Structural Analysis of Test Flight Vehicles with Multifunctional Energy Storage

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Under the NASA Aeronautics Research Mission Directorate (ARMD) Convergent Aeronautical Solutions (CAS) project, NASA Glenn Research Center has been leading Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS) research efforts. The technology of integrating load-carrying structures with electrical energy storage capacity has the potential to reduce the overall weight of future electric aircraft. 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. Experimental M-SHELLS energy-storing coupons were fabricated and tested in the laboratory for their electrical and mechanical properties. In this paper, finite element model development and structural analyses of two small test aircraft candidates are presented. The finite element analysis of the initial two-spar wing is described for strain, deflection, and weight estimation. After a test aircraft *Tempest* was acquired, a load-deflection test of the wing was conducted. A finite element model of the *Tempest* was then developed based on the test aircraft dimensions and construction detail. 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. Although the flight test was cancelled because of programmatic reasons and time constraints, the structural analysis results indicate that the mid-fuselage floor composite panel could provide structural integrity with minimal weight penalty while supplying electrical energy. To explore potential future applications of the multifunctional structure, analyses of the NASA X-57 Maxwell electric aircraft and a NASA N+3 Technology Conventional Configuration (N3CC) fuselage are presented. Secondary aluminum structure in the fuselage sub-floor and cargo area were partially replaced with reinforced five-layer composite panels with M-SHELLS honeycomb core. The N3CC fuselage weight reduction associated with each design without risking structural integrity are described. The structural analysis and weight estimation with the application of composite M-SHELLS panels to the N3CC fuselage indicate a 3.2% reduction in the fuselage structural weight, prior to accounting for the additional weight of core material required to complete the energy storage functionality.

I. Introduction

Under the NASA Aeronautics Research Mission Directorate (ARMD) Convergent Aeronautical Solutions (CAS) project, NASA Glenn Research Center (GRC) has been leading Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS) research efforts. The technology of integrating load-carrying structures with electrical energy storage capacity has the potential to reduce the overall weight of future electric aircraft. NASA Langley Research Center (LaRC) is working with GRC to fabricate and test lightweight, laminated honeycomb composites with special anode, cathode, and separator materials that will be 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 & Electro-chemistry Division at GRC has conducted extensive research on multifunctional structural composites that are capable of generating electrical power and carrying mechanical loads.

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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 (Fig. 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 Fig. 1a. An expanded view of the Ragone plot is shown in Fig. 2 for additional discussion. The honeycomb sandwich structure for the M-SHELLS concept is shown in Fig. 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.

