



Modelling and Optimization of Strut Configurations in Aircraft Landing Gear Assembly for Effective In-Service Duty Cycle

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ABSTRACT

The landing gear configuration system is one of the most critical systems, subjected to intense dynamic loads and failure during landing and taxiing operations. The optimization of this system is of key importance to the aviation industry, with clear and direct effects ranging from integrity, safety, and fuel efficiency to maintenance dynamics. The present study focuses on the modelling and optimization of strut configurations in an aircraft landing gear assembly for an effective in-service duty cycle. Two strut configurations, consisting of a conventional single strut and an optimized dual strut, were modelled and comparatively analyzed using parametric CAD tools as well as Finite Element Analysis (FEA) within the SolidWorks simulation environment. The modelling and simulation involve the load and stress analysis of critical components, ranging from the main strut, retraction mechanisms, torque links, torque bars, and wheels to the actuator and main support. This approach was geared towards the premise of analyzing and optimizing the landing gear system by achieving weight reduction without compromising structural integrity. This was achieved through FEA of the design model. The simulation results showed that achieving a conservative 5% reduction in weight would translate into a decrease of approximately 1,045 kg in the aircraft's operating empty mass, which further translates into a reduction in the aircraft's energy consumption during its in-service duty cycle. The results further revealed that the developed model can effectively support the prediction and analysis of the mechanical behaviour of the landing strut.

1. Introduction

The continuous quest for research in advancing material of lightweight with superior characteristic has propelled the aviation industry stakeholders to seek for collaboration with academic institutions to develop aircraft component that are robust and enduring [1, 2]. Among the component most crucial to a smooth, safe and efficient aircraft operation is the landing gear assembly. It occupies a unique demanding position which bears full dynamic impact on landing, support grand operation and manoeuvring load. The impact is repeated across thousands of duty

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cycles with minimal maintenance intervention. Conventional aircraft are now transitioning into enhanced capability which they have evolved in their weight, size and performance [3, 4]. The strut configuration is one critical part of the landing gear assemblies which bears significant impact on the aircraft performance, durability, and efficiency throughout its service duty cycle. Therefore, the optimization of a typical strut configuration with respect to the landing gear assemblies remains a humongous challenge that warrants balancing the multifaceted factors which ranged from structural integrity, shock absorption as well as weight reduction. This challenge is also compounded by the need to satisfy the stringent airworthiness certification requirements imposed by regulatory authorities such as Federal Aviation Administration (FAA) under FAR Part 25 and the European Union Aviation Safety Agency (EASA) under CS-25. The optimization process of the assembly system requires comprehensive understanding of the load profiles (dynamic loads) at each phase of the flight and its ground operation [5-7]. The comprehensive understanding of the material properties as well as its geometrical constraints of the landing gear assemblies remains another issue of concern. Thus, the modelling and simulation methodologies have become a critical design tool which the optimization of the landing gear strut assemblies can be further enhanced [8, 9]. Computational approach is one unique way which engineers deploy in predicting structural behaviour under complex multi-axial loading conditions without the prohibitive cost and time demand of the physical prototype fabrication and testing. This approach will allow stakeholders in the aviation sector to critically analyze and predict the characteristics of each strut design assembly under distinct range of operating conditions with sustainability. This approach is a necessary for cost savings and will eliminate the prototype formulations which are usually time consuming and expensive. Modelling and simulation using computational tools like finite element analysis (FEA) offers a unique representation of the complex load's conditions at each phase of the aircraft landing gear in-service duty cycle and its structural responses [10, 11]. This optimization process will involve several phases such as the fatigue's life improvement of the strut configuration in order to reduce the dynamic stress concentration. Shock absorption optimization process is another phase of enhancing the total energy dissipation capabilities of the strut in order to mitigate the load impact during landing and taxing operation of the aircraft. Adopting optimization technique is one approach of designing strut configuration to maximize its reliability throughout the in-service duty cycle. Optimization enhanced the integration of the aircraft system in order for the strut configuration to meet the ever dynamics regulation of the aviation sector standards [12-14]. The aircraft landing gear configuration system remains one of the most functional and structural critical system in modern aviation system and aerospace engineering which serves as the pivot for dynamic load bearing structure. The complexity of its design ranges from weight balancing, damping, strength, and its reliability under this dynamic stress conditions [15]. Advances in computational modelling with optimization algorithm has played a significant role in remodelling the strut assemblies during the in-service duty cycle to ensure safety [16].

Recent studies conducted by Lin *et al.* [17] had a concatenation of FEA with modal testing approach in the optimization of the strut assembly's configuration under high-speed towing condition in nose landing situations. The findings of the studies showed an approximate 22 % mass reduction without any interference in the structural integrity and dynamic stability. This study was further corroborated by Zhou *et al.* [18] in the application of modelling and simulation aircraft landing gear dynamics. Their studies further reveal the advances achieved in simulation studies, integrated analysis employing theoretical analysis with 3D modelling and experimental analysis in landing gear optimization.

In the area of energy dissipation mechanism and shock absorption of the strut assembly, Gan *et al.* [19] observed that the landing gear strut plays the function of energy absorber which is a crucial

determinant in the aircraft touchdown smoothness and well as fatigue resistance. Their studies showed that 35 % of the landing energy dissipation are attributed to the frictional forces from the strut assembly system while the optimized model reduce the sprung mass by 4.8%. Tumiati [20] in investigative studies introduce an optimized multiparameter model for the oil gas separation shock strut. Their result demonstrated a 4% increase in the buffer efficiency with 8 % reduction in the overload which reinforces the need for integrated optimization of the hydraulic and pneumatic subsystem in the landing gear assembly. Akçay & İlkılıç [21] adopted optimization approach using light weight material component which genetic algorithm and dandelion optimization algorithm. The result of optimization and modelling help in weight reduction of nose landing gear fork from 14.25 kg to 12.99 kg, which represent an 8.84% weight reduction. Sun *et al.* [22] in their investigative studies observed that the traditional empirical methods are plagued with significant uncertainties and limitations in addressing the complex multiaxial loading conditions in the landing gear strut. They further observed that machine learning approach suffer the depth of interpretability in critical safety application. They proposed a multiagent reinforced symbolic regression (MA-RSR) framework to address the dynamic load challenges in modelling.

Notwithstanding, a gap remains in the systematic comparative assessment of single versus dual configuration within a unified multi-objective optimization framework that addresses mass reduction, stress distribution efficiency, structural redundancy and factor of safety improvement. Thus, the goal of this research study is developing a high-fidelity multidisciplinary design optimization of a conventional commercial strut configurations in aircraft landing Gear assembly for effective in-service duty cycle analysis. This present study addresses this strategic gap by developing a model of conventional commercial strut configurations in aircraft landing gear assembly for effective in-service duty cycle analysis.

2. Methodology

The model consists of main strut, retraction mechanisms, torque links, torque bars, wheel, actuator and main support.

2.1 System configuration and Material characterization

A typical single strut and dual strut assembly in a conventional aircraft landing gear assembly were selected for analysis with three dimensional geometrical models of the strut, retraction mechanisms, torque links all developed with a parametric CAD environment. The geometrical constraints and its associated assembly were defined to address the realistic in-service load transfer conditions as well as the in-service configuration. The component structure configuration and its associated properties were aligned with the linear elastic isotropic alloy steel properties alongside the material parameters ranging from elastic modulus, Poisson ration, yield strength, tensile strength and density. These parameters were adopted strictly from aerospace grade steel standards and they were applied consistently to ensure a fair comparative assessment. On the mass and inertial property evaluation, the mass property, centre of gravity and inertia tensors of the individual component and achieved through the SolidWorks CAD model. The inertia tensors of the global coordinates and the moments of inertia were extracted in order to access the dynamic stability and load transfer and its associated properties during the ground and landing operation. The finite element models were also generated with a blended curvature based meshing scheme which the mesh refinement guided by geometric complexity and stress concentration regions.

2.2 Boundary Conditions, static analysis and optimization framework

The realistic boundary conditions were superimposed through constraining the interfaces between the aircraft fuselage and the landing gear. The landing loads (vertical) were applied as normal forces applied at wheel axle interfaces which represents the operational landing scenarios. The load magnitude was carefully selected in order to simulate the typical in-service duty cycles with respect to high total loads which was assigned to a single strut configuration as well as the distributed loads applied in the dual strut system. For the static Structural analysis, the stress distribution was determined from the linear static analysis as well as the deformation and the load paths within the assemblies. Additionally, the von misses were also applied and adopted as the failure criterion. The moment and reaction forces were extracted to determine the structural efficiency and load sharing between the single and dual strut configuration system. The duty cycle performance assessment was evaluated using the stress level, deformation and resultant reaction. This was achieved through the comparative metrics that were define to assess the load distribution effectiveness and redundancy benefits of the dual strut configuration. On the other hand, the multiple objective optimization framework was adopted with the goal of minimizing the peak stress and structural mass while satisfying the strength and stiffness constraints. At the configuration level, the structural optimization objective was formally defined as: (1) minimize the peak von Mises stress; (2) minimise the structural mass which is subject to the constraints: von Mises stress $\leq$ yield strength (620.422Mpa); factor of safety ≥ 1.5 ; and maximum displacement within acceptable deformation limits. The design variable involved the strut wall geometry parameters.

