Chapter

Structural Analysis of Electric Flight Vehicles for Application of Multifunctional Energy Storage System

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Abstract

The Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS) research project goals were to develop M-SHELLS, integrate them into the structure, and conduct flight tests onboard a remotely piloted small aircraft. Experimental M-SHELLS energy-storing coupons were fabricated and tested for their electrical and mechanical properties. In this chapter, finite element model development and structural analyses of two small test aircraft candidates are presented. The component weight analysis from the finite element model and test measurements were correlated. Structural analysis results with multifunctional energy storage panels in the fuselage of the test vehicle are presented. The results indicate that the mid-fuselage floor composite panel could provide structural integrity with minimal weight penalty while supplying electrical energy. Structural analyses of the NASA X-57 Maxwell electric aircraft and an advanced aircraft fuselage structure are also presented for potential application of M-SHELLS. Secondary aluminum structure in the fuselage subfloor and cargo area are partially replaced with reinforced five-layer composite panels with M-SHELLS honeycomb core. The fuselage weight reduction associated with each design without risking structural integrity are described. The structural analysis and weight estimation with composite M-SHELLS panels in the fuselage floor indicates 3.2% structural weight reduction, but with increased stress.

Keywords: advanced composite, multifunctional structure, green aviation, electric flight vehicle design, finite element analysis, honeycomb panel, electrical energy storage, structural weight estimation and reduction, aircraft design

1. Introduction

For sustainable green aviation, the innovative electric flight vehicle structures should be lighter, yet safer than the existing technology can offer, in order to reduce the overall weight and subsequently fuel consumption and emission. This chapter describes structural design of advanced electric flight vehicle concepts, which are potential candidates to meet some of the environmental friendly performance goals. Under the NASA Aeronautics Research, Convergent Aeronautical Solution Program, Glenn Research Center (GRC) has been leading Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS) research. The technology of integrating load-carrying structures with electrical energy storage capacity has the potential to reduce the overall weight of future electric aircraft. Langley Research Center (LaRC) along with GRC fabricated and tested lightweight, laminated honeycomb composites with special anode, cathode, and separator materials that are dually capable of generating electrical power and carrying mechanical loads. Storing and releasing electrical energy with hybrid super-capacitors combined with advanced composite structures has the potential to reduce both the charging time and overall weight. Krause and Loyselle [1] at GRC proposed developing, analyzing, and testing this multifunctional structures technology. The Materials and Electro-chemistry Division at GRC has conducted extensive research on multifunctional structural composites that are capable of generating electrical power and carrying mechanical loads.

Figure 1 shows a roadmap of the multifunctional structures technology development and systems analysis [2]. At GRC, advanced multifunctional composite laminate and hybrid super-capacitor energy storage systems are being developed. Numerical models of electrochemical reactions and energy storage concepts are also being developed at GRC. Newman [3] presented the specific energy and specific power characteristics of existing fuel cell and battery technologies and conventional energy sources in the Ragone plot (**Figure 1a**). The initial performance goal for the M-SHELLS system was to demonstrate a specific energy of 75 Wh/kg at a specific power of 1000 W/kg. These modest M-SHELLS specific energy and power targets are also shown in **Figure 1a**. An expanded view of the Ragone plot is shown in **Figure 2** for additional discussion. The honeycomb sandwich structure for the M-SHELLS concept is shown in **Figure 1b**. Specimens were fabricated and tested in the structures concept laboratory at GRC and LaRC to characterize both the electrochemical and mechanical properties. **Figure 1c** shows one tensile test result of an initial single layer experimental M-SHELLS honeycomb specimen.

The remotely piloted small airplane, named *Tempest*, developed by UASUSA Inc., was acquired for retrofitting with a multifunctional system to provide partial power and augment the existing Lithium-Polymer (Li-Po) battery (**Figure 1d**). The Li-Po battery provides 4 amperes of current for peak power during catapult launching and 2 amperes of continuous current for cruise power. A separate battery supplies steady power to the flight control system. The objective of the flight test project was to augment the present 18.5-volt Li-Po battery with an M-SHELLS power pack to demonstrate its functionality and flight worthiness. Although the planned flight test was eventually cancelled due to project constraints, the initial structural model development and associated structural analyses are presented.

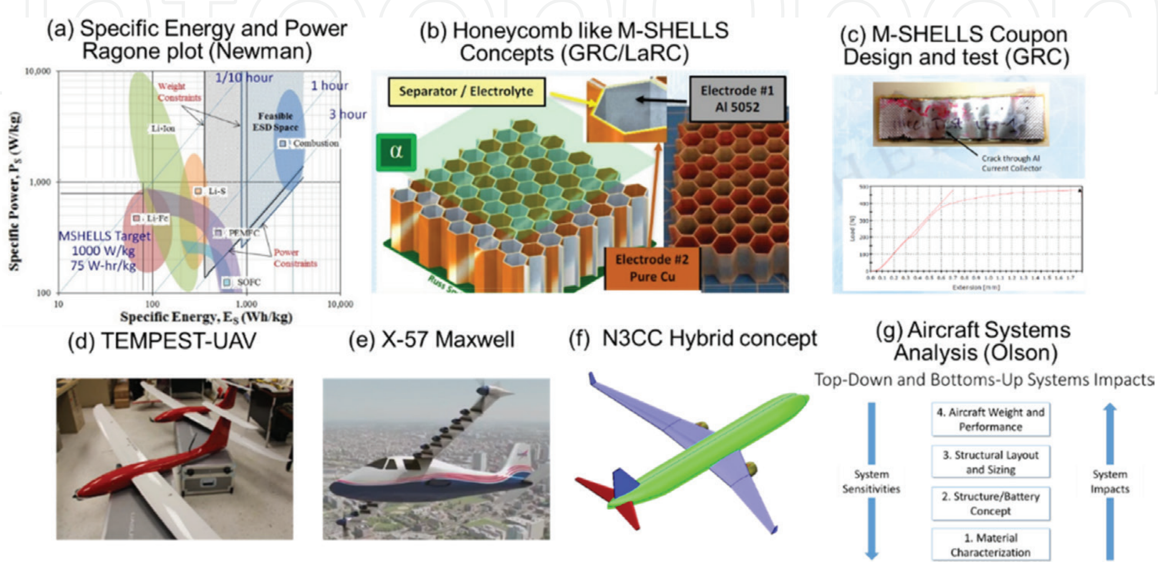


Figure 1.
Multifunctional load bearing structure and systems analysis roadmap.

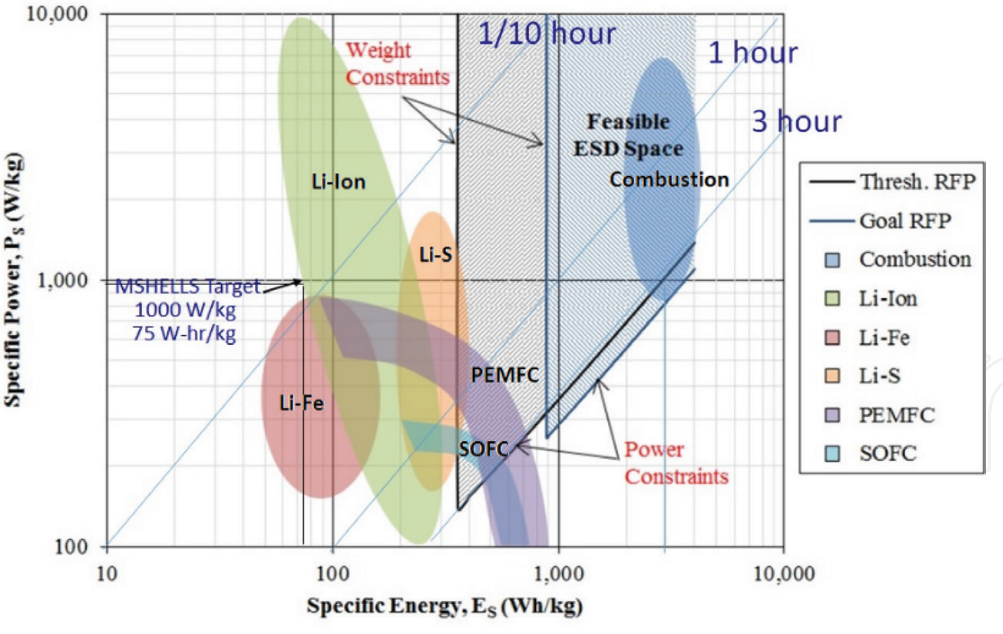


Figure 2.
Ragone plot for specific energy and specific power characteristics of energy source devices.

