Conceptual Multifunctional Design, Feasibility and Requirements for Structural Power in Aircraft Cabins

Sang N. Nguyen,[1] Alexis Millereux,[2] Aymeric Pouyat,[2] Emile S. Greenhalgh,[3] Milo S. P. Shaffer[4] and Anthony R. J. Kucernak[5]
Imperial College London, South Kensington, London, SW7 2AZ, United Kingdom

and
Peter Linde[6]
Airbus Operations GmbH, Kreetslag 10, D-21129 Hamburg, Germany and Chalmers University of Technology, S-41296 Gothenburg, Sweden

This paper presents a theoretical investigation into the potential use of structural power composites in regional aircraft passenger cabins and the corresponding challenges to widespread use, including fire-resistance, long-term cycling performance, and cost. This study focusses on adapting sandwich floor panels with structural power composite face sheets, designed to power the in-flight entertainment system. Using a simple mechanical model to define the structural requirements, based on state-of-the-art laminated structural power composites, a series of electrochemical energy storage performance targets were calculated: a specific energy > 144 Wh/kg, a specific power > 0.29 kW/kg, an in-plane elastic modulus > 28 GPa and in-plane tensile and compressive strengths > 219 MPa. Significantly, the use of a distributed energy storage system offered a significant range of other mass and cost savings, associated with a simplified power system, and the use of ground-generated electrical energy. For an Airbus A220-100, the analysis predicted potential mass and volume savings of approximately 260 kg and 510 *l* and annual reductions in CO_2 and NO_x emissions of approximately 280 tonnes and 1.2 tonnes respectively. This extended design analysis of a

---

[1] Research Associate, Department of Aeronautics.
[2] Masters Graduate in Aeronautical Engineering, Department of Aeronautics.
[3] Professor of Composite Materials, Department of Aeronautics.
[4] Professor of Materials Chemistry, Departments of Chemistry and Materials.
[5] Professor of Physical Chemistry, Department of Chemistry.
[6] Research Engineer and Professor, Department of Industrial and Materials Science.

specific component highlights both the far-reaching implications of implementing structural power materials and the potential extensive systemic benefits.

Nomenclature

D = flexural rigidity (N m^2)
E = in-plane longitudinal elastic modulus (GPa)
E^* = specific energy (Wh/kg)
P = power (kW)
P^* = specific power (kW/kg)
t = thickness (mm)
X = strength (MPa)
v = Poisson’s ratio

Subscripts

C = compressive
c = core
$conv$ = conventional floor panel
f = face sheet
T = tensile

Introduction

MULTIFUNCTIONAL structural systems [1] offer transformational opportunities to reduce weight, especially in space [2], aeronautics [3], road transport [4] and portable electronic applications. In the context of this paper, the non-structural function is electrical energy storage and this technology can be divided into two classes: ‘conventional power structures’ (CPS) and ‘structural power composites’ (SPC). Conventional power structures comprise conventional energy storage devices embedded within conventional load-bearing structures. The embedding process is such that the conventional power device can contribute to the structural function, without any major alteration to the physical or chemical form of the power device or structure; CPS are relatively simple to implement but offer limited benefits. Typically, some of the parasitic mass associated with the device casing supports some mechanical load through adhesion to the structure. Structural power composites on the other hand are multifunctional materials that are intrinsically imbued with both structural and energy storing functions because one or more of the constituents of the material simultaneously perform(s) multiple functions. For example, carbon fibres are used to carry forces, store energy and act as current collectors to conduct electrons; similarly, structural electrolytes transfer both stresses and ionic charge. As well as the potentially very significant mass [5] and volume benefits, SPCs enable new design concepts that cannot be achieved using conventional monofunctional materials. For example, SPC-powered aircraft could achieve lower drag coefficients by having more slender wings [6,7] or blended wing-body designs containing smaller (or even no) fuel tanks. By storing energy intrinsically in large scale materials and structures, the energy and power densities required to deliver the same total energy or power can be reduced, potentially leading to safer power sources with reduced risks of thermal runaway compared to conventional power sources. However, the current lack of a universally-agreed *multifunctional design* methodology is a barrier to adoption in industrial applications. New approaches are needed to evaluate the systemic performance of multifunctional materials to optimise the overall mass or volume savings, and justify their use.

