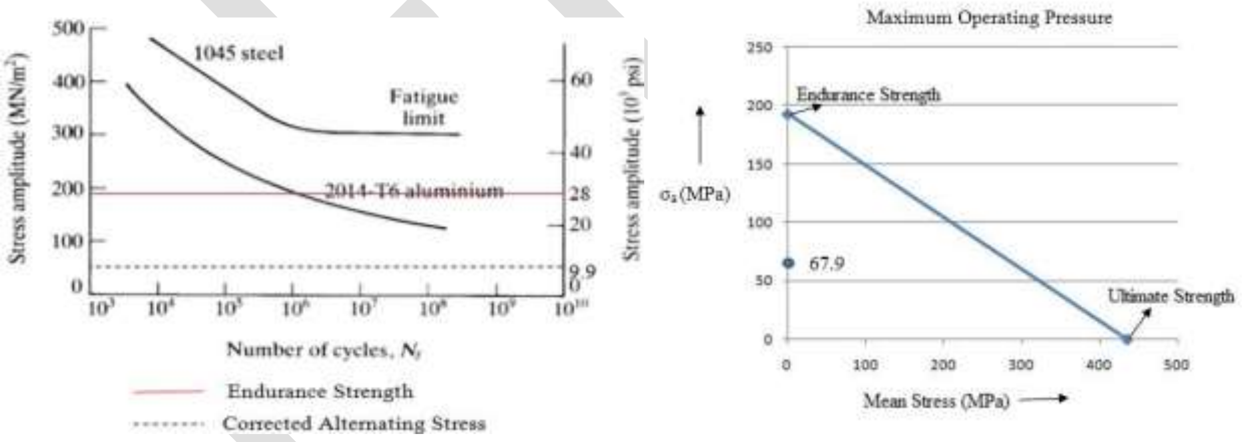


Figure5.2(i) (ii) Graphs Showing SN curve and Infinite Design Life Curve.

From the above graph it's clear that, the corrected stress value lies below the Infinite life curve hence the design is safe.

6. TIE BOLT STRENGTH ANALYSIS.

6.1 Boundary Conditions

Aircraft Torque Tube is constrained in all degrees of freedom as shown in Figure 6.1.

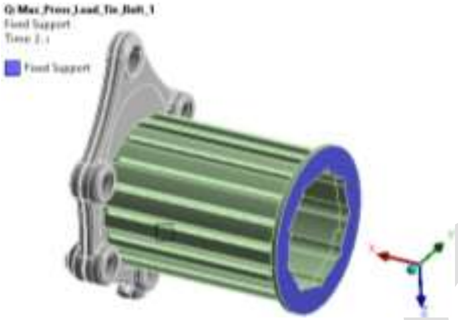


Figure 6.1: Boundary condition applied to Torque Tube.

6.2 Tie Bolt Preload (Load Step-1)

Tie bolt assessment is analyzed in two load steps. Bolt preload is defined in load step-1 and its deformation is retained for load step-2 where other mechanical loads (proof and burst loads) are defined. To be on the conservative side, applied preload is 30% less as compared against the yield load limit. Based on torque tension relationship, bolt preload at yield is 91505 N. Bolt preload of 64054 N is applied in load step-1 with respect to local ordinate system in axial direction as shown in Figure 6.2.

Figure 6.2 Bolt Pretensions.

6.3 Maximum Operating Pressure

In Load Step 2, Piston end load of 27.27 kN is applied on the end face with respect to local coordinate system in negative X-direction and Brake pressure of 21.37 MPa is applied in Cylinder.

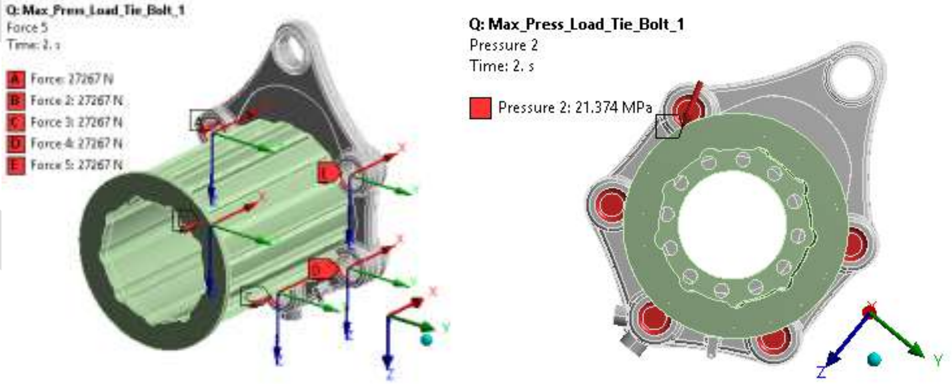


Figure 6.3 Load conditions.