Figure 1e shows the NASA X-57 Maxwell experimental test aircraft concept [4] with a distributed electric propulsion system that has 12 electric-motor-driven propellers on the high-lift wing. The synchronized motors are powered by a 358 kg battery pack. Presently, construction of the X-57 Maxwell test vehicle is occurring under the Scalable Convergent Electric Propulsion Technology Operational Research (SCEPTOR) project. The X-57 Maxwell vehicle will test the performance of this specially designed wing with distributed electric propulsion to evaluate mission benefits for this class of vehicle. Structural analysis of the fuselage floor modeled with a reinforced M-SHELLS composite panel is briefly described.

As a final application, structural and aircraft systems analysis for the NASA N+3 Technology Conventional Configuration (N3CC) derivative with hybrid-electric propulsion (**Figure 1f**) were conducted by Olson and Ozoroski [2] in order to predict the multifunctional performance and weight benefits of the M-SHELLS technology (**Figure 1g**). In this report, secondary aluminum structure in the N3CC fuselage sub-floor and cargo area are partially replaced with M-SHELLS composite panels for structural stress and weight analysis.

Newman [3] presented an extensive feasibility and design study of a small, manned aircraft with electric powered propulsion. His report included the range of specific energy and specific power characteristics for existing Lithium-based batteries, Proton-Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), and aviation fuel. **Figure 2** is his summary plot of the specific power and energy specifications, which is often referred to as a Ragone plot. Newman concluded that, besides conventional combustion, PEMFC and SOFC were the only two feasible energy source devices given the selected set of mission and aerodynamic (weight and power) constraints and the design specifications for his project. The initial performance goal for the M-SHELLS battery system was to demonstrate a specific energy of 75 Wh/kg at a specific power of 1000 W/kg. These M-SHELLS energy and power targets are superimposed on Newman's plot in **Figure 2**. While this target is modest compared to Li-Ion, Li-Fe, and Li-S based batteries, the main advantage of the M-SHELLS technology is that it could replace part of the load bearing structure, particularly in small drones and in lightly loaded fuselage structure of experimental electric aircraft such as the X-57 Maxwell.

2. M-SHELLS coupon test

The proposed M-SHELLS research goals were to develop test specimens and subcomponents, integrate them into a small test vehicle structure, and conduct low-risk flight tests. The M-SHELLS test coupons in the form of honeycomb panels were fabricated and tested by Russell Smith (LaRC) and Brett Bednarcyk (GRC) for mechanical and electrical properties. **Figure 3** shows the normal compression load shakedown test of a small, stabilized aluminum honeycomb coupon fabricated for mechanical property assessment. The compressive crushing strength and compressive modulus were computed and compared with the published characteristics of a Hexcel 1/4-5052-0.002 honeycomb. The flatwise compression modulus of the aluminum honeycomb coupon with 1/4-inch cell and 0.002-inch foil thickness is 139,000 psi and the crushing strength is 436 psi. The published in-plane shear modulus of the Hexcel 1/4-5052-0.002 honeycomb is 66,000 psi and the shear strength is 300 psi in the length direction. In the width direction, the in-plane shear modulus is 30,000 psi and the shear strength is 120 psi. Since the normal compression strength test result and Hexcel published data were very close, the mechanical properties of Hexcel honeycomb were used by Olson and Ozoroski [2] for the initial structural and multifunctional performance benefit analysis of the N3CC derivative with hybrid-electric propulsion. They also accounted for the additional weight of core material required to complete the energy storage functionality.

Figure 4 shows the in-plane tensile load versus extension plot from an initial tensile test of an early M-SHELLS active coupon prototype with anode/cathode elements and electrolytes. The honeycomb test coupon dimensions were 6.0 inch (150 mm) in length, 2.0 inch (50.8 mm) in width, and 1.0 inch (25.4 mm) in depth. The face-sheets were 0.002 inch thin aluminum foil. The electrical tests were conducted at NASA Glenn Research Center. Considering only the linear part of the deformation, a 90 lb (400 N) load produces an extension of 0.6 mm. Thus, relative to the unloaded specimen, the linear elastic strain was 0.004 at the 90 lb (400 N) load. The specimen yielded beyond the 400 N load and developed a crack at 480 N. The linear Young's modulus (stress/strain) was computed to be 11,188 psi ($77.52 \times 106\ N/m^2$). The corresponding in-plane shear modulus was 4024 psi for the Poisson's ratio of 0.39. The in-plane tensile and shear modulus computed from the coupon test results were very low for flight application. Hence, for the present analysis, additional outer face-sheets were added on each side to add strength to the honeycomb core (**Figure 1b**). Several detailed finite element models (FEM) of three flight vehicles were developed having certain fuselage areas replaced with this reinforced composite panel having a honeycomb core. Structural analyses of these models are described. The complete summary of all material properties used in this

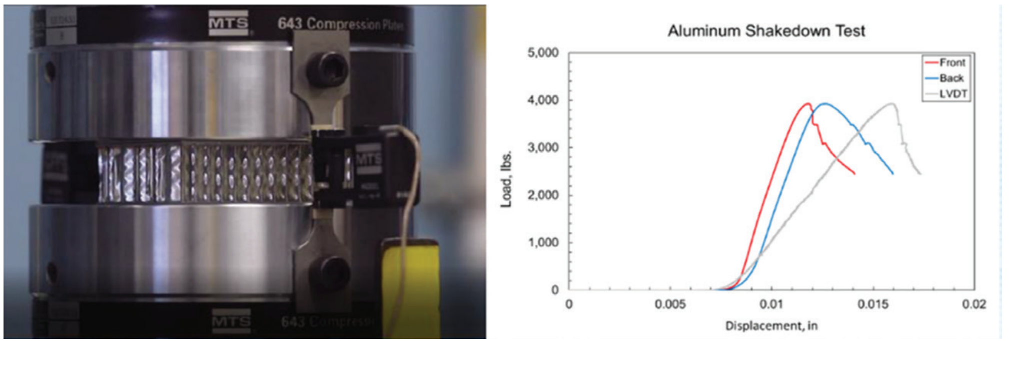


Figure 3.
Normal-compression load shakedown test of a small, stabilized aluminum honeycomb coupon fabricated for mechanical property assessment.

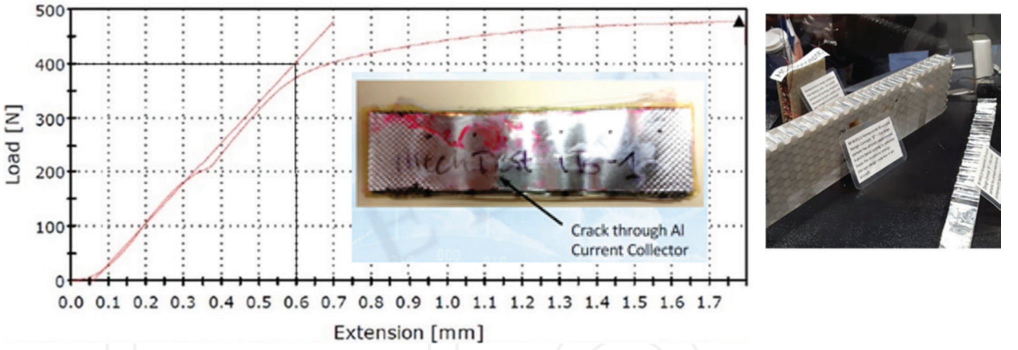


Figure 4.
Initial tensile test result of an experimental M-SHELLS coupon prototype.

chapter are presented in Appendix A. The M-SHELLS panel design properties and computed density are presented in Appendix B.

