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Full scale aircraft structural optimization for electric flight concepts

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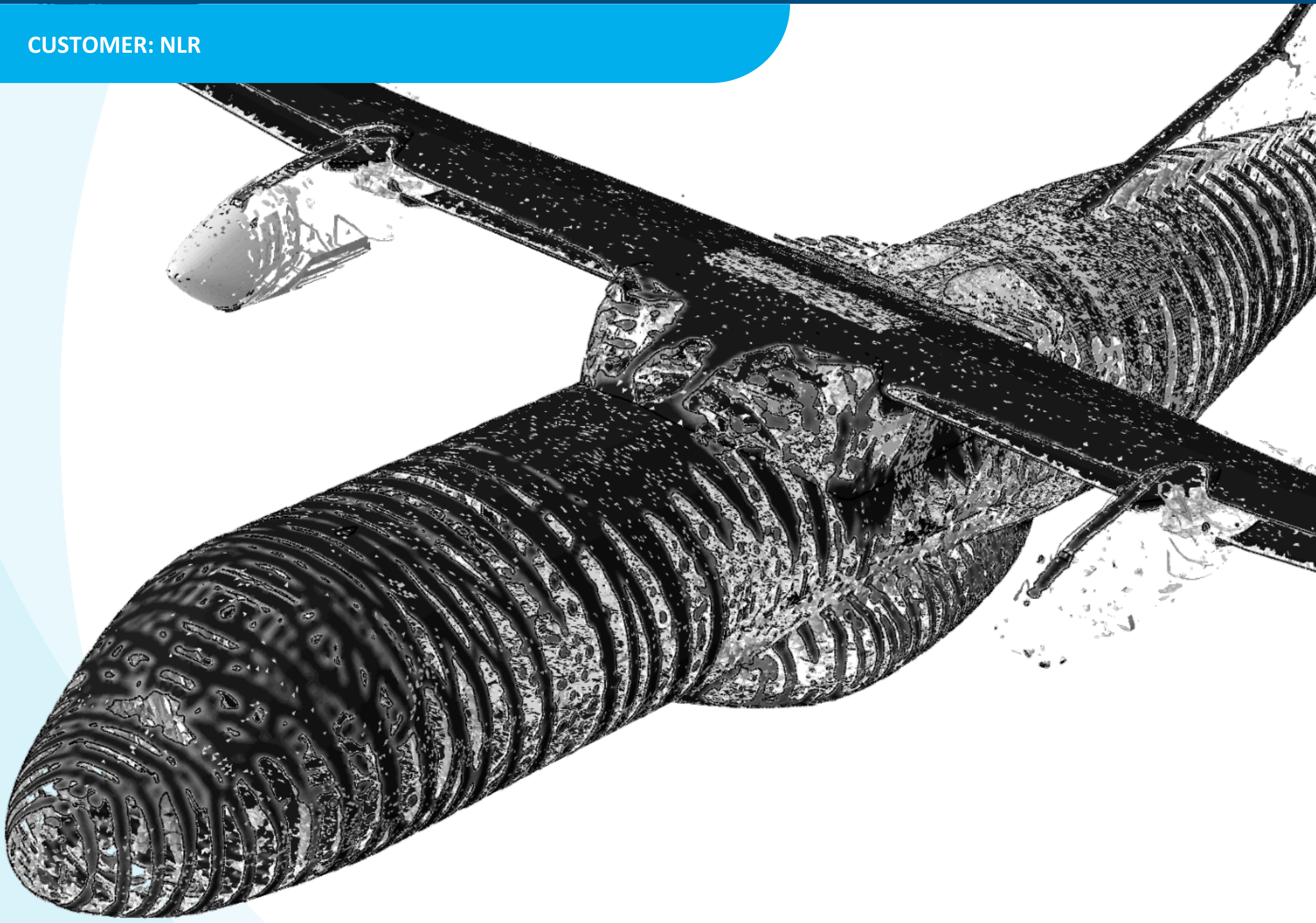

Royal NLR - Netherlands Aerospace Centre

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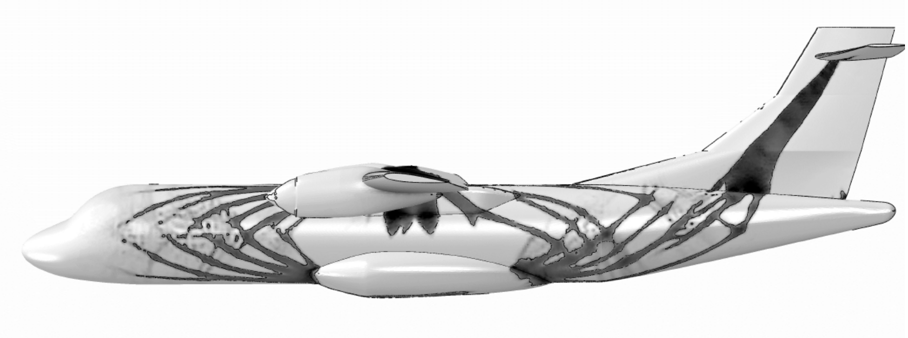

Figure 1: illustration of Optimized internal structure (grey lines) of the ATR-42 600 reference aircraft

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The aviation industry, responsible for about 2% of global CO2 emissions and for local air pollution around airports, faces a need for transition to more sustainable propulsion systems. Electric aircraft driven by battery-powered propulsion have emerged as a potential solution. However to achieve a useable range for these battery powered electric aircraft very large battery packs are needed. These batteries are significant in weight and will increase the structural load of the aircraft and in particular the fuselage to wing connection. Therefore the structural airframe design of battery electric aircraft needs to be changed and potentially further optimized. This research explores the potential for structural topology optimization of a battery-powered ATR 42-600 with a focus on minimizing weight while ensuring structural integrity.

Description of work

A detailed analysis of loads including gravity, internal pressure, flight controls, battery loads, cockpit pressure and others was conducted. The study employed a comprehensive methodology based on 3D finite element modelling that combined

shell and solid elements, utilizing Abaqus software. Topology optimization was carried out with strain energy and structural volume as design responses, subject to specified volume and symmetry constraints. Three distinct battery placement configurations were investigated, each impacting load paths and structural performance. A start has been made to translate the optimized design to actual aircraft structural features such as frames and door surround structures.