The design parameters include the strut geometry and the load sharing ratios. This optimization approach was evaluated against the baseline configuration to critically determine the performance improvement of the strut configuration during in-service condition. The various component of the strut model as adopted in this study presented in Tables 1-9 and Figures 1-8.

Table 1

Main Strut

Mass properties of Main Strut		Center of mass: (millimeters)
Mass = 55873.82 g		X = 0.00
Volume = 55873823.72 mm ³		Y = 884.21
Surface area = 2198924.31 mm ²		Z = 1.89
Principal axes of inertia Taken at the center of mass (grams * square millimeters)		principal moments of inertia Taken at the center of mass (grams * square millimeters)
Ix = (0.00, 1.00, -0.01)		Px = 4369657986.59
Iy = (-1.00, 0.00, 0.00)		Py = 7977669916.26
Iz = (0.00, 0.01, 1.00)		Pz = 12002349845.08
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
Lxx = 7977669916.26	Lxy = -873.48	Lxz = 1497.76
Lyx = -873.48	Lyx = 4370708029.65	Lyz = -89518447.99
Lzx = 1497.76	Lzy = -89518447.99	Lzz = 12001299802.02
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
lxx = 51661766369.51	lxy = -6085.21	lxz = 1486.60
lyx = -6085.21	lyy = 4370908190.10	lyz = 3989778.43
lzx = 1486.60	lzy = 3989778.43	lzz = 55685196094.82

2.3 Structural Interpretation for Main Strut

From Table 1, the main strut with a mass of 555,873.82g with a centre of mass displaced to Y= 884.21 mm from its origin which exhibit significant inertial asymmetry. There is a clear difference between Lxx (9.98×10^9 g.mm²) indicates that the dynamic loads during landing will induce unequal

bending moments about axes. This position confirms the importance of configuration-level optimization in achieving balance sharing. Non-zero off diagonal inertia product $L_{yz} = -8.95 \times 10^7 \text{ g.mm}^2$ which further indicates coupled dynamic responses during lateral vertical load application. This behaviour of the dual strut system shows improve structural redundancy and load path distribution.

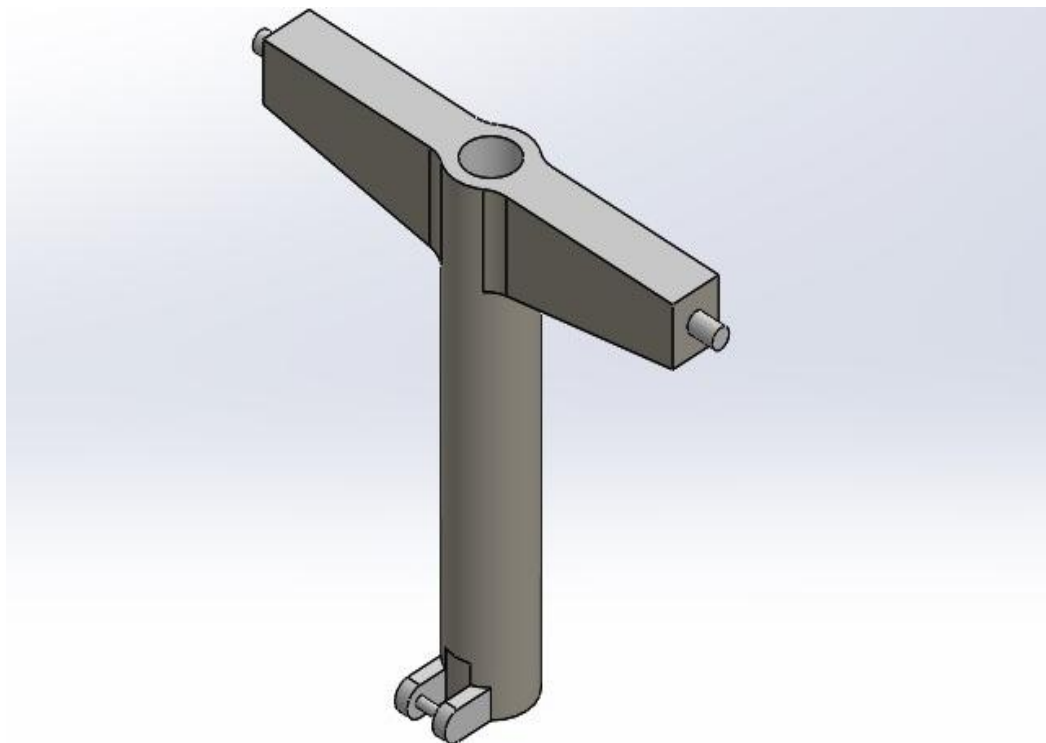


Fig. 1. Landing gear main strut

Table 2

Retraction Mechanism (Upper Side Bar)

Mass properties		Center of mass: (millimeters)
Mass = 8924.32 grams		X = 9.30
Volume = 8924317.03 mm ³		Y = -50.91
Surface area = 487236.10 mm ²		Z = 38.00
Principal axes of inertia Taken at the center of mass (grams * square millimeters)		principal moments of inertia Taken at the center of mass (grams * square millimeters)
I _x = (0.00, 1.00, 0.00)		P _x = 23860593.52
I _y = (-1.00, 0.00, 0.00)		P _y = 621565971.51
I _z = (0.00, 0.00, 1.00)		P _z = 636770973.93
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
L _{xx} = 621565925.20	L _{xy} = -252313.22	L _{xz} = 30335.71
L _{yx} = -252313.22	L _{yy} = 23860760.29	L _{yz} = -192177.38
L _{zx} = 30335.71	L _{zy} = -192177.38	L _{zz} = 636770853.46
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
I _{xx} = 657587792.76	I _{xy} = -4479263.30	I _{xz} = 3185674.98
I _{yx} = -4479263.30	I _{yy} = 37523077.18	I _{yz} = -17459746.01
I _{zx} = 3185674.98	I _{zy} = -17459746.01	I _{zz} = 660675203.16

2.4 Structural Interpretation for Retraction Mechanism

Table 2 structural interpretation reflects the upper side bar exhibiting a principal moment of $P_z = 636,770,973.93 \text{ gmm}^2$ when compared to $P_x = 23,860,593.52 \text{ gmm}^2$ indicating high inertial resistance to rotation about the retraction axis. The implication is the direct impact to the actuator sizing and retraction force requirement. This situation confirms the retraction mechanism design is within the expected performance envelopes for conventional commercial landing gear systems. This also applies to the lower side bar (see Table 3) with $P_z = 334434062.01 \text{ gmm}^2$ and $P_x = 5041984.60 \text{ gmm}^2$ as well as the torque link (see Table 4) with $P_z = 30007688.71 \text{ gmm}^2$ and $P_x = 3661401.38 \text{ gmm}^2$.

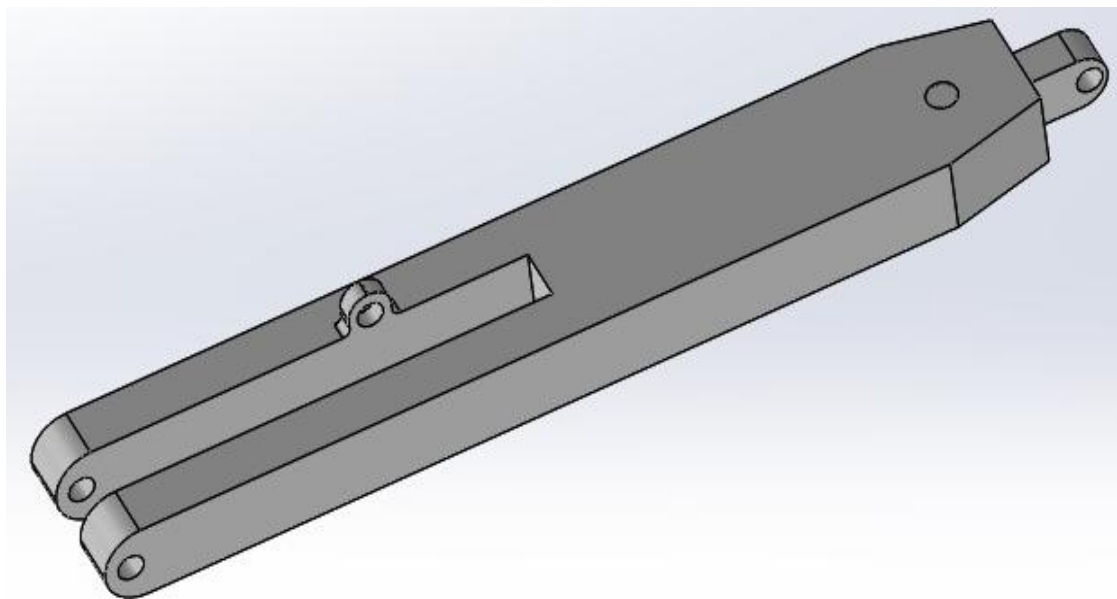


Fig. 2. Retraction Mechanism (Upper Side Bar)