3. Flight test vehicle structural model development

Initially, several low-cost, small model aircraft were considered for finite element analysis and simulation, with multifunctional lightweight composite panels replacing part of the wing and fuselage structure. A remotely piloted small aircraft was selected with a 127 inch wingspan and a takeoff weight of 16 lb. Adequate details about the internal structure and fabrication of this model airplane were not known, so a notional FEM of this small aircraft was quickly developed for initial structural analysis with design flight loads. **Figure 5** shows a preliminary structural model development of a similarly sized small hobby model airplane, which offered an initial low-risk candidate for flight testing of the M-SHELLS specimen. A typical wing FEM with a standard two-spar and rib configuration was initially developed. This structural arrangement would enable easy integration of small test coupons, between the two spars in the inboard section, close to the electric motor in the fuselage nose. The test specimen could also be integrated into the fuselage floor.

Figure 6 shows the wing deflection and strain distribution from initial structural analysis of the wing in level flight. The analysis assumed front and rear spar thicknesses of 0.15 inch with advanced composite material properties [5]. The linear elastic property values used for the front and rear spar are as follows: Young's modulus 9,750,000 psi, shear modulus 2,570,000 psi, and mass density 0.06 lb/in^3. The wing, fuselage, horizontal tail, and vertical tail skin thicknesses were 0.04 inch and were made of standard thermoplastic material. The linear elastic properties are as follows: Young's modulus 290,075 psi, shear modulus 47,250 psi, and mass density 0.04 lb/in^3. The wing deflections and skin strain distributions shown are with a fixed wing root and a 16 lb lift load, distributed elliptically along the wing. The maximum deflection and nodal strain were 1.95 inches at the wing tip and 0.00106 at the wing root, respectively. With this two-spar wing construction, the maximum wing-tip deflection and strain values at level cruise flight were considered high for a model airplane. The two-spar wing FEM weight was calculated to be 4.63 lb. The fuselage weight, with empennage, was calculated to be 3.8 lb.

When NASA Langley acquired two UASUSA-manufactured remotely piloted aircraft named "Tempest" for the planned flight test, additional information on the internal construction of the physical model was available. A *Tempest* model was dismantled to observe the internal construction at the wing root. The weight of each component of the disassembled model was also measured. Since the material properties of the *Tempest* wing and other model parts were not known, a bench test

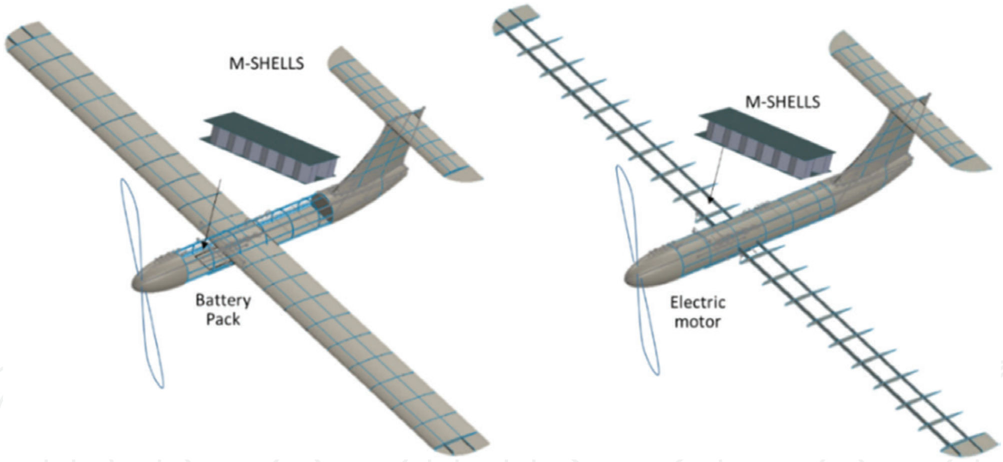


Figure 5.
Preliminary structural model development of the two-spar wing airplane.

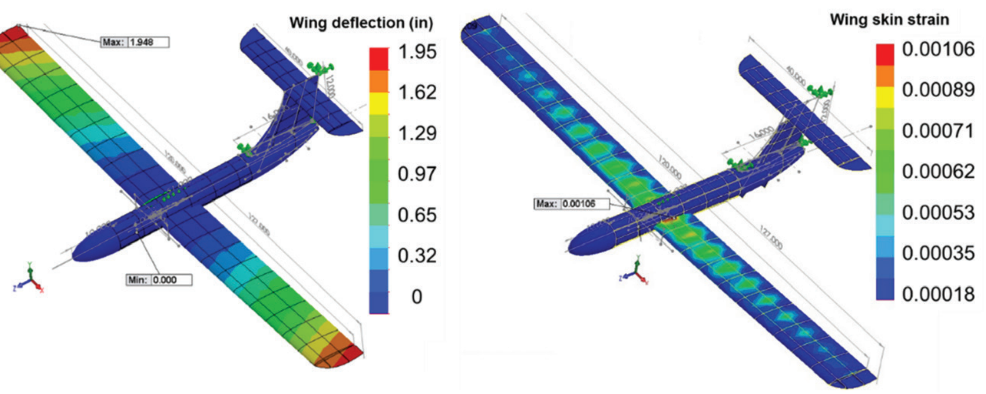


Figure 6.
Wing deflection and strain of the two-spar wing model airplane.

was performed to evaluate the wing deflection and stiffness under a simulated lift load. Gregory Howland and David Hare performed the bench load-deflection test at the NASA Langley model shop on a layout table. The loading configuration was based on the test setup scheme shown in **Figure 7**. The model was inverted and then leveled and supported by two foam blocks. The wing load application points were positioned at 24 inches from the centerline. Eight-pound weights were placed on the right and left wings symmetrically at those reference points. The average wing-tip displacement was ~0.94 of an inch. The load was removed from each wing and then the loading was repeated. The second time, the average wing-tip deflection was 0.96 of an inch. The inset photos in **Figure 7** show the bench test arrangement in the NASA Langley model shop.

Upon close examination of the model with the canopy removed, it was observed that the *Tempest* wing is constructed as two symmetric pieces of hollow, molded composite that are joined together with a short central stub-spar and two solid root-rib pieces, each 2 inches wide. **Figure 8** shows the *Tempest* wing construction. A new finite element model of the wing was developed to represent this construction. The central stub-spar and two wide ribs were modeled with solid advanced composite material properties as before. The molded fiberglass skin of the two wings was modeled as 0.025 inch thin composite material. The rest of the model used custom thermoplastic material.

The horizontal tail skin and ribs were modeled as 0.02 inch thin molded thermoplastic. The fuselage and vertical tail skins and ribs were modeled with 0.04 inch thin thermoplastic. The horizontal and vertical tail twin-spar thicknesses were

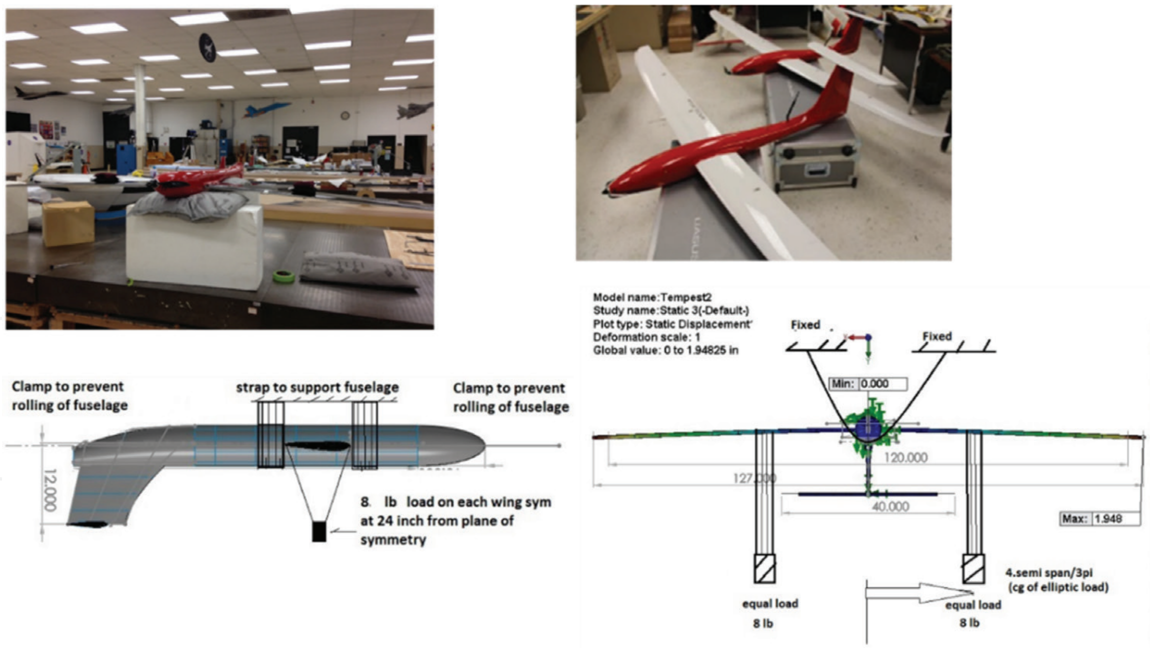


Figure 7.
Wing deflection test of the tempest aircraft with 16 lb total lift load on the wing.