Results and conclusions

The results showed interesting insights into the intricate load paths within different battery placement configurations. These configurations not only demonstrated the adaptability of the structure to varying loads but also highlighted the critical role of battery placement in shaping load distribution. As the findings indicated, a balance between weight reduction and structural robustness can be attained through innovative structural design, effectively addressing the challenges of battery integration. However currently due to the topology optimization approach in combination with the relative coarse mesh with centimetre sized element the optimized structural mass is too high. Therefore it is challenging to derive representative metrics on weight reduction and robustness of the structure. Further research is needed to translate these new insights into actual structural design and detailed design from which weight metrics can be derived.

Applicability

The research addresses questions concerning aircraft-level feasibility, optimization features, inertia relief, and mesh size influence. The findings show the potential for optimizing battery-powered aircraft wings through innovative structural design, contributing to potentially lower weight and further reduced environmental impact. This study serves as a first step towards future electric aircraft design and underscores the importance of integrating innovative solutions to reduce climate impact of the aviation industry.

GENERAL NOTE

This report is based on a presentation held at the Royal Aeronautical Society’s 8th Aircraft Structural Design Conference, on 3-4 October 2023 in London.

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Summary

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A detailed analysis of loads including gravity, internal pressure, flight controls, battery loads, cockpit pressure and others was conducted. The study employed a comprehensive methodology based on 3D finite element modelling that combined shell and solid elements, utilizing Abaqus software. Topology optimization was carried out with strain energy and structural volume as design responses, subject to specified volume and symmetry constraints. Three distinct battery placement configurations were investigated, each impacting load paths and structural performance. A start has been made to translate the optimized design to actual aircraft structural features such as frames and door surround structures.

The results showed interesting insights into the intricate load paths within different battery placement configurations. These configurations not only demonstrated the adaptability of the structure to varying loads but also highlighted the critical role of battery placement in shaping load distribution. As the findings indicated, a balance between weight reduction and structural robustness can be attained through innovative structural design, effectively addressing the challenges of battery integration. However currently due to the topology optimization approach in combination with the relative coarse mesh with centimetre sized element the optimized structural mass is too high. Therefore it is challenging to derive representative metrics on weight reduction and robustness of the structure. Further research is needed to translate these new insights into actual structural design and detailed design from which weight metrics can be derived.

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Abbreviations

ACRONYM	DESCRIPTION
ATR	A Franco-Italian aircraft manufacturer
FEA	Finite element analyses
MDOF	Mega degrees of freedom
MTOW	Maximum take off weight
NLR	Royal NLR - Netherlands Aerospace Centre
OEW	Operating Empty weight
SIMP	Topology optimization method, Solid Isotropic Material with Penalisation

1 Introduction

The aviation industry faces a need to address its carbon footprint. A way towards achieving this transition is the development of electric and non-conventional design for aircraft powered by advanced battery technologies, see Figure 2. The adoption of electric propulsion systems promises to significantly reduce greenhouse gas emissions and mitigate the environmental impact of aviation.

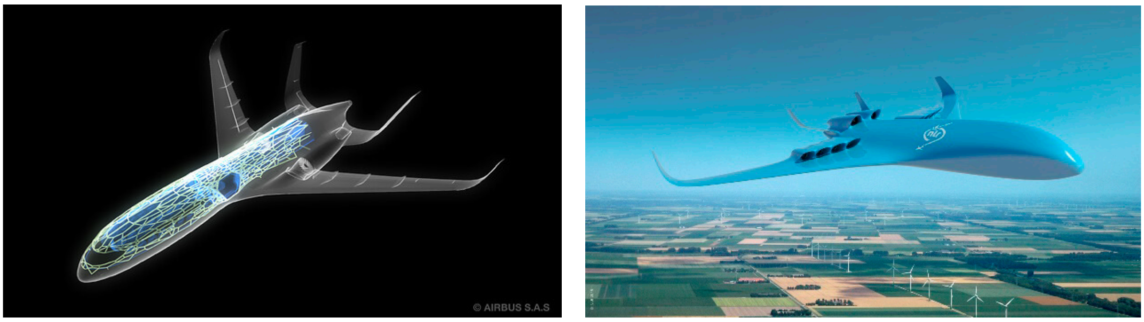


Figure 2: (left) Example of non-conventional design of a bionic aircraft design vision by Airbus (Source: Airbus SAS [1]) and on the right the NLR future aircraft vision.[2]

At the forefront of this evolution, the propeller aircraft in general and in particular the ATR 42-600 aircraft, see Figure 3, emerges as a model for this transformative change tot electric flight. This regional aircraft serves as an ideal platform for exploring the integration of battery-powered propulsion. However, this transition is not free of challenges. The introduction of batteries, while promising greener flight operations, necessitates a fundamental re-evaluation of structural design principles. The redistribution of weight, alteration of load paths, and optimization of structural components become important considerations in the search for both efficiency and safety.

The present research undertakes a comprehensive investigation into the structural topology optimization of a battery-powered ATR 42-600 fuselage and wing structure. Central to this research is the objective of achieving an optimal balance between weight reduction and structural integrity. This study responds to the demand for innovative design methodologies that enable electric aircraft.