The application of SPCs in the automotive sector has been investigated resulting in the fabrication of two full-scale components for a Volvo S80: a structural battery plenum cover and a structural supercapacitor boot lid [8]. These demonstrators provided valuable insights into the manufacturing of such parts, as well as the lifetime performance of the material. The approach for application of SPCs in the aerospace industry is expected to involve investigating engineering challenges and demonstration at a similar component-level scale before applying this technology to entire structures when it reaches a greater level of maturity.

Structural power composites are particularly attractive within the aviation sector, in which each kilogram removed from an aircraft results in many tonnes of fuel saved over its lifetime and increases the potential flight range [9]. In addition, there is increasing interest in the electrification of aircraft systems [10] where there is a compelling case to explore multifunctional design using SPCs. Full electrification of aircraft propulsion systems remains extremely challenging; existing batteries remain essentially insufficient for the replacement of current aircraft capabilities [11];

new approaches, such as the use of SPCs, are required. In the immediate future, however, structural power materials will not replace, but instead supplement, existing power sources [12] including hydrogen fuel cells [13].

In aircraft structures, SPCs could potentially be used at two levels: at the level of primary structures or at a level with less stringent certification requirements, such as in the cabin. To date, research has considered the implications of the former, replacing most or all of the airframe materials with SPCs. For example, the electrical requirements for SPCs to save weight in small all-electric aircraft (AEA), namely the Airbus E-Fan and the EcoFlyer, have been evaluated [14]. Based on a relatively simple model, replacing the entire airframe with SPCs, it was estimated that the minimum specific power requirements, were 0.23 kW/kg for the E-fan and 0.11 kW/kg for the EcoFlyer; the minimum specific energy requirements were 85 Wh/kg and 52 Wh/kg, respectively.

However, the progress of larger multi-passenger all-electric aircraft faces significant challenges, including the total energy storage demands, dissipation of thermal energy and electric motor technology. Therefore, the industry has turned to a near-term solution: hybrid electric aircraft [15] which use a combination of conventional jet fuel and electrical power for conventional propulsion [16] or distributed electric propulsion [17,18]. Boeing has unveiled the Sugar Volt concept in collaboration with NASA [19], which would contain two banks of batteries located underneath its high wing to reduce fuel burn and emissions by 70% [20]. Whilst these case studies give quantitative material property targets for researchers investigating and developing SPCs, the technology needs to reach a much higher level of maturity before it can be certified for use as a primary structural material. It is, therefore, important to study the feasibility of using SPCs at smaller scales, which can act as testbeds prior to more widespread use.

There is a need for industry to have an insight into the potential benefits and practicalities of the application of structural power and there are a range of opportunities where SPCs, with more modest structural and electrochemical performance, might already provide a benefit. As yet, no research has been published on the use of SPCs at cabin level for commercial civil aerospace applications. Applications in the cabin are particularly attractive, since the cabin has advantages in ease of access for inspection and maintenance, and a controlled environment (relatively benign temperature and pressure ranges which match electrochemical device requirements). The cabin electrical system accounts for a large part of the non-safety-critical energy consumption and is a spatially distributed electrical load. In principle, distributed energy sources might reduce some of the wiring demands that account for a significant contribution to overall aircraft weight. The cabin electrical system is, therefore, a prime candidate to receive electrical power from SPCs located throughout the cabin. Hence this investigation focusses on applications within aircraft cabins, specifically cabin floor sandwich panels that power the in-flight entertainment system. This investigation takes a widely used aircraft (A220-100) as a case study to demonstrate a methodology used to determine the mechanical, mass specific energy (*E**) and mass specific power (*P**) requirements, as well as the mass, volume and emissions savings achievable. This paper also presents a new electrical distribution system design and discusses the technical, environmental, safety and economic implications of structural power composite cabin floor panels. The analysis presented in this study is based on the development and availability of an alternative electrochemical energy storage technology that is safer than existing commercial lithium ion batteries which have an unacceptable fire risk. This new multifunctional technology would not need to have an energy density as high as that of conventional lithium ion batteries and would pose a substantially smaller risk of fire by having a better resistance to mechanical abuse or electrical short circuits that cause thermal runaway.

The objectives are to understand how SPCs can offer benefits over conventional systems, what performance levels are needed to provide benefits, and how best to integrate SPCs in conceptual design. *E** and *P** for the SPCs can be determined using accurate estimates of the electrical demands and structural component masses. These performance targets indicate the feasibility of SPCs for such applications and aid benchmarking against existing technologies. Most of the research on the use of SPCs in aircraft design has focused on the electrical requirements. This study also determines the mechanical requirements, namely the elastic modulus and in-plane tensile and compressive strengths.

