Review Article

Advances in Lightweighting Strategies for Aerospace: Materials, Structures, and Fuel Innovations

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ABSTRACT

This paper explores the practice of lightweighting in aerospace, which involves reducing a vehicle's weight without compromising its functionality. Lightweighting is a rapidly advancing field with significant impact on commercial, private, and federal air/spacecraft. It is a top priority in aerospace research due to its broad benefits, including improved performance, reduced environmental impact, and increased operational efficiency. Additionally, lightweighting offers value to industries beyond aerospace, such as manufacturing and transportation. This paper delves into three main approaches to lightweighting: material innovations, structural optimization, and fuel advancements. Lightweight materials like alloys, composites, and polymers each have distinct advantages and drawbacks. Alloys are cost-effective and have a strong strength-to-weight ratio, while composites offer higher strength at lower weight but are more expensive and complex. Polymers can be tailored for specific functions, making them versatile in their applications. Structural optimization involves balancing durability and weight through advanced designs like ribbed fuselage shells and hybrid wing-body structures. Meta-heuristic algorithms help find optimal solutions to the structural problem of size, shape, and topology. Lastly, alternative fuel sources are explored for their energy density and potential to support lightweighting. Overcoming the challenges presented by new fuel sources and their characteristics proves an ongoing endeavor, however. Some radical and new ideas exist to reduce energy consumption uncorrelated with fuel source, also progressing lightweighting. Together, these methods contribute to significant advancements in aerospace technology.

Keywords: Lightweighting; Aerospace; Materials; Structures; Fuel; Aerodynamics; Alloys

INTRODUCTION

In aerospace, lightweighting is the practice of making aerospace vehicles weigh less while maintaining the standard function, ideally without making any significant sacrifices. An ongoing practice, lightweighting is a constant pursuit of improvement and advancement. Engineers and scientists are constantly working to develop lighter machines, an endeavor that improves the aerospace field as a whole.

Lightweighting is one of the most crucial considerations for advancement of the overall aerospace field, as its benefits are widespread and universal. A lighter machine requires less fuel, which in turn lightens it further,

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reducing the strain of providing fuel for some of the more fuel intensive vehicles. A spacecraft, for example, requires an immense amount of fuel to perform, making spaceflight unsustainable in some cases. With a lower fuel requirement, however, an aerospace vehicle developer can send more craft into space at a lower cost. A lighter machine is also able to carry a heavier load, as the lower weight of the vehicle makes more room available for added weight such as passengers, cargo, and more. This benefits vehicles universally, whether it be commercial airlines looking to take on more passengers with heavier luggage, cargo transport vehicles that can carry more in a single trip, combat vehicles such as jets that can carry more weapons, or spacecraft that can now afford more protective measures. All vehicles, in fact, can install better systems or improve existing systems with the excess weight they are now able to add on. Moreover, there is an intrinsic link between weight and performance. A lighter machine is able to fly quicker with the same amount of fuel as a heavier one, make turns better and have better overall agility, and require less energy to move, leading to more efficient performance. Machines generally — considering no or minimal sacrifices in other areas — accomplish tasks more efficiently when lighter.

The benefits of a lighter aerospace vehicle go beyond the machine itself, however. The carbon emissions caused by air/spaceflight are a key drawback to aerospace as a whole, but a lighter craft will use less fuel to accomplish the same task, reducing both the harm of usage and the amount of usage an aerospace vehicle needs to get its job done. The lower level of carbon emissions caused by this benefit makes the environmental strain of air/spaceflight less of a problem and is very good for the future of our environment as a whole.

Costs are another area in which lightweighting has benefits. Manufacturing such an advanced and powerful vehicle costs a lot, but lightweighting can help reduce the financial strain on the manufacturing industry. More efficient materials mean a lower amount needs to be used to achieve the same level of performance, and so the manufacturing sector needs to work with less. Less material costs less, is less time consuming, and overall reduces the costs of manufacturing. The fact that less material is needed has benefits elsewhere as well, fewer raw materials are required. Lower strain on other industries necessary for acquisition of those materials and lower costs for them as well as the manufacturers. On top of this, the transport costs for components and materials are lowered with lighter components and less raw material in need of transporting. With successful lightweighting, the manufacturing and packaging costs, transport costs, and material costs are all lowered, alleviating some strain on a plethora of industries involved in each step of the process of making an aerospace vehicle. Lightweighting makes the aerospace industry a more sustainable one. Aerospace can progress and advance while providing less strain on the surrounding industries as well as doing less harm to the environment. Successfully advancing in this field is a positive cycle of improvement, constantly providing benefits that only incentivize further advancement rather than complacency.