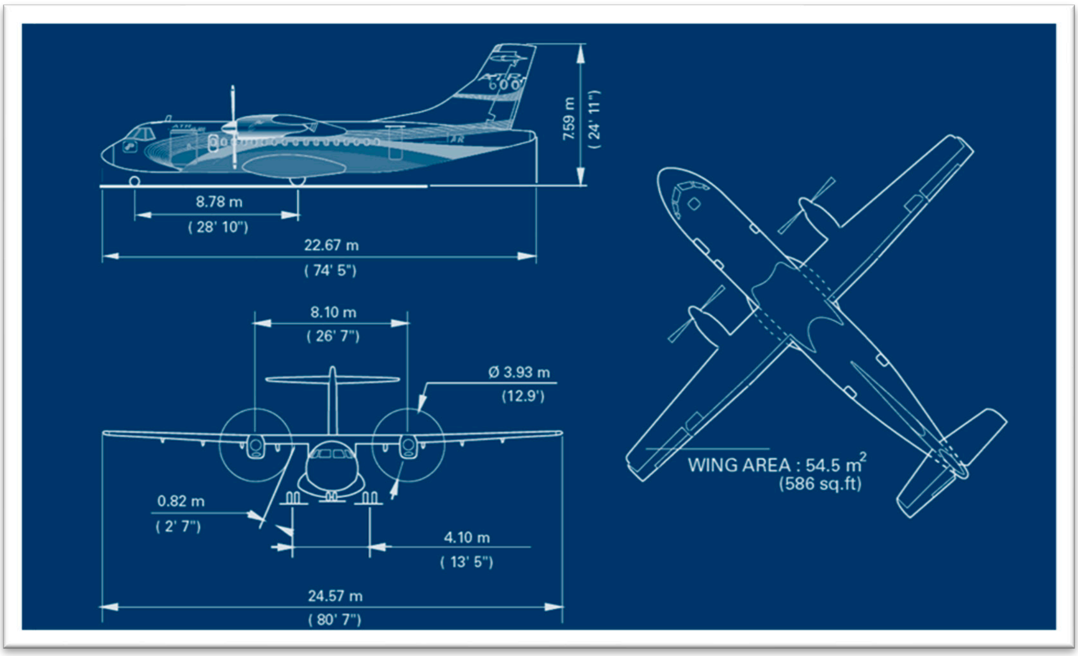


Figure 3: Illustration of the ATR 42-600 propeller aircraft, the platform for this research for exploring the integration of battery-powered propulsion [3]

1.1 Research Objectives

The principal aim of this research is to explore optimizing the structural design of an electric aircraft's fuselage and wing structure to accommodate the introduction of batteries for propulsion. The objectives encompass the following key aspects:

- Load Analysis and Characterization: Quantifying and analysing the diverse array of loads that act on the aircraft, including gravity, internal pressure, control surfaces, battery weight, and operational conditions.
- Hybrid Modelling Approach: Employing advanced modelling techniques that blend shell and solid elements to simulate the structural behaviour of the fuselage and wing accurately.
- Topology Optimization: Utilizing strain energy and structural volume as design responses to achieve an optimal structural configuration that balances weight reduction with structural robustness.
- Battery Placement Configurations: Investigating various configurations for battery placement within the fuselage and wing, evaluating their influence on load paths and structural performance.

The outcomes of this research hold the potential to evaluate aircraft design paradigms, offering novel insights into the interaction between structural integrity, weight distribution, and battery integration. The resulting framework could help further development of future electric aircraft, resulting in an aviation landscape that is not only environmentally conscious but also technologically advanced. In the subsequent sections the literature review is discussed, methodologies and results are shown and the implications of this research for the aviation industry towards sustainable propulsion systems are finally discussed..

2 Literature Review

The evolution of aviation towards more sustainable and eco-friendly practices has shown increasing research into electric aircraft propulsion and innovative structural design methodologies. This literature review relates the present study within the broader landscape of electric aircraft development, battery integration, and topology optimization.

2.1 Electric Aircraft Advancements

The concept of electric aircraft is not new, but recent advancements in battery technology and electric propulsion systems have increased interest in their feasibility. One of the primary challenges in electric aircraft design is the integration of battery systems. The work of Sogeclair (2016) emphasizes the significance of optimizing structural design to accommodate the unique weight distribution and load paths introduced by battery-powered propulsion. Liu et al. (2019) showed an impressive new design approach for a wing section.

2.2 Topology Optimization in Aviation

Researchers like Aage et al. (2017) have explored computational morphogenesis for structural design, highlighting its potential for optimizing complex geometries in aircraft. The work by Kawski (2015) demonstrated topology optimization techniques applied to aircraft fuselages, showcasing the efficacy of lightweight designs in the context of electric propulsion. Topology optimization has gained traction as a powerful tool in aircraft design, enabling engineers to create lightweight and robust structures. Heilemann (2018) into laser metal deposition showcased the potential for optimizing complex aluminium structures, thereby reducing energy input for additive manufacturing in aircraft components. This study aligns with the growing interest in leveraging topology optimization to address structural challenges in the context of electric aircraft.

The literature underscores the need for innovative design methodologies to meet the challenges given by electric aircraft integration. In the subsequent sections, the approach in this research is shown, which combines hybrid modelling and topology optimization to address the interaction between structural integrity and weight reduction in a battery-powered ATR 42-600 fuselage and wing.

3 Methodology

In this section the methodology is explained. The aircraft specifications can be seen in Figure 3 and Table 1, including battery energy density, maximum take-off weight, flight parameters, and load components. The following assumptions have been made and are taken into account;

- Cruise conditions, a steady horizontal flight, are taken into account for the topology optimization of the wing. Along with a constant velocity and altitude. For the full scale optimization the load-cases cruise, gust load, landing, negative and side loads are used.
- As the battery powered propulsion system is not officially certified and in use in the field of aviation, there are not yet clear regulations and requirements for this. Therefore, during the design of the wing no regulations or requirements are taken into account.
- The limits for the center of gravity are based on the original Maximum Take-off Weight of the ATR 42-600.
- The horizontal and vertical forces; lift, weight, drag, thrust, are taken into account.
- An engine configuration of four engines is used.
- The hydraulic and pneumatic systems are covered by the electric system.
- For the load analysis the MTOW is used as the total weight during cruise flight conditions. As the batteries do not decrease in weight compared to kerosene, this is a valid assumption.
- The lift only acts on the wing and is equally distributed per side of the wing

In this research the following conditions and parameters are selected. The cruise altitude is 5,800 m (19,000 ft), the cruise velocity 155 m/s and a range of 400 km. The kerosene powered ATR 42-600 has a range of approximately 1300 km. The specific energy of batteries is much lower than kerosene. Therefore, it is not realistic to design an electric ATR 42-600 for the same range and is therefore reduced to 400 km.

3.1 Aircraft Specifications and Load Analysis

To determine the power required (P_{req}) and thus the energy (J) and batteries needed, the amount of flight time (T) has to be calculated, see Figure 4.