Table 3

Retraction Mechanism (Lower Side Bar)

Mass properties of Main Strut		Center of mass: (millimeters)
Mass = 4717.78 grams		X = 19.05
Volume = 4717783.50 mm ³		Y = 0.00
Surface area = 295887.16 mm ²		Z = 25.40
Principal axes of inertia Taken at the center of mass (grams * square millimeters)		principal moments of inertia Taken at the center of mass (grams * square millimeters)
Ix = (0.00, 1.00, 0.00)		Px = 5041984.60
Iy = (-1.00, 0.00, 0.00)		Py = 331421227.55
Iz = (0.00, 0.00, 1.00)		Pz = 334434062.01
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
Lxx = 331421227.55	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyy = 5041984.60	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 334434062.01
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
Ixx = 334464952.75	Ixy = 0.00	Ixz = 2282793.90
Iyx = 0.00	Iyy = 9797805.22	Iyz = 0.00
Izx = 2282793.90	Izy = 0.00	Izz = 336146157.43

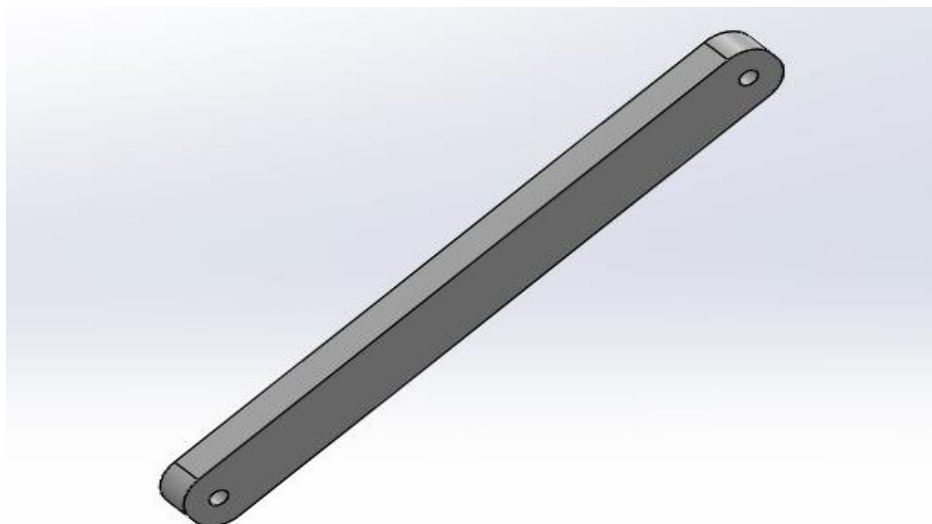


Fig. 3. Retraction Mechanism (Lower Side Bar)

Table 4

Torque Link

Mass properties		Center of mass: (millimeters)
Mass = 1673.88 grams		X = 0.00
Volume = 1673884.11 mm ³		Y = 19.05
Surface area = 165680.83 mm ²		Z = -113.63
Principal axes of inertia Taken at the center of mass (grams*square millimeters)		principal moments of inertia Taken at the center of mass (grams*square millimeters)
Ix = (0.00, 0.00, 1.00)		Px = 3661401.38
Iy = (1.00, 0.00, 0.00)		Py = 26874623.77
Iz = (0.00, 1.00, 0.00)		Pz = 30007688.71
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
Lxx = 26874623.77	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyx = 5041984.60	Lyx = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 3661401.38
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
lxx = 49094330.74	lxy = 0.00	lxz = 0.00
lyx = 0.00	lyy = 51619938.95	lyz = -3623328.14
lzx = 0.00	lzy = -3623328.14	lzz = 4268858.11

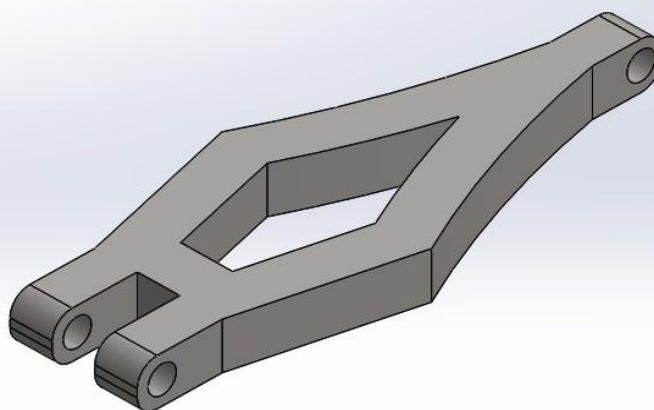


Fig. 4. Torque Link

Table 5

Torque bars

Mass properties		Center of mass: (millimeters)
Mass = 3089.65 grams		X = 0.00
Volume = 3089651.76 mm ³		Y = 0.00
Surface area = 248503.09 mm ²		Z = 0.00
Principal axes of inertia Taken at the center of mass (grams * square millimeters)		principal moments of inertia Taken at the center of mass (grams * square millimeters)
Ix = (0.00, 1.00, 0.00)		Px = 8175507.38
Iy = (0.00, 0.00, 1.00)		Py = 87364922.68
Iz = (1.00, 0.00, 0.00)		Pz = 92078335.70
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
Lxx = 92078335.70	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyx = 8175507.38	Lyz = 0.00
Lzx = 0.00	Lzy = 0.00	Lzz = 87364922.68
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
lxx = 92078335.70	lxy = 0.00	lxz = 0.00
lyx = 0.00	lyy = 8175507.38	lyz = 0.00
lzx = 0.00	lzy = 0.00	lzz = 87364922.68

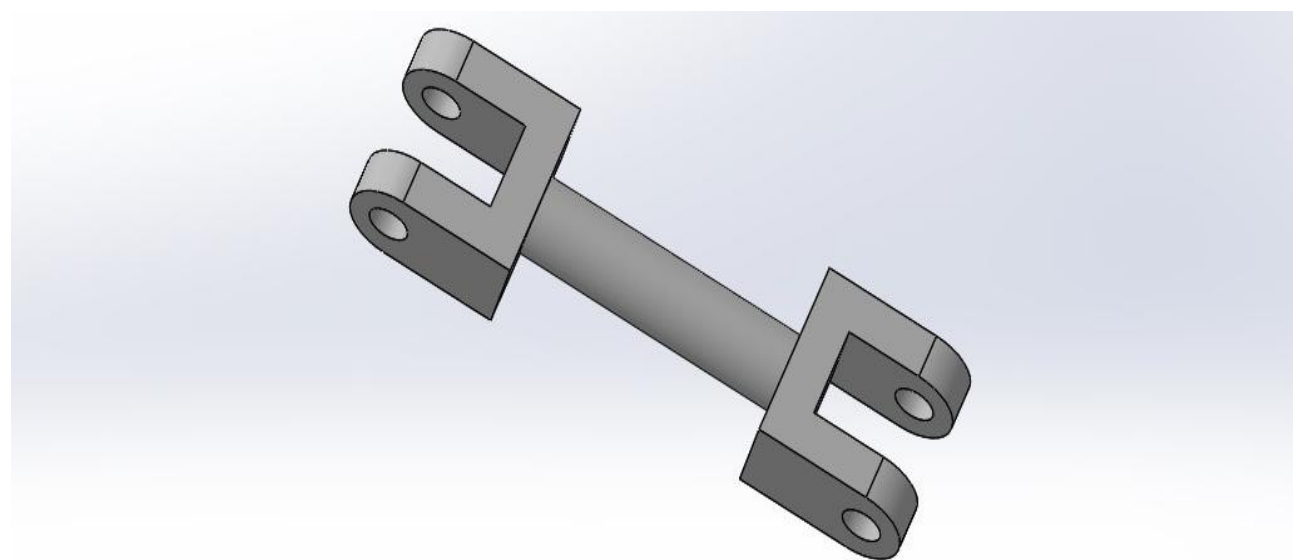


Fig. 5. Torque bar

2.5 Structural Interpretation Main Support

Table 6 represents the structural representation where the main support with the largest assembly mass of 267,788.44 g and a principal inertia of $P_x = 5.716 \times 10^{10} \text{ gmm}^2$ serves as the structural backbone of the gear assembly. The assembly has its gravity at (0, 531.11, 730.38) mm which confirms the elevated and laterally cantered mass distribution which is consistent with its role in transmitting the landing loads to the aircraft fuselage. The off-diagonal inertia product $I_{yz} = 1.371 \times 10^{11} \text{ g.mm}$ signals a significant cross coupled dynamic loading which the roll and pitch motion at touch down. This shows tremendous impact reinforcing the need for a conservative factor of safety in the structural design of the gear assembly.