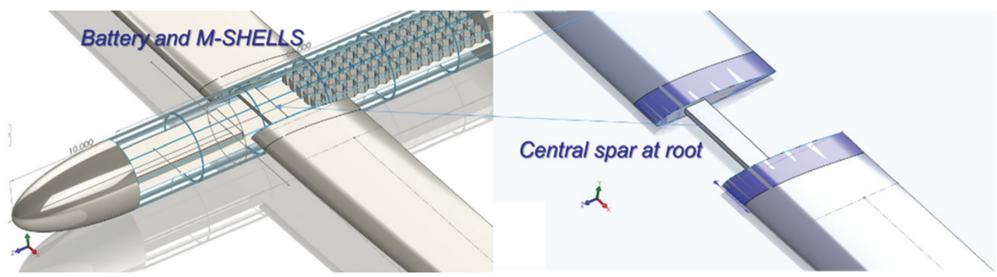


Figure 8.
Structural model and wing root internal detail of the tempest aircraft.

0.10 inch and 0.15 inch, respectively. **Figure 9** shows the wing deflection and nodal strain distributions from the FEM analysis with level flight load, assuming a 16 lb takeoff gross weight. See Appendix A for all the material elastic properties and density used in this chapter. With the improved FEM of the wing structure, the wing-tip deflection was 1.11 inch and the maximum strain at the wing root was 0.00067. The strain values were noted to be well within the allowable limits. The wing-tip deflection was closer to the experimental results than the preliminary FEM analysis results with the two-spar wing (**Figure 6**). This improved FEM analysis result was considered satisfactory for the structural component weight estimation.

Table 1 shows the measured component weights of the test vehicle and estimated weight for the initial two-spar wing model and the improved model of the **Tempest** wing. Some of the structural component weights and the electronic system weight inside the fuselage could not be measured separately, since the fuselage and vertical tails are molded as a single part. Hence, the weights of those components are grouped together in **Table 1**. The two-spar wing weight was estimated to be 4.63 lb. With the better FEM of **Tempest**, the estimated total wing weight of 3.54 lb is closer to the measured combined weight of 3.46 lb for its right and left wings and stub spar. The measured fuselage weight, 5.62 lb, included the co-molded vertical tail and electronic components inside the fuselage. It compared well with the improved FEM combined weight of the fuselage and vertical tail, including an estimated 2 lb weight for electronic components, telemetry system, and motors.

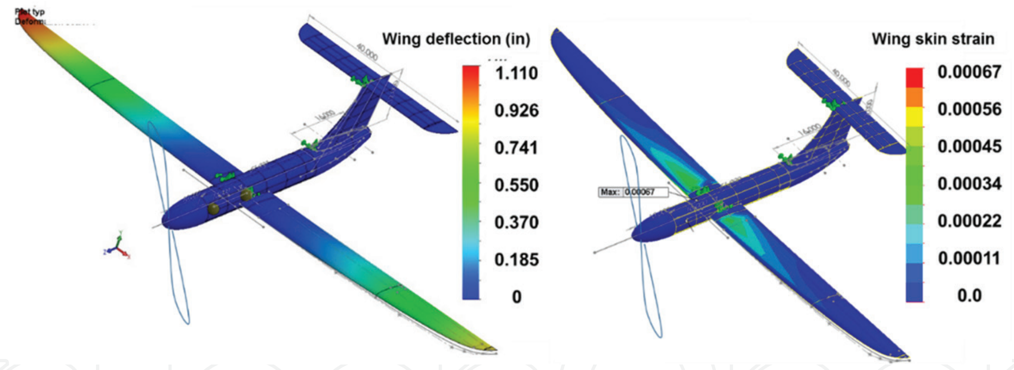


Figure 9.
Wing deflection and strain of the improved finite-element model of the test vehicle in level flight.

Component	Measured Weight (lbs)		FEM model with two spar wing (lb)		Improved Tempest FEM (lb)		Notes
Electronic			2.00	lb	2.00	lb	Estimated
Fuselage + vtail	5.62	lb	3.01	lb	3.01	lb	fus+vt w/o electronic
Canopy	0.27	lb	0.18	lb	0.18	lb	Estimated
Horizontal Tail	0.43	lb	0.66	lb	0.66	lb	
Wing	3.14	lb	4.63	lb	3.54	lb	with stub spar
Stub Spar	0.32	lb					
Flight Battery	2.30	lb	2.30	lb	2.30	lb	from 1st col.
Ballast Required for C.G	1.23	lb	1.23	lb	1.23	lb	from 1st col.
Baseline Op. Wt Total	13.30	lb	14.00	lb	12.91	lb	lb with electronic

Table 1.
Comparison of component weights of the tempest test vehicle, initial two-spar wing model, and improved tempest FEM.

The performance goal for the M-SHELLS development was to demonstrate a specific power of 1000 W/kg at an energy density of 75 Wh/kg. The flight test goal was to augment the existing Li-Po battery with 33% of the required energy for 30 minutes of flight or, equivalently, to supply the full electrical energy for 10 minutes of level flight. The Li-Po battery capacity is 7600 mAh and it provides 7.4 volts with two 3.7 volt cells in series. With a gross weight of 2.3 lb (1.04 kg), the energy density of the Li-Po battery is 55 Wh/kg. The ideal power required by the aircraft at cruise is computed from weight × velocity/(L/D), where L/D is the lift-to-drag ratio. Considering the propeller and motor efficiencies, the total power required to be supplied to the electric motor spinning the propeller is:

$$\text{Power Required} = \text{weight} \times \text{velocity}/\left[L/D \times (\text{propeller efficiency}) \times (\text{motor efficiency})\right] \quad (1)$$

For the *Tempest* test vehicle, let us assume a baseline cruise weight of 20 lb (88 N), a cruise velocity of 40 mph (17.9 m/s), and a typical L/D of 20. Assuming a motor efficiency of 85% and a propeller efficiency of 80%, the power required = 88 × 17.9/(20 × 0.85 × 0.80) = 116 W and the energy required for 10 minutes of level flight is (116 × 10/60) = 20 Wh. Hence, ideally, 0.58 lb (20/75 kg) of M-SHELLS material could provide full power for 10 minutes of level flight. The actual weight of the M-SHELLS power package would depend on the flight test voltages and current demand of the electric motor and the ability to package each unit in suitable series and parallel configurations to match the available power supply and required power demand.

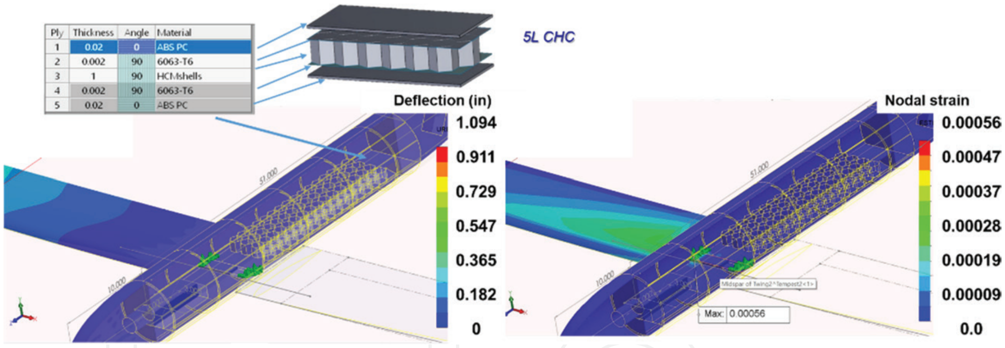


Figure 10.
Tempest FEM analysis with M-SHELLS composite panel fuselage floor.