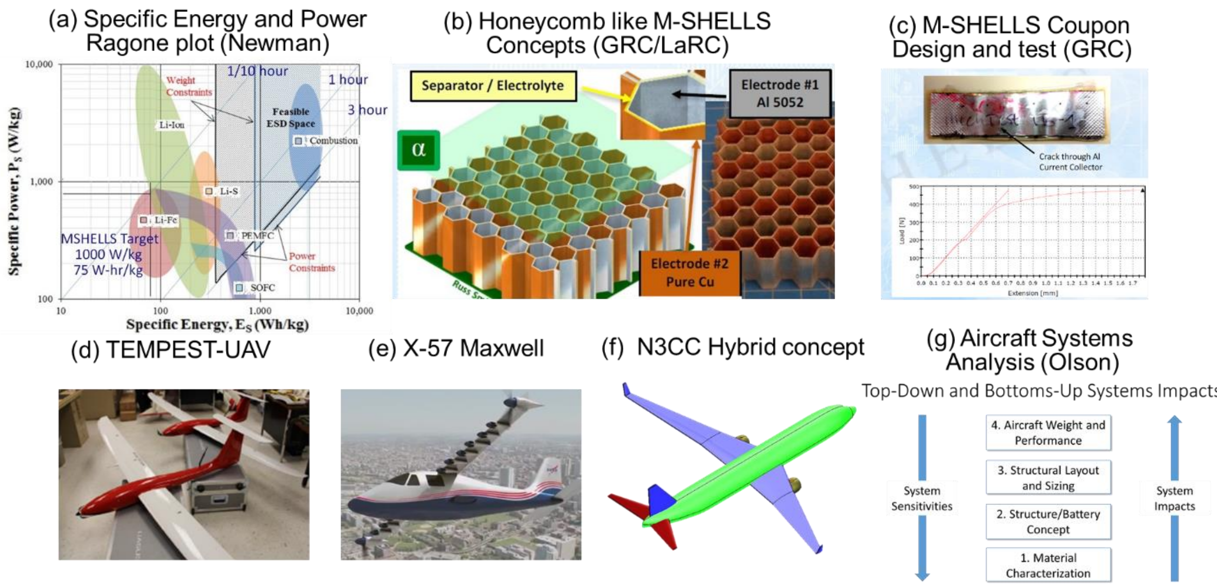


Fig. 1 Multifunctional load bearing structure and systems analysis roadmap.

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 (Fig. 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 in this paper.

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. In this paper, 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 (Fig. 1f) were conducted by Olson and Ozoroski [2] in order to predict the multifunctional performance and weight benefits of the M-SHELLS technology (Fig. 1g). In this paper, 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 Fig. 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.

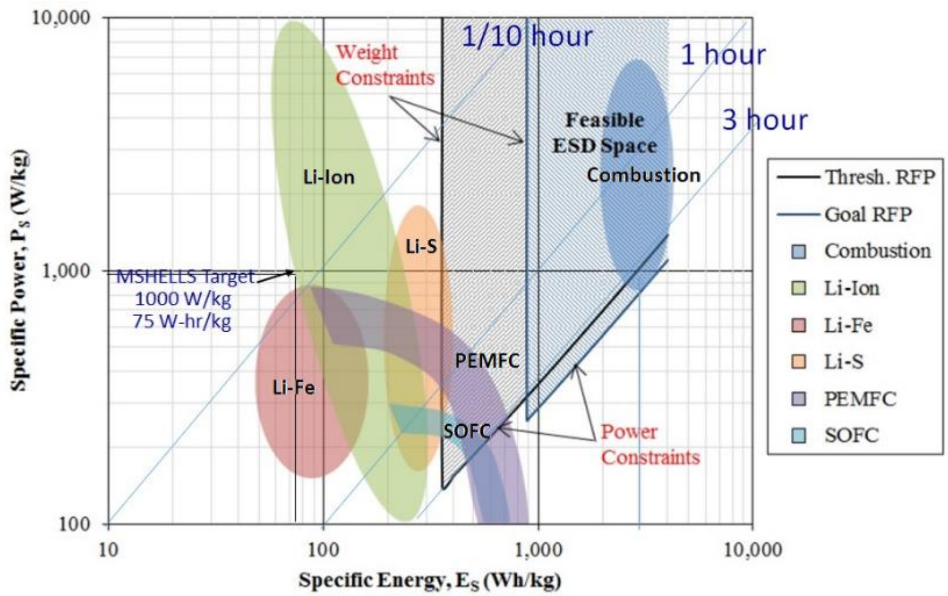


Fig. 2 Ragone plot for specific energy and specific power characteristics of energy source devices.

II. M-SHELLS Coupon Tests

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-in cell and 0.002-in 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.

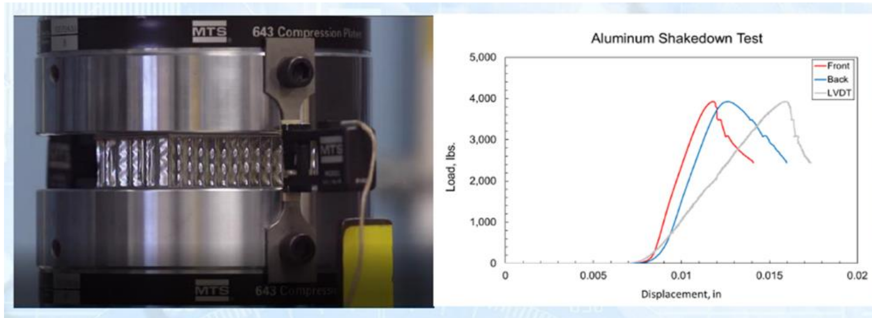


Fig. 3 Normal-compression load shakedown test of a small, stabilized aluminum honeycomb coupon fabricated for mechanical property assessment.

