

Characterization of Boeing 777 Nose Landing Gear to Better Withstand Rough Landing

Abdulbaqi Jinadu^{1,a*}, Olalekan Adebayo Olayemi^{1,b}, Quadri Tijani^{1,c},
Abdulwasiiu Salaudeen^{1,d}

¹Department of Aeronautical and Astronautical Engineering, Faculty of Engineering,
Kwara State University, Kwara State, Nigeria.

^aabdulbaqi.jinadu@kwasu.edu.ng, ^bolalekan.olayemi@kwasu.edu.ng, ^ctijaniquadri97@gmail.com,
^dooluwasegun44@gmail.com

Keywords: Nose Landing Gear, Stress Analysis, Loads, Solidworks, FEA Analysis.

Abstract. An important role a landing gear plays is that it aids in the landing and takeoff of aircraft. The landing gear must be designed in such a way that it can take these stresses in static and dynamic situations. This is to accommodate both rough and smooth landings that result from various loads acting upon it, such as drag force, vertical load, and side load. In the aviation industry, landing gear stress is a key concern, and different research in this field has previously yielded excellent results. However, the time has come to raise the bar even higher. This research will focus on the improvement of the Boeing 777's nose landing gear to better withstand rough landings. During the timeframe of this research, motion study in SOLIDWORKS 2020 (Stand-alone license) was utilized to model and analyze various components of the landing gear. The results summarize that a single material should be avoided throughout the components of the landing gear. Components such as pistons with a larger stress allocation should be made of titanium alloy, while components with a lesser stress allocation should be made from aluminum alloy.

Abbreviations

Parameters	Definition	Unit
σ	Stress	(N/mm^2 , MPa)
ϵ	Strain	(dimensionless)
f	Force	(N)
A	Area	(m^2)
D	Displacement	(mm)
L	Length	(m)
K	Stiffness	(N/m)
ΔL	Change in Length	(m)

1.0 Introduction.

Aircraft landing gear assemblies comprise various subsystems working in unison to enable functionality [1]. The landing gear system is one of the most important subsystems on an aircraft, and it is frequently configured alongside the aircraft structure due to its significant impact on the aircraft's structural configuration. Due to the long product development cycle time, landing gear detail design is done early in the aircraft design cycle. Landing gear designers and practitioners face numerous obstacles, including the necessity to design landing gear with minimal weight, volume, and life cycle cost, as well as a short development cycle time. Advanced technologies, materials, and analysis methods must be used to meet these problems. The landing gear is an assembly of various structural members that support the aircraft airframe. Any materials used for a landing gear must have sufficient strength to withstand heavy take-off and landing loads [2]. During landing, the gear is subjected to high impact forces due to sink velocity [3].

In relation to safety in civil aviation, landing has been researched to control the compression and extension rates while preventing self-damage due to the different loading conditions it faces [4]. Over the years, retractable landing gear malfunctions and/or human errors have resulted in countless air mishaps. This point was buttressed by Ossa [5], who implied nose landing gear failure is not limited to a material defect. Between 1998 and 2003, there were roughly 100 gear-up landing mishaps per year in the United States due to distraction and preoccupation during the landing procedure [6]. Also, according to the Boeing reports, an estimated 55% of aircraft failures occur during take-off and landing [7]. It is detailed in Fig. 1 below how this is a major concern regarding the safety of civil air transport.

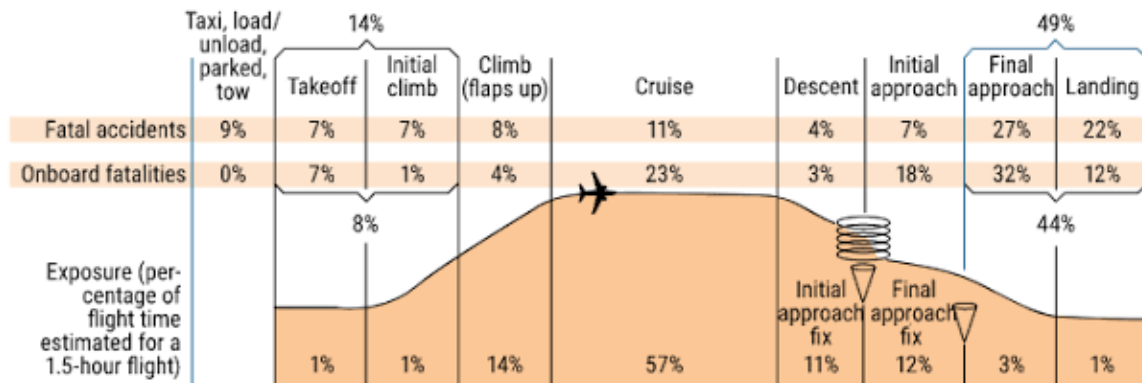


Fig. 1: Percentage of fatal accidents and onboard fatalities [7]

To buttress the danger, the same report shown in Fig. 2 below cited the world's commercial air mishaps by flight phases and pointed at the same landing phase as leading to a higher percentage of accidents.

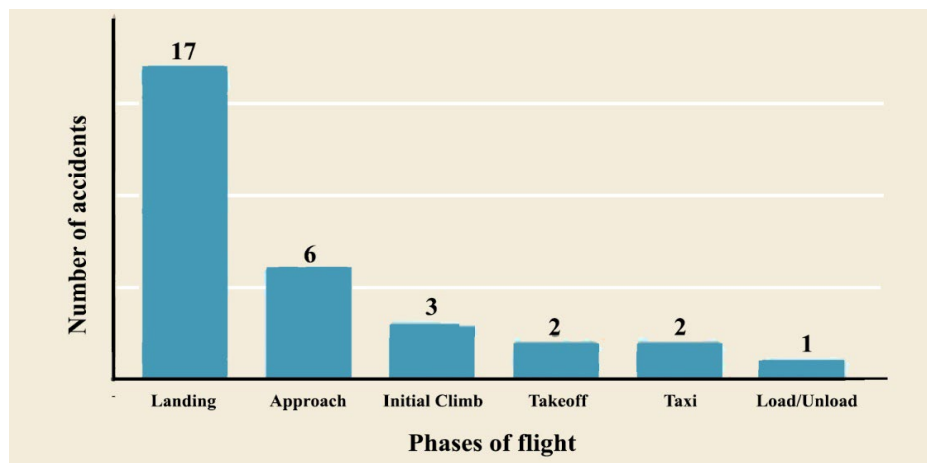


Fig. 2: Accident fatalities by flight phase [7]

Ross and Edson [8] investigated first to consider an actively controlled landing gear to reduce the effect of landing loads by designing an active control landing gear system for a supersonic aircraft, with the goal of reducing the forces experienced by the aircraft during landing, rollout, takeoff, and taxi operations.

Horta et al. [9] built a facility to test several active landing gear control methods and their performance as a follow-up to the previous study using a landing gear with an additional hydraulic supply controlled by servo valves.

Dileep [10] aimed to develop a landing gear suitable for rough landing by creating a 3-D model of the landing gear in CATIA V5 software and subjecting it to ANSYS to determine the variation in the displacement and Von Miss stress behavior for three materials (steel, aluminum, and titanium) subjected to static loading, and then plotting the results for the same loading condition and suggesting the suitable material. Inagaki [11] cited that the application of titanium in the aerospace industry can be extended beyond its use within the airframe and engines.

Mohanraj [12] analyzed the main landing gear axle shaft to estimate the fatigue stress behavior and displacement of an aircraft landing gear axle during ground taxing. The failure of a Boeing 737-400's left main landing gear was investigated in this paper, and forces and tensions on the landing gear and axle were computed. The present material has been replaced with ASTM Grade 5 titanium alloy which is stronger but also more expensive. The fatigue cycles have been doubled compared to the current axle which in turn enhanced safety.