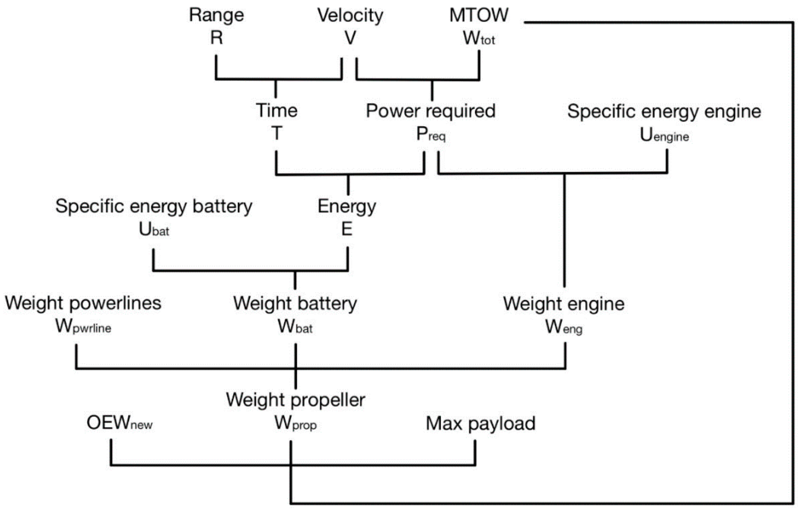


Figure 4: Schematic for determining the parameters for the design optimization

The velocity given by the ATR company is said to be the maximum cruise velocity. This means that for a propeller aircraft the P_{req} is found where the previous combustion power and the new electric required power P_{req} are equal. Hence, the P_{req} is calculated with the following formula and thus the amount of energy needed (Bills, Sripad, Fredericks, Singh, & Viswanathan, 2020); Four forces act on an aircraft in flight: thrust (force generated by the propulsion system), drag (aerodynamic force opposite to velocity), weight (gravitational force), and lift (aerodynamic force normal to velocity). Neglecting acceleration, thrust can be calculated by solving the equations for each of these forces, which are a function of the geometry and operating conditions of the aircraft, including instantaneous velocity relative to the surrounding air (V), the zero lift drag coefficient (C_{D0}), propulsive efficiency (η_{prop}), mechanical efficiency (η_{mech}), wing area (S), the aspect ratio (the ratio of the square of the wingspan to the wing area), and climb or descent angle (γ).

$$P_{req} = \frac{\frac{1}{2}V^3 S C_{D_0}\rho + \frac{2KW^2}{\rho V S} + WV sin(\gamma)}{n_{prop} n_{mech}} \tag{1}$$

$$E = P_{req} * time \tag{2}$$

This result in an impressive amount of 2300 kWh of battery storage needed. For this research a future lithium-ion battery gravimetric energy density has been chosen to be 350 Wh/kg along with the volumetric energy density of 680 Wh/L. The weight of the batteries is therefore calculated with the following equation;

$$W_{battery} = \frac{E}{U_{battery}} \tag{2.10}$$

The total battery weight is calculated to be 6400 kg or 64 kN and a volume of 3.4 m^3. In the Table 1 and Table 2 the reference and electric aircraft specifications are shown.

Table 1: Overview Parameters

Parameter ATR42-600	Value	Unit
Maximum Take-off Weight (MTOW)	182500	N
Empty Weight OEW_{org}	113300	N
Surface area S	54.50	m^2
Wing width b_{wing}	24.57	m
Fuselage width $b_{fuselage}$	2.57	m
Fuselage length $l_{fuselage}$	22.67	m
η_{mech}	0.92	-
η_{prop}	0.80	-
γ	0	degrees
Gravity g	9.81	m/s^2
ρ	0.67	kg/m^3
$N_{passenger}$	48	-
N_{crew}	3	-
$N_{engines}$	4	-

Table 2: Weight parameters electrified ATR aircraft

Parameter	Value	Unit
MTOW (W_{tot})	250000	N
Flight time (T)	2600	seconds
Power required (P_{req})	$3.2 \cdot 10^{6}$	Watt
Energy (E)	$8.3 \cdot 10^{9}$ (~2300 kWh)	Joule
Battery weight ($W_{battery}$)	64000	N
Battery volume ($V_{battery}$)	3.4	m^3
Engine weight (W_{eng})	3200	N
Engine prop weight (W_{pwr})	4250	N
Nacelle weight ($W_{nacelle}$)	1000	N
Powerplant weight ($W_{pwr\ plt}$)	5250	N

3.2 Modelling and Analysis

For the research several finite element analyses (FEA) models were used to evaluate approaches used and study the optimization behaviour. The models simulate the structural behaviour of the components under various loading conditions. In the case of the ATR 42-600 the geometry is discretized into finite elements, and the mechanical response is calculated based on material properties, boundary conditions, and applied loads.

The models studied are:

- Wing and wing connection to fuselage model (solid and shell elements), see Figure 5
- Full aircraft model internal structure only (solid elements)
- Full aircraft model with external shell element structure and solid element structure for optimization, see Figure 6

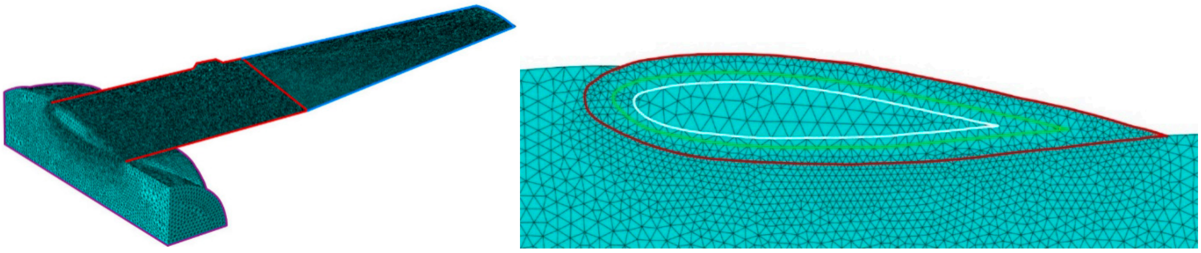


Figure 5: Wing study solid and shell finite element model. The surface shell elements are placed on the outside of the wing geometry indicated with the red line on the right figure