The practice and study of lightweighting revolves around multiple approaches, each with its own risks and merits. One of these approaches is the practice of advancing the materials used in aerospace to be lighter. Challenges arise when considering the numerous other characteristics an engineer must consider when looking at an essential material for an air/spacecraft. These other characteristics must be maintained in order for the lightweighting of the material to have any net benefits. Certain components require high tensile strength, others must withstand harsh conditions, and many must support great loads in order keep a craft intact during flight, landing, or takeoff.

There are many more characteristics essential for different parts of a vehicle that also provide significant challenge to engineers and scientists in lightweighting. Another approach focuses on the very structure of the vehicle. The structure can be changed and modified to require less material or mass and therefore be lighter. An optimally structured vehicle can make significant weight savings. The challenge resides in the inherent way the structure of a vehicle affects its function. Structure is crucial to alleviating some of the challenges of successful air/spaceflight, the most obvious one being the aerodynamics of the vehicle. A structure created to reduce weight cannot compromise the aerodynamics of the vehicle. Another consideration is the conditions an aircraft must endure. One example of this is the pressure difference between the inside and outside of the vehicle, which causes stresses that must be endured. The shape of the components helps with this, with certain shapes having inherent properties, such as hoop tension, without the need for the material itself to have more advanced properties. A structure that is less resistant to different pressures may require more bolstering through other means, which can bring about more complications.

The third and final approach covered by this paper is the fuel and propulsion of the aircraft. The blanket term fuel encapsulates some of the greatest challenges engineers and designers face when building aerospace vehicles. A vast amount of fuel is required for a successful flight, especially spaceflight. This of course adds a lot of weight. Such a problem can be alleviated in a few different ways, including changing the fuel itself or changing the systems in a vehicle to make the usage of the fuel more efficient. One can make the fuel itself release more energy when combusted so that less of it is required. Alternatively, adding multiple fuel systems to make use of more than one power source can work well as long as adding the required systems does not outweigh what the previous single system of fuel would have weighed. Changes can also be made to the air/spacecraft's energy systems to make the usage of the fuel more efficient.

Enhancing the materials in an air/spacecraft is a fundamental practice in aerospace, and one that experiences ongoing advancements and innovations. Materials have strengths and drawbacks in their characteristics, requiring engineers to carefully consider what they use and where they use it. Among many other characteristics, some are prized for pure tensile strength and ability to take on heavy loads, others are prized for their resistance to extreme conditions such as heat, and more still are prized for a good strength to weight ratio. Despite this, the demands and drawbacks for some of these materials can prove to be a significant drawback. The blanket term of materials can be divided into 3 main categories: alloys, composites, and polymers. Alloys are made up of at least 1 metallic material working with other materials, like copper and zinc being mixed to make bronze. Steel is an example of a different type of alloy, as it is made up of iron and carbon, only one of which is a metal. The primary appeal of alloys comes from their comparative simplicity and unparalleled durability. For the components that require considerable strength, alloys provide the strength at a lower weight. Composites are less homogenous by comparison, being made up of multiple components working together to form a more effective whole. They require precise manufacturing but are the cornerstone of weight reductive materials. The concept of a composite material is the basis of much of lightweighting. Composites are also among the most versatile options for component materials, being effective in a wide range of applications. Polymers are materials that are defined by their molecular structure, being made up of all or a large number of similar units being bonded together. Advanced polymers are tailored to display particular properties for specific applications. Polymers are organic chemical materials such as resins and plastics. They can be synthesized and are used for their unique mechanical properties such as heat or corrosion resistance, chemical resistance, and even self-healing properties. Polymers are best suited for harsh conditions and unique requirements other more basic materials cannot offer. Table 1 offers a view of some material classes and their properties, including specific examples.

Alloys are metallic, they contain at least one metallic component. In any aerospace vehicle, there are likely a wide variety of alloys being used, more than one might expect. The number of alloys that can be made are nearly limitless, as any combination of metals at varying concentrations will create a new alloy. The most commonly used in aerospace are aluminum, steel, and titanium, though there are a vast number of others with good application potential.