Using strain-life criteria, Neuber's Rule was merged with the finite element method to accurately predict the initiation life of fatigue cracks. [13]. The cumulative damage in the fatigue crack initiation phase was calculated using Miner's rule. This method was then used on a plate with a central hole (structural elements with concentrations), and the findings were compared to analytical local strain methods and existing experimental data. The fatigue life calculated using the provided approach is quite close to the experimental data. The defined approach can address uni-axial and multi-axial loading with constant and variable amplitude for fatigue life prediction of notched aircraft structural components up to crack onset. Material selection is important, and the importance of such materials was highlighted by Boyer in 1992 [14]. It elaborated on its wide range of uses, citing its use as forgings for Lockheed and Boeing aircraft.

Dutta [15] noted that the landing gears accounted for 5% of the total aircraft weight and showed, with the aid of a CAD design, the nose landing gear design of the Boeing 747-8 with the aim of evaluating the results of stresses and deformation when different materials are used. Also, Nguyen [16] determined the stress behavior and the displacement of the nose landing gear. Using external forces that were determined analytically, he obtained results that were consistent with the Federal Aviation Administration's physical testing recommendations.

Plabita et al. [17] used Titanium alloy and High strength Stainless Steel for the analysis to check the behavior of stress and compare the strength of the model for both the materials. The result shows that the model of high strength stainless steel has lesser stress and deformation. It also showed that the model of high strength stainless steel has a higher factor of safety but lesser stress formation in comparison to the titanium alloy model.

In another review, Nishant P. et al. [18] observed that the most affected part a nose landing gear was the shock strut, prompting a material change from Ti-10Al-2Fe-3V to Ti6Al-4V. It was concluded that use of the material Ti-6Al-4V over Ti-10Al-2Fe-3V is better because of less deformation, stress and strain.

Aftab et al. [19] modelled and meshed a typical aircraft landing gear with around 34,414 number of elements using materials like Aluminum alloy 7075, Titanium 6Al4v, and Alloy steel 4340. It was noticed that the stress induced in Aluminum alloy 7075 is lesser and in the case of Titanium 6Al-4v yields slightly more stress than Aluminium Alloy 6Al-4v and less stress than Alloy Steel 4340 offering longer fatigue life and better Safety factor for better safety and longer life.

Patra et al. [20] modelled constituents of the landing gear using CATIA software and analysis using ANSYS software. He observed that Titanium alloy is found to be one of the most cost-efficient materials that can also withstand high levels of impact, with lowest stress levels in comparison to alloys in the same category.

1.1 Aims of the Research

This research aims at

1. Investigating the performance of the Boeing 777 nose landing gear under rough landing conditions.
2. Identifying the factors contributing to the failure or damage of the nose landing gear during rough landings.
3. Developing a comprehensive understanding of the structural behavior of the nose landing gear components during rough landings.
4. Exploring potential structural modifications or improvements that can enhance the nose landing gear's ability to withstand rough landings.

5. To evaluate the impact of rough landings on the overall safety and longevity of the Boeing 777 aircraft.

1.2 Objectives of the Research.

1. Conduct a literature review to gather existing knowledge on the behavior of aircraft landing gear during rough landings and related failure modes.
2. Design Models, run simulations and computational analyses to assess the structural response of the nose landing gear components under different rough landing scenarios.
3. Analyze the collected data to identify patterns, trends, and common failure modes associated with rough landings.
4. Identify and propose potential design modifications or improvements that can enhance the strength, durability, and shock absorption capabilities of the nose landing gear.
5. Evaluate the proposed design modifications using simulations and analysis to assess their effectiveness in improving the nose landing gear's performance.
6. Contribute to the body of knowledge in the field of aircraft landing gear design and improve the overall safety and reliability of Boeing 777 aircraft operations.

2.0 Material and Methods.

Computing power was lacking which led to the inability to run an in-depth dynamic analysis that assumes load changes with time, hence the use of static load with the worst loading conditions.

The landing gear was modeled in Solidworks 2020 with standard dimensions derived from both manufacturer manuals and related literature reviews. Following the creation of individual parts, an assembly was made to form a single component. Material application is applied to the different components of the landing gear, after which interface detection is performed. The landing gear assembly is set at 8 inches above the runway to represent the initial height before impact.

Application of boundary conditions such as gravity and force that act at the top of the shock strut to represent aircraft mass loading at the nose landing gear assembly. Application of damping parameters of the shock absorber; In this case, the spring constant is used to represent the damping ability of the hydraulic fluid in the shock absorber due to the inability to apply shock absorber fluid FEA simulation. The application of group contact between tires and platform (runway), and the specification of the type of contact between tires and platform, i.e., rubber for the tires and steel for the platform.

Create a simulation goal using motion flow where we specify a simulation time of 0-1.5 seconds since this is the time frame where the landing gear contacts the runway. The motion load imposed on each modelled part is observable as pink lines with arrows. Generate a mesh and refine it from coarse to fine. After the meshing is completed, motion loads are well imposed on the model along their coordinate system, e.g., loads or forces acting along the X, Y, and Z coordinates are applied to each model part. Motion analysis is run to see how the landing gear impacts the runway and reacts to forces. Upon simulation completion, imported motion loads are displayed for deeper studies on stress deformation and strain. A mesh is recreated (a blended curvature mesh for parts having holes and circular faces) using the fine setting, after which fixtures are applied and the simulation is run again, giving a more accurate result.

2.1 Boundary Conditions.

A static load is given to each component, considering the weight of each component.

Eq. 1 is the stress which is the force per unit area.

$$\sigma = \frac{F}{A} \quad (1)$$

The strain is represented by Eq. 2 below. It is the change in length per unit length.

$$\varepsilon = \frac{\Delta L}{L} \quad (2)$$

Eq. 3 shown below describes Hookes law. This is the force applied to the spring.

$$F = \frac{k}{D} \quad (3)$$

Displacement in the spring is shown by Eq. 4 below

$$D = \frac{k}{F} \quad (4)$$

Table 1. Unit System

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Table 1 above is an indicator of the unit systems used in the methodology. Units such as displacement, temperature and angular velocity were implemented.

The properties of the mesh were Identified for the methodology. A solid mesh of high quality was used for that simulation. Other mesh properties are shown below in table 2.

Table 2. Mesh Properties

Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	0.440371 in
Minimum element size	0.0880742 in
Mesh Quality	High
Total Nodes	129235
Total Elements	86577
Maximum Aspect Ratio	4.576
% of elements with Aspect Ratio < 3	99.9
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh:mm:ss):	00:00:10
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Solver type	FFEPlus
Soft Spring:	Off
Inertial Relief:	On
Incompatible bonding options	More accurate (slower)
Large displacement	Off
Compute free body forces	On
Friction	On
Friction Coefficient	5.000000e-02
Use Adaptive Method:	Off

The motion sensor details that shows structural changes in the model for both base and improved model are stated below in table 3.