The *multifunctional design* methodology proposed in this paper entails five main stages:

1. define performance requirements to determine the feasibility of using multifunctional materials;
2. explore how best to integrate multifunctional materials into new systems, configurations or architectures;
3. select a multifunctional system configuration using a simplified analysis based on requirements for the proposed application;
4. understand how integrating a multifunctional material affects the design of the associated mechanical and electrical systems;
5. evaluate the benefits and challenges of using multifunctional materials for a given application.

Methodology

This section presents the methods used to determine the specific energy and power requirements. Firstly, the aircraft specifications considered for this study are presented. Next, the mechanical requirements are calculated and the mass of SPC needed to meet these requirements determined. An audit of cabin electrical demands was collated and used to calculate the specific electrical performance values needed. Finally, a power distribution system to enable charging and supply of the power is proposed.

Application scenario

The regional aircraft sector is predicted to be a fast-growing market segment [21] because most flights have a duration of approximately one-hour. The modest range makes the power and energy requirements more attainable for electrical energy storage than those for long haul flights. Certification authorities are more likely to permit new and relatively immature materials on-board narrow body, regional aircraft than on aircraft with 15-hour flights crossing oceans. To obtain accurate and relevant results, this investigation uses existing aircraft data on cabin system power usage and certification requirements. The Airbus A220-100 was chosen as a case study for this investigation, as it is the latest narrow-body aircraft currently flying. This aircraft also adopts many ‘more electric aircraft’ features, including the very first electric braking system as standard, and extensive use of composite materials. In its standard all-economy, configuration, the A220-100 carries 125 passengers, in a 3-2 seating configuration (Fig. 1). All passengers have access to a seat-back screen and three power sockets per row in between the seats. This high-density configuration was chosen as it provides an upper limit to the electrical requirements. To ensure conservative results, it was assumed that the flight operates such that all seats are occupied. This assumption would imply a flight operating near the maximum payload, which affects the range (down to 3700 km [10], from the maximum 5500 km) and endurance of the aircraft (just over four hours at Mach 0.82). A four-hour-long flight is assumed to give conservative results, since this duration is close to the maximum flight time at maximum payload.

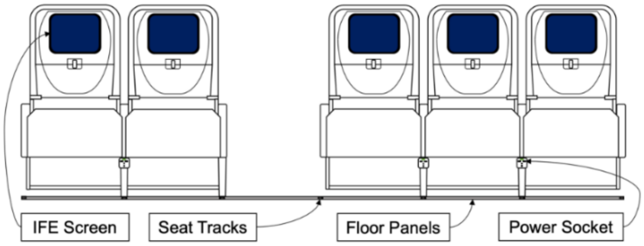


Fig. 1 A220-100 seating row layout [22]**.**

To maximise the mass savings, the SPCs are assumed to be charged whilst the aircraft is on the ground. To minimise the time the aircraft is kept on the ground and therefore maximise revenues, the charge time of this system should be no longer than the normal on-ground time. Analysis of typical on-ground time of several A220-100 aircraft revealed most turnarounds are between 40 to 60 minutes [22]. For this study, the selected charge time was 30 minutes to allow flexibility for other turnaround operations.

Within the aircraft cabin, structural power composites could be adopted for several structural and electrical functions. Three structural functions were considered through preliminary analyses before proceeding with a more detailed study on one of the three options. The three structural options considered were seats, passenger service unit (PSU) panels and floor panels. Other common composite applications, such as ceiling and sidewall panels, overhead storage compartments, window surrounds, bulkheads, partitions, ducting, brackets and galley and lavatory components could have been considered as possible candidates. The selection criteria were based on having a significant amount of structural material within which to potentially store electrical energy; proximity of the structures to where electricity would be used to reduce wiring; simplicity of the geometry; ease of maintenance and replacement; and well-defined load cases to facilitate analysis of the structural requirements. After the preliminary research into the adoption for the seats, passenger service units and floor panels [22], the latter application was selected for a more detailed investigation. The main reasons were the large area of material, the flat geometry, and the well-defined load cases provided in the airworthiness documentation (versus the more complex and variable load cases for the seats, for example).

