RESEARCH PAPER

Design Optimization And Additive Manufacturing Of Aircraft Seat Buckles: A Review Of Performance, Safety, And Regulatory Challenges

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Abstract

The aviation industry continually strives to enhance efficiency, safety, and sustainability through technological innovation. One of the most effective strategies to achieve these goals is by reducing the weight of aircraft components without compromising [7]structural integrity or passenger safety. This project focuses on the design, material optimization, and additive manufacturing (3D printing) of a lightweight seat buckle used in Airbus aircraft. Traditional aluminium seat buckles contribute significantly to aircraft mass. By implementing additive manufacturing and using PC-ABS material, the project aims to reduce weight while maintaining mechanical strength. The optimized design produced using CATIA V5 and analysed with ANSYS achieves a 55% weight reduction. Applied to an Airbus A380, the total weight savings are approximately 77 kg, resulting in significant fuel cost savings. The project demonstrates the potential of additive manufacturing in aerospace applications for sustainable and cost-effective component design. The selection of suitable material is critical to ensure that the 3D-printed Airbus seat buckle meets aerospace requirements for strength, safety, durability, lightweight efficiency, and manufacturability. Since the buckle is a safety-critical component, the material must withstand high tensile loads, resist impact, and maintain dimensional stability while also supporting efficient 3D printing.

Keywords: Design Optimization, 3D Printing, Airbus Seat Buckle,Stress Analysis,Thermoplastic Composite, PC-ABS, Performance Evaluation,Weight reduction, Rapid prototyping

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1.Introduction

In today's aerospace industry, making aircraft lighter is very important. Lighter planes use less fuel, reduce costs, and produce fewer emissions. Even small parts, like seat buckles, can make a big difference because there are so many of them on a plane. 3D printing, also called Additive Manufacturing, allows us to make parts that are lighter, stronger, and more complex than what traditional manufacturing can achieve. Companies like Airbus and Boeing already use 3D printing for different airplane components, proving that it works in real-world applications. This project focuses on redesigning an Airbus seat buckle using 3D printing. The goal is to make the buckle lighter and stronger without affecting its safety or durability. By optimizing the design and using modern materials, we can improve performance and contribute to overall fuel savings for the aircraft.In today's aerospace industry, weight reduction has become one of the most critical design objectives. Every component used inside an aircraft, whether structural or cabin-related, directly contributes to the overall mass of the aircraft. Since aircraft fuel consumption is highly dependent on total weight, even a small reduction in component mass can produce noticeable improvements in fuel efficiency, operating cost, and environmental sustainability.Commercial aircraft such as Airbus models contain hundreds of passenger seats, and each seat includes a buckle mechanism that must provide reliable restraint during take-off, landing, turbulence, and emergency loading conditions. Although a single seat buckle may appear to be a small component, the combined weight of all buckles in the cabin becomes significant when multiplied across the entire aircraft fleet. Therefore, optimizing such a component offers a practical opportunity for lightweight design and long-term fuel savings.This project specifically focuses on the design optimization and development of an Airbus seat buckle using 3D printing technology. The main purpose is to redesign the existing buckle geometry to achieve minimum possible weight with maximum strength and

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safety performance. By using modern CAD modelling tools, structural analysis, topology optimization, and suitable printable materials, the buckle can be developed in a way that improves load distribution, reduces stress concentration, and increases strength-to-weight ratio.Another important aspect of this project is to study the effect of buckle weight reduction on aircraft performance and fuel efficiency. A lighter buckle design reduces the cumulative cabin weight, which directly lowers fuel required for flight operations. Over thousands of flight cycles, this can lead to substantial savings in fuel cost, reduced carbon emissions, and improved sustainability, which are major goals in modern aviation engineering.

Material And Methods

Material Selection

The selection of suitable material is critical to ensure that the 3D-printed Airbus seat buckle meets aerospace requirements for strength, safety, durability, lightweight efficiency, and manufacturability. Since the buckle is a safety-critical component, the material must withstand high tensile loads, resist impact, and maintain dimensional stability while also supporting efficient 3D printing.

The following factors were considered during the material selection process:

Material Selection Criteria

 Mechanical Strength & Load-Bearing Capacity
 Weight Reduction & Density Efficiency
 Impact, Wear & Fatigue Resistance
 Fire & Thermal Resistance (Aerospace compliance)
 3D Printing Compatibility & Print Orientation Performance
 Cost, Availability & Repeatability

List Of Materials

PARTS	MATERIAL
Seat Buckle (Main Body)	Steel
Prototype Version (Testing)	ABS/PC-ABS (FDM)
High-strength Version (Final Aerospace Grade)	Aluminium Alloy 7075-T6 (if metal-printing or CNC is used

Table 1 . List of materials with parts

316L Stainless Steel (Primary Material)

316L stainless steel is widely used in aerospace applications due to its exceptional strength, corrosion resistance, and durability. For a safety-critical component like an aircraft seat buckle, 316L offers high load-bearing capacity, excellent performance under tensile and shear forces, and superior resistance to wear, temperature variations, and humidity, making it suitable for long-term aviation use. Its ductility ensures that the buckle can withstand repeated fastening cycles without cracking, while its low carbon content improves weldability and prevents weakening during fabrication. Although heavier than aluminium or titanium, its safety reliability and resistance to failure make 316L stainless steel a dependable primary material for buckle manufacturing and validation.