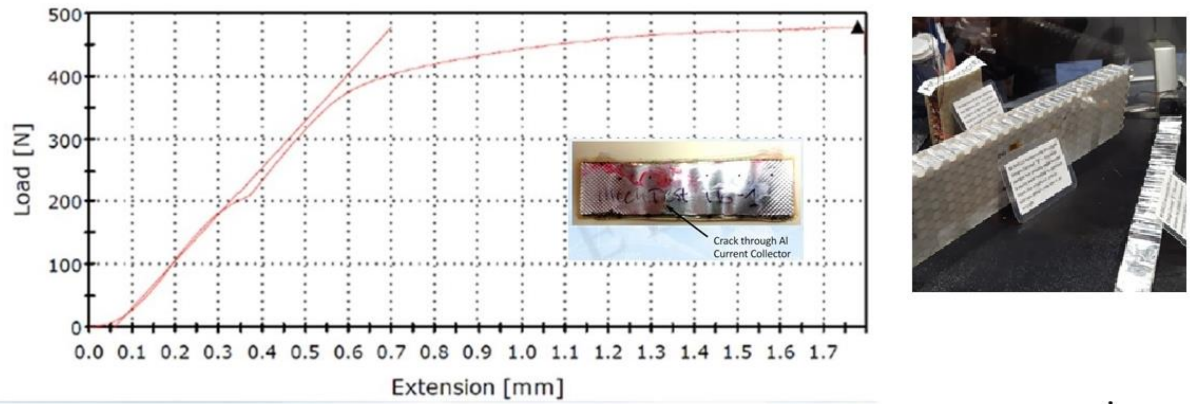


Fig. 4 Initial tensile test result of an experimental M-SHELLS coupon prototype.

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 in (150 mm) in length, 2.0 in (50.8 mm) in width, and 1.0 in (25.4 mm) in depth. The face-sheets were 0.002 in 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 (77.52×10^6 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 (Fig. 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 in this paper.

III. 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 in 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.

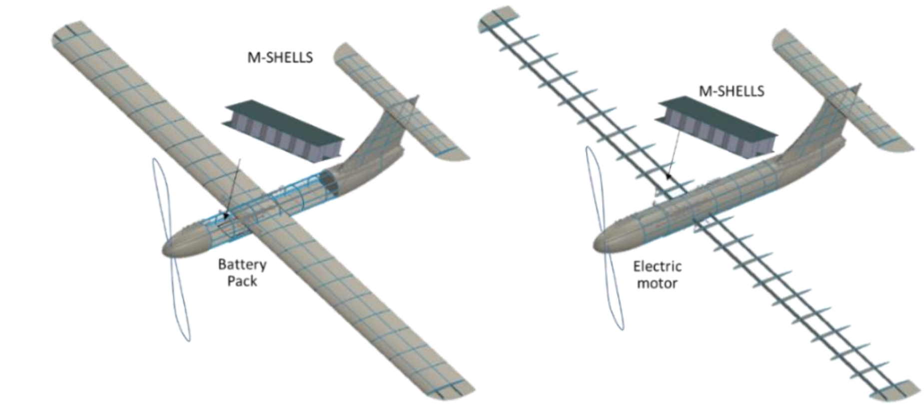


Fig. 5 Preliminary structural model development of the two-spar wing airplane.

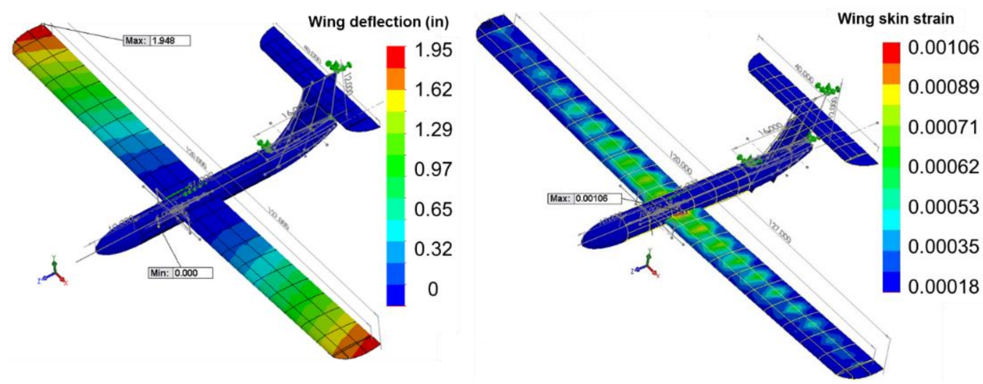


Fig. 6 Wing deflection and strain of the two-spar wing model airplane.