Selection of the electrical functions within the cabin were based on similar criteria and aiming to exploit the distributed nature of the energy provided by structural power. These criteria identified lighting, audio and charging functions within the PSUs and in-flight entertainment (IFE) systems as suitable candidates. Some of the largest electrical loads in aircraft cabins come from the galleys. At peak, they can account for over a third of the total electrical consumption of the aircraft [23] (typically immediately after take-off, when the ovens are turned on to heat up the meals). Using SPCs to supply electrical power to the galleys faces two problems: the high power requirements (over 50 kW at peak [23]), and the localisation of the load, which is not distributed but rather positioned at either end of the cabin. In this case, the wiring demand might be increased to collect the required energy from a large area of distributed SPCs. Electrical heating (e.g. for meals) was deemed too energy- and power-intensive and therefore not feasible as an application for near-term adoption of structural power. Unlike the galleys however, the IFE electrical load is distributed throughout the cabin, with a seat-back screen and power socket available for every passenger. This distributed demand has two clear benefits: redundancy, as each SPC component powers only part of the cabin electrical system, and potential mass savings on wiring. The electrical system in the cabin, which comprises the IFE system and power sockets, also represents a significant share of non-essential total electrical consumption, up to 33% [9]. The entire IFE system on-board a wide-body airliner can weigh up to 5000 kg [22], which presents an opportunity for significant mass savings; hence the IFE system was selected for this multifunctional design study.

Mechanical requirements

Conventional cabin floor panels typically have a sandwich construction [24] with glass fibre reinforced polymer (GFRP) face sheets (Table 1 [25]) for low cost and an aluminium honeycomb core for its light weight. Some recent lighter floor panels have CFRP/GFRP face sheets and a Nomex honeycomb core. Since CFRP is already used in this application, the risks associated with adopting SPC floor panels are reduced. The primary purpose of the floor panels is to sustain the weight of the passengers, galley carts and other loads, with limited bending deflection. For a sandwich construction, the flexural rigidity [26] is given by

$$D = \frac{E_f t_f}{2(1-\nu_f{}^2)}\left[\frac{t_f^2}{3} + \left(t_c + t_f\right)^2\right] + \frac{E_c}{1-\nu_c{}^2}\frac{t_c^3}{12}. \tag{1}$$

Table 1 Basic properties of sandwich panels used for civil aircraft cabin floors [25]

Floor panel product name	4105	4205	4322	4323
Face sheet material	Woven GFRP epoxy	GFRP-CFRP	GFRP phenolic	GFRP phenolic
Top face sheet thickness, mm	0.64	0.64	0.61	0.76
Bottom face sheet thickness, mm	0.64	0.64	0.56	0.51
Total thickness, mm	9.5	9.5	9.5	12.6
Areal weight, kg/m^2	3.30	3.44	3.40	3.69
Distributed surface load, kN at 10.9 mm deflection	NA	4.45	NA	NA
Distributed surface load, kN at 17.0 mm deflection	NA	7.78	> 6.29*	> 10.83*
Ultimate distributed surface load, kN	22.2	20.0	16.9	24.8
Concentrated load, kN without permanent deformation	> 0.89	> 0.85	> 0.89	> 0.89
Impact strength, J	NA	NA	9.5	24.4

All panels have 4.8 mm cell 96.1 kg/m^3 aramid honeycomb cores bonded with modified epoxy adhesive. NA = Not applicable.

* Minimum load without permanent deformation.

The design of cabin floor panels must meet both static and dynamic requirements. The static requirements are typically specified by the aircraft manufacturer, whilst the dynamic requirements are stated in certification documentation. The static requirements are: 136 kg over any 0.093 m^2 in non-seat areas without permanent deformation; 77 kg over any 0.093 m^2 in seat areas without permanent deformation; and 0.9 kN on any 12.7 mm diameter circular area without appreciable deformation [22]. The floor panels must also withstand the emergency landing conditions [27] governed by sustained acceleration limits of 6 g downward and 9 g forward acting on the flooring, seats and passengers.