Table 3. Motion Sensor Details

Sensor name	Base Model	Improved Model
VON: von Mises Stress	1.041e+08 N/m ²	6.359e+07 $\frac{N}{m^2}$
P1: 1st Principal Stress	1.051e+08 N/m ²	6.420e+07 $\frac{N}{m^2}$
P2: 2nd Principal Stress	7.483e+07 N/m ²	4.557e+07 $\frac{N}{m^2}$
P3: 3rd Principal Stress	3.668e+07 N/m ²	2.225e+07 $\frac{N}{m^2}$
URES: Resultant Displacement	1.323e-01 mm	1.453e-01 mm
INT: Stress Intensity(P1-P3)	1.119e+08 N/m ²	6.842e+07 $\frac{N}{m^2}$
ESTRN: Equivalent Strain	5.646e-04	6.148e-04
VON: von Mises Stress	1.041e+08 N/m ²	6.359e+07 $\frac{N}{m^2}$
P1: 1st Principal Stress	1.051e+08 N/m ²	6.420e+07 $\frac{N}{m^2}$
P2: 2nd Principal Stress	7.483e+07 N/m ²	4.557e+07 $\frac{N}{m^2}$
P3: 3rd Principal Stress	3.668e+07 N/m ²	2.225e+07 $\frac{N}{m^2}$
URES: Resultant Displacement	1.323e-01 mm	1.453e-01 mm
INT: Stress Intensity(P1-P3)	1.119e+08 N/m ²	6.842e+07 $\frac{N}{m^2}$
ESTRN: Equivalent Strain	5.646e-04	6.148e-04
VON: von Mises Stress	1.041e+08 N/m ²	6.359e+07 $\frac{N}{m^2}$
P1: 1st Principal Stress	1.051e+08 N/m ²	6.420e+07 $\frac{N}{m^2}$
P2: 2nd Principal Stress	7.483e+07 N/m ²	4.557e+07 $\frac{N}{m^2}$
P3: 3rd Principal Stress	3.668e+07 N/m ²	2.225e+07 $\frac{N}{m^2}$
URES: Resultant Displacement	1.323e-01 mm	1.453e-01 mm
INT: Stress Intensity(P1-P3)	1.119e+08 N/m ²	6.842e+07 $\frac{N}{m^2}$
ESTRN: Equivalent Strain	5.646e-04	6.148e-04

2.2 Material Selection.

2.2.1 Base Simulation

Titanium: An alpha-beta alloy is a grade (Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si (SS)) alloy. R.M.I. (Reactive Metal Incorporation) developed titanium alloy in the early 1970s as a material that could undergo deep hardening. high strength, moderate creep strength, and fracture toughness. According to a tensile strength study, titanium alloy (Ti-6Al-2Sn-2Zr-2MO-2Cr-0.25Si (SS)) is the strongest of all titanium alloys and can endure temperatures as high as 600°C. More of its properties are listed in Table 4 below.

Table 4: Properties of Titanium Alloy (Ti 6Al 2Sn 2Zr 2Mo 2Cr 0.25Si (SS))

Property	Value	Unit
Elastic Modulus	1.230000018e+11	$\frac{N}{m^2}$
Poisson's Ratio	0.33	($\frac{N}{A}$)
Shear Modulus	4.599999975e+10	$\frac{N}{m^2}$
Mass Density	4650.0001	$\frac{kg}{m^3}$
Tensile Strength	1160000029	$\frac{N}{m^2}$
Compressive Strength	1169999978	$\frac{N}{m^2}$
Yield Strength	1070000004	$\frac{N}{m^2}$
Thermal Expansion Coefficient	9e-06	/K

2.2.2 Optimized Simulation

Aluminium: Table 5 below describes one of the aluminum grades with the greatest global usage. Aluminum 6061 is the material of choice for a variety of applications, including the construction of boats, furniture, and airplanes.

As with any grade, it begins with the metal's chemical composition. Magnesium (1.0 percent) and silicon are the two main alloying components in 6061. (0.6 percent). This gives it a high level of corrosion, stress, and crack resistance. This implies that the grade has good welding ability and formability.

Table 5. Properties of Aluminium Alloy (6061-T6 (SS))

Property	Value	Unit
Elastic Modulus	69000.00067	N/m^2
Poisson's Ratio	0.33	(N/A)
Shear Modulus	26000.00013	N/m^2
Mass Density	2700	kg/m^3
Tensile Strength	310.0000021	N/m^2
Thermal Conductivity	166.9	$N/(m.K)$
Yield Strength	275.0000009	N/m^2
Thermal Expansion Coefficient	2.4e-05	/K

2.3 Material Comparison.

The Material composition for the base and optimized models of the landing gear are highlighted in Table 6 below.

Table 6. Material comparison between base and optimized model.

Parts	Material Used (Base Model)	Material Used (Optimized Model)
Tire	Rubber	Rubber
Axel, Cylinder, Piston	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si (SS)	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si (SS)
Allen Key 1, Allen Key 2, Upper link, Lower link, Pin Connector.	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si (SS)	6061-T6 (SS)

2.4 Landing Gear Free-Body.

In this process, each part of the landing gear is modeled in Solidworks 2020 using the dimensions corroborated from manufacturers manual and various literature reviews and then assembled as shown in figure 3 below.

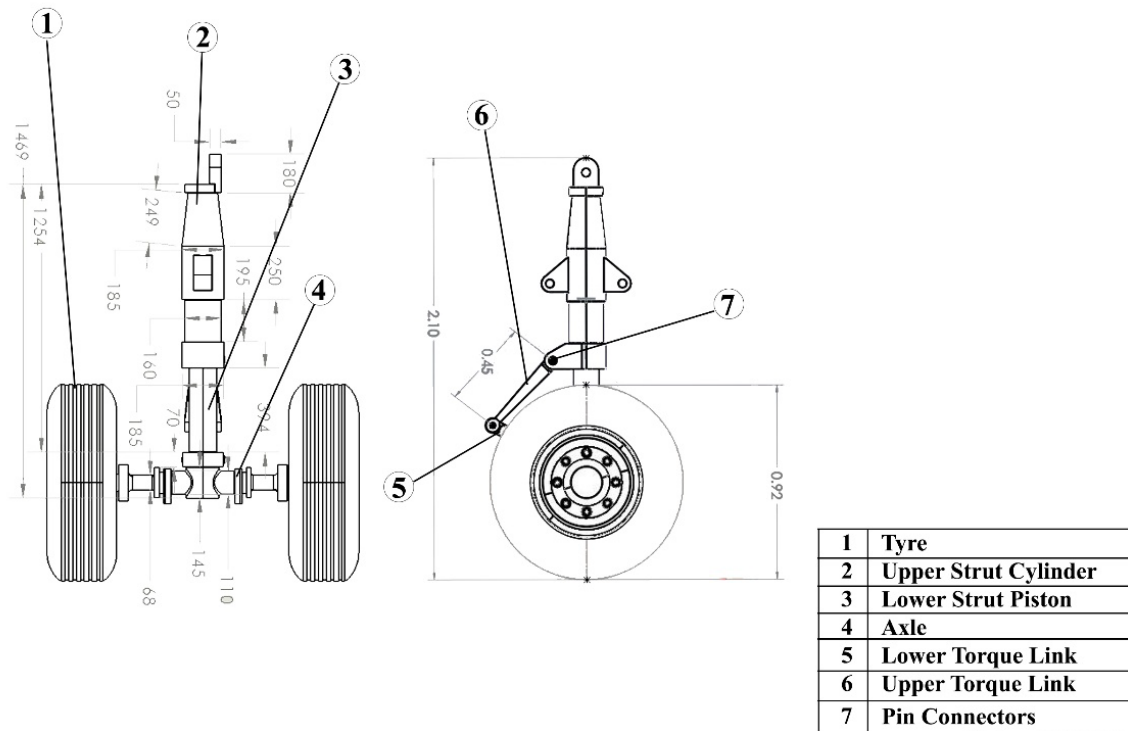


Fig. 3: Landing Gear Free body diagram (mm) (Author)

3.0 Results and Discussion.

3.1 Static Structural Analysis for Cylinder

The displacement and stress analyses for the landing gear cylinder are shown in Figs. 4 (a and b) below. The attachment lugs are under additional stress, and there is some displacement there as well. Von Mises stresses read maximum at 355 MPa while displacement of the structure is maximum at 1.07 mm which can be noticed in reddish orange at the top of the upper link connector.