Material Selection

Material selection is critical in aerospace component design. The goal is to balance strength, durability, manufacturability, and weight.

Property	AISI 304 Stainless Steel	Carbon Fiber Reinforced ABS
Density(g/cm^3)	7.80	1.60
Tensile Strength(MPa)	515	180-250
Modulusof Elasticity(GPa)	193	7-9
Corrosion Resistance	Excellent	Good
Manufacturability (3Dprint)	Difficult	Excellent
Weight Reduction Potential	-	65%

. Table 2. Material Selection properties

Rationale:

The Carbon Fiber Reinforced ABS was chosen for:
Lower density (lightweight)
High stiffness and impact resistance
Suitability for FDM (Fused Deposition Modeling) 3D printing
Environmental and cost benefits

Modeling In SolidWorks

Figure 1 Original Buckle

Stress Anlysis of Optimized Rectangular Cutout Airbus Seat Buckle:

 Equivalent (Von-Mises) Stress Result

Figure 2. Equivalent (Von Mises) Stress of Rectangular Cutout Buckle Assembly

• Equivalent (von Mises) Stress
• Maximum Stress: 756.93 MPa
• Average Stress: 18.64 MPa
• Minimum Stress: 0.011 Pa
• Maximum Stress Location: Front load-bearing region of Buckler Base (Red Zone)
• Minimum Stress Location: Upper buckle body near fixed region (Blue Zone)

Explanation

The equivalent stress analysis indicates that the maximum stress of 756.93 MPa occurs at the front load-bearing portion of the Buckler Base where the external force is transferred through the assembly. Most regions remain under significantly lower stress levels, indicating effective load distribution throughout the buckle structure.

 Total Deformation Result

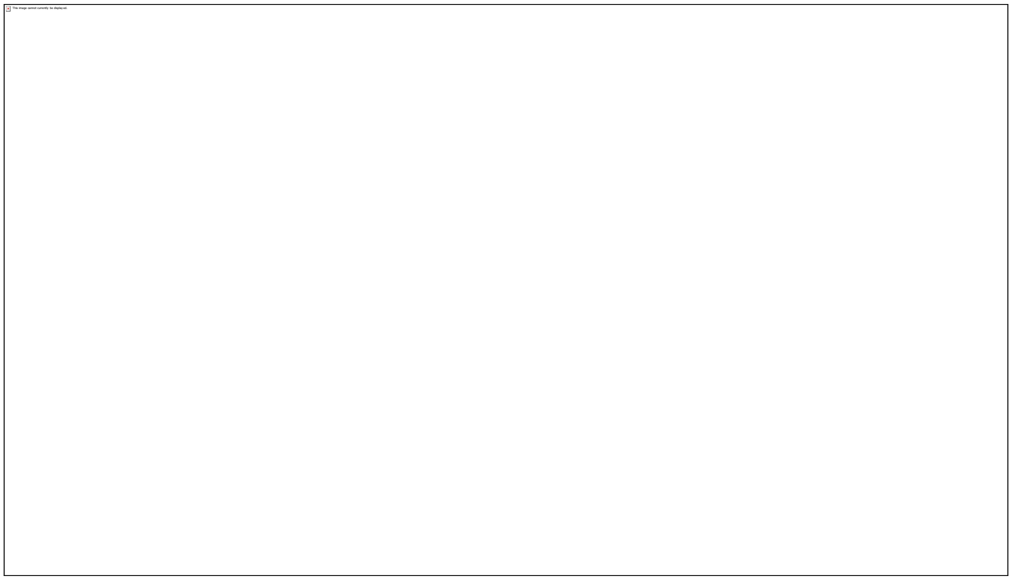

Figure 3 .Deformation Result of Rectangular Cutout Buckle Assembly

- Maximum Deformation:
- Average Deformation: 0.0731 mm
- Minimum Deformation: 0.00292 mm
- Maximum Deformation Location: Front free end of Buckler Base (Red Zone)
- Minimum Deformation Location: Fixed support region near buckle body (Blue Zone)

Explanation

The total deformation analysis shows that the maximum deformation of 0.0731 mm occurs at the free end of the Buckler Base, which is farthest from the fixed support and therefore undergoes the greatest displacement under loading. The minimum deformation of 0 mm occurs at the fixed support region because the component is completely constrained and cannot move. The very small deformation value indicates that the optimized buckle assembly possesses sufficient stiffness and structural stability under the applied load condition.