A traditional design approach would aim to minimise the floor panel mass by optimising the thickness and number of cells whilst matching the conventional floor panel out-of-plane deflection and maximum load. However, the approach taken in this study was to ensure that the SPC floor panels would maintain compatibility with the existing cabin configuration and have the same geometry throughout the cabin to enable direct replacement and simplify manufacturing and maintenance. Therefore, rather than optimizing the panel mass, a constraint was placed such that the SPC floor panel thickness would be the same as that of the conventional panels. Conservative mechanical performance requirements were determined to match the thickest floor panel type (12.6 mm) used for civil aircraft cabin floors (product 4323 in Table 1) which already meet the requirements stated above.

It was assumed that the SPC face sheet thickness and interfacial bond strength with the core are both not less than those for the GFRP face sheets to ensure the out-of-plane deflection and maximum load carrying capability match or exceed those of the conventional floor panels. Whilst this design approach did not optimise the absolute mass saving for the floor panels, it was deemed appropriate to be conservative when working with such an immature technology. From the perspective of generating a design suitable for early applications of SPCs, another important consideration was the feasibility of the electrochemical performance targets. Compared to the minimum mass design, using face sheets that may be thicker than that required to match the deflection and maximum load would result in lower specific performance requirements, which would make the design more achievable in the near term.

Mass analysis

Since more experimental data related to thickness, mass, constitutive properties and stacking sequence at a full device level is available for structural supercapacitors [28,29] than for structural batteries, the entire analysis presented here is based on data for the former. The basic architecture used in structural batteries is similar to that of the structural supercapacitor architecture assumed in this analysis, i.e. spread tow carbon fibre electrodes of similar thickness and areal density and a multifunctional polymer electrolyte which combines a structural epoxy with an ionic liquid. The key parameters for this analysis are the cell thickness and the cell areal mass. For the purposes of preliminary design/feasibility estimates, it was assumed that these key properties could be representative of those for structural batteries [30], as well as structural supercapacitors. As SPC develop, this methodology can easily be applied to any configuration of laminated [31] or 3D structural batteries [32], by altering the device thicknesses and areal weights assumed. For laminated structural batteries and structural supercapacitors, the discrete thickness of a single cell means that the total thickness of each face sheet is determined by the number of cells stacked together (Table 2). Note that a two-cell device is thinner than the sum of two one-cell devices, since the former device can use a bipolar plate between the cells if they are stacked to form a series connection.

Table 2 Structural supercapacitor thickness and mass for a given number of cells [22]

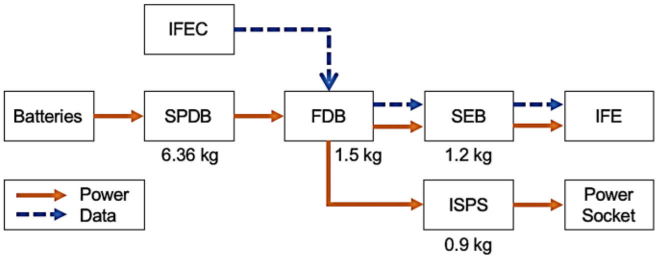
Number of cells	1	2	3	4
Device thickness, mm	0.36	0.68	1.00	1.32
Device areal mass, kg/m^2	0.31	0.57	0.83	1.09

The mass of the floor panels was determined from the total panel thickness assuming a Nomex core (density 48 kg/m^3 [33]) and four-cell SPC devices for each face sheet. Since these quad-cell face sheets have twice the thickness of the average thickness of the conventional panel face sheets, this configuration would improve the bending resistance by increasing the flexural rigidity of the sandwich panel. Eight cells through the thickness of a panel connected in series would be amenable to achieving the typical operating voltage of cabin electronics, which is discussed in the next Section. An alternative analysis method has been developed using a Matlab script to minimise the total mass of the floor panels as a function of the total panel thickness [22].

Electrical requirements

The IFE system can be divided in two parts (Fig. 2): the power system and the data system. The former provides electrical power to each passenger, while the latter provides media content. IFE screens typically run at 28 V DC, which requires converters and other electronics to be adapted from the aircraft's 115 V AC system [23]. To improve reliability, manufacturers have decentralised IFE systems. These traditional IFE systems rely on a plethora of electronic boxes spread throughout the cabin to direct power and data to the seat-back screens and power sockets:

secondary power distribution boxes (SPDBs), floor disconnect boxes (FDBs), seat electronics boxes (SEBs) and in-seat power supplies (ISPS). On wide-body airliners, this can result in hundreds of electronic modules, which often impinge on passenger foot space, resulting in lowered satisfaction. The A220-100 requires nine secondary power distribution boxes (one per fifteen seats[1]), fifty floor-disconnect boxes, fifty seat electronic boxes and fifty in-seat power supplies; in total, there are 238 kg of electronic boxes. In this architecture, secondary power distribution boxes distribute power to floor disconnect boxes (one per group of seats), which feed the seat electronic boxes and the in-seat power supplies (one per group of seats for both). The in-seat power supplies operate at 110 V AC.