Aluminum in particular is prized for being one of the more cost effective and easily manufactured options. Aluminums from the 7000 family of alloys are used in many aircraft components. They are cost effective and provide the necessary strength for many components while being quite light, sporting a tensile strength of 400 - 500 megapascals and a density of around 2,800 kgs per

Table 1. Table depicting example of material class, includes tensile strength, elastic modulus, density, specific strength, specific stiffness, and comparative price of material class example (10)

Material Class	Example	Tensile Strength/ Mpa	Elastic modulus /Gpa	Density/ (Kg/m^3)	Specific Strength /(kN.m/kg)	Specific stiffness/ 10^{-3} (Gpa.m^3/kg)	Price
Al alloys	AA2024-T3	483	73.1	2.78	173.7	26.3	Medium
	AA7075-T6	572	71.7	2.81	203.6	25.5	
Ti alloys	Ti-6AI-4V	1170	114	4.43	264.1	25.7	High
Steels	AISI 4130	703	193	7.86	89.4	24.6	Low
Composites	CFRP	1500	135	1.6	937.5	83.75	Very high
	GLARE	1214	66	2.52	481.7	26.2	

meter cubed (10). Aluminum is used in the fuselage and wings of most modern aircraft. Aluminum alloys present a drawback in corrosion resistance and raw strength, however. This can be remedied through corrosion resistant coatings, or, in some cases, may deem the use of aluminum unviable. In said cases, titanium alloys may be used instead.

Titanium offers much better corrosion resistance and more strength, at a higher weight, however. Titanium is therefore used in components that require the extra strength despite the increased weight, and also components that require longevity. It has a tensile strength of 1170 megapascals (10). Titanium's resistance to corrosion means components that employ it will have that extra longevity and will not succumb to the breakdown all metals face nearly as fast as other alloys like aluminum. This alloy can be found in structural components, engine parts, and landing gears, all of which are components that need to be strong or last for a while. In some cases, however, even titanium's strength is not enough for certain components. It is not the densest material that can be used, sporting a density of 4,430 kgs per meter cubed, meaning its strength for a certain volume will be lower than something like steel.

Steel is an ideal option for those parts that need to withstand particularly heavy loads and require great tensile strength to withstand pressures. Steel is the densest of the three alloys mentioned in this section, sporting a density of 7,860 kgs per meter cubed, and being far denser than titanium and therefore far heavier. Steel is only used when necessary, as the tensile strength it provides, 703 megapascals, comes with a lot of drawbacks (10). Despite this, however, steel is used even when lightweighting because while it is comparatively heavy, its strength to weight ratio keeps up with modem demands. Steel is employed within the components requiring the most strength and durability such as the most demanding structural components and parts of the landing gear (1).

Composites are not metallic and, in many cases, more complex than alloys, being made up of two or more non-metallic materials bound together into one stronger composite material. These advanced structures are a step forward from alloys, in terms of advancement in lightweighting. Composites display superior properties in more or less every field. Their purpose is to be stronger and lighter, the basis of material lightweighting. On top of this, they boast greater corrosion, chemical, and temperature resistance. They succumb less to fatigue and corrosion, making them longer lived and require less maintenance. Composites can also claim to be more flexible in both design and usage. They can be molded to shape more precisely than materials such as alloys, enhancing their cooperation with structural considerations and can be used in far more situations due to their superior properties. Composites such as carbon fiber reinforced polymers (CFRPs) and fiberglass composites have become standard in many air/spacecraft (1). These materials replace traditional metals and alloys, providing greater strength and lower weight. Figure 1 offers a view of different methods used to reinforce composites. Composites are far more complicated to produce, however, and much more expensive to purchase. Their inherent complexities, namely the number of different materials combined and precise molecular changes on top of the precision needed to make them force composites into a less practical category, though modern aerospace and industrial advancements make them more practical for commercial use every day. Some aircraft today feature primarily composite components, such as the Boeing 787 Dreamliner boasting a primarily CFRP fuselage.

Spacecraft, however, can make the greater claim to composites. Due to space travel being far more demanding and difficult, with spacecraft needing to withstand the harsh conditions of space and high speeds required to reach space, innovative materials are comparatively more necessary. On top of this, space travel is not commercial and is oftentimes not done for profit, meaning profit margins are not a constraint unlike commercial aircraft. This is among the reasons space travel is far more expensive, its