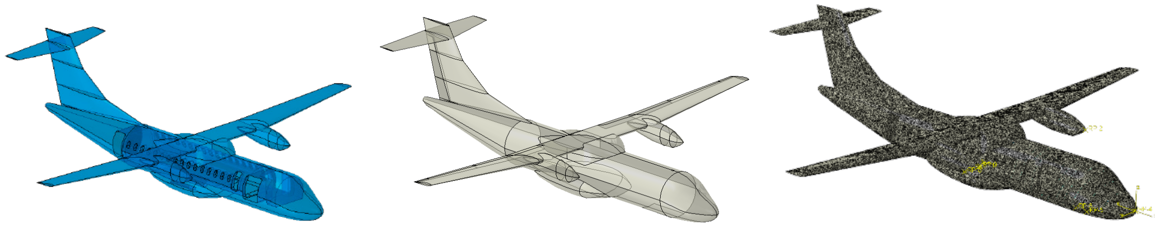


Figure 6: Full aircraft model with left the solid geometry (design space) and in the middle the outer surface shell representing the skin of 1 mm thickness. On the right the combined hybrid mesh of shell and solid elements

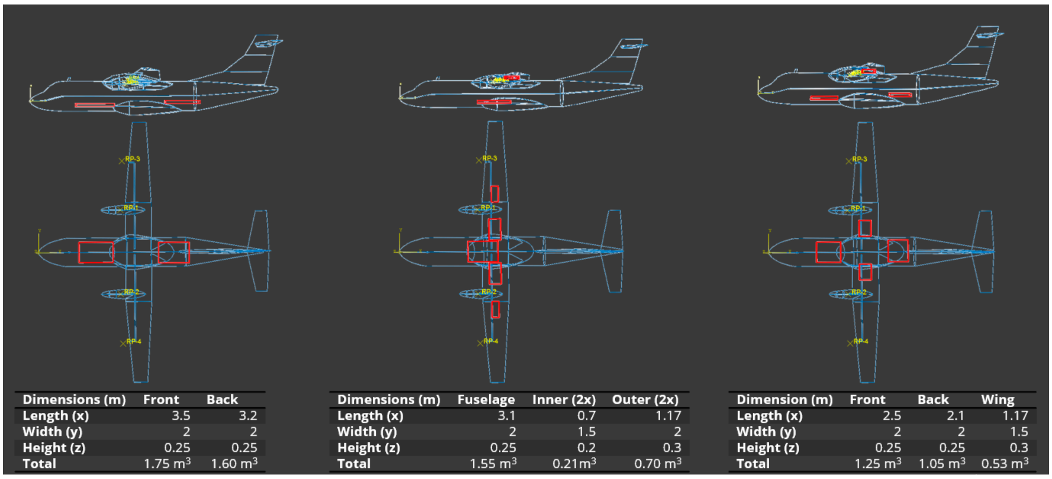
The material used is standard aerospace grade aluminium for the shell and solid geometries. The skin/outer shell elements have a thickness of 1 mm. The shell skin elements are connected to the solid design space elements using so-called tie-constraints. Loads are applied on surface areas (e.g. wing surface) or using coupling constraints for discrete loads. For the full scale optimizations all loads are applied for five load-cases, cruise, gust load, landing, negative and side loads, see Table 3. For the full scale aircraft optimization the following loads are applied. The element size ranges from 0.2 m to 0.032 mm and this results in a mesh with over 12 MDOF.

Table 3: Overview of load parameters and load-case (LC) scale factors. These values are indications

	Parameter	Cruise LC	Gust LC	Negative LC	Sideload LC	Landing LC
Gravity	9.8 m^3/kgs	1	1	1	1	1
Internal pressure	30000 N/m^2	1	1	1	1	0.01
Ailerons	5000 N/m^2	0.1	1	0.2	0.5	0.5
Battery load on mounts	42500 N/m^2	1	2	-0.2	1	1
Cockpit pressure drag	3000 N/m^2	1	1	1	1	0.1
Flap loads	5000 N/m^2	0.1	1	0.1	1	0.5
Floor PAX	4000 N/m^2	1	2	-0.2	1	1
Front land gear F	60000 N	0.01	0.01	0.01	0.01	1
Front land gear M	-50000 Nm	0.01	0.01	0.01	0.01	1
Horizontal	-2000 N/m^2	0.5	1	0.5	2	1
Motor thrust	-7600 N	1	1	1	1	0.1
Motor weight	-5250 N	1	2	-0.2	1	1
Rudder	5000 N/m^2	0.01	1	1	2	1
Wing loading	4600 N/m^2	1	1	-0.2	1	0.1
Rear landing gear	80000 N	0.01	0.01	0.01	0.01	1
Inertia relief	-	-	-	-	-	-

3.3 Configurations

In total three battery placement configurations were analysed. The configurations of battery placement shown in Figure 7: Battery placement configurations were analysed.



Dimensions (m)	Front	Back
Length (x)	3.5	3.2
Width (y)	2	2
Height (z)	0.25	0.25
Total	1.75 m^3	1.60 m^3

Dimensions (m)	Fuselage	Inner (2x)	Outer (2x)
Length (x)	3.1	0.7	1.17
Width (y)	2	1.5	2
Height (z)	0.25	0.2	0.3
Total	1.55 m^3	0.21m^3	0.70 m^3

Dimension (m)	Front	Back	Wing
Length (x)	2.5	2.1	1.17
Width (y)	2	2	1.5
Height (z)	0.25	0.25	0.3
Total	1.25 m^3	1.05 m^3	0.53 m^3

Figure 7: Battery placement configurations indicated with red boxes placed in the wing and/or the fuselage

3.4 Topology Optimization

Topology optimization is a powerful computational tool used to systematically design and refine structures by determining the optimal distribution of material within a given design domain. The objective of topology optimization is to achieve the most efficient use of material while satisfying specific performance and design criteria. In the context of electric aircraft structural design, topology optimization plays a crucial role in ensuring the lightweight yet robust configuration of components such as wings. For this research the Solid Isotropic Material with Penalization (SIMP) method is used with strain energy and structural volume as design responses, subject to specified volume and symmetry constraints.

4 Results

In this section, the outcomes of the topology optimization and load path analysis are presented. The results provide insights into load distribution, strain energy values, and structural robustness for each configuration.