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 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 Fig. 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 approximately 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 Fig. 7 show the bench test arrangement in the NASA Langley model shop.

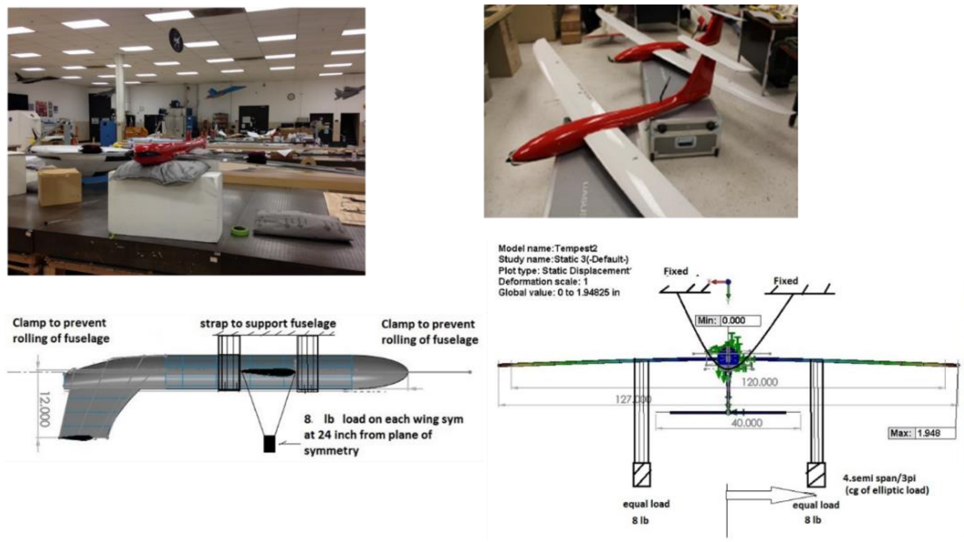


Fig. 7 Wing deflection test of the *Tempest* aircraft with 16 lb total lift load on the wing.

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 in thin composite material. The rest of the model used custom thermoplastic material.

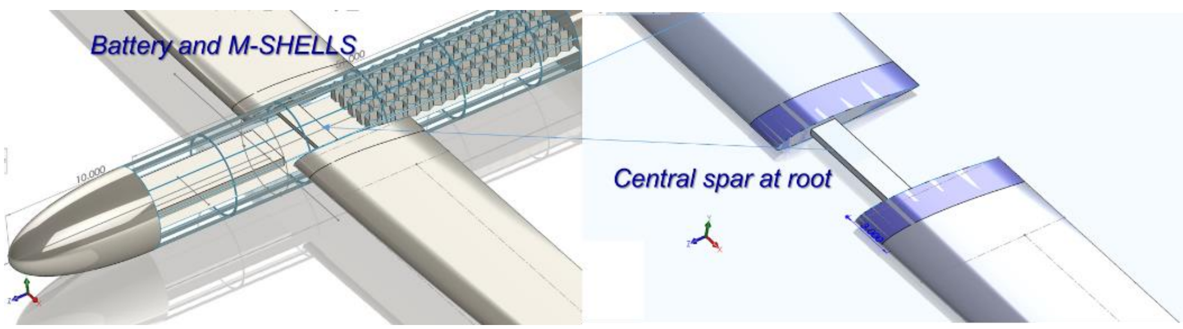


Fig. 8 Structural model and wing root internal detail of the *Tempest* aircraft.

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 0.10 in and 0.15 in, 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. With the improved FEM of the wing structure, the wing-tip deflection was 1.11 in 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 (Fig. 6). This improved FEM analysis result was considered satisfactory for the structural component weight estimation.