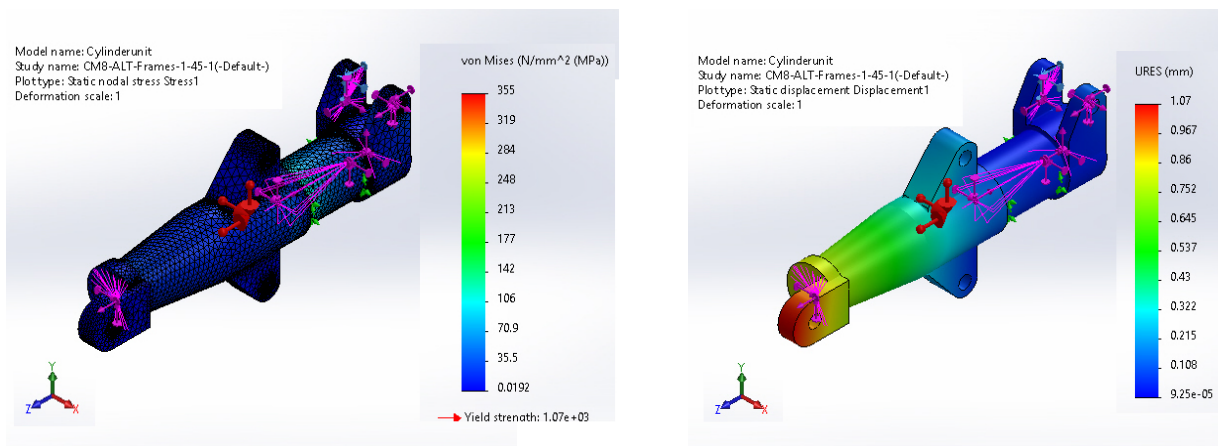


Fig. 4: Ti-6Al Cylinder (a) Stress analysis (b) Total displacement

3.2 Upper Link

3.2.1 Static Structural Analysis for Upper Link

Compared to its equivalent made of 6061-T6, the upper link made of Ti-6Al exhibits higher levels of stress (SS). The following Figs. 5(a and b) makes this clear. However, Figs. 6(a and b) shows a constant displacement display between the two upper links constructed of various materials at 0.132mm and 0.145mm respectively for both the base and optimized material composition.

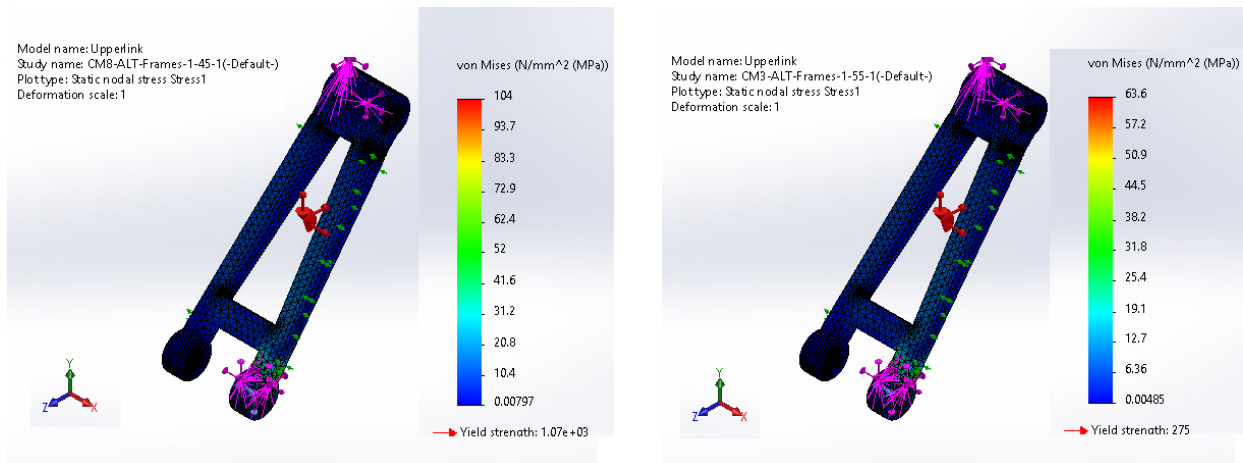


Fig. 5: Stress analysis for Upper Link (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized)

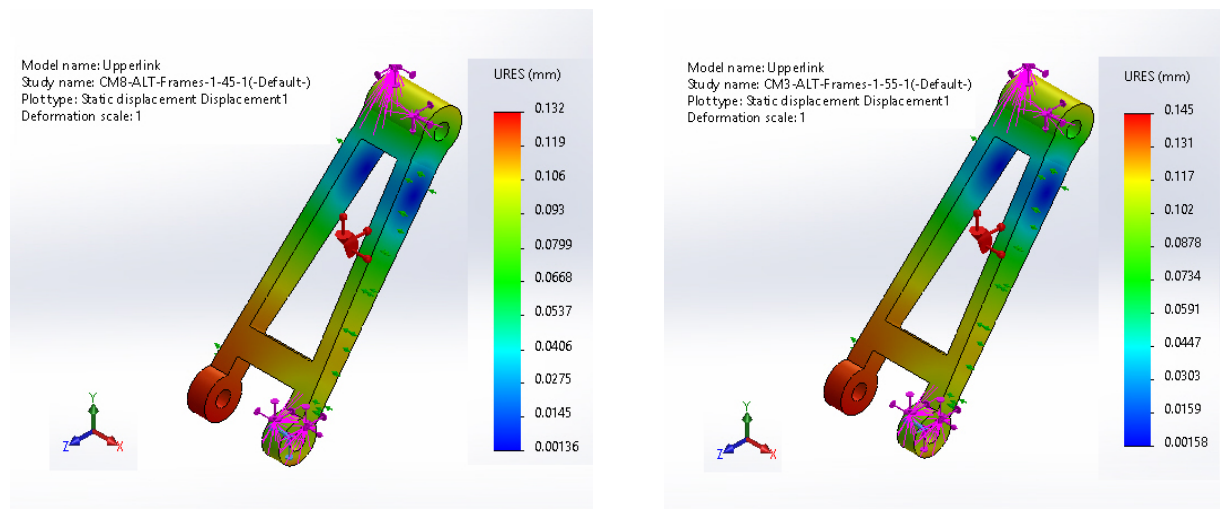


Fig. 6: Upper Link displacement (a) Ti-6Al (Base Model) (b): 6061-T6 (SS) (Optimized Model)

3.2.2 Comparative Analysis for Upper Link

Focusing on the upper link, the base model exhibits a greater stress distribution than the optimized 6061-T6 (SS) model. More displacement is also seen in the base model. This is clear in Figs. 7(a and b) below.

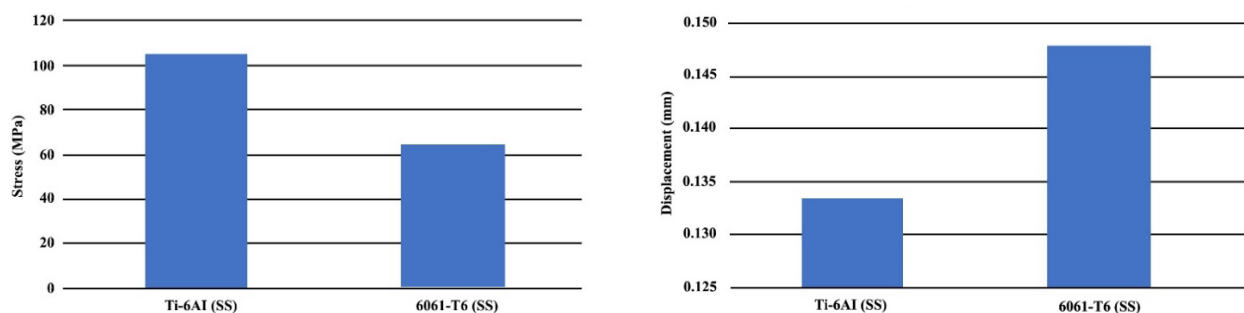


Fig. 7: Comparison of Upper Link (Base and Optimized) (a) Stress (b) Maximum Displacement

3.3 Lower Link

3.3.1 Static Structural Analysis for Lower Link

As compared to the 6061-T6 (SS) version in Fig. 8b, the Ti-6Al lower link in Fig. 8a has a higher stress concentration that can reach as high as 69.1 MPa. Additionally, as can be seen in Fig. 9(a and b) below, the improved version shows more displacement.