Table 6

Main Support

Mass properties		Center of mass: (millimeters)
Mass = 267788.44 grams		X = 0.00
Volume = 267788437.86 mm ³		Y = 531.11
Surface area = 7181009.79 mm ²		Z = 730.38
Principal axes of inertia Taken at the center of mass (grams * square millimeters)		principal moments of inertia Taken at the center of mass (grams * square millimeters)
Ix = (0.00, 0.25, 0.97)		Px = 57159051920.79
Iy = (0.00, -0.97, 0.25)		Py = 193468859567.56
Iz = (1.00, 0.00, 0.00)		Pz = 204224541473.99
Moments of inertia (grams * square millimeters) taken at the center of mass and aligned with the output coordinate system using positive tensor notation		
Lxx = 204224541474.00	Lxy = 0.00	Lxz = 0.00
Lyx = 0.00	Lyy = 184836311512.15	Lyz = 33199097563.11
Lzx = 0.00	Lzy = 33199097563.11	Lzz = 65791599976.20
Moments of inertia (grams * square millimeters) taken at the output coordinate system using positive tensor notation		
lxx = 422615770316.65	lxy = 0.00	lxz = 0.00
lyx = 0.00	lyy = 327689325900.54	lyz = 137078169739.89
lzx = 0.00	lzy = 137078169739.89	lzz = 141329814430.47

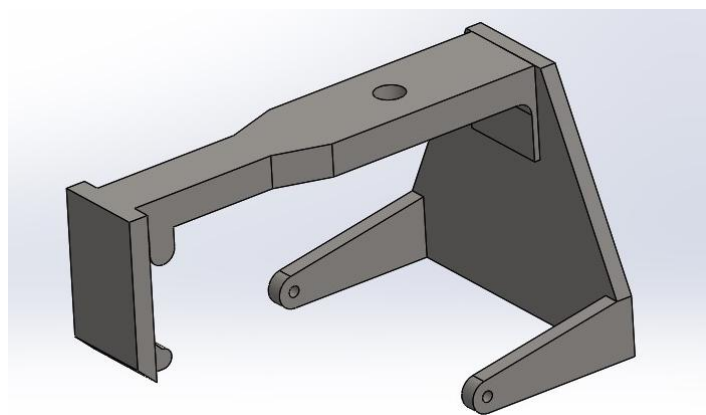


Fig. 6. Main Support

2.6 Final Landing Gear Assembly

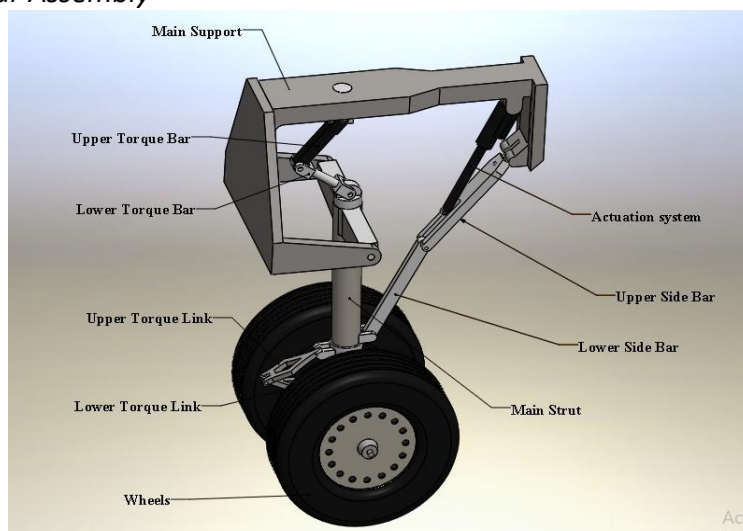


Fig. 7. Final Landing Gear Assembly

2.7 Retraction Process

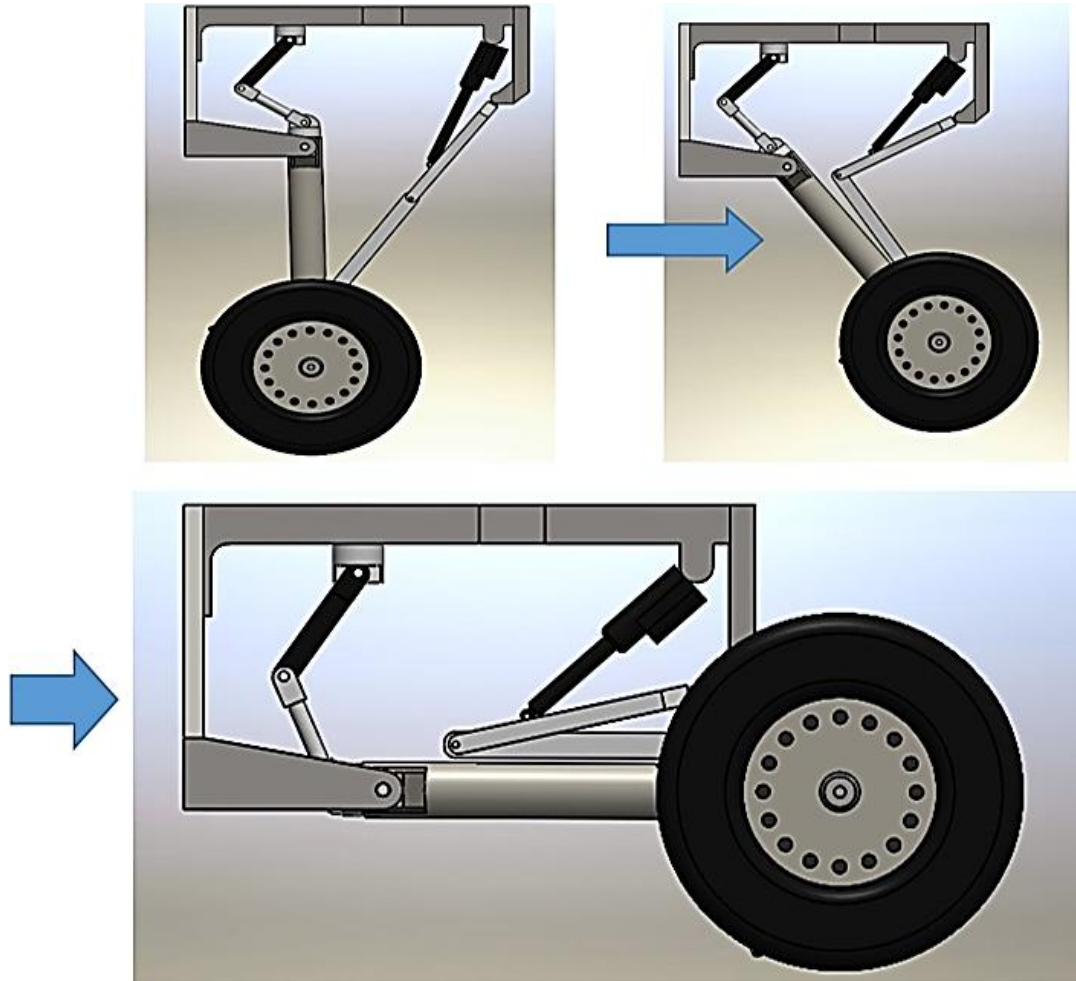


Fig. 8. Retraction Process

Table 7

Model Information for conventional single strut and dual strut

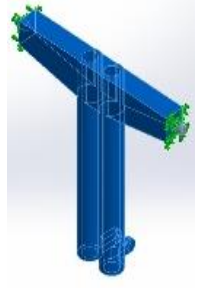
Single Strut Model	Material Properties				Dual Strut Model	Material Properties				
	Name	Alloy Steel				Name	Alloy Steel			
	Model	type	Linear	Elastic		Model	Linear	Elastic		
			Isotropic			type	Isotropic			
	Default failure	Max	von	Mises		Default failure	Max	von	Mises	
		Stress					Stress			
	Yield strength	6.20422e+08 N/m^2				Yield strength	6.20422e+08 N/m^2			
	Tensile strength	7.23826e+08 N/m^2				Tensile strength	7.23826e+08 N/m^2			
	Elastic modulus	2.1e+11 N/m^2				Elastic modulus	2.1e+11 N/m^2			
	Mass density	7700 kg/m^3				Mass density	7700 kg/m^3			
	Shear modulus	7.9e+10 N/m^2				Shear modulus	7.9e+10 N/m^2			
Volumetric Properties					Volumetric Properties					
	Mass	430.228 kg				Mass	420.01 kg			
	Volume	0.0558738 m^3				Volume	0.0545467 m^3			
	Weight	4216.24 N				Weight	4,116.1 N			

Table 8

Mesh Information for single and dual strut

Mesh Information	Single Strut	Dual Strut
Mesh type	Solid Mesh	Solid Mesh
Mesher Used	Blended curvature-based mesh	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points	16 Points
Maximum element size	76.8974 mm	69.6961 mm
Minimum element size	9.72016 mm	9.72016 mm
Mesh Quality	High	High
Total Nodes	6240	10965
Total Elements	3298	5755
Maximum Aspect Ratio	24.313	8.1992
% of elements with Aspect Ratio < 3	94.7	93.3
Percentage of elements with Aspect Ratio > 10	0.728	0
Percentage of distorted elements	0	0
Time to complete mesh(hh:mm:ss)	00:00:04	00:00:06