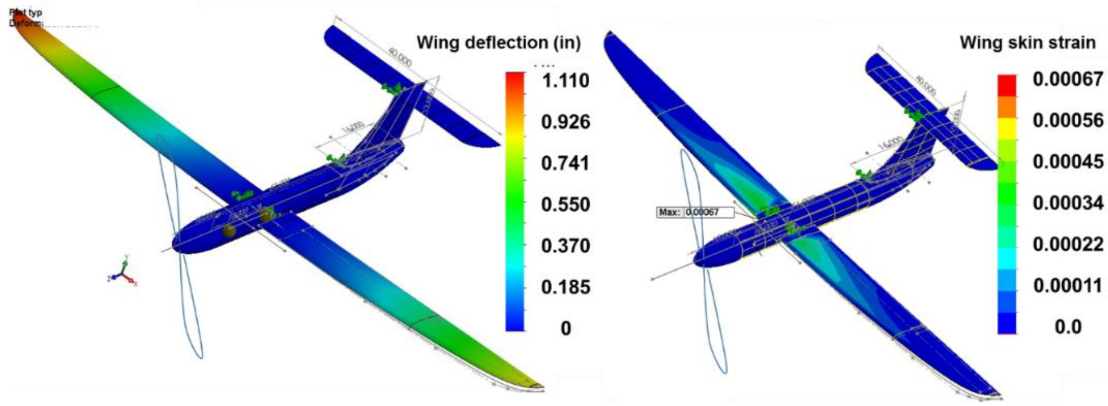


Fig. 9 Wing deflection and strain of the improved finite-element model of the test vehicle in level flight.

Table 1 Comparison of Component Weights of the Tempest Test Vehicle, Initial Two-Spar Wing Model, and Improved Tempest FEM

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 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.

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:

Power Required = weight x velocity / [L/D × (propeller efficiency) × (motor efficiency)].

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 = $88 \times 17.9 / (20 \times 0.85 \times 0.80) = 116$ W and the energy required for 10 minutes of level flight is $(116 \times 10/60) = 20$ 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.

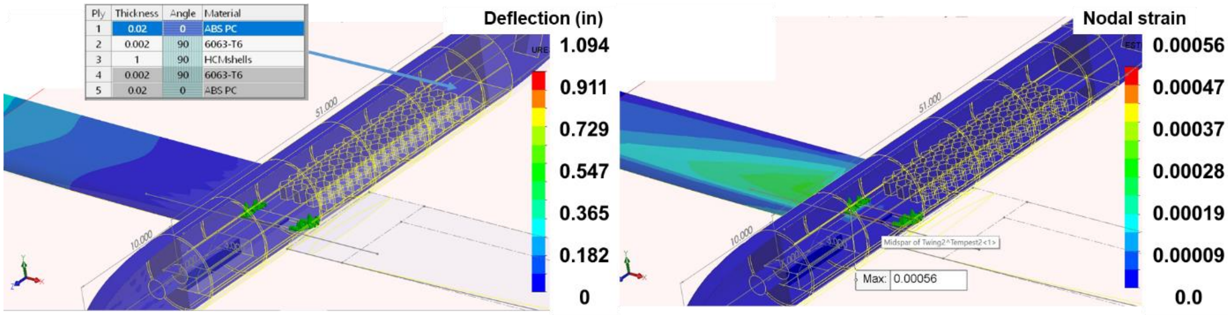


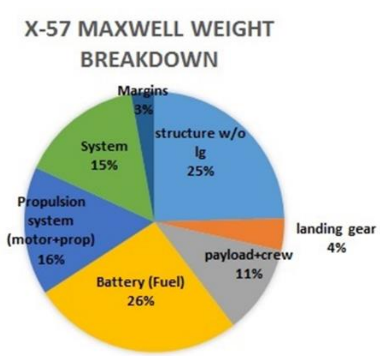
Fig. 10 Tempest FEM analysis with M-SHELLS composite panel fuselage floor.

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 Fig. 10. The five-layer bonded sandwich panel consisted of 0.02 in thermoplastic sheet for insulation on the outer faces, 0.002 in 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 Li-Po battery.