4.1 Wing and wingbox optimization

The focus of this research was to find a lightweight structure of the wing support for an electrified ATR 42-600 aircraft in cruising flight conditions for a range of 400 km at a velocity of 155 m/s with an altitude of 5,800 m (19,000 ft). Leaving the other specifications to be equal to the kerosene powered ATR 42-600.
Three different battery configurations were created. The 1st configuration does not contain any battery packs within the wing. The 64 kN of battery weight are distributed over the fuselage only. The 2nd configuration holds two sets of battery packs of a total of 1.82 m^3 within the wing structure. The remainder of the batteries are placed within the fuselage. The 3rd configuration holds 1.05 m^3 within the wing, placing the remainder of the batteries in the fuselage as well.
For every configuration the load paths within the wing are comparable for the different volume constraints. The main difference is found around the attachment point of the wing to the fuselage. Where the second configuration not only has the highest strain energy but is also the only one where the wings are connected to each other by means of an extra reinforcement. This can be explained by the amount the batteries placed within the wing as they are significantly larger than the other configurations.

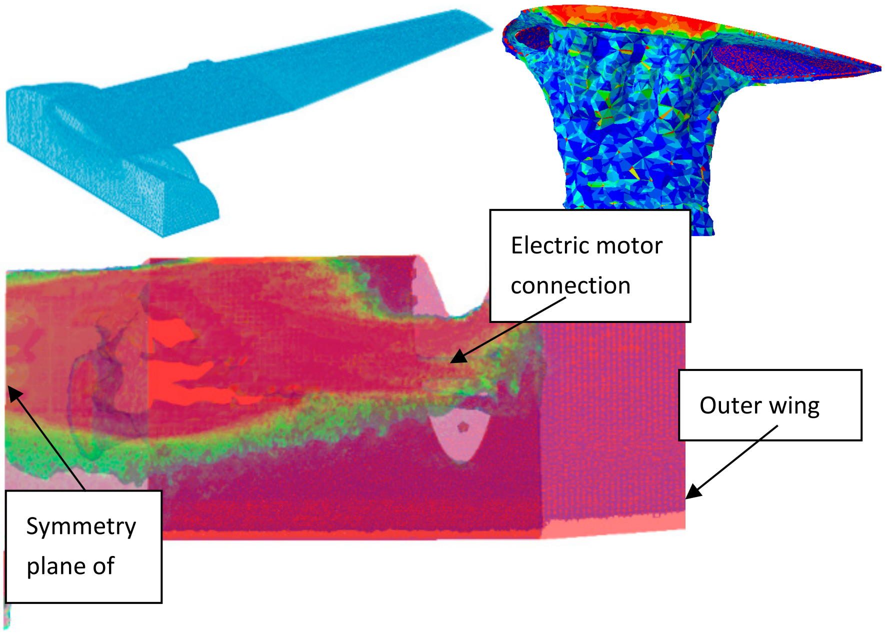


Figure 8: Cross section view and below the top view of the wing support section for configuration 1. It is quite challenging to interpret the results because of the combined shell and solid elements. It can be seen that a spar forms in the wing and load paths towards the fuselage and electric motor connection

In the 1st configuration structures are created within the straight part of the wing that could be described as spars. They are freely placed as there is no other structures interfering. For the other configurations, containing battery

packs in the straight part of the wing, the reinforcement (spars) are directly placed next to the battery as they have an additional task; to support the wing in withstanding the weight of the battery packs.
In addition, the majority of material is placed on the upper part of the wing for all configurations to counteract the relatively large lift force acting in this region. From a comparison of the strain energy it can be concluded that the 1st configuration has the smallest strain energy values for the volume constraint at 10% and thus has the highest stiffness of all three configurations. Resulting in a lightweight wing structure with a higher structural integrity compared to the 2nd and 3rd configuration.

However, the total volume used by the battery packs within the electrified ATR 42-600 is excessive. Placing battery packs inside the wing will reduce the amount needed in the fuselage. Leaving room for other necessary equipment. When comparing the strain energy values of the configurations it can be concluded that the strain energy of the 3rd configuration is only slightly larger for the same volume constraint of 10% compared to the 1st configuration. The load paths are comparable and it has sufficient structural integrity. Therefore, the placements of the battery packs presented in the 3rd configuration partly in the wings is a viable option as well for the electrified ATR 42-600.

4.2 Load Path Analysis

Follow up research on the full aircraft was performed of which results are shown in this section. Load path analysis offers a visual representation of how forces are distributed across the fuselage structure under different battery placement scenarios. Figure 10: and Figure 10 illustrates the load paths for the 1st configuration. Notably, load paths adapt to varying battery placements, with significant load transfer evident around battery attachment points.

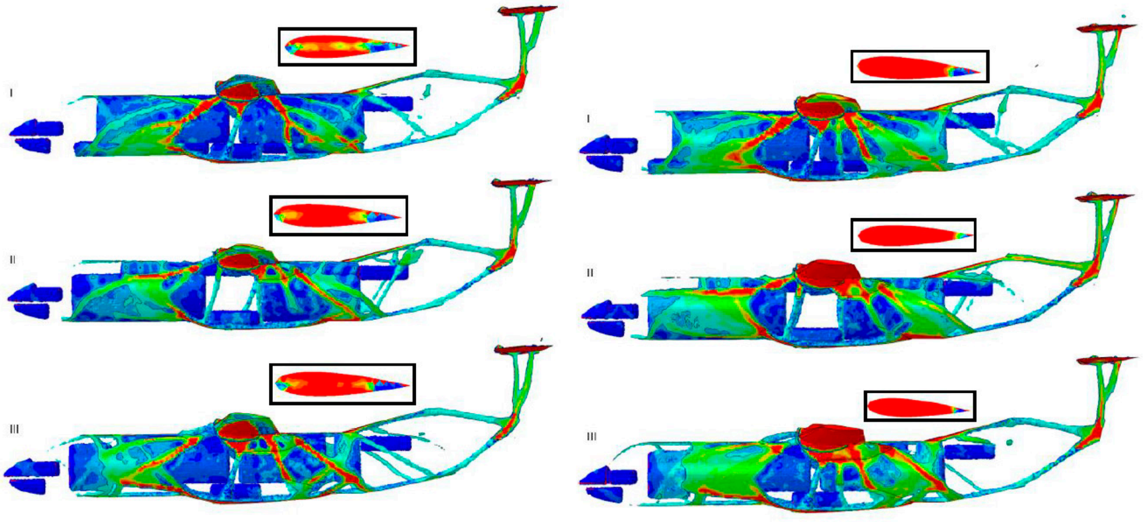


Figure 9: Material usage on the left of all optimized configurations with a volume constraint of 25%. On the right material usage of all optimized configurations with a volume constraint of 30%. In these results material is placed around the passenger area which is not needed and solved with later results