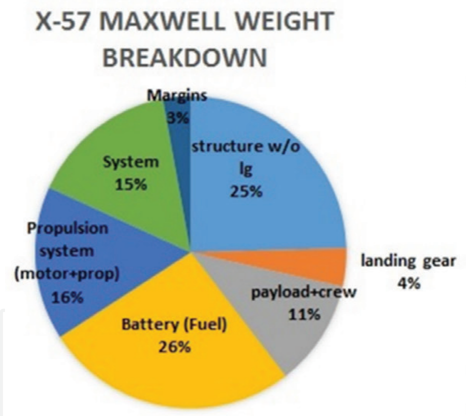
The structural deflection and nodal strain distribution from the FEM analysis results of the *Tempest* vehicle with a lightweight M-SHELLS composite panel replacing the fuselage floor are shown in **Figure 10**. The five-layer bonded sandwich panel consisted of 0.02 inch thermoplastic sheet for insulation on the outer faces, 0.002 inch aluminum sheet on the inner faces and 1.0 inch deep honeycomb M-SHELLS core. The original fuselage floor weight was 0.32 lb. One stack of this five-layer sandwich energy storage panel replacing 180 in^2 of mid-fuselage floor would weigh 1.25 lb. The mid-fuselage floor composite, multifunctional panel would provide both structural integrity and supply electrical energy to supplement the existing Li-Po battery of this vehicle.

4. NASA X-57 Maxwell test vehicle

Under the Scalable Convergent Electric Propulsion Technology Operational Research (SCEPTOR) project, the X-57 Maxwell test vehicle wing is presently being constructed at NASA Armstrong Flight Research Center. **Figure 1e** showed the NASA X-57 Maxwell experimental test aircraft concept [4] with a distributed electric propulsion system featuring 12 electric-motor-driven propellers on an innovative high-lift wing. The X-57 Maxwell vehicle will test the performance of this specially designed wing with distributed electric propulsion in order to evaluate mission benefits for this class of vehicle.

Figure 11 shows the weight breakdown of the NASA X-57 Maxwell experimental test aircraft. The original wing of the Italian *Tecnam P2006T* aircraft will be replaced with a specially designed distributed electric propulsion wing with 12 electric-motor-driven propellers. The wing-tip propellers help reduce the induced drag from the tip vortex. The synchronized motors are powered by a 358 kg Nickel-Cobalt-Aluminum (NCA) battery pack. The electric power system is organized into eight battery modules, split into two packs with 4 battery modules and a control module each. Cooling is provided through 18,650 cells spaced evenly, 4 mm apart. The NCA cells provide sufficient energy density and the required discharge rate for the flight test mission. Each pack supplies 47 kWh of useful energy, with a peak discharge power of 132 kW. The total battery package weight is estimated to be 790 lb (358 kg), or 26% of the total aircraft takeoff gross weight of 3006 lb (1364 kg). The aluminum fuselage weight is 302 lb (136 kg), and the total estimated structure weight without the landing gear is 738 lb (335 kg).

Figure 12 shows initial power requirement estimates for the standard mission of the X-57 Maxwell [6] flight test vehicle. The energy requirement for each phase of the mission is obtained by integrating the power requirement over time



Category	Weight %	weight (lb)	weight (kg)
structure w/o lg	25%	738 lb	335 kg
landing gear	4%	119 lb	54 kg
payload+crew	11%	333 lb	151 kg
Battery (Fuel)	26%	790 lb	358 kg
Propulsion system (motor+prop)	16%	480 lb	218 kg
System	15%	460 lb	209 kg
Margins	3%	86 lb	39 kg
Total	100%	3006 lb	1364 kg

Figure 11.
Component weight fractions for the X-57 Maxwell electric distributed propulsion vehicle.

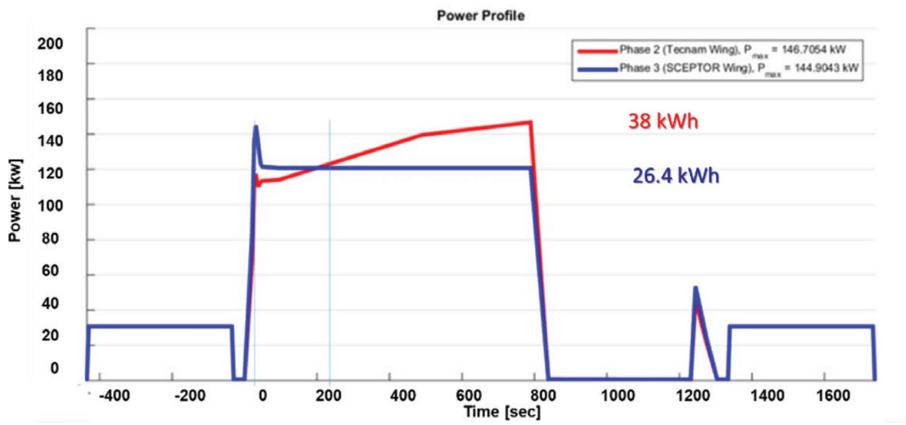


Figure 12.
X-57 Maxwell standard mission power requirement estimates.

(area under the power requirement curve). For example, during the cruise time interval of 800 seconds (0.22 hours), at constant power the energy required is 120 × 0.22 = 26.4 kWh with the X-57 wing (blue line). Based on the current mission analysis utilizing the original *Tecnam* wing, 38 kWh is required to meet the peak power demand of 145 kW (red line).

Assuming M-SHELLS could produce 1000 W/kg specific power at a 75 Wh/kg specific energy, a 120 kg M-SHELLS package would ideally provide 120 kW of power and 9 kWh of energy. Given the 120 kW of power required during cruise with the X-57 wing (blue line), the M-SHELLS package could supply energy for a duration of 0.075 hours, or 270 seconds, at level cruise.

A brief structural analysis of the fuselage was conducted, where a reinforced M-SHELLS multifunctional panel can be safely substituted to partially replace the lightly loaded aluminum floor structure. **Figure 13** shows an example of fuselage floor deflection and shear stress with the original floor replaced by a reinforced composite panel with the M-SHELLS core. The five-layer composite sandwich panel consisted of two 0.05 inch thermoplastic sheets for reinforcement and insulation on the outer faces, which were bonded to the two 0.002 inch aluminum sheets on the inner faces over the 1.0 inch deep M-SHELLS core. For this example, the total distributed floor load is 265 lb (120 kg) distributed over the forward fuselage floor area. The fuselage floor deflection is nominal and the majority of the shear stresses across all plies are generally within the allowable limits except at the end support areas, where local reinforcements will be needed.