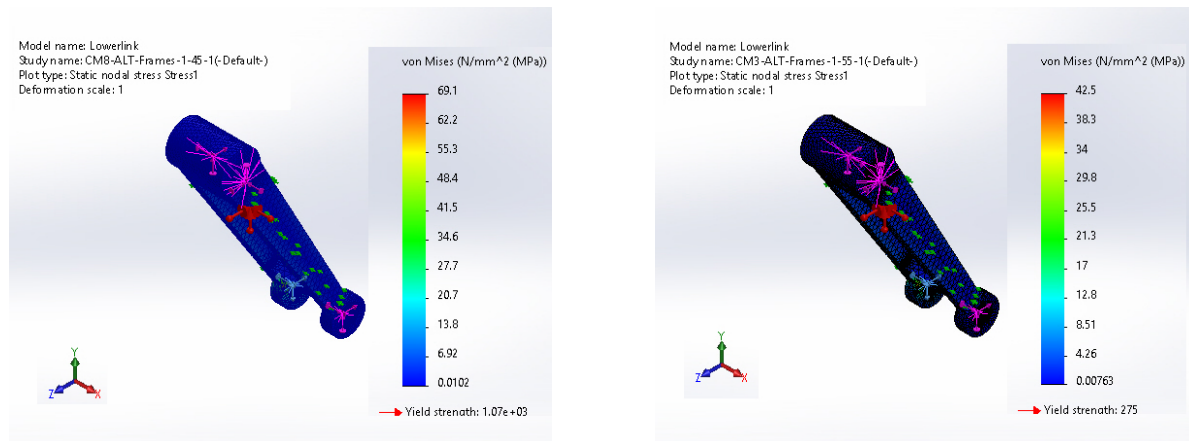


Fig. 8: Lower Link stress analysis (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

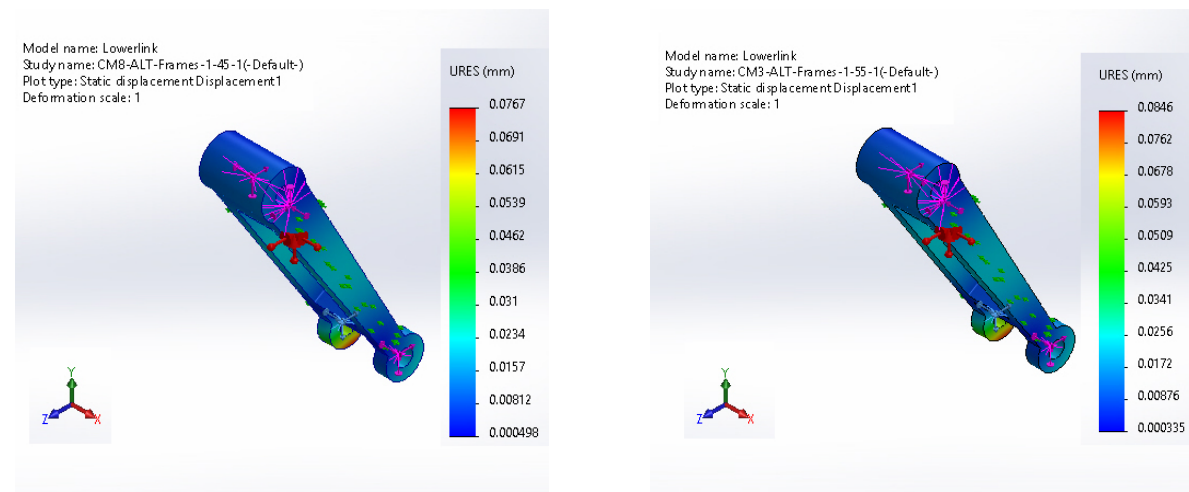


Fig. 9: Lower Link total displacement (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

3.3.2 Comparative Analysis for Lower Link

In contrast, as demonstrated in Fig. 10, the 6061-T6 version of the lower link exhibits greater displacement whereas the Ti-6Al version exhibits higher levels of stress.

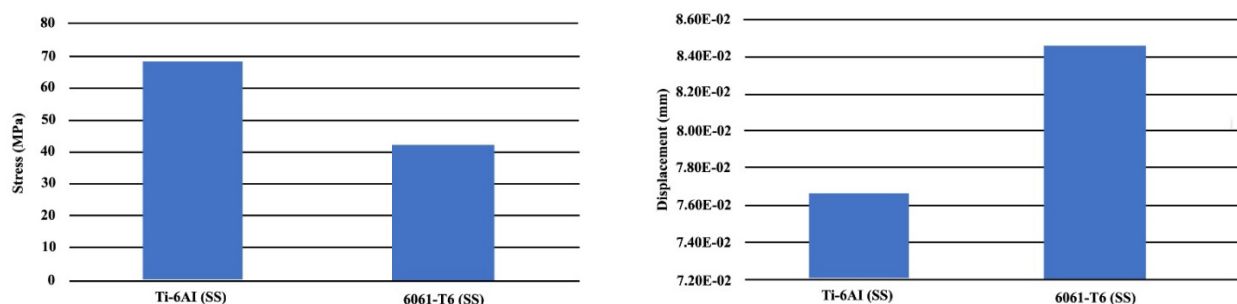


Fig. 10: Comparison of Lower Link (Base and Optimized) (a) Stress (b) Maximum Displacement

3.4 Static Structural Analysis for Axle

Figs. 11(a and b) below, respectively, display the axle stress and displacement. As it experiences vertical and drag response loads, its extremities are subjected to more stress and deformation. Von Mises stresses are maximum at 624 MPa while axle displacement is maximum at 0.339mm.

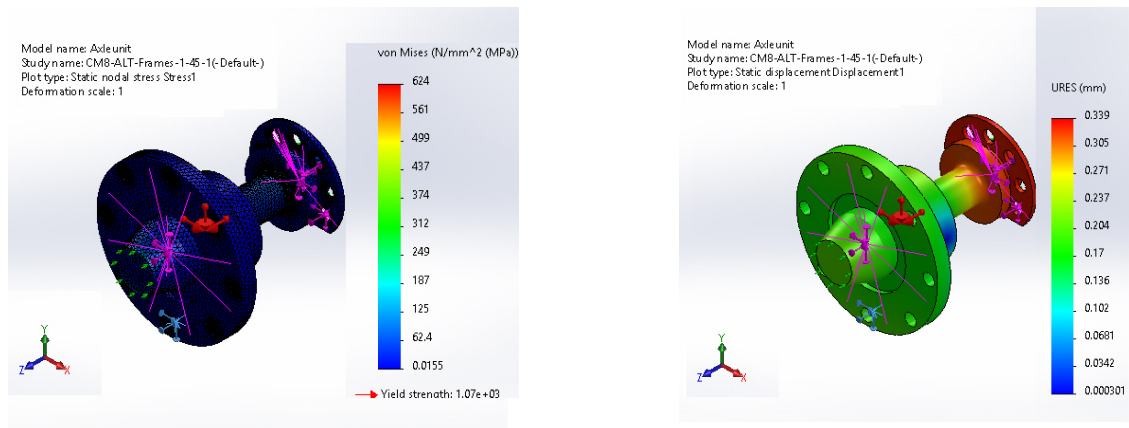


Fig. 11: Axle (Ti-6Al) (a) Stress analysis (b) Total displacement

3.5 Static Structural Analysis for Piston

In Figs. 12 below, the piston stress and displacement analysis are described in detail (a and b). 7.93 mm displacements and stress levels as high as 845 MPa can both be seen.