Table 9

Fixture and Load details for single and dual strut configurations

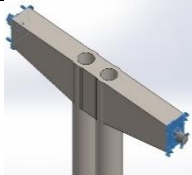
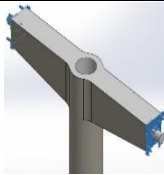
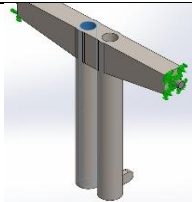
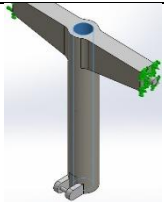
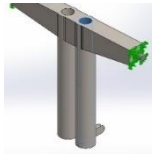
Dual Strut Configuration				Single Strut Configuration			
Fixture name	Fixture Image	Fixture Details		Fixture name	Fixture Image	Fixture Details	
Fixed-1		Entities	2 face(s)	Fixed-1		Entities	2 face(s)
		Type	Fixed Geometry			Type	Fixed Geometry
Load name	Load Image	Load Details		Load name	Load Image	Load Details	
Force-1		Entities	1 face(s)	Force-1		Entities	1 face(s)
		Type	Apply normal force			Type	Apply normal force
		Value	50,000 N			Value	100,000 N
Force-2		Entities	1 face(s)			Entities	1 face(s)
		Type	Apply normal force			Type	Apply normal force
		Value	50,000 N			Value	

Table 9

Resultant forces for single and dual strut configuration

Resultant Forces for Single Strut Configuration					
Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-1.10237	-0.00478338	5.84791	5.95091
Reaction Moments					
Entire Model	N.m	0	0	0	0
Free Body Forces					
Entire Model	N	-0.00413179	-1.11908e-05	0.00678992	0.00794826

Table 9

Continued

Free Body Moments					
Entire Model	N.m	0	0	0	1e-33
Resultant Forces for Dual Strut Configuration					
Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-1.25222	0.000412524	5.19179	5.34067
Reaction Moments					
Entire Model	N.m	0	0	0	0
Free Body Forces					
Entire Model	N	-0.000244141	-8.20868e-06	0.000878334	0.00091167
Free Body Moments					
Entire Model	N.m	0	0	0	1e-33

3. Results and Discussion

3.1 Optimization for High Strength-to-Weight Ratio

As earlier stated, the goal of this project is to analyse and optimize the landing gear system by means of achieving weight reduction without compromising on structural integrity. Achieving a conservative 5% reduction in weight would translate to a decrease of approximately 1,045 kg in the aircraft's operating empty mass which further translates to a reduction in energy consumption by 0.66 hours, leading to decreased journey costs [23-26]. Notwithstanding, the economic impact in the reduction of weight while seemingly at the component level, this becomes a substantial when it is considered across a conventional commercial aircraft fleet operating thousands of duty cycles annually. It is evident that based on IATA benchmark fuel cost data and typical long haul aircraft operating profiles, a 1045 kg reduction in operating mass over a 20-year aircraft service life translate to cumulative fuel savings of several hundred tonnes per aircraft. This in particular represent a multi-million-dollar economic benefit at fleet scale. Also, it is abundantly clear that the structures operating at reduced stress-to-strength ratios as seen in the dual strut configuration demonstrates an extended fatigue life, potentially increasing the intervals between the schedule maintenance event thus reducing the aircraft lifecycle costs.

These seemingly insignificant weight savings will have quite an impact that would echo throughout the aviation sector. To this end, honeycomb structure was explored for optimizing the weight of the strut model. Honeycomb structures are a type of engineered material characterized by a hexagonal cellular structure, resembling the honeycomb of a beehive. These structures consist of hollow cells with thin walls, creating a lattice-like pattern. The geometry of honeycomb structures imparts a high strength-to-weight ratio, making them particularly advantageous in weight-sensitive applications. The honeycomb's cellular configuration provides excellent strength and rigidity with relatively low material density. They maximize material efficiency by utilizing minimal amounts of material while maintaining structural integrity. The hexagonal shape of the cells distributes loads evenly across the structure, allowing for optimal use of resources. By utilizing an internal honeycomb structure in the parts of an aircraft landing gear which do not contribute much to load bearing we can reduce the weight of the system while maintaining the same factor of safety.

The model above represents an analysis of the main strut showing the areas that contributed to load bearing when the part is about 95% loaded, carried out using the "Design insight" feature of Solidworks simulation (Figure 9). The translucent portions of the design insight plot carry the applied load less effectively than the solid portions and they make up the best locations to apply an internal honeycomb structure to minimize weight without reducing factor of safety. The optimized design as compared with the conventional design as presented in Figures 10a-b.

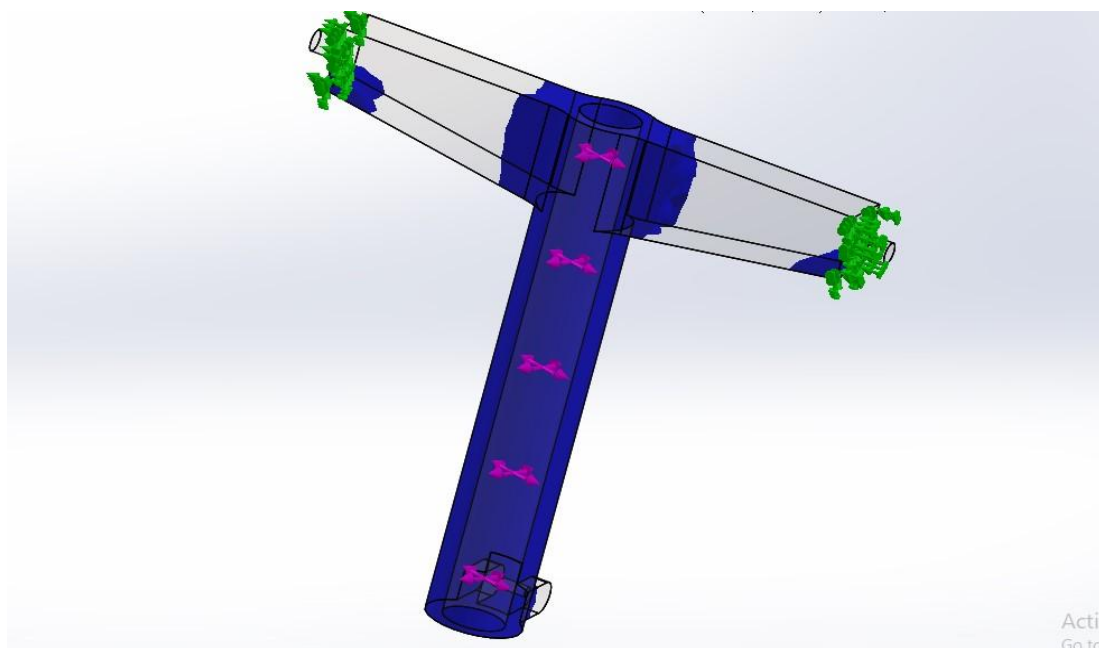


Fig. 9. Design insight plot for main strut

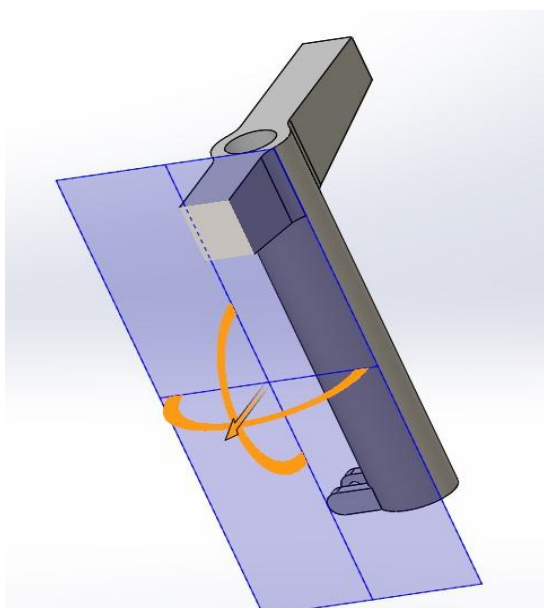


Fig. 10a. Section view of conventional strut

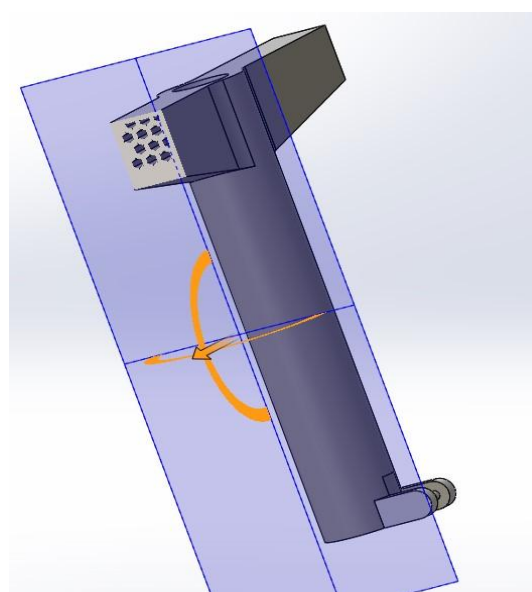


Fig. 10b. Section view of optimized strut

3.2 Optimization for Minimal Deflection and Improved Load Bearing Capacity

A dual strut system in landing gear design involves the use of two struts, typically arranged in a parallel configuration, to support and stabilize the aircraft during landing and ground operations. With optimization, the design principle is to replace one large single strut with two smaller struts whose combined internal volume equals that of the original single strut. The action will then maintained equivalent material volume while distributing the load across two structural members. The idea is to use two smaller struts in place of one large strut but in such a way that the combined volume of the smaller struts is equal to the volume of the large single strut. A dual configuration could lead to enhanced load distribution, improved stability and control, better shock absorption, better performance in variable loading conditions, and better performance on uneven surfaces.