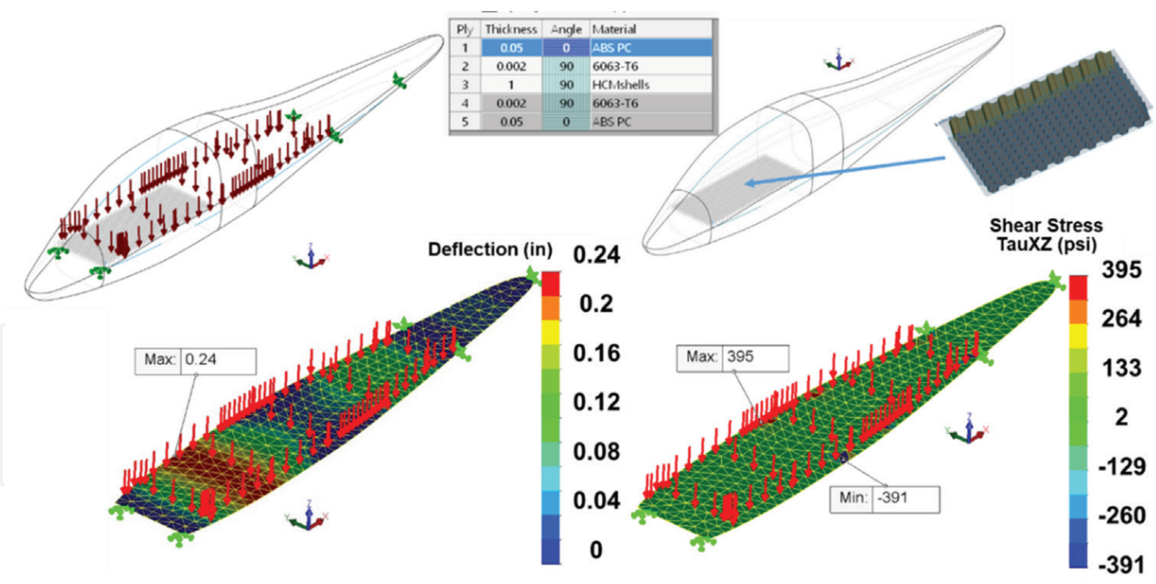


Figure 13.
X-57 floor deflection and shear stress analysis with 265 lb (120 kg) M-SHELLS distributed over the forward fuselage floor area.

5. Hybrid-electric aircraft

In the ARMD Advanced Air Transport Technology (AATT) project, several aircraft concepts are presently being studied to quantify the performance improvements and emissions reduction afforded by hybrid-electric propulsion. Jansen et al. [7] have conducted extensive systems analysis to evaluate the risks and benefits of a conversion from an all-fuel turbofan to a hybrid-electric turbofan engine concept. Among the propulsion options considered by this study, the "hFan" concept is a gas turbine-electric hybrid engine capable of operating in all-gas turbine, all-electric, or combined mode, depending on mission requirements. Conventional and truss-braced wing concepts with hybrid-electric propulsion were also investigated by Bradley and Droney [8, 9] at the Boeing Company.

Objectives of the NASA Electrified Aircraft Propulsion (EAP) research are to increase fuel efficiency and to reduce the emissions and noise levels of commercial transport aircraft. Primary EAP propulsion concepts include turboelectric, partially turboelectric, and hybrid-electric systems. Applications are presently being evaluated for regional jet and larger sized single-aisle aircraft. The overall goal is to demonstrate the viability of at least one of the EAP concepts. A hybrid-electric derivative of the N+3 technology conventional configuration (N3CC) is an ideal candidate for future applications of the M-SHELLS technology, by replacing lightly loaded portions of the fuselage structures where use of lightweight honeycomb panel is possible. The outer mold line (OML) of this aircraft concept [5] was developed using the Open Vehicle Sketch Pad tool [10, 11]. The internal structure of a fuselage segment of this vehicle was developed using SolidWorks [12] for finite element analysis. The structural analysis included a combination of aluminum and reinforced M-SHELLS composite panels for stress, deflection, and weight estimation. A block diagram of the FEM development and sizing process is presented in Appendix C.

Figure 14a shows the N3CC vehicle model with internal structure, and the detailed FEM of a fuselage segment is shown in **Figure 14b**. The fuselage section design loads consist of an internal cabin pressure of 18.4 psi, passenger floor load of 1 psi, and cargo floor load of 2 psi. The weight analysis of the N3CC hybrid concept fuselage segment with Al 7075-T6 construction is shown in **Table 2**. The total FEM weight of this all-aluminum fuselage segment is 4992 lb. This includes a passenger floor weight of 876 lb,

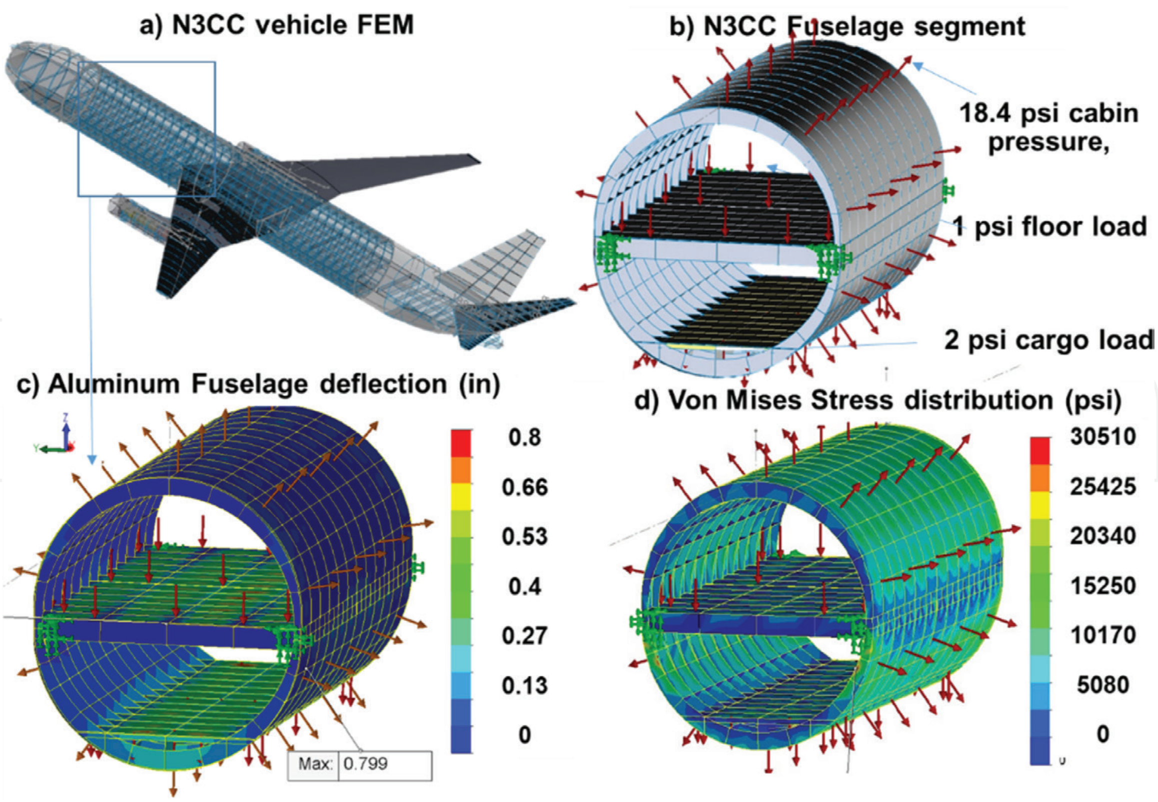


Figure 14.
N3CC fuselage segment analysis with aluminum 7075-T6 material construction.

Fuselage Assembly	height (in) 160	width (in) 148			length/segment 288 in			frame spacing 24 in		FEM		fuselage
Segment Structural Items	length	width	area	thickness	volume	material	density	item weight	no. of items	total weight		segment component
segment 1	inch	inch	in^2	in	in^3		lb/in^3	lb			unit	weight (lb)
fuselage frame (oval)	segment		3699	0.208	769	AL	0.1015	78	13	1015	lb	per segment
fuselage outer skin	288	493	141984	0.156	22150	AL	0.1015	2248	1	2248	lb	pass floor
passenger floor	288	148	42624	0.104	4433	AL	0.1015	450	1	450	lb	876
passenger floor beam	148	12	1776	0.104	185	AL	0.1015	19	13	244	lb	
passenger floor frame	288	12	3456	0.104	359	AL	0.1015	36	5	182	lb	outer shell
cargo floor skin	288	99	28512	0.104	2965	AL	0.1015	301	1	301	lb	3461
cargo floor frames	3	99	297	0.104	31	AL	0.1015	3	13	41	lb	Cargo floor
wing carry-thru beam	150	20	3000	0.104	312	AL	0.1015	32	2	63	lb	342
keel beam	288	19	5472	0.15	821	AL	0.1015	83	3	250	lb	keel+wing beam
longitudinal stringers	288	5	1440	0.104	150	AL	0.1015	15	13	198	lb	313
fuselage segment weight			295	sq ft passenger floor area				16.9	lb/sq ft	4992	lb	4992

Table 2.
Weight analysis of N3CC fuselage segment with aluminum 7075-T6 construction.

an outer shell weight of 3461 lb, a cargo floor weight of 342 lb, and the total keel-beam and cross-beam weight of 313 lb. **Figure 14c** shows the all-aluminum fuselage deflection and **Figure 14d** shows the von Mises stress distribution.