Acronyms

IFEC = In-flight entertainment & connectivity
SPDB = Secondary power dist. box
FDB = Floor disconnect box
SEB = Seat electronic box
ISPS = In-seat power supply

Fig. 2 The power and data connectivity for a conventional in-flight entertainment system.

Theoretically, IFE power requirements have been estimated to be between 70 and 100 W/passenger [23]. However, actual flight data reveals a lower power consumption of 37 to 45 W/passenger [22]. The remainder can largely be attributed to power sockets. For this study, passenger surveys and airlines statistics have been used to estimate the number of passengers using the IFE, power sockets etc. On average, 20% of passengers flying in the UK do so for business [22]. This study assumed that business passengers keep their laptops plugged in throughout the flight. The remaining passengers, according to surveys [22], either access content through the built-in IFE system (44%), use their personal electronic devices (PEDs) (46%) or switch between the two (10%). This study assumed passengers using their PEDs keep them plugged in and charging for the duration of the flight.

The power drawn by a charging laptop varies greatly depending on the device, but is typically around 70 W. Similarly, PEDs require anywhere from 5 W for a mobile phone to 18 W for a tablet. To ensure enough energy and power for all passengers, the upper end of 18 W was chosen. For a seat-centric IFE system, it is reasonable to assume that the seat-back screen is the only component using electrical power, as data is transferred wirelessly. A seat-centric

---

[1] Since the A220 and the B787 both belong roughly to the same generation of aircraft, they share many features and suppliers. Therefore, it was considered reasonable to assume the A220 has an electrical architecture like that in the B787 (twenty-one SPDBs for three hundred passengers).

IFE system constantly transfers content between various units throughout the cabin, which is likely to increase the total energy consumption of the IFE system. To provide a conservative estimate, it was assumed that every unit draws 15 W [22] for the duration of the flight, regardless of whether the passenger is using it or not. To ensure adequate margins and avoid under-capacity, a safety factor was applied to the total electrical power (Table 3). A safety factor of 15% ensures more than 99% availability [23]. Hence, the final IFE power requirement was calculated to be 5.2 kW, or 42 W per passenger, which correlated with actual flight data [22].

To supply enough energy for the maximum flight time of four hours, the SPC floor panels must be able to provide 21 kWh. For a full charge to be achieved in 30 minutes, the charging power requirement would be 42 kW. These requirements do not account for losses, which are considered in the next sub-section.

Table 3 In-flight entertainment system electrical loads

Load	Users	Individual power, W	Total power, kW
Laptop	25	70	1.75
PED	51	18	0.92
IFE	125	15	1.88
		Total	4.54

Power distribution

To obtain a mass estimate of the charging system, it was necessary to know the masses of the converter units and wiring. The mass of each converter unit (CU) (Table 4) was determined from the power requirements (Table 3). The wiring mass was estimated by calculating the lengths of cables (Fig. 3) required: 1.5 m long wiring to seat-back screens and 0.5 m wiring for power sockets. The required current was used to determine the wire gauge. Aluminium wires were assumed for this study, as they are lighter and are superseding copper wires on-board airliners. A breakdown of the total cabin wiring mass is shown in Table 5: the estimated total mass for the converters and wiring was 146 kg.

Table 4 Converter unit mass estimation

Device	Conversion, V	Power, W	Mass, kg	Quantity	Total mass, kg
Converter unit 1	270 DC / 2.7 DC	5210	0.9	2	3.6
	2.7 DC / 270 DC	5210	0.9		
Converter unit 2	270 DC / 2.7 DC	5210	0.9	8	35.2
	2.7 DC / 270 DC	5210	0.9		
	2.7 DC / 28 DC	270	0.3		
	2.7 DC / 110 AC	384	2.3		

One crucial aspect of the introduction of SPC on aircraft is charging of the panels. Charging during flight through the engine generators could be an issue if the aircraft lands with minimal energy left in the floor panels and no means to charge on the ground. Until the aircraft is back in the air and the system is sufficiently charged, the IFE would be inoperable. Therefore, it was considered preferable to charge the SPC panels directly on the ground, through conventional DC ground power units (GPUs). The proposed solution presented in the following paragraphs was chosen to minimise mass, primarily in terms of the wiring and generator masses.