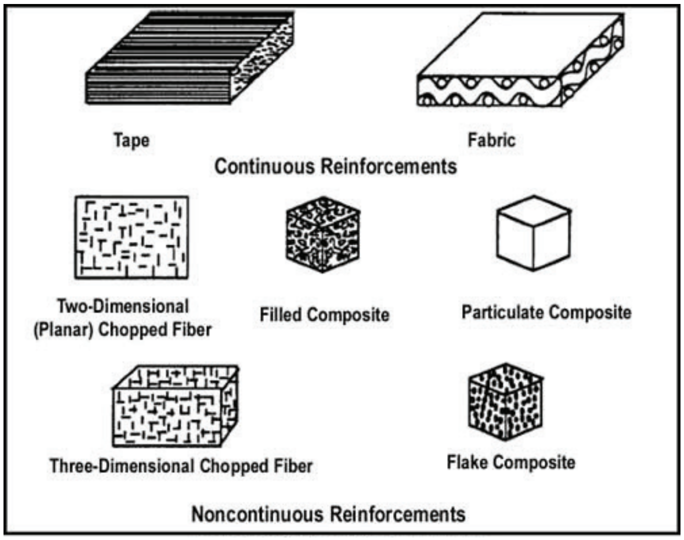

Figure 1. Schematic of composite materials. Adapted from (17).

need for more advanced materials such as composites. Modern structures such as satellites employ composites within their structure for the best strength to weight ratio possible. They can be combined with polymers to create an even stronger and more effective material. Fiber reinforced polymers, for example, are composites that are renowned for their strength to weight ratios. Some of their properties can be changed or influenced by changing the orientation and arrangement of the fibers within the material's matrix. This shows the versatility of composites and how they can be modified to meet specific requirements. Manufacturing these composites can be difficult. It requires precise modifications as well as expensive material. Various techniques to make them exist, such as filament winding (12), autoclave and resin transfer molding (14), and other automated techniques such as additive manufacturing (15) and computerized numerical control (13). These methods are necessary to ensure precision and accuracy required in complex components. Figure 2 depicts some of the different material classes that can be placed under the term 'composites.'

Polymers are unique in that they cannot be substituted like alloys and composites and serve their own unique purposes within an aerospace vehicle. They are indispensable for the creation of materials with enhanced mechanical properties. Their ability to be modified, similar to composites, makes them versatile while maintaining a low weight profile. Polymers are different from composites and alloys in that they are chemical materials that can be sourced organically or synthesized (1). Prime examples of polymers include resins and plastics. High performance polymers are prized for their good strength to weight ratios and resistance to harsh conditions, whether they be environmental or not. Polyetheretherketone (PEEK) is one example of a high-performance polymer. PEEK in particular has high heat and chemical resistance. Its thermal stability and ability to withstand harsh chemical factors makes it appropriate for use in aerospace components that are under harsh environmental conditions and high temperatures, having a melting point of 334 degrees celsius (11). Epoxy resins are used for their adhesive qualities and their versatility, being able to be modified for specific uses. Thanks to their exceptional heat resistance, polyimides are used in engine components as well as thermal shielding (1). Polymers can be taken a step further when nanocomposites are incorporated within them. Nanocomposites can enhance the characteristics of a polymer, and the two can combine to increase tensile strength, heat resistance, conductivity, and more, similar to composites. Polymeric materials shine in the creation of unconventional, flexible structures. They can be used in adhesives, sealants, insulation, and other components that protect and enhance systems, as well as in structural components (1). Figure 3 provides a molecular representation of the addition of equal monomers for polymerization.

Successful implementation of material innovation has occurred throughout the history of aerospace research. They propel the aerospace industry as a whole forward, as new precedents and goals are set. The boundaries of what is possible are pushed further. Previously, composite materials were only able to be used in moderate or low temperatures, leading to their application being severely limited despite the potential we know composites have thanks to their modern use. This changed with the development of PMR-15, a high temperature polyimide

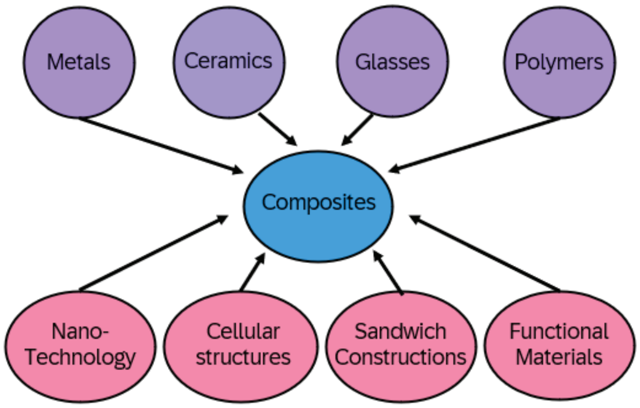

Figure 2. Diagram depicting materials and material development techniques defined under the blanket term of 'composites.'