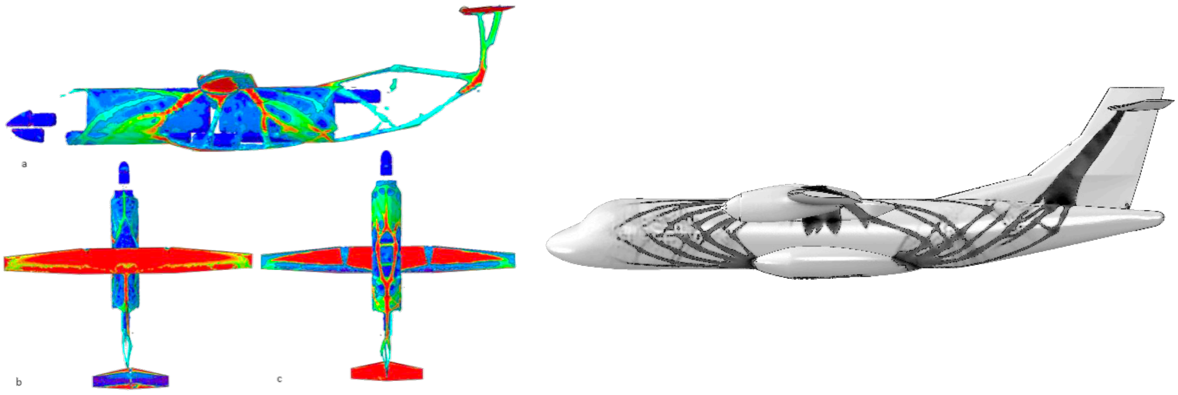


Figure 10: Illustration of the load paths represented by the material density. It can be observed that from these results without internal pressure load, structural connections form from the wing to the fuselage. The result on the right shows an updated result where material is not placed around the passenger area with clear load-paths

The optimization gives an insight into how the load paths develop and indicates potential design directions. Contrary to conventional aircraft, the topology optimization of the electric configurations shows (undesired) structure development in the interior of the fuselage. Moreover, the optimized structure reveals that the wings in all configurations require a significant amount of material in relation to the material needed in the fuselage. The relatively large mesh size, in perspective with the aircraft size, potentially causes the structure in the wings to be dense. Furthermore, the optimized structures of all configurations show that a small layer of material covers the systems parts. This takes up a lot of volume, whereby less volume is available for the rest of the optimization. This has been resolved in the follow up studies. The next step in the study is to combine the wing support and load path studies for the full scale aircraft with multiple load-cases which will be presented in the next section.

4.3 Topology Optimization Full Aircraft

In this section the results of the model for the full scale aircraft, multiple load-cases and hybrid mesh are presented. Topology optimization was aimed to find the optimal material distribution and load-paths within the entire structure while adhering to the constraints. Mesh refinement was performed and internal pressure was added to the loads. Internal pressure showed to have a large influence in the resulting design with frame type of structure appearing. Also this load led to convergence issues for the topology optimization.

From the resulting optimized aircraft using a 17% volume constraint interesting structures appeared to carry and distribute the battery loads and wing loads, see Figure 11 and Figure 12.

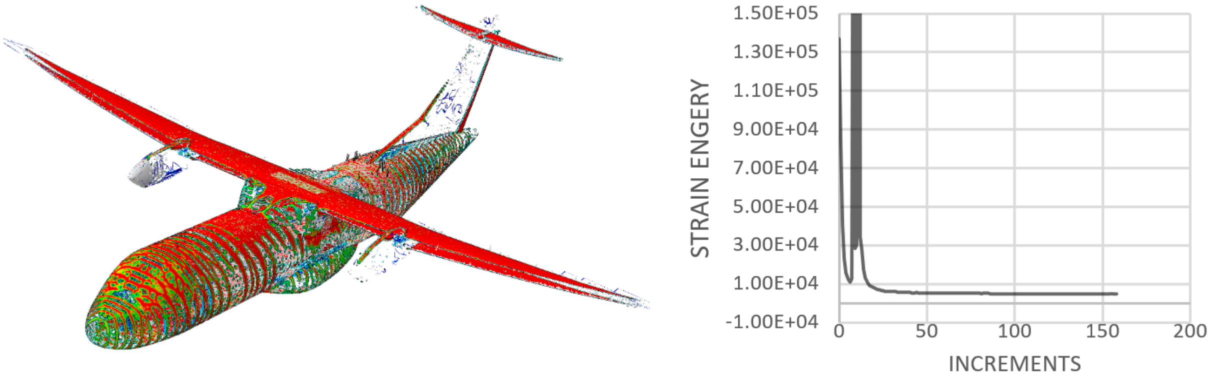


Figure 11: Result of the ATR42-600topology optimization material distribution with mesh size 0.032 m and multiple load-cases. The internal solid element structure is shown here where feature appear such as wing to structure connections and frames. On the right the convergence issues observed during the topology optimization over the increments

The model was further detailed with window and door cut-outs and space for passengers that could not be utilized for the structure. Also for these analyses convergence issues appeared which in some cases resulted in non-feasible designs. The resulting design could be used for further electric aircraft development.