IV. 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).



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

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

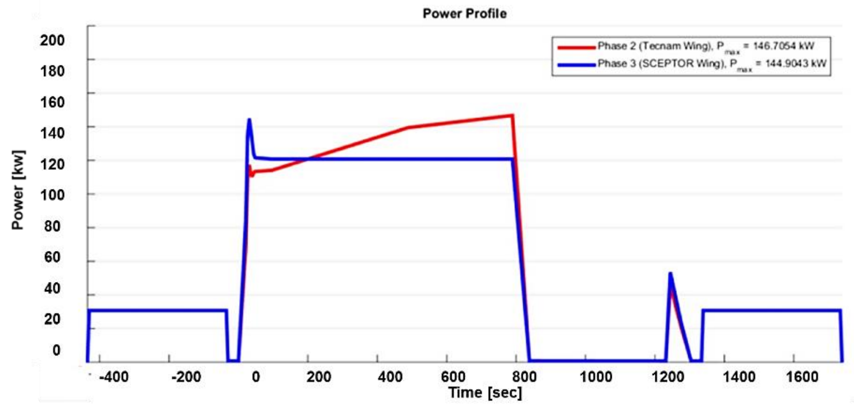


Fig. 12 X-57 Maxwell standard mission power requirement estimates.

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 (area under the power requirement curve). For example, during the cruise time interval of 800 seconds (0.22 hour), at constant power the energy required is 120 x 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.

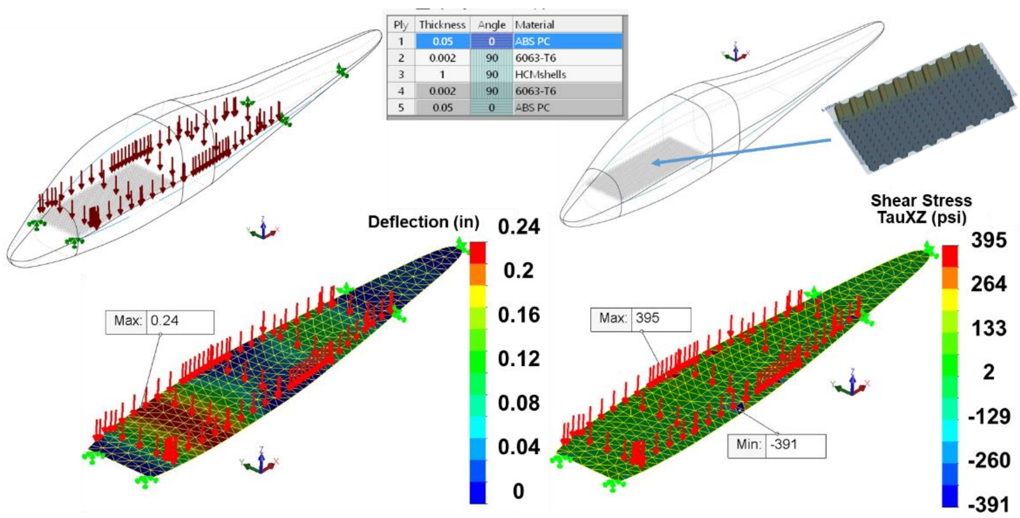


Fig. 13 X-57 floor deflection and shear stress analysis with 265 lb (120 kg) M-SHELLS distributed over the forward fuselage floor area.

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 in thermoplastic sheets for reinforcement and insulation on the outer faces, which were bonded to the two 0.002 in aluminum sheets on the inner faces over the 1.0 in 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 plys are generally within the allowable limits except at the end support areas, where local reinforcements will be needed.