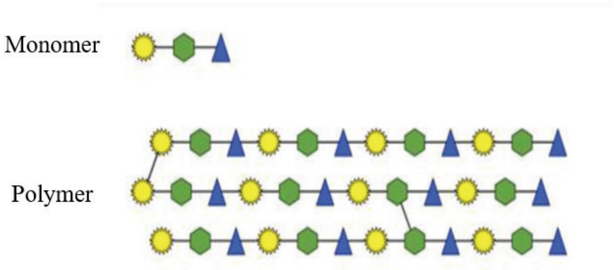

Figure 3. Molecular diagram depicting the addition of equal monomers for polymerization (18).

resin. PMR-15 was interwoven with a graphite fiber, forming a composite able to be used at extreme heat conditions. This composite was then used in the engine of a navy fighter jet, and by 1986, was qualified for commercial production and use (4).

ANALYSIS OF STRUCTURAL OPTIMIZATION IN AEROSPACE

Lightweighting can be effectively carried out in many vastly different fields. Among these is the structure of an air/spacecraft. Ensuring that the structure of an air/spacecraft is optimized for its purposes is crucial to aerospace practices. Structural weight reduction is an endeavor taken by both federal and commercial sectors. It does not require expensive or advanced materials, only a good understanding of structural strengths and drawbacks as well as good ideas. Structural innovations are a priority in many research divisions both governments based and civilian. Advancements come in the form of new and innovative shapes and structures to incorporate within aircraft components to reduce the weight while maintaining a satisfactory level of strength and resistance to pressures. Aircraft components are subject to different forms of stresses from multiple sources, including pressure from the altitude and the weight of the aircraft. Advancements go a long way to improve the efficiency of aircraft, reducing their weight profile in a way unlike any others. Structure alone, ignoring weight or tensile strength can introduce benefits and drawbacks inherent in their shape. For the purposes of this section, we will be setting aside other forms of lightweighting apart from structural lightweighting and working under the assumption that the structure is the only variable changing.

The fuselage structure in an aircraft is crucial to its functionality and ability to withstand stresses placed on it by the outside environment as well as the loads the craft will need to carry. Setting aside other methods of lightweighting, the stronger one wishes an aircraft fuselage to be, the heavier it must be, due to the strength conventionally being consistent with weight and the added weight from bolstering a structure. To work around this, designers employ tensions inherent in structure as a way to ensure strength without too much weight. Figure 4 depicts a circular fuselage's strain and displacement. Circular fuselages are seen in most commercial aircraft, and this is due to hoop tension. When the cross section of a structure is circular, hoop tension comes into effect and goes a long way to resist any pressures and stresses. This can be seen in any tubelike structure but is exemplified in aerospace fuselages. Hoop tension reduces the amount of bolstering required to ensure the strength and durability of an aircraft. Challenges occur when attempting to use other structures for the fuselage. One example of this is in the hybrid wing-body (HWB) fuselage. Figure 5 depicts an HWB fuselage in an exploded view. An HWB fuselage is one without a clear and distinct line between the wing and main body of the craft. This structure provides a benefit in aerodynamics, having more streamlined edges than other fuselages, namely the circular fuselage structure seen in commercial aircraft. HWB fuselages can be seen in more advanced military craft, as counteracting and working around/through the drawbacks of an HWB fuselage are expensive and therefore more realistic for the military than commercial airlines. On top of this, the benefits of an HWB structure are more useful in military craft. One considerable drawback of an HWB structure is the significantly higher stress it is put under (5). Circular structures are put under hoop pressure while HWB structures, with their flatter exterior, are subject to bending pressure. Bending pressure is considered an order of magnitude worse than hoop pressure. Furthermore, axial stresses lead to the beam-column effect, which occurs due to axial pressure being combined with bending pressure. The beam-column effect then leads to additional structural buckling and uncertainty. This leads to further measures being needed to ensure an HWB fuselage is functional.

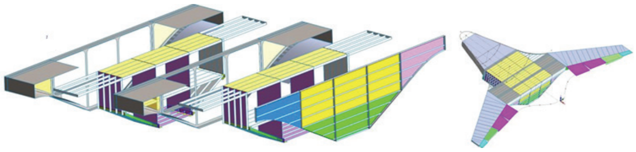

Figure 4. Diagram depicting strain and displacement of circular fuselage for aircraft (9).