However, such configuration will have to be limited to the main landing gears. It cannot be applied on the nose landing gear because such a configuration will not allow for rotation about the aircraft's vertical axis (Figures 11-13).

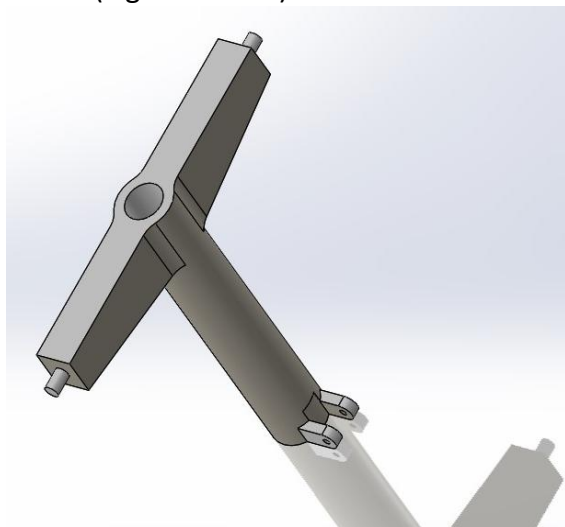


Fig. 11. Single strut landing gear Configuration

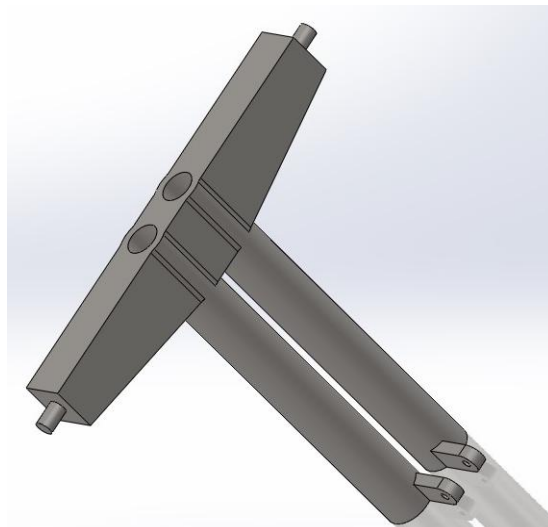


Fig. 12. Dual strut landing gear gear configuration

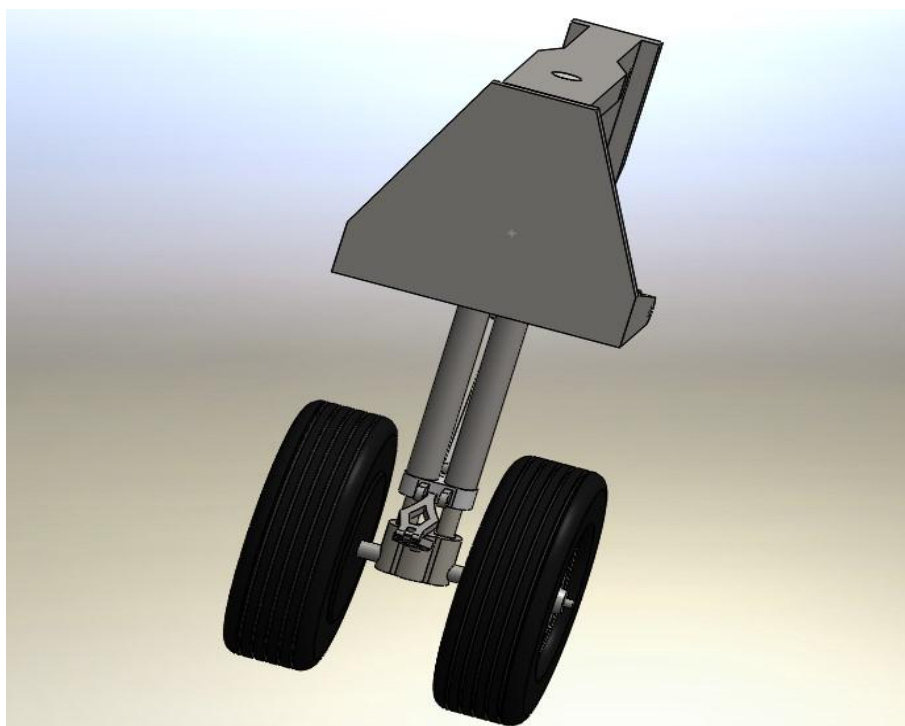
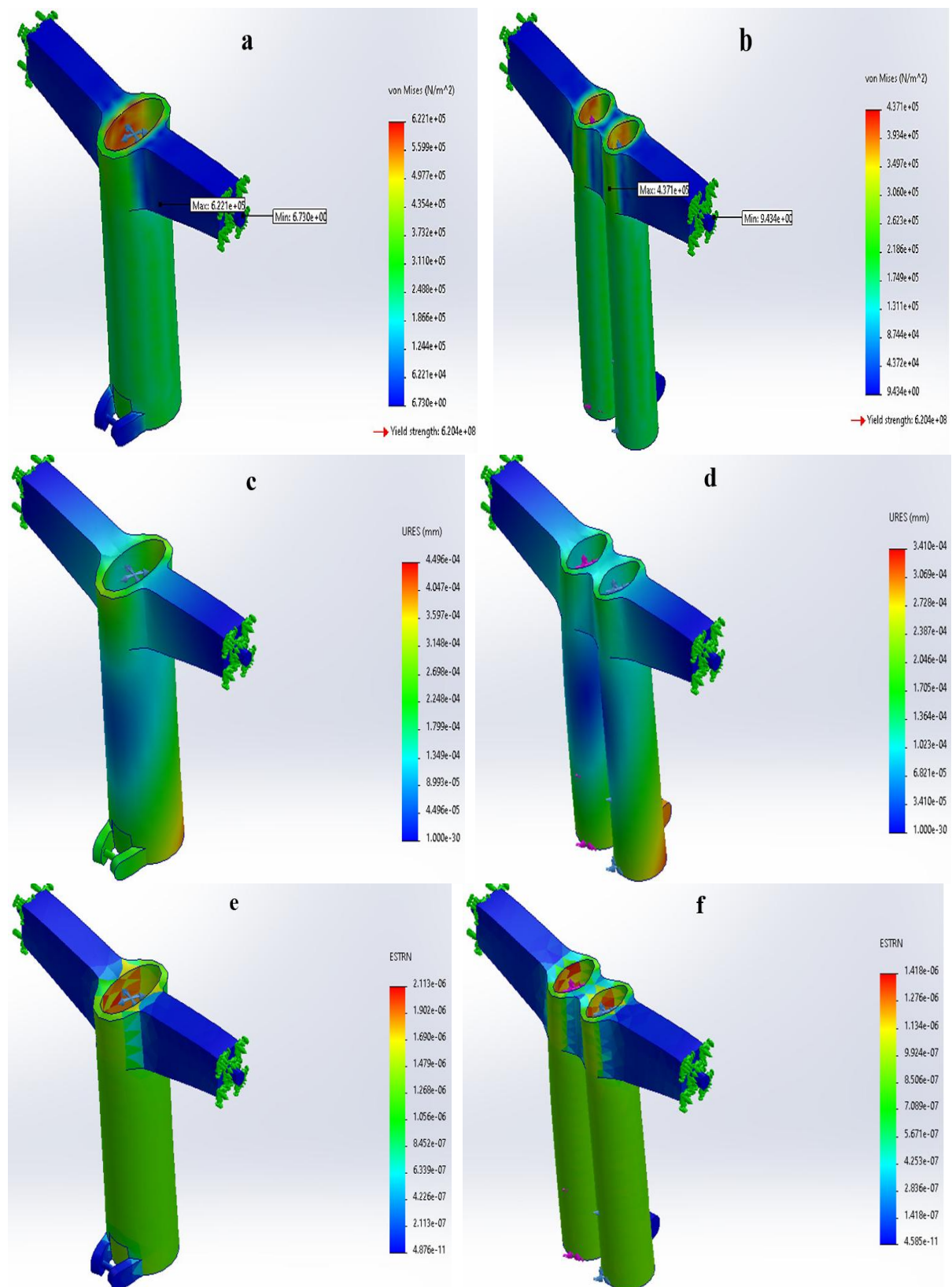


Fig. 13. Dual strut system in a landing gear

The simulation report provides us with a few key data required to draw necessary conclusions on the main objective of this research; weight reduction without compromising on structural integrity. These data include weight comparison of both concepts, maximum (von mises) stress and minimum factor of safety. Other data from the study result that are worth looking at include maximum displacement and maximum strain. The Von mises stress, displacement, equivalent strain and FoS the single and dual strut configurations are shown in Figure 14a-h.