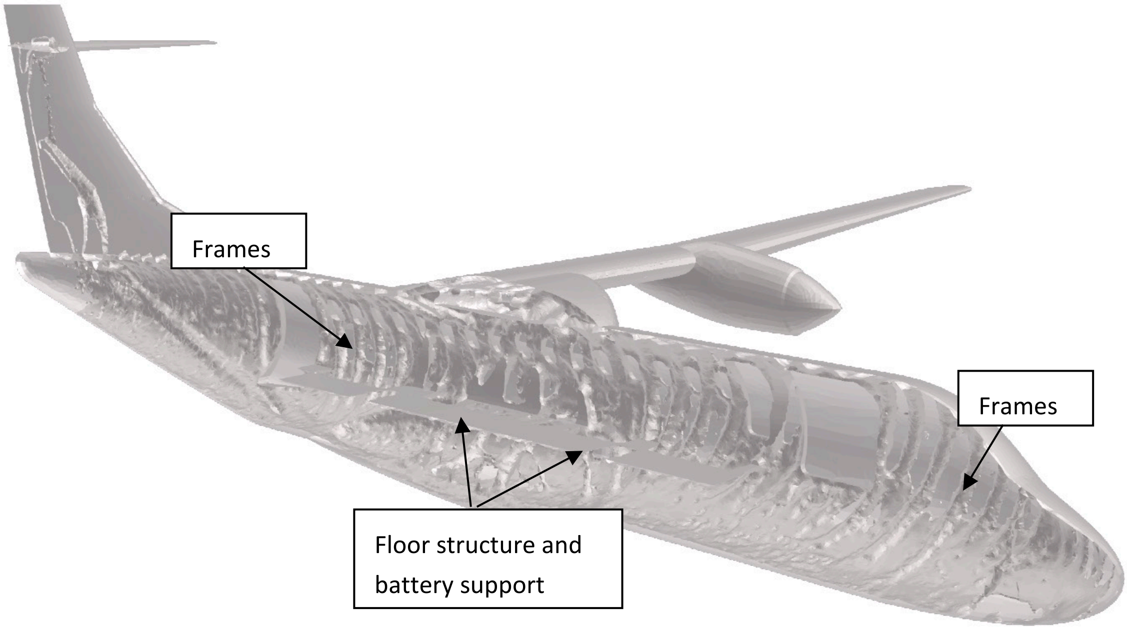


Figure 12: Cross section of the topology optimized aircraft with 0.05 m mesh size. Features can be identified that could be used for further electric aircraft development

From these results it was concluded that the use of topology optimization could give new insight in electric aircraft structural concepts and placement of the battery packs. However currently due to the topology optimization in combination with the relative coarse mesh the mass is too high. Therefore it is challenging to derive metrics on weight reduction and robustness of the structure. Further research is needed to translate these new insights into actual structural design and detailed design. An example is to translate the non-conventional frame designs from the topology optimization to beam elements and include this in the structure, see Figure 13.

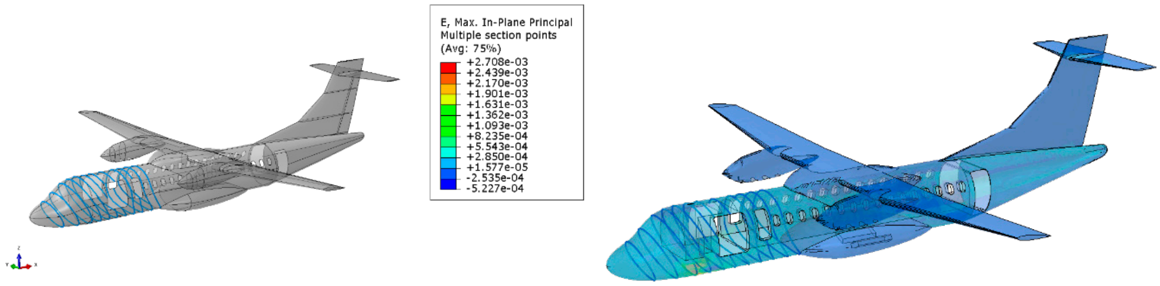


Figure 13: Example of translating the optimized result in a shell and non-conventional frames represented by beam elements (blue) model with on the right results of the analyses

5 Conclusion

The need to reduce the environmental impact of aviation leads to an increased interest in electric propulsion systems. In this context, this study presents a comprehensive exploration into structural topology optimization of the fuselage and wing structure of an ATR 42-600 retrofitted for battery-electric propulsion. The goal was to achieve an optimal balance between weight reduction and structural robustness while accommodating the unique challenges posed by battery integration.

Through an analysis of diverse loads, ranging from gravity and internal pressure to battery loads and cockpit pressure, the study showed the complex interaction of forces that influence the design. The utilization of a hybrid 3D model, blending shell and solid elements, facilitated a detailed representation of the structural behaviour under varying conditions. This modelling approach was the starting point for topology optimization, where strain energy and structural volume were used as primary design responses.

The results showed interesting insights into the intricate load paths within different battery placement configurations. These configurations not only demonstrated the adaptability of the structure to varying loads but also highlighted the critical role of battery placement in shaping load distribution. The optimization process further highlighted the structural strengths of the 1st configuration for the wing design. As the findings indicated, a balance between weight reduction and structural robustness can be attained through innovative structural design, effectively addressing the challenges of battery integration. However currently due to the topology optimization approach in combination with the relative coarse mesh with centimetre sized element the optimized structural mass is too high. Therefore it is challenging to derive representative metrics on weight reduction and robustness of the structure. Further research is needed to translate these new insights into actual structural design and detailed design from which weight metrics can be derived.

In conclusion, this study shows an innovative approach in the structural design of battery-powered aircraft concepts. By merging advanced modelling techniques with topology optimization, the research provides a valuable framework for engineers and researchers to further enhance the design of electric aircraft. As the aviation industry continues its search for eco-friendly alternatives, this research contributes to a promising future where innovation and sustainable design are combined.

6 Limitations and Future Work

Future work could involve exploring various directions that build upon the current research findings and contribute to a more comprehensive understanding of battery-powered aircraft structural optimization. Some potential directions for further research:

- Multi-objective Optimization: While the current study focused on minimizing strain energy while meeting structural volume and geometry constraints, future research could consider multiple objectives, such as minimizing weight, maximizing stiffness, and optimizing stress distribution simultaneously. This would provide a more holistic approach to achieving an optimal structural design.
- Battery Integration Challenges: Deeper research into the challenges of battery integration, such as thermal management and structural support. Investigation could point towards how these challenges influence the structural design and how topology optimization can address them.
- Advanced Material Selection: Exploration of using advanced materials, such as composites or lightweight alloys, in the structural design. Investigate how these materials affect the topology optimization process and the resulting structural performance.
- Battery Technology Development: Include the potential advancements in battery technology beyond the estimated 2030 specifications. Investigate how evolving battery energy density and other characteristics could influence the optimal structural design.

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