6.4 Results

a) Tie Bolt Axial Displacement (Z-Direction)

Total deformation from Ansys is 0.09 mm.

From Empirical relations we have

i. Deflection equation for Tensile Load $= \frac{PL}{AE}$

ii. Where, Bolt Pre Load (P) = 64054 N.

iii. Length of the shank (L) = 41.91 mm.

iv. Diameter of the shank (D) = 12.7 mm.

v. Area = 126.68 mm^2.

vi. Young’s Modulus (E) = 2x10^5 N/mm^2.

Therefore,

$$\text{Deflection} = \frac{64054 \text{ x } 41.91}{126.68 \text{ x } 2e\ 5} = 0.1 \text{ mm.}$$

Estimated tie bolt displacement of 0.09 mm closely matches with the empirical result of 0.1 mm.

b) Normal Stress Plot

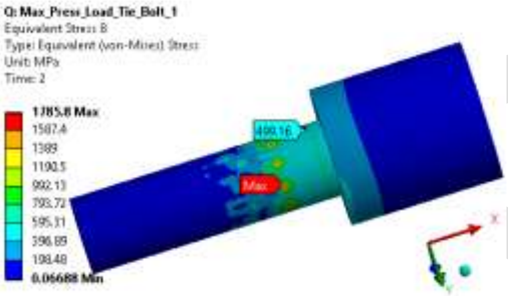


Figure 6.4: Normal Stress Plot

Maximum normal stress of 499.16 MPa observed at the shank is considered as shown in Figure 6.4 and validated to normal stress using empirical results.

$$\text{Normal Stress} = \frac{Load}{Area} = \frac{64054}{126.68} = 505.64 \text{ N/mm}^2.$$

Estimated normal stress of 499.16 MPa is less than material allowable yield limit of 552 MPa and thereby having a positive design margin of 0.1. The estimated normal stress of 499.16 MPa closely matches with empirical result of 505.64 MPa.

c) Shear Stress Plot

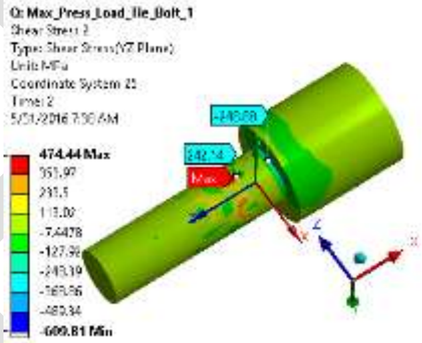


Figure 6.5 Shear stress plot.

Maximum Shear stress of 248.88 MPa observed on the shank is considered as shown in Figure 6.5 and validated to Shear stress using empirical results.

i. Tie Bolt Allowable Shear Strength = 353.3 MPa

ii. Diameter of shank (D) = 12.7 mm.

iii. Length of shear (L) = 20.95 mm.

iv. Shear Area = D x L = 12.7 x 20.95 = 266.12 mm.

v. Shear load =63.89 kN

vi. Shear Stress = $\frac{shear\ Load}{shear\ Area} = \frac{63890}{266.12}$ = 240 N/mm^2.

vii. Shear Margin of Safety = $\frac{353.3}{240}$-1 = 0.5

Maximum shear stress of 248.88 MPa is less than allowable shear strength of 353.3 MPa and thereby having a positive design margin of 0.5. The estimated shear stress is closely matches with empirical result of 240 MPa.

Similarly the analysis can be done for Proof and Burst Pressure requirements.

7. CONCLUSION

It is concluded that Additive Manufactured aircraft brake housing design provides the best solution with regards to acceptable maximum operating, proof and burst pressure design margins as per the TSO-C135 minimum performance standards. The following analysis for the aircraft brake housing proves the design substantiation as per the TSO-C135 guidelines. Results shows that aircraft brake housing and tie bolt are safe under all brake operating pressure conditions.

1) Structural analysis of the aircraft brake housing shows the maximum displacement is observed at lug top edge region and the maximum von-Mises stress is observed in passage hole region. All observed stress values are within the safe limits for the aluminum 2014 - T6 material.

2) Aircraft brake housing is having infinite fatigue life of more than 1e6 cycles. It satisfies the design requirements of 1e5 cycles for design landing pressure and 5000 cycles for maximum operating pressure conditions.

3) Aircraft brake housing tie bolt meets tensile and shear strength requirements. Estimated results are within the safe limits for the Inconel-718 material and closely match with empirical results.

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