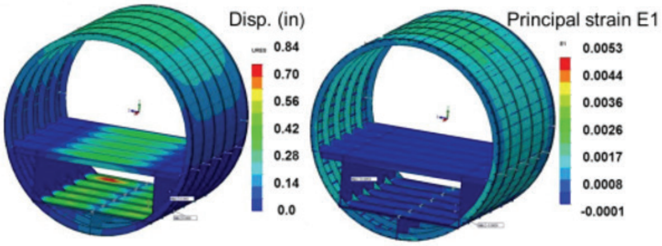

Figure 5. Exploded view of multi-bay, bulkhead, and inter-bay joint model HWB fuselage with vehicle assembly (9).

To resist bending pressures, the shell of the aircraft can be modified. Deep sandwich shell structure involves two thinner layers "skins" sandwiching a thicker core material. This structure in particular is made for withstanding strong pressures and helps resist them while maintaining a lightweight profile. It is commonly used in marine engineering, construction, and automobiles as well as aerospace (16). This pressure resistance translates and can be applied to the field of aerospace. Double skin ribbed shell structure involves two thin layers separated by ribbing throughout. Ribbing, or cylindrical structures running at an angle to the skin, bolsters the structural integrity of any structure. In this case, the ribbing also leaves a lot of empty volume within the shell, leading to decreased weight while maintaining a good level of strength. Honeycomb structures are another option, involving structures reminiscent of a honeycomb to maintain structural strength while leaving empty volume within. This, similar to the aforementioned ribbing structure, leaves the weight profile low while ensuring support throughout the shell.

Optimizing aircraft components, however, sometimes does not need significant design changes and instead minor ones to get what is required at the lowest weight possible. In some cases, the size can be reduced slightly, or the shape, or the distribution of materials within the component. Achieving ideal size, geometry, and material distribution can further reduce the weight of already effective designs. These miniscule adjustments can have disproportionately significant effects on the performance of a craft thanks to the weight reduction. Algorithms are a pioneering step towards the goal of optimization. Optimization algorithms can find solutions better than human engineers and can do so much quicker. There are numerous different algorithms that can do this, such as genetic algorithm, dandelion optimization algorithm, grey wolf optimization algorithm, and more (2). These all take a meta-heuristic approach, a problem-solving strategy that builds upon heuristics by giving them a higher-level framework and guidance system. The algorithms go over every possible solution to a problem, eventually finding one that offers the desired characteristics. While this is effective, it is not perfect and does not always guarantee perfection. Despite this, the algorithms will still find a good solution, or one near perfect, so they maintain their status as an effective problem-solving tool. In structural optimization, this leads to the finding of the ideal size, shape, and topology for a given component within specific guidelines and restrictions. For example, a landing gear must be quite strong and durable to withstand the heavy loads it is put under. A properly configured optimization algorithm will find the best or near best size, shape, or topology for the landing gear to reduce its weight to the maximum while maintaining a threshold of strength.

ANALYSIS OF FUEL INNOVATIONS IN AEROSPACE

Innovations in the fuel of air/spacecraft present a direct connection to lightweighting, with the fuel systems of a craft contributing a significant portion of the total weight. Simply due to the fact that more efficient fuel reduces the amount needed and therefore the weight added to the craft due to fuel, a more efficient and effective power source will cause weight reduction. Conventional jet fuel works well, but comes with drawbacks, leaving room for innovation and improvement. Some alternative sources of fuel applicable to aerospace include hydrogen fuel, alcohol, biofuel, and synthetic jet fuel (7).

Hydrogen is commonly seen as among the most environmentally friendly options, as the combustion of liquid hydrogen emits no carbon dioxide (7). However, liquid hydrogen combustion requires a complete overhaul of storage and transport systems. It will require more complex ground transport, storage, vent capture, and distribution systems due to its inherent differences from conventional jet fuel, including but not limited to its much lower density. Liquid hydrogen's combustion has very poor volumetric heat, leading to low energy density and forcing further design changes and compromises. Alcohol fuels, methanol and ethanol, are similar to hydrogen fuel in its poor mass and combustion volumetric heat, posing the similar challenges to liquid hydrogen (7). Both these fuels would not serve to positively impact lightweighting, as the energy density and efficiency of the fuels are inferior, on top of the extra systems required to successfully implement them.