Fig. 12: Piston (Ti-6Al) (a) Stress analysis (b) Total displacement

3.6 Allen Key

3.6.1 Static Structural Analysis for Allen Key 1

The Allen key 1 produced from Ti-6Al exhibits higher stress concentrations than its 6061-T6 (SS) counterpart, as seen in Figures 13 (a and b), whereas the 6061-T6 (SS) counterpart displaces slightly more at 0.00301, as shown in Figures 14 (a and b) below.

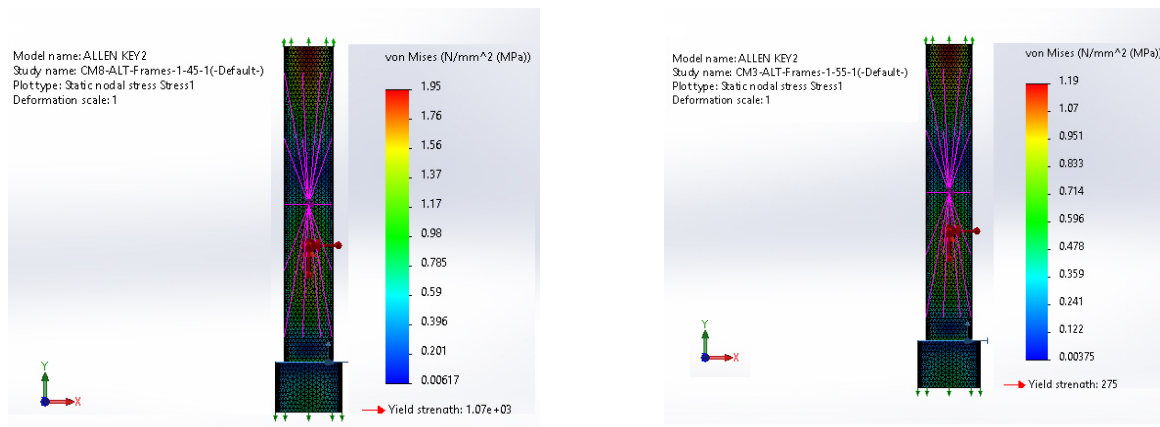


Fig. 13: Allen Key 1 stress analysis (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

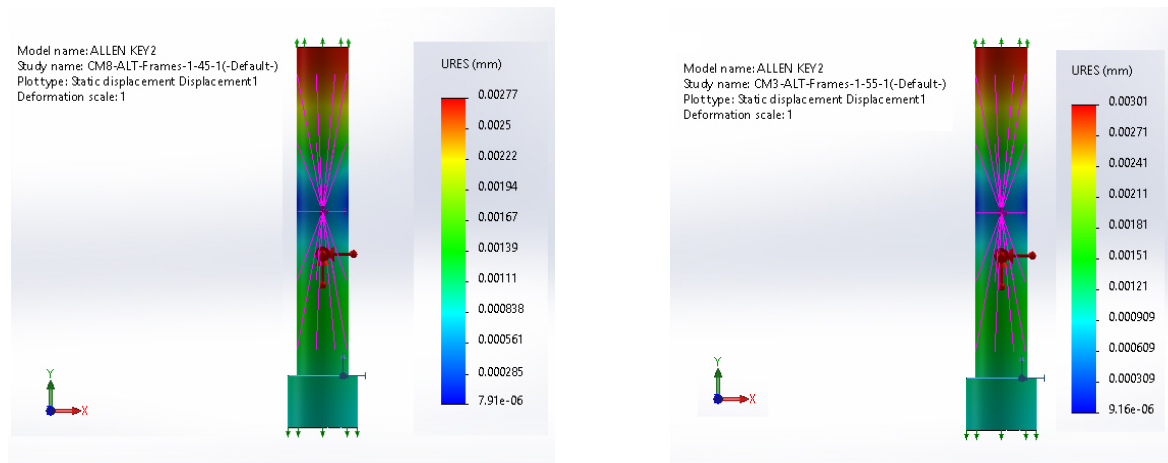


Fig. 14: Allen Key 1 total displacement (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

3.6.2 Comparative Analysis for Allen Key 1

Figure 15 (a and b) below compares two versions of the Allen key 1, with the Ti-6Al version showing greater stress and the 6061-T6 version showing greater displacement.

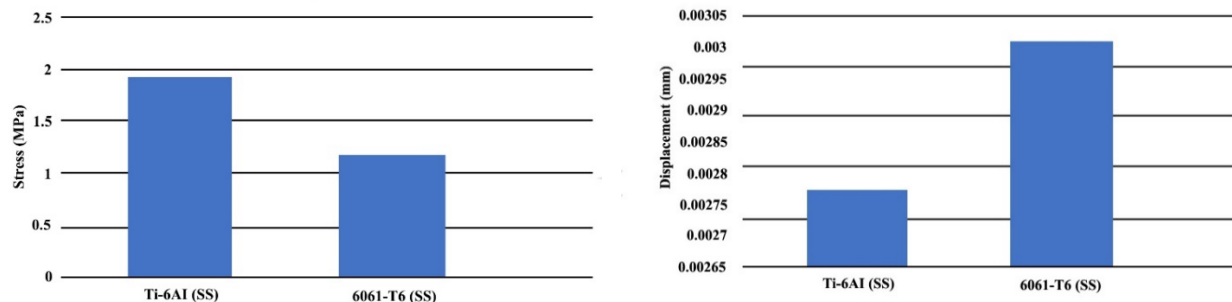


Fig. 15: Comparison of Allen Key 1 (Base and Optimized) (a) Stress (b) Maximum Displacement

3.6.3 Static Structural Analysis for Allen Key 2

The Allen key 2 constructed of Ti-6Al exhibits higher stress concentrations than its 6061-T6 (SS) counterpart, as seen in Figs. 16 (a and b), whereas the 6061-T6 (SS) counterpart displaces slightly more at 0.00301, as shown in Figs. 17 (a and b) below.

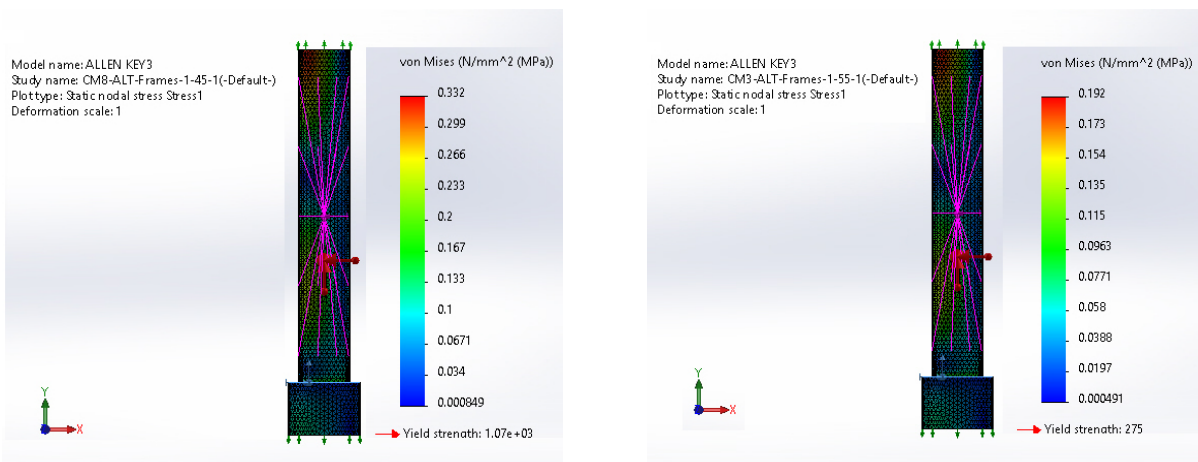


Fig. 16: Stress analysis for Allen key 2 (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