Figure 15 shows the modified fuselage section in which the passenger and cargo subfloor cross-beams were replaced with the five-layer reinforced composite panels with honeycomb core (5LCHC). The sandwich panels consisted of 1 inch deep M-SHELLS honeycomb core and 0.002 inch aluminum ply and 0.05 inch thermoplastic ply on each side. **Figure 15a** shows the N3CC fuselage model and design load. As before, the fuselage section design loads consisted of an internal cabin pressure of 18.4 psi, passenger floor load of 1 psi, and cargo floor load of 2 psi. The passenger subfloor and cargo subfloor cross-beams are now replaced with this five-layer bonded composite panel with M-SHELLS honeycomb core (**Figure 15b**). **Figure 15c** shows a significant increase in the maximum floor deflection compared to the all-aluminum construction shown in **Figure 14c**. **Figure 15d** shows maximum von

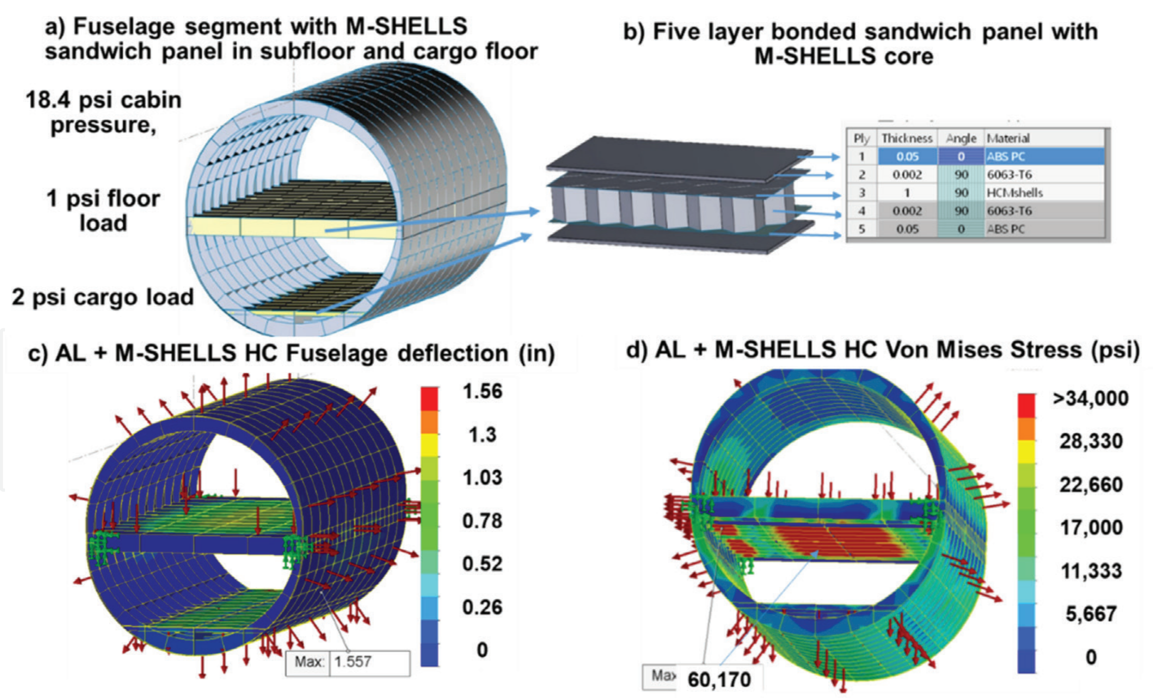


Figure 15.
N3CC fuselage segment analysis with passenger and cargo subfloor cross-beams replaced by reinforced composite panels with M-SHELLS core.

Fuselage Assembly	height (in)	160 width (in)		148 length/segment 288 in				frame spacing 24 in		FEM		fuselage
Segment Structural Item	length inch	width inch	area in ^{2}	thickness inch	material	property	unit	item weight lb	no. of items	total weight	unit	segment-1 component weight (lb)
fuselage frames (oval)	segment 1		3699	0.208	AL	0.1015	lb/in ^{3}	78	13	1015	lb	per segment
fuselage outer skin	288	493	141984	0.156	AL	0.1015	lb/in ^{3}	2248	1	2248	lb	pass. floor
passenger floor	288	148	42624	0.104	AL	0.1015	lb/in ^{3}	450	1	450	lb	728
passenger floor beam	148	12	1776	1.104	5LCHC	0.00689	lb/in ^{2}	12	13	159	lb	
passenger floor frame	288	12	3456	1.104	5LCHC	0.00689	lb/in ^{2}	24	5	119	lb	outer shell
cargo floor skin	288	99	28512	0.104	AL	0.1015	lb/in ^{3}	301	1	301	lb	3461
cargo floor frame	3	99	297	1.104	5LCHC	0.00689	lb/in ^{2}	2	13	27	lb	cargo floor
wing carry-thru beam	150	20	3000	0.104	AL	0.1015	lb/in ^{3}	32	2	63	lb	328
keel beam	288	19	5472	0.15	AL	0.1015	lb/in ^{3}	83	3	250	lb	keel+wing beam
longitudinal stringer	288	5	1440	0.104	AL	0.1015	lb/in ^{3}	15	13	198	lb	313
one fuselage segment weight			295	sq ft passenger floor area				16.37	lb/sq ft	4830	lb	4830

Table 3.
Weight analysis of N3CC fuselage segment with aluminum 7075-T6 and M-SHELLS honeycomb composite panel.

Mises stress distribution across all ply, which are significantly higher locally in the passenger sub-floor cross-beam.

The weight analysis of the N3CC hybrid concept fuselage segment with aluminum and M-SHELLS composite panels is shown in **Table 3**. The total FEM weight of this fuselage segment is 4830 lb. The passenger floor weight is reduced to 728 lb from 876 lb for the previous case. The aluminum outer shell weight remains 3461 lb. The cargo floor weight is reduced to 328 lb from 342 lb. The total keel-beam and cross-beam weight remains 313 lb. Thus, the weight reduction for one fuselage segment is 162 lb or 3.2%, at the cost of higher fuselage deflection and stress, but without risking the structural integrity (**Figure 15c** and **d**).

Since this substitution resulted in large increases in deflection and stress in the passenger floor (**Figure 15c** and **d**), additional sub-floor support in the cargo hold area was examined as shown in **Figure 16a** and **b**. The corresponding structural deflection and stress distribution are shown in **Figure 16c** and **d**. The maximum deflection was reduced significantly and the von Mises stress distributions were within the allowable limits. The additional M-SHELLS weight was 173.5 lb. Hence, the net weight increase was 11.5 lb (0.3%) per segment, compared to all aluminum construction, while adding 56 cubic foot of M-SHELLS storage volume. The fuselage section weight comparison summary from the three designs is presented in **Figure 17**.

These weight calculations with the reinforced M-SHELLS panel did not include copper current collectors, separator layers, and electrolyte that are required to complete the energy storage functionality but do not add to the structural strength. Appendix B shows the M-SHELLS panel density and properties. A full vehicle structural and systems analysis for the N3CC derivative with hybrid-electric propulsion was presented by Olson and Ozoroski [2] to predict the multifunctional performance and weight benefits with higher specific energy M-SHELLS replacing major primary structure. Their study showed that by offsetting the weight of some of the vehicle's primary batteries or mission fuel, an overall weight savings can be achieved through multifunctionality. An initial version of the paper was proposed for presentation in [13].