 Rectangular Cutout Buckle Assembly – Stress Results: -

No	Parameter	Value
1	Maximum	756.93 MPa
2	Average	18.64 MPa
3	Minimum	0.011 Pa
4	Maximum Stress Location	Front load-bearing region of Buckler Base (Red Zone)
5	Minimum Stress Location	Upper buckle body near fixed region (Blue Zone)

Table3. buckle Assembly- stress result)

Explanation

The equivalent stress analysis indicates that the maximum stress of 756.93 MPa occurs at the front load-bearing portion of the Buckler Base where the external force is transferred through the assembly. Most regions remain under significantly lower stress levels, indicating effective load distribution throughout the buckle structure

Total Deformation Result: -

Table4.Optimize Buckle Assembly -Deformation Result

No	**Parameters**	**Value**
1	Maximum	0.0731 mm
2	Average	0.00292 mm
3	Maximum Deformation Location	Front free end of Buckler Base (Red Zone)
4	Minimum Deformation Location	Fixed support region near buckle body (Blue Zone)

Explanation

The deformation analysis shows a maximum deformation of 0.0731 mm occurring at the free end of the Buckler Base, while the fixed support region experiences zero displacement. The extremely low deformation value demonstrates that the optimized buckle assembly maintains high structural stiffness under the applied loading conditions.

Result and Discussion

Explanation of Graph :-

The graph compares the performance of the original Airbus seat buckle assembly and the optimized rectangular cutout buckle assembly. ANSYS analysis showed that the optimized design reduced the assembly mass from 172.11 g to 161.90 g, resulting in a net weight reduction of 10.21 g (5.93%). When applied across multiple seat belt assemblies in an aircraft, this reduction contributes to a total aircraft weight saving of approximately 0.414 kg, leading to an estimated fuel saving of 250 Liters per year and a cost saving of ₹23,750 per year. Despite the material removal, the optimized buckle maintained nearly the same stress and deformation characteristics as the original design, demonstrating that weight reduction was achieved without compromising structural performance or safety. The results confirm that the rectangular cutout optimization method is an effective lightweighting approach for aerospace seat buckle applications.

Conclusion

The design and development of the Airbus seat buckle using 3D printing marks a major advancement in aerospace manufacturing technology.

•Design optimization significantly reduced material usage while maintaining or improving structural integrity and safety.

•Additive manufacturing enabled the creation of complex, lightweight geometries not possible with traditional manufacturing methods.

•3D-printed seat buckles demonstrated notable weight reduction without compromising strength, durability, or passenger safety.

•Reduced component weight contributes to better aircraft fuel efficiency and overall performance.

•Rapid prototyping through 3D printing accelerates design evaluation and testing, shortening development cycles.

•Additive manufacturing minimizes material waste, supporting sustainability and cost efficiency goals.

•Challenges remain, including certification of materials, surface finishing, and longterm fatigue testing for aviation standards.

•Despite challenges, 3D printing combined with design optimization shows strong potential for future lightweight, high-performance aircraft components.

References

1. **Subalakshmi Venkatesan & Vasanth S. — Review on AM in aircraft**
   Venkatesan, S., & Vasanth, S. (2024). Review on additive manufacturing process in aircraft industries. acceleration2(3),204–208.https://doi.org/10.61359/11.2106-2412.acceleron.org.in
2. **Kovuri Adithya & P. Senthil — Seat buckle (Carbon Fiber T700 vs AISI304S) Source:IJASEM**
   Kovuri, A., & Senthil, P. (2023). A comparative analysis of the static strength of airplane seat buckle and latch made with Carbon Fiber T700 and AISI 304 S.S. International Journal of Advanced Scientific Engineering and Management (IJASEM). Retrieved from https://www.ijasem.org/previousissue.php?issue=3&year=2023. ijasem.org
3. **Wawryniuk, Brancewicz-Steinmetz & Sawicki — Revolutionizing transportation (3D printing overview)** Wawryniuk, Z., Brancewicz-Steinmetz, E., & Sawicki, J. (2024). 134, 3083–3105.

https://doi.org/10.1007/s00170-024-14226-y. SpringerLink+1

4. **Zhu, Li & Childs — Light-weighting in aerospace component and system design (review) Zhu, L., Li, N., & Childs,** P. R. N. (2018). Light-weighting in aerospace component and system design. Propulsion &Power Research, 7(2), 103–119.https://doi.org/ 10.1016/j.jppr. 2018.04.001. sciencedirect.com+1
5. **Manoj Kundu (and co-author Arnab Mandal) — AM: Critical review of techniques, applications & future scope**
6. Published on IJERT (International Journal of Engineering Research & Technology). IJERT entries sometimes lack formal DOIs; IJERT is an open-access conference/journal platform. IJERT+1 Kundu, A. M., & Mandal, A. (2022). Additive manufacturing process (3D printing): A critical review of techniques, applications & future scope. International Journal of Engineering Research & Technology (IJERT), 11 (10), 171–193. https://www.ijert.org/. IJERT+1