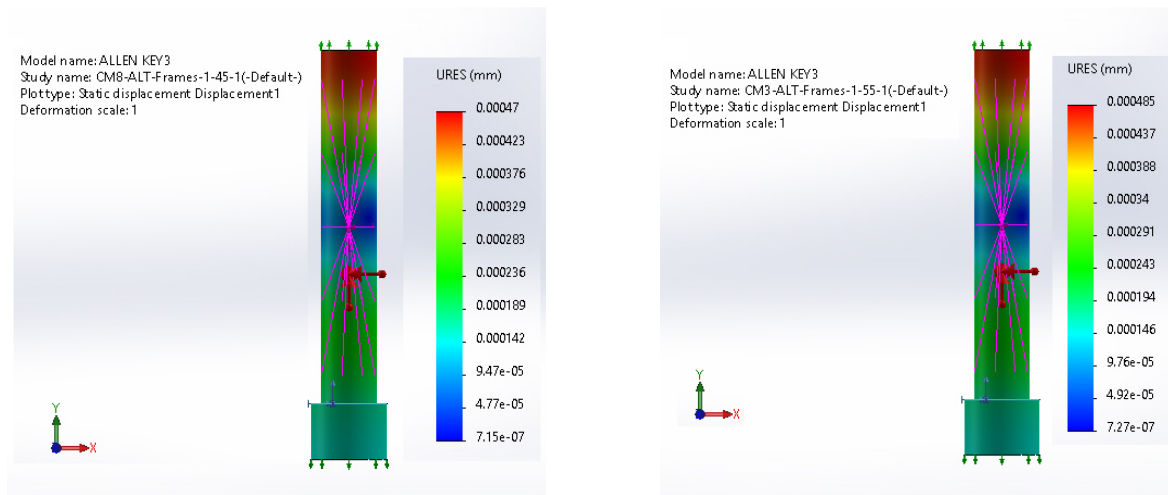


Fig. 17: Total displacement for Allen key 2 (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

3.6.4 Comparative Analysis for Allen Key 2

The Allen key 2, just like the Allen key 1, shows a similar trait (Figs. 18 a and b) below, with the Ti-6Al version showing more stress and the 6061-T6 version showing more displacement.

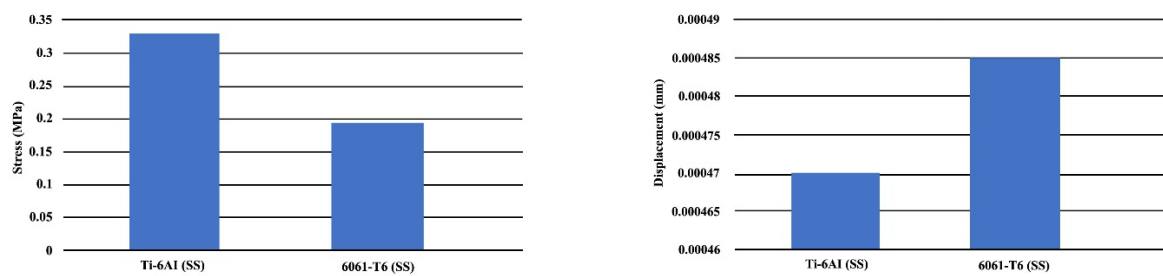


Fig. 18: Comparison of Allen Key 2 (Base and Optimized) (a) Stress (b) Maximum Displacement

3.7 Pin Connector

3.7.1 Static Structural Analysis for Pin Connector

The pin connector shows more stress concentrations that are noticeably uniformly patterned around the structure. This is seen in Figs. 19 (a and b) with Von Mises stress at a maximum of 0.169 MPa as against the optimized model with 0.103 MPa. Whereas Figs. 20 (a and b) show the upper section of the pin connector undergoes more displacement for both variants.

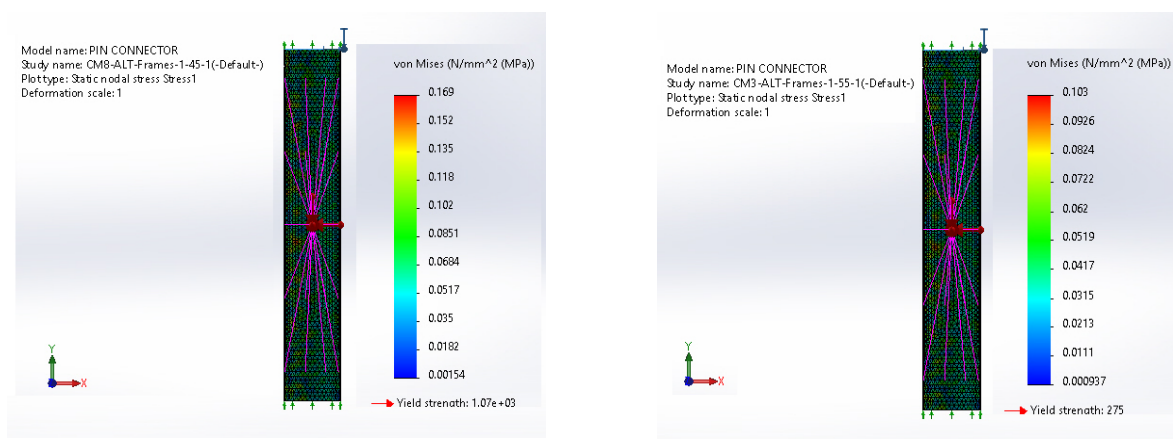


Fig. 19: Stress analysis for Pin Connector (a) (Ti-6Al) (Base Model) (b) 6061-T6 (SS) (Optimized Model)

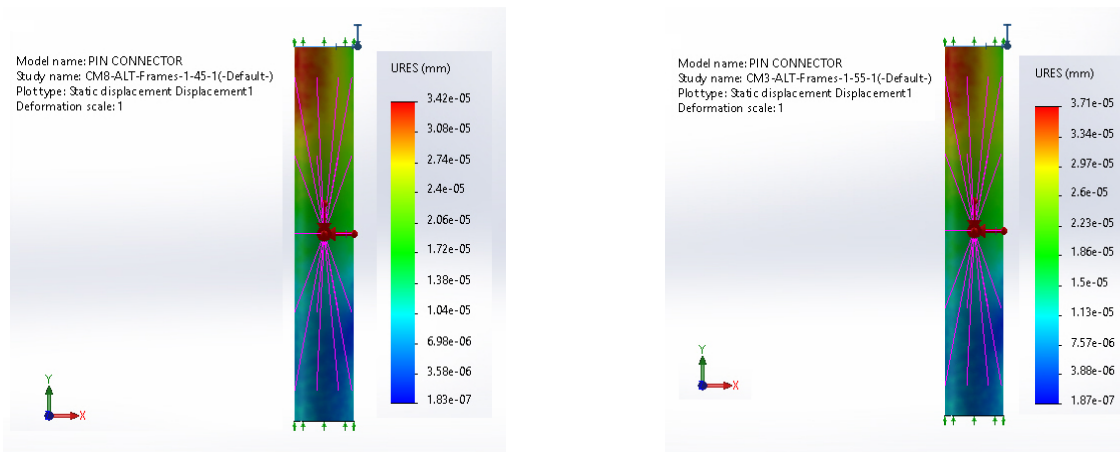


Fig. 20: Total displacement for Pin Connector (a) Ti-6Al (Base Model) (b) 6061-T6 (SS) (Optimized Model)

3.7.2 Comparative Analysis for Pin Connector

The pin connector compares below in Figs. 21 (a and b), with the Ti-6Al model showing more stress at 0.168 MPa while the 6061-T6 model shows more displacement at 0.0000371mm.