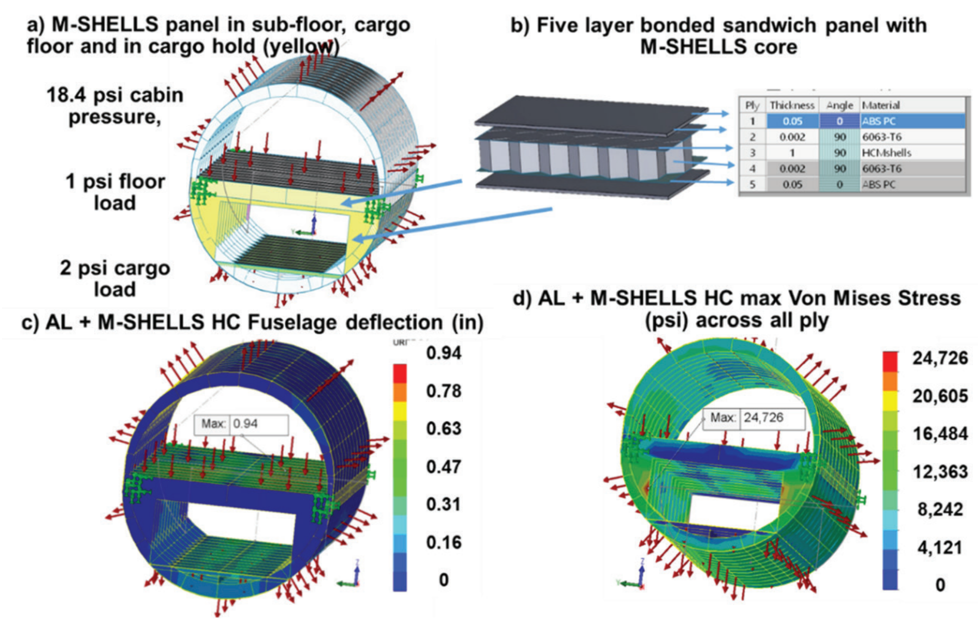


Figure 16.
N3CC fuselage segment analysis with additional reinforced M-SHELLS panel added to the subfloor cargo area.

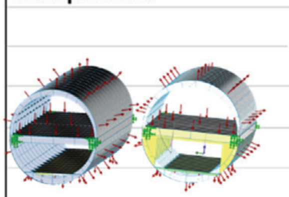
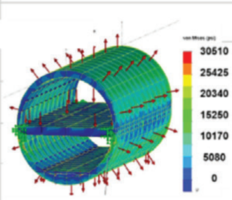
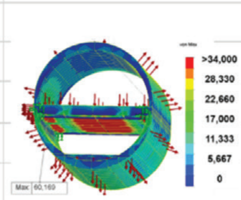
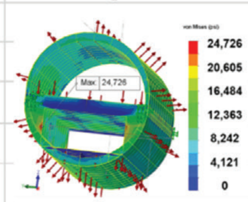
fuselage segment Component	ALL AL fuselage	AL + M-SHELL sub-floor	AL + M-SHELL sub-floor and Cargo area	unit
				
passenger floor	876	728	728	lb
fuselage outer shell	3461	3461	3461	lb
Cargo floor+ stiffener	342	328	501	lb
keel+wing cross beam	313	313	313	lb
Total wt /segment	4992	4830	5003	lb
% change in weight		-3.2%	0.23%	

Figure 17.
Summary of weight comparison from the three fuselage segment design.

6. Concluding remarks

The Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS) research project is described. The proposed project goals were to develop M-SHELLS in the form of honeycomb coupons and subcomponents, integrate them into the structure, and conduct low-risk flight tests onboard a remotely piloted small aircraft. The M-SHELLS sample units were scheduled for flight testing onboard a remotely piloted small aircraft named *Tempest*. Detailed finite element models of this small test aircraft were developed for basic structural strength and accurate weight analysis. The *Tempest* wing FEM was refined to include the unique wing construction and provide a closer match with the wing deflection results from a bench test. The component weight analysis from the finite element analysis and load test data were correlated. Finite element analysis results of *Tempest* with a reinforced five-layer M-SHELLS composite panel replacing the mid-fuselage floor were presented. Approximately, 2.2 lb of M-SHELLS would provide power for 10 minutes of cruise flight. Although the planned flight test was cancelled due to the project constraints, the analysis results indicate that the mid-fuselage floor composite multifunctional panel could provide both structural integrity and electrical energy to supplement the existing battery.

The NASA X-57 Maxwell distributed electric propulsion test vehicle was used as an example for potential application of the M-SHELLS technology. The fuselage floor structure was selected for substituting a reinforced composite panel with M-SHELLS core. A structural analysis of the fuselage floor indicated that it could self-support a 265 lb (120 kg) M-SHELLS system, providing sufficient power and energy for 270 seconds of cruise flight. The fuselage floor deflection is nominal and the majority of the shear stresses are generally within the allowable limits. For future applications of M-SHELLS, structural analysis of an advanced transport aircraft fuselage segment is presented. Secondary aluminum structure in the fuselage sub-floor and cargo area were replaced with reinforced composite panels with M-SHELLS honeycomb core. Fuselage structural analyses associated with three cases were described. The weight estimation with the reinforced composite M-SHELLS panels replacing the passenger sub-floor indicated a 3.2% reduction in fuselage weight, at the cost of higher deflection and stresses, but without risking the structural integrity. With additional M-SHELLS panels in the cargo hold area, the deflection and stresses were reduced. But, the net weight of the fuselage segment increased by 11.5 lb (0.3%) compared to all aluminum construction, while adding 56 cubic foot of M-SHELLS volume and ~22 kWh of energy capacity/segment. These weight calculations were with the reinforced M-SHELLS panel with 11.9 lb/ft^3 density. This calculation did not include reactive materials that are required to complete the energy storage functionality.

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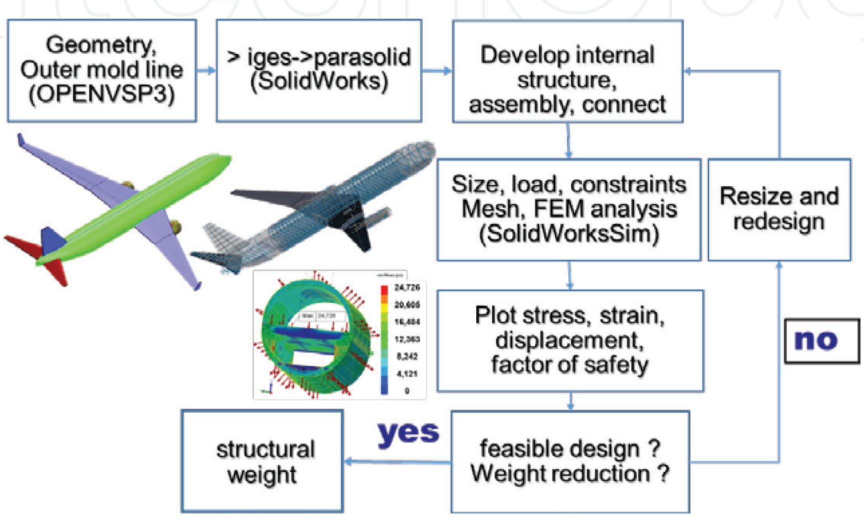
Appendix A. Material elastic property and density

Material property	Advanced stitched composite	AL 7075 T6	ABS Thermoplastic	M-SHELLS test specimen	unit
Elastic Modulus (T)	9750000	10442710	290075	11188	psi
Poisson's ratio	0.4	0.33	0.394	0.39	
Shear mudulus	2570000	3901515	46250	4024	psi
Mass density	0.0526	0.0101	0.04	0.0039	lb/in^3
Tensile strength	105100	82760	4350	90	psi
Compressive strength	79200	80000	4000	120	psi
Yield strength	46500	73244	4355	90	psi

Appendix B. Sandwich panel density

Sandwich Panel	Description	cell	density	density	unit
Hexcel Sandwich	AL-Hexcel HC	1/4 5052-0.002	$4.3\ lb/ft^3 =$	0.0025	lb/in^3
Hexcel Sandwich	AL-Hexcel HC	1/4 5052-0.004	$7.9\ lb/ft^3 =$	0.0046	lb/in^3
5 layer bonded MSHC	5LMSHC (0.002)	core 1/4 5052-0.002	$11.9\ lb/ft^3 =$	0.0069	lb/in^3
5 layer bonded MSHC	5LMSHC (0.004)	core 1/4 5052-0.004	$16.19\ lb/ft^3 =$	0.0094	lb/in^3

Appendix C. Structural model development and analysis process



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