V. 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. Jensen *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.

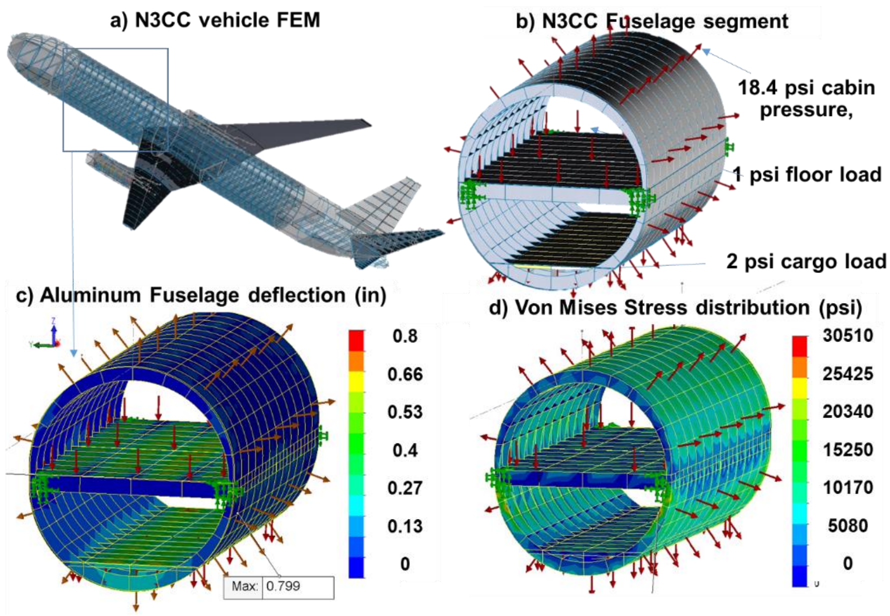


Fig. 14 N3CC fuselage segment analysis with aluminum 7075-T6 material construction.

Figure 14a shows the N3CC vehicle model with internal structure, and the detailed FEM of a fuselage segment is shown in Fig. 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, 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 Fig. 14d shows the von Mises stress distribution.

Table 2 Weight Analysis of N3CC Fuselage Segment with Aluminum 7075-T6 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

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 in aluminum ply and 0.05 in 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 **(**Fig. 15b). Figure 15c shows a significant increase in the maximum floor deflection compared to the all-aluminum construction shown in Fig. 14c. Figure 15d shows maximum von 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 (Figs. 15c and 15d).

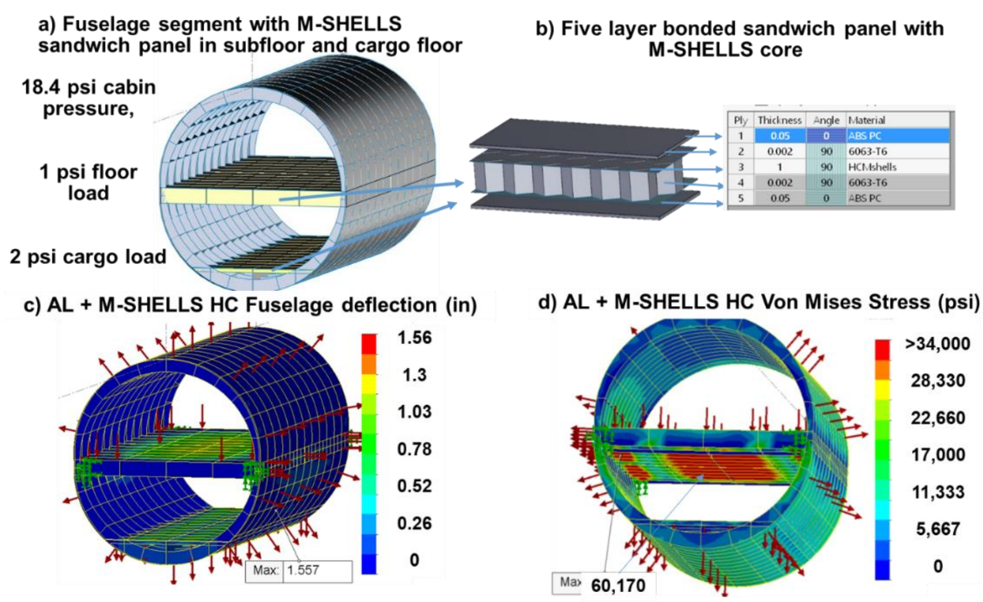


Fig. 15 N3CC fuselage segment analysis with passenger and cargo subfloor cross-beams replaced by reinforced composite panels with M-SHELLS core.

Table 3 Weight Analysis of N3CC Fuselage Segment with Aluminum 7075-T6 and M-SHELLS Honeycomb Composite Panel

Fuselage Assembly	height (in)	160	width (in)	148	length/segment 288 in			frame spacing 24 in		FEM		fuselage
Segment Structural Item	length	width	area	thickness	material	property		item weight	no. of items	total weight		segment-1 component
	inch	inch	in ^{2}	inch			unit	lb			unit	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