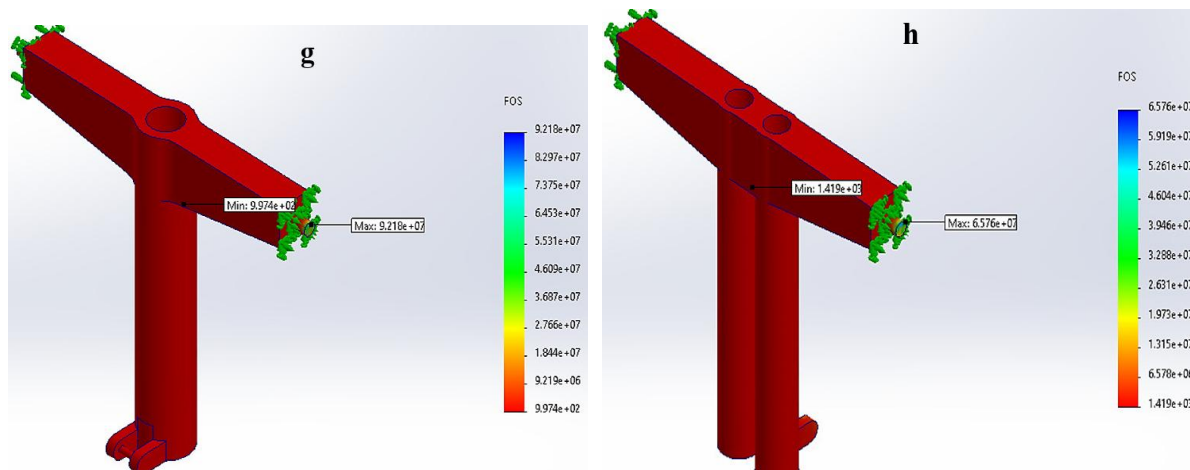


Fig. 14. Von mises stress, displacement, equivalent strain and FoS the single and dual strut configurations

3.3 Analytical Interpretation of FEA Results

The following analysis were drawn from the comparative simulation results:

- i. **Weight Reduction:** From the FEA result, the dual strut model achieves a 2.375% weight reduction relative to the single strut model. This is modest at a component level as the reduction is consistent with the study's design goal of an equivalent internal volume. This situation confirms the geometric redistribution of material rather than material reduction which in turn achieves structural improvement.
- ii. **Stress Distribution Efficiency:** There is a 29.74% reduction in peak von Mises stress in the dual strut configuration which demonstrates a superior load distribution. Additionally, there is a linear relationship between the load and average stress. With a slope of 2.185 kPa/kN. The dual strut accompanying with 3.11kPa/kN as seen in Table 11 distributes stress more effectively and this advantage is amplified as applied load increases. This situation is of particular relevance to high-load landing event such as firm touch down and crosswind landings.
- iii. **Deformation and Stiffness:** The simulation results reveal a 24.15% reduction in maximum displacement, demonstrating a superior stiffness in the dual strut configuration. The reduction in deformation minimises the risk of geometric interference between the landing components during extreme loading conditions and the scenario contributes to the improvement of aircraft handling stability during ground operations.
- iv. **Factor of Safety:** The minimum factor of safety of 1,419 was achieved by the dual strut configuration. This impact substantially exceeds both the single strut value (997.4) and the minimum certification thresholds stipulated in FAR Part 25 and CS-25 (loading condition). This factor of safety provides a critical buffer against important parameters like the variability of material properties, manufacturing tolerance as well as in-service load that are inherent in real-world aircraft in-services operation.
- v. **Structural Redundancy:** This is critical in an event of partial failure of one strut in service due to fatigue cracking, component damage or hydraulic actuator malfunction, the presence of the remaining strut in the dual configuration retains the capacity to support the applied impact load. It is evidence that each individual dual strut carries only 50,000 N under normal operations when compared to 100,000 N for a single strut. This means that each strut operates at a substantial fraction below its design capacity. Additionally, this inherent redundancy aligns with the Fail-Safe structural design philosophy that is mandated under MIL_HDBK_516C and CS-25.302 for primary structural elements. These

standards are designated for primary structural element and it represents a significant safety benefit in the context of airworthiness certification.

Placing these data for both single strut and dual strut system side by side, comparisons can be made and the percentage drop in the value of a parameter from single to dual has been calculated and displayed. A negative value in the percentage drop as shown in Table 10 indicates that there has been an increase in that parameter for the dual strut over the single.

Table 10

Comparison of relevant data from simulation result

Parameters	Single Strut	Dual Strut	Percentage drop
Weight (N)	4216.24	4,116.1	+2.375%
Maximum Stress (N/m ²)	6.221e+05	4.371e+05	+29.738%
Maximum Displacement (mm)	4.496e-04	3.41e-04	+24.155%
Maximum Strain	2.113e-06	1.418e-06	+32.892%
Minimum Factor of Safety	9.974e+02	1.419e+03	-42.27%
Applied load (N)	100,000	100,000 (50,000 x2)	-
Internal Volume (m ³)	0.0191	0.0191 (0.00953 x2)	-

$$\text{Percentage Drop} = \frac{\text{Single strut} - \text{Dual strut}}{\text{Single strut}} * 100 \quad (1)$$

The following interpretations can be made from the Table 10

- i. The dual strut model weighs approximately 2.375% less than the single strut model.
- ii. The dual strut model was able to distribute load more effectively than the single strut model by achieving an almost 30% drop in maximum stress.
- iii. The dual strut model experienced about 24% less deformation than the single strut model.
- iv. The dual strut model achieved a maximum strain which was approximately 33% less than the single strut model.
- v. The dual strut model is shown to have a higher factor of safety than the conventional strut model, by 42.27% despite weighing less than the single strut model.

From the results it can be deduced that for an applied load of 100KN, utilizing a dual strut system in place of a single strut system can help reduce weight while not only maintaining structural integrity but also improving it by nearly 50% as shown by the simulation result. The outcome derived from structural analysis of the present study correlates with the findings from literature. For example, over 22% mass reduction was achieved by Lin *et al.* [17] via FEA approach for optimizing aircraft landing gear strut without compromising the structural integrity of the gear assembly. Moreover, in parametric simulation of strut dynamics, validation of analogous FEA forecast via experimental technique was achieved by Gan *et al.* [19], Ahmad *et al.* [27] and Xiao *et al.* [28], which aligns with the computational output in this study. The dual strut system also proves better at distributing load largely due to the fact that each individual strut bears lesser load in a much more effective manner than a single large strut would bear a larger load. To determine the extent to which a dual strut system achieves a more effective stress distribution than single strut system, stress simulations were carried out under different loads for both concepts to determine the average stress for each case. Afterwards, plot of load against average stress is presented and comparisons are made. Table 11 shows the average stress experienced by both strut single and dual struts under different loads

Table 11

Average stress in both single and dual strut systems

Load (KN)	Average Stress (N/m ²) (Dual)	Average Stress (N/m ²) (Single)
100	2.186e+05	3.110e+05
200	4.371e+05	6.221e+05
300	6.557e+05	9.331e+05
400	8.743e+05	1.244e+06
500	1.093e+06	1.555e+06

From the result obtained in Table 11, there is a positive linear correlation between the impact applied load and the average stress for both configurations. The stress increase rate per unit load lies at 2.185kPa/kN for the dual strut system and 3.11kPa/kN for the single strut system. This is a 42.5% lower stress accumulation rate in the dual strut system which confirms a good load distribution efficiency with the performance advantage in the aircraft in service condition. This is particularly significant for repeated high load landing event where cumulative stress governs the fatigue life and the structural integrity in a long term.

The results presented in Figure 15 indicates a positive correlation between load and average stress, as an increase in load corresponds to an increase in average stress. But while the ratio of this increase is approximately 2 for a dual strut system, it is approximately 3 for a single strut system. This indicates that the average stress for a single strut increases faster with increase in load than that of a dual strut. This shows that the dual strut system distributes stress more effectively than the single strut even especially as the load increases.