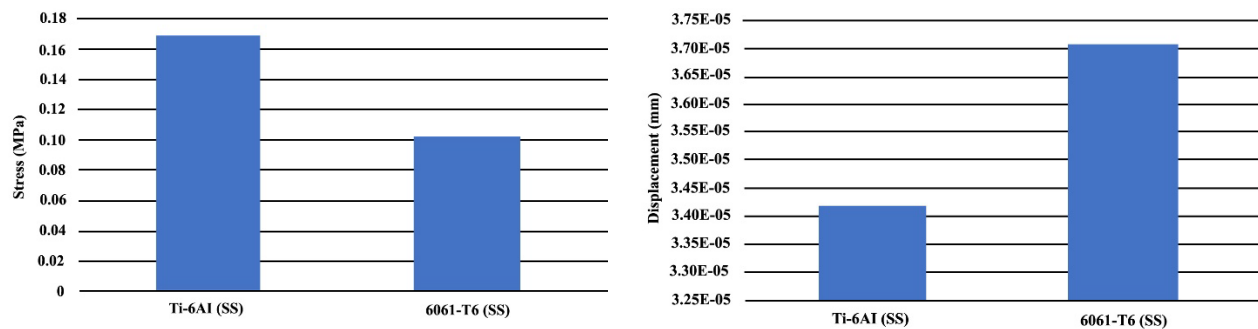


Fig. 21: Comparison of Pin Connector (Base and Optimized) (a) Stress (b) Maximum Displacement

3.8 Comparison with Previous Literature

Some part comparison with past literature in table 7 below indicates the (6061-T6 (SS)) from the current study fares best for the lower and upper link, while its advisable to stick to AL3040 for the inner cylinder rod.

Table 7. Comparison with previous literature

	Aftab et al. [19]	Patra et al. [20]	Current Study
Lower link displacement (mm)	0.293	0.365	0.0846
	AL3040	Titanium alloy	(6061-T6 (SS))
Upper Link displacement (mm)	0.409	0.722	0.145
	AL3040	AL1030	(6061-T6 (SS))
inner cylinder rod displacement (mm)	0.468	0.707	1.07
	AL3040	EN19	(Ti-6Al)

4.0 Conclusions

The analysis of all the data and graphs led to the conclusion that because each component serves a specific purpose, it is not advised to use a single material throughout. As a result, it was decided that titanium alloy should be used to make the parts (Piston, Axel, Cylinder, and Upper Link) with the highest stress allocation. As a result, titanium alloy is subject to the most stress.

The aluminum alloy should be used since the lower link, Allen key 1, Allen key 2, and Pin Connector are under a good amount of stress and displacement and reduce the weight. Further study utilizing a larger variety of materials is advised due to the constraints encountered. Research needs to be done on additional landing gear parts that weren't considered, such as steering control cables, sensors, landing gear doors, and tire relief valves.

Acknowledgements

I would like to express my sincere gratitude to my co-authors who have been supportive throughout the timeframe of this research. Their expertise and insights have been invaluable in overcoming challenges toward the successful completion of this research.

References

- [1] J. Wong, L. Ryan, I. Y. Kim, Design optimization of aircraft landing gear assembly under dynamic loading. *Structural and Multidisciplinary Optimization*, 57(3) (2018) 1357-1375. <https://doi.org/10.1007/s00158-017-1817-y>
- [2] R. Chaudhary, S. Singh, V. Saxena, Static structural analysis of landing gear for different titanium alloy (2019). <https://doi.org/10.35940/ijeat.f8692.088619>
- [3] A.S.A. Al-banaa, S.M. J. Ali, R. Pires, Stress analysis on main landing gear for small aircraft. *Al-Rafidain Engineering Journal (AREJ)*, 22(1) (2014) 26-33. <https://doi.org/10.33899/rengj.2014.87009>
- [4] M.P. Hebsur, S. N. Kurbet, M. S. Pinjar, M. S. Adavihal, Failure Analysis of Landing gear of the Aircraft through Finite Element Method 4(2.81) (2019) 7-87.
- [5] E. A. Ossa, Failure analysis of a civil aircraft landing gear. *Engineering failure analysis*, 13(7), (2006) 1177-1183. <https://doi.org/10.1016/j.engfailanal.2005.04.008>
- [6] S. Prabha, S. Raghavendra, Overview on the development of multi-dimensional aircraft arresting system at the time adverse failure of landing gear. *Materials Today: Proceedings* 45 (2021) 318-326. <https://doi.org/10.1016/j.matpr.2020.10.830>
- [7] Information on <http://www.boeing.com/new/techissues>.
- [8] I. Ross, R. Edson, Application of active control landing gear technology to the A-10 aircraft (No. NAS 1.26: 166104) (1983).
- [9] L. G. Horta, R. H. Daugherty, V. J. Martinson. Modeling and validation of a Navy A6-Intruder actively controlled landing gear system (No. NAS 1.60: 209124) (1999).
- [10] E. Dileep, L. Oblisamy, R. S. Krithiga, J. Jacob, Structural Analysis of Aircraft Landing Gear During Rough Landing. *International Journal of Engineering Trends and Technology* vol. 41(5) (2016) 256-261. <https://doi.org/10.14445/22315381/ijett-v41p247>
- [11] I. Inagaki, T. Takechi, Y. Shirai, N. Ariyasu. Application and features of titanium for the aerospace industry. *Nippon steel, sumitomo metal technical report*. 106 (204) 22-27.
- [12] P. Mohanraj, S. Balaji, S. Senthilkumar. Fatigue analysis in aircraft landing gear axle shaft to develop the life cycles. *International Journal of Engineering Research and Technology* 2(6) (2013) 2265-2272.
- [13] S. Maksimović. Fatigue life analysis of aircraft structural components. *Scientific Technical Review* 55(1) (2005) 15-22.
- [14] R.R. Boyer, A.E. Caddey, An overview on the use of titanium in the aerospace industry. *Material science and engineering A*, 213(1-2) (1996) 103-114. [https://doi.org/10.1016/0921-5093\(96\)10233-1](https://doi.org/10.1016/0921-5093(96)10233-1)

-
- [15] A. Dutta, Design and analysis of nose landing gear. *International Research Journal of Engineering and Technology (IRJET)* 3(10) (2016) 261-266
 - [16] T.D. Nguyen, Finite element analysis of a nose gear during landing (2010).
 - [17] S. Plabita, K.M. Pandey, K.K. Sharma. Design and static analysis of landing gear shock absorber of commercial aircraft. *Materials Today, Proceedings* 45 (2021): 6712-6717. <https://doi.org/10.1016/j.matpr.2020.11.1032>
 - [18] P. Nishanth, N. Prabakaran, R. W. Akshay, I. Rakesh, R. N. Ravishankar, Vijay. Material Replacement and Fatigue Analysis of Nose Landing Gear's Shock Strut. *ACS Journal for Science and Engineering* 3.1 (2023): 32-41. <https://doi.org/10.34293/acsjse.v3i1.59>
 - [19] S.G. Aftab, Sirajuddin, B. Sreedhara, E. Ganesh, N. Ramesh Babu, S. Kiran Aithal. Finite element analysis of a passenger aircraft landing gear for structural and fatigue safety. *Materials Today: Proceedings* 54 (2022): 152-158. <https://doi.org/10.1016/j.matpr.2021.08.199>
 - [20] Patra, Prangya Paramita, and Mr Jitendra Naik. "Finite Element Analysis of Aircraft Landing Gear for Structural and Fatigue Safety." *Recent Trends in Automation and Automobile Engineering* 5.2 (2022).