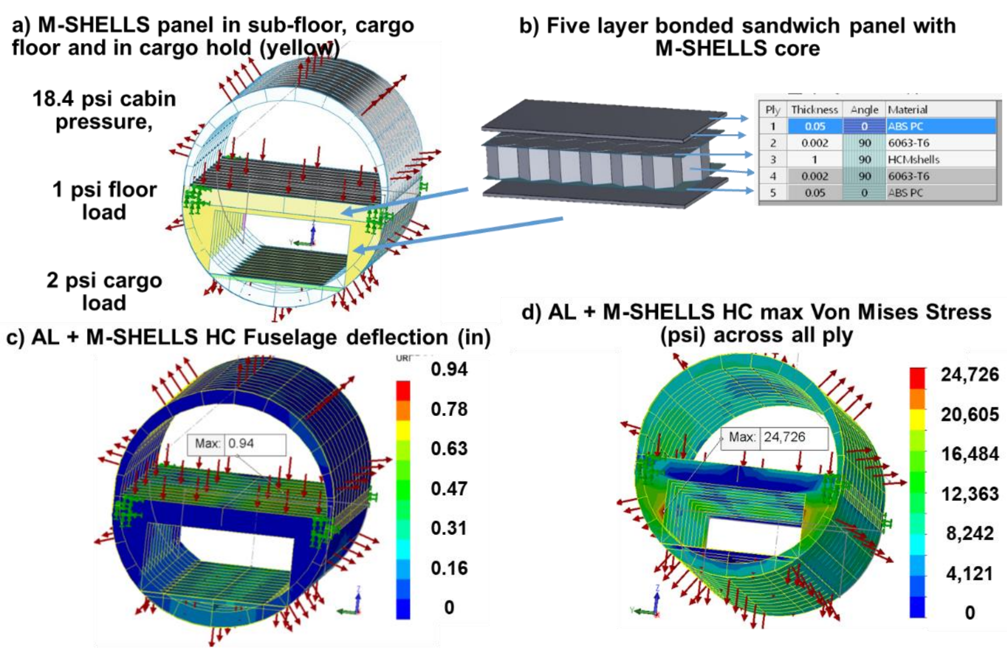


Fig. 16 N3CC fuselage segment analysis with additional reinforced M-SHELLS panel added to the subfloor cargo area.

Since this substitution resulted in large increases in deflection and stress in the passenger floor (Figs. 15c, 15d), additional sub-floor support in the cargo hold area was examined as shown in Fig. 16a and 16b. The corresponding structural deflection and stress distribution are shown in Figs. 16c and 16d. 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. 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. 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.

VI. 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. 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 fuseage segment increased by 11.5 lb (0.3%) compared to all aluminum construction, while adding 56 cubic foot of M-SHELLS volume. These weight calculations with the reinforced M-SHELLS panel did not include reactive materials that are required to complete the energy storage functionality. The focus of this paper was solely on the local structural aspects of the multifunctional storage. For projected multifunctional performance analysis and overall benefits of the full vehicle with multifunctional storage, please see Olson and Ozoroski [2]. 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 when major primary structure in the wing and fuselage is replaced with higher specific energy M-SHELLS.

Acknowledgments

The authors thank the NASA Transformative Aeronautics Concepts Program (TACP), directed by Dr. John Cavolowsky for funding this research. The M-SHELLS sub-project is part of the Convergent Aeronautical Solutions (CAS) project under the TACP Program. CAS is directed by Isaac Lopez, Project Manager, Marty Waszak, Deputy Project Manager and Daniel Williams, CAS Liaison Officer at Langley. We thank Dr. Nicholas Borer, Jeff Viken, and the X-57 Maxwell Systems Analysis & Integration team for their guidance. Thanks are also due to Kevin Roscoe, Greg Howland, David A. Hare, Luke Laub, David Klassman, and Frank Leone for performing the *Tempest* structural weight measurement and deflection tests, and to Russell Smith and Brett Bednarcyk for leading the fabrication team, and for providing the M-SHELLS coupon structural test results. Authors also acknowledge technical support from Dr. Dave Krause and Dr. Patricia Loyselle, NASA Glenn Research Center, William Kimmel, Chief Technologist, Systems Analysis and Concepts Directorate (SACD), Philip Arcara, Branch Head, and Mark Guynn, Assistant Branch Head, Aeronautics Systems Analysis Branch (ASAB). Thanks are also due to all the technical reviewers for improving the paper significantly. Technical discussions with Dr. Wu Li, Dr. Natalia Alexandrov, Jason Kirk and Dr. Jesse Quinlan for improving the paper are greatly appreciated.

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