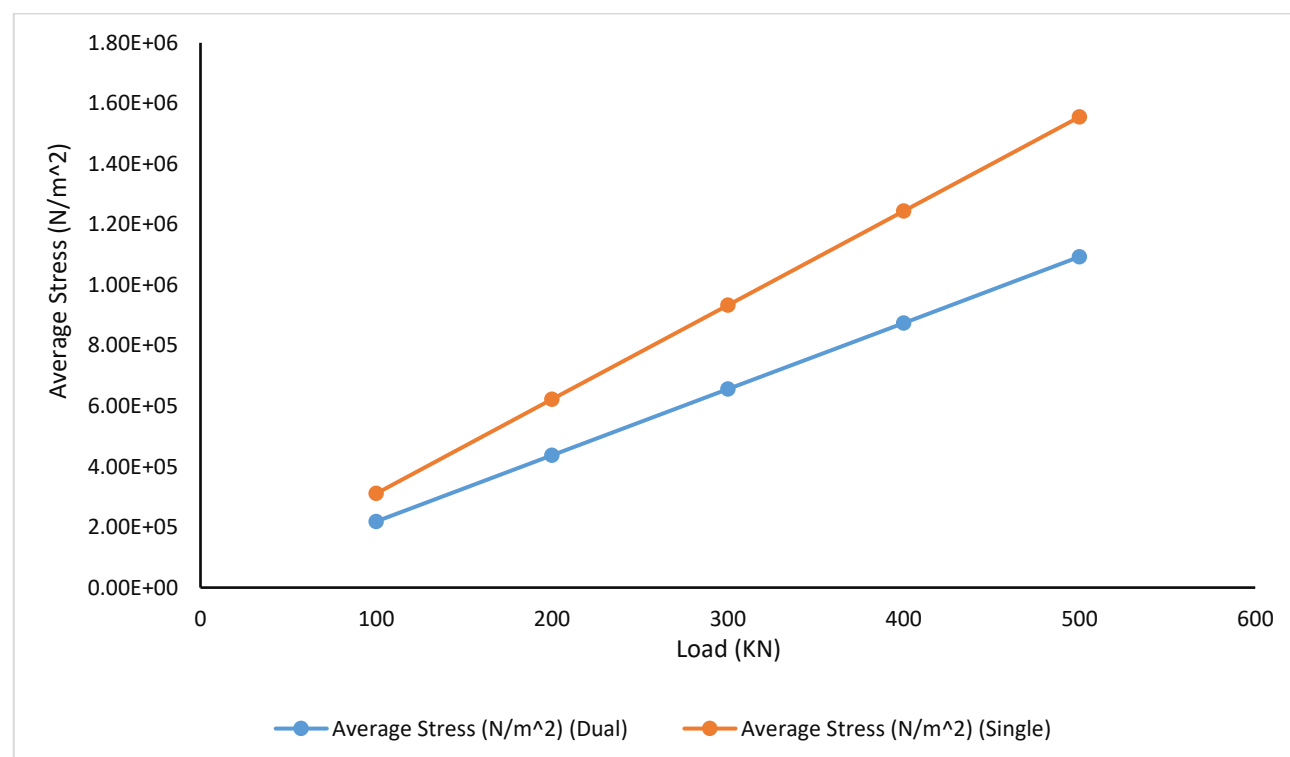


Fig. 15. Plot of Average Stress against Load for a single and dual strut system

Slope of dual strut system

$$\text{Slope} = \frac{\Delta y}{\Delta x} = \frac{437.1 - 218.6}{200 - 100} = \frac{218.5}{100} = 2.185 \quad (2)$$

Slope of single strut system

$$\text{Slope} = \frac{\Delta y}{\Delta x} = \frac{622.1-311}{200-100} = \frac{311.1}{100} = 3.11 \quad (3)$$

3.4 Regulatory, Safety, Economics Implications

Regulatory and certification context, fail-safe design philosophy and economic and operational benefits associated with this study are enumerated as follows:

- i. *Regulatory and Certification context.* Aviation industry is governed by airworthiness certification whose requirement for commercial aircraft landing gear are regulated by FAA FAR Part 25(Subpart C -Structure) and EASA CS -25. These governing conditions imposes ultimate load factors, fatigue life requirements, and minimum allowable factor of safety for ground loading events. The simulation result obtained from this study shows minimum factors of safety of 997.4 for single strut and 1,419 for dual strut which substantially exceed the certification threshold thus providing a generous design margin. The optimization applied in the study employed the honeycomb topology which selectively removes material from non-loading bearing zones without the compromising the structural load path. This approach and methodology are conceptually consistent with optimization that is endorsed by aviation structural design framework [12]. However, future work involving physical prototyping under simulated loading conditions and varying loads scenarios in accordance with RTCA-160. This is recommended in order to validate the computational predictions and support formal airworthiness certification. pr 25.
- ii. *Fail-Safe Design Philosophy.* Within this philosophy, the dual strut configuration inherently embodies the Fail-Safe structural design philosophy which is mandated for primary aircraft structures under MIL-HDBK -516 and CS-25.302. The philosophy of this framework is that structural system must retain load-carrying capability following failure of any single structural element. This dual strut system presented in this study satisfies this requirement. This is because if one strut is experiencing failure initiation due to fatigue or damage, the remaining strut which is already operating at 50% of the total applied can sustain the aircraft landing weight. This provides an operational time required for safe inspection and maintenance intervention as well. Dual strut system offers redundancy capacity which represent a safety benefit which cannot be achieve in a single strut design system.
- iii. *Economic and Operational benefits.* The economic and operational benefits have great implication on the optimization findings which extends across multiple dimensions of aircraft operations. The optimization result revealed at fuel economy level, there is 5% reduction in landing gear assembly structural mass which in turn translate to 1,045 kg reduction in aircraft operating empty weight. It must be observed that based on IATA fuel burn conventions, the benchmarks for commercial widebody aircraft lies approximately at 0.066kg/km/tonne [29]. This mass reduction will yield a considerable fuel saving. For 15,000-hour design service life with an average stage length of 5000km, this figure translates to a cumulative fuel saving of approximately 207 tonnes per aircraft. This for instance represents a significant financial savings at current fuel prices. At maintenance angle, this improvement in factor of safety (42.27%) at dual strut configuration. This also represents an extended fatigue life under cyclic loading condition with an increased inspection intervals with reduced unscheduled maintenance events.

3.4 Limitation and Future Work

It must be observed that the present study is subject to several limitations that must be acknowledge. These limitations ranged from the analysis which deploys a linear elastic isotropic material model. The analysis of this model does not capture the non -linear material behaviour,

plastic deformation as well as the material anisotropy that may be present in a certain aerospace alloy grades under extreme loading cyclic conditions. Another limitation is the FEA models are subjected to static and quasi-static loading conditions. This is because the dynamic impact loading during an actual touch down events which involved strain-rate dependent material response and contact dynamics are not fully represented in the model of the present study. Similarly, the present study does not incorporate the physical prototype fabrication or experimental testing and the simulation prediction have not been directly be validated against physical measurement data or certified landing gear performance specifications from Original Equipment manufacturers (OEMs). The present study employs the material properties that are based on aerospace standard values which are widely validated in literature and they are directly consistent with findings that is independently validated [17, 19]. This approach provides a surrogate confidence in computational outcomes however experimental validation remains a recommended approach in the next step.

3.4.2 Recommendation for Future Work

The present study has identified future direction three future directions. The first recommendation lies in the integration of advance metaheuristic optimization algorithms which involve genetic algorithm (GA), particle swarm optimization (PSO) or the dandelion optimization as applied by Akçay & İlkılıç [21]. Another recommendation will be application of dynamic FEA simulation that will incorporate explicit time-domain load profiles which represents FAR Part 25 landing load spectra that enhances the fidelity of the fatigue life prediction. The last recommendation is the physical prototype fabrication and drop test validation which is will be conducted in accordance with RTCA DO-160 or any equivalent standards that will offer experimental verification required to obtain airworthiness certification.

4. Conclusion

In this study, strut configurations (single and dual) in aircraft landing gear assemblies were successfully modelled, simulated and optimized for effective in-service duty cycle. From the findings, dual strut configuration exhibited less weight, less displacement in terms of deformation, less von-mises stress and less equivalent strain compared to the single strut configuration. In addition, the dual strut model despite weighing less than the single strut model exhibited a higher factor of safety by 42.27% than the conventional strut model, indicating improved load bearing capacity, strength and rigidity as well as improved shock absorbing tendencies. This implies that improved lateral stability is achieved via dual strut configuration which is particularly essential for landing scenarios such as crosswind conditions. Speaking of landing scenarios, landing forces and loads are shared across a broad spectrum, minimizing axial and tangential stresses acting on different components. Moreover, dual strut configuration outperformed the single strut in terms of redundancy, as one of the struts can still support the landing weight of the aircraft if the other one fails or about to fail. Also, the application alloy steel which is a conventionally smart material is essential for adaptive damping and absorption of shocks during aircraft landing conditions. For the multi-physics simulation, this advanced material has demonstrated the feasibility of the optimized strut geometry in this context. This can reshape the landing gear design morphology and architectural framework, rendering improved efficiency in terms of minimal cost maintenance and fuel consumption.

Abbreviations

FEA	Finite Element Analysis
MARSR	Multiagent reinforced symbolic regression
CAD	Computer Aided Design

FoS	Factor of Safety
FAA	Federal Aviation Authority
FAR	Federal Aviation Regulation
EASA	European Union Aviation Safety Agency
IATA	International Air Transport Association

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Conflicts of Interest

The author declares no conflicts of interest.

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