Biofuels are another alternative fuel, one sourced from agriculture. The fatty acids in crops are used as the fuel source, and are combusted similar to alcohol and hydrogen fuels to power an aircraft (7). However, biofuels are more complicated to produce as they should be used within six months of their manufacturing. Biofuels are therefore mixed in with petroleum fuel to combat this drawback (7). Not only are biofuels more complicated to make, but they are also less energy dense than conventional jet fuel. To use biofuel would be to increase the weight added by fuel, not decrease like is the goal of lightweighting.

Synthetically developed fuels made particularly for energy density present a viable solution. Traditional jet fuels typically have a density of 0.77-0.83 g/ml, being more dense than some of the more environmentally friendly alternatives (8). The energy density of fuel is related to density and volumetric net heat of combustion, the latter of which is nearly linearly positively related to the former, as seen below. Figure 6 depicts a graph representing this nearly linear relation. Synthetic HED hydrocarbon fuels are denser alternatives to conventional jet fuel. They can reach densities of over 0.93 g/ml, roughly 20% superior to conventional RP-3 fuels (8). Despite the improved density, new fuels come with new problems that must be addressed before their use in aviation. RJ-5, a liquid hydrocarbon fuel with a density of over 1.0 g/ml, has a very high freezing point and RJ-7, a similar fuel, has very high viscosity (8). These properties both can cause engine shutdown. Once such issues are addressed, liquid synthetic fuels and HED fuels can be the future of aerospace. The increased energy density lowers the volume of energy required. It also improves performance considerably. Less fuel and less volume both go a long way to advance lightweighting, reducing the weight of one of the most essential and important systems on an air/spacecraft.

Alternative fuel sources can help but can also result in massive changes needed to maintain the same efficiency level. Some are simply far heavier, take up more space, or are less powerful. Others have such different properties that they need a complete overhaul of the energy systems in an aircraft. Despite this, the potential does exist for a new fuel source that can provide superior efficiency to conventional sources and therefore reduce the weight of the craft it is used in. The pursuit of advanced energy is one that transcends aerospace. It is universal in nearly every field, and every field is affected by energy. Aerospace is one of the trickier fields to innovate in by nature but benefits just like any other. Energy advancements are some of the most crucial in aerospace and provide significant benefits to lightweighting as well.

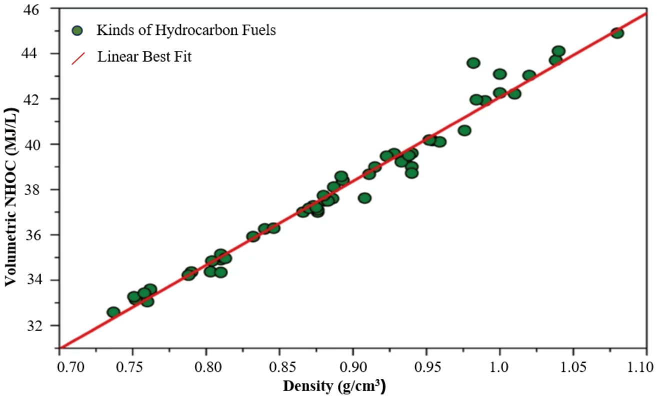

Figure 6. Graph depicting volumetric net heat of combustion (NHOC) vs. density, showing nearly linear positive correlation (8).

CONCLUSION

Lightweighting presents a constantly advancing field or aerospace, one that makes constant innovations and shows no signs of stopping. Lightweighting is a field that has no clear end goal, and therefore leaves research open to continuous innovation, progressively and steadily improving the field of aerospace and its technology. Materials are the substance of the air/spacecraft itself, and reduction in the weight of the materials is among the most important endeavors a lightweighting engineer can take. Composites present a more complex and costly but better alternative to alloys, which themselves are more complex and costly but better compared to plain metals. Composites can be the future of material advancements, and can be incorporated into polymers as well, creating some of the most complex and advanced materials while improving their characteristics in an unparalleled way. Advancements and complexity in structures can help improve their weight profile as seen in ribbed and honeycomb structures, though simpler physical properties such as hoop tension, bending stress, and axial stresses are important to be considered when the shape of a component such as the fuselage of an aircraft is in question. Algorithms help with the simpler tasks of structural lightweighting, such as finding the optimal shape, size, and topology of a component. While biofuels, alcohol fuels, and hydrogen fuels all go against principles of lightweighting, synthetic fuels such as liquid hydrocarbons and HED fuels present a viable solution. They are denser and better for lightweighting concerns, giving them a future in aerospace once their many problems are overcome. Combined, lightweighting methods and research advance aerospace beyond any other field. Future directions in aerospace lightweighting include the use of multifunctional materials that combine mechanical strength with sensing or thermal management capabilities (1). Techniques such as additive manufacturing (15) and out-of-autoclave processing (14) offer promising alternatives to traditional manufacturing methods. Additionally, emerging bio-based polymers and nanostructured materials have the potential to further reduce weight without sacrificing performance (1, 16). Looking ahead, limitations remain in the cost and complex manufacturing requirements of advanced materials, computational demands of structural optimization, and the hurdles of integrating new fuel systems into existing ones.

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DECLARATION OF CONFLICT OF INTERESTS

The author declares that there are no conflicts of interest regarding the publication of this article.

REFERENCES

1. Singh J, *et al*. Advancements in Lightweight Materials for Aerospace Structures: A Comprehensive Review. *Acceleron Aerospace Journal*. 2024; 2 (3): 173–183. https://doi.org/10.61359/11.2106-2409
2. Akçay Ö & Ilkılıç C. Light-weight design of aerospace components using genetic algorithm and dandelion optimization algorithm. *International Journal of Aeronautical and Space Sciences*. 2025; 1-12. https://doi.org/10.1007/s42405-025-00900-2
3. Lukkassen D & Meidell A. Advanced materials and structures and their fabrication processes. *Narrik University College, Hin*. 2003; 174-182.
4. Composites for Lighter Structures. Nasa Technical Reports Server. 1986. https://ntrs.nasa.gov/api/citations/20020090883/downloads/ 20020090883.pdf
5. Mukhopadhyay V. (2012). Hybrid-wing-body pressurized fuselage modeling, analysis and design for weight reduction. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA* (p. 1999). https://doi.org/10.2514/6.2012-1999
6. Rohacs J, *et al*. Radically new solutions for reducing the energy use by future aircraft and their operations. *Energy*. 2022; 239: 122420. https://doi.org/10.1016/j.energy.2021.122420
7. Daggett D, *et al*. (2006). Alternative fuels and their potential impact on aviation. In *25th Congress of the International Council of the Aeronautical Sciences (ICAS 2006)* (No. E-15568).
8. Nie J, *et al*. Development of high-energy-density liquid aerospace fuel: a perspective. *Transactions of Tianjin University*. 2022; 28: 1-5. https://doi.org/10.1007/s12209-021-00302-x
9. Mukhopadhyay V & Sorokach MR. (2015). Composite structure modeling and analysis of advanced aircraft fuselage concepts. In *AIAA modeling and simulation technologies conference* (p. 3096). https://doi.org/10.2514/6.2015-3096
10. Zhu L, *et al*. Light-weighting in aerospace component and system design. *Propulsion and Power Research*. 2018; 7 (2): 103-119. https://doi.org/10.1016/j.jppr.2018.04.001
11. Yuan M, *et al*. Influence of molecular weight on rheological, thermal, and mechanical properties of PEEK. *Polymer Engineering & Science*. 2011; 51 (1): 94-102. https://doi.org/10.1002/pen.21785
12. Minsch N, *et al*. Analysis of filament winding processes and potential equipment technologies. *Procedia CIRP*. 2017; 66: 125-130. https://doi.org/10.1016/j.procir.2017.03.284
13. Li Y, *et al*. From computer-aided to intelligent machining: Recent advances in computer numerical control machining research. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 2015; 229 (7): 1087-1103. https://doi.org/10.1177/0954405414560622
14. Umemoto Y, *et al*. (2011). Out of autoclave material «semi-preg». Technical development of resin transfer molding. In *Proceedings of the 18th International Conference on Composite materials (Korea International Conference on Composite Materials)*.
15. Wong KV & Hernandez A. A review of additive manufacturing. *International scholarly research notices*. 2012; 2012 (1): 208760. https://doi.org/10.5402/2012/208760
16. Kausar A, *et al*. State-Of-The-Art of Sandwich Composite Structures: Manufacturing—to—High Performance Applications. *Journal of Composites Science*. 2023; 7 (3): 102. https://doi.org/10.3390/jcs7030102
17. Design and Manufacturing Guideline for Aerospace Composites. (1999) https://llis.nasa.gov/lesson/682
18. Zhianmanesh M, *et al*. Plasma surface functionalization: A comprehensive review of advances in the quest for bioinstructive materials and interfaces. *Appl. Phys. Rev.* 2023; 10 (2) (2023 Apr 4), Article 021301. https://doi.org/10.1063/5.0130829