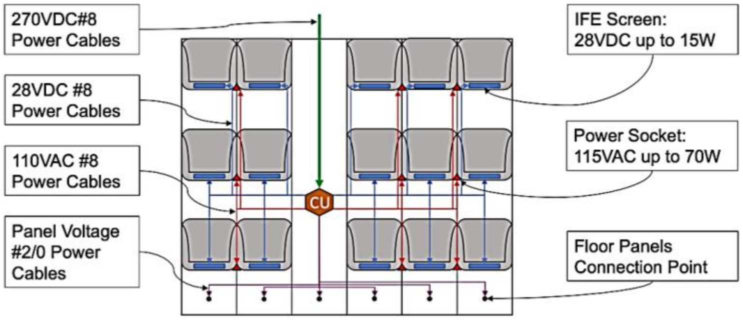


Fig. 3 Diagram of a section, showing wiring and a converter unit.

Table 5 Total cabin wiring mass estimation

Wiring	Current, A	Gauge	Linear mass, g/m	Length, m	Mass, kg
Ground to converter unit	19.3	#8	40	155	6.2
Converter unit to panels	108.5	#2/0	255	240	61.2
Converter unit to IFE	0.5	#8	40	704	28.2
Converter unit to power sockets	0.7	#8	40	272	10.9
				Total	106.9

It was necessary to estimate the losses associated with the transfer of energy from the ground to the SPC panels and then to the IFE. The proposed layout (Fig. 4) comprises ten sections, each made of six 2.5 m × 0.5 m SPC panels. Large panels are preferred to reduce the amount of wiring required. Here, it was assumed that any SPC developed to meet the specific power requirements determined in this study would incorporate suitable current collection. The current collection effectiveness was assumed to be such that the in-plane resistivity is small enough to minimise power losses. For the operation current required, the internal resistance would need to be small enough to avoid excessive resistive heating or voltage drops that would prevent proper function of the electronics. For commercial supercapacitors, the equivalent series resistance is of the order of 10-700 mΩ [34], and it is therefore anticipated that a similarly low resistance would be needed. To achieve 10 mΩ for a 0.5 m × 0.5 m panel, it was calculated that a thickness of at least 1.7 µm of copper or 2.8 µm of aluminium foil would be required for each electrode. Copper is preferred for corrosion resistance if passivated using a coating such as conductive carbon ink. Aluminium would have the advantage of adding only half the mass compared to copper foil. For the subsequent mass analysis, the current collector was taken to be 1.7 µm thick passivated copper foil for each electrode. This current collection would add 0.25 kg/m^2 for panels containing four-cell face sheets.

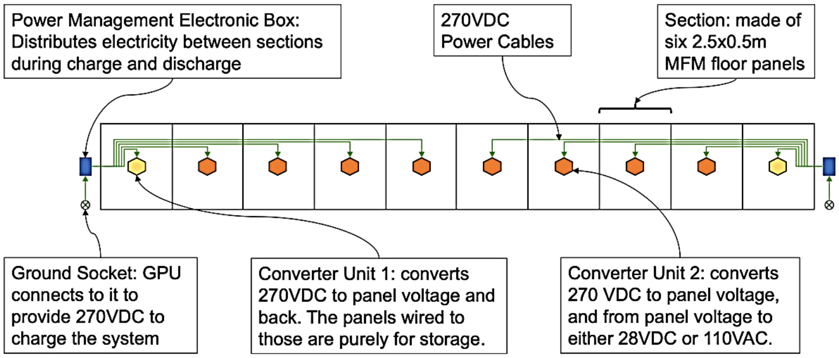


Fig. 4 Schematic showing the proposed power distribution system for structural power floor panels.

To better distribute power throughout the cabin and enable efficient charging, it is suggested that the aircraft would be equipped with two ground sockets, one fore and one aft (Fig. 4). When the ground power units are plugged in, power first goes to the power management electronic boxes (PMEBs), which distribute the electrical energy throughout the cabin. Each section is equipped with a converter unit (CU) to convert high ground voltage at 270 V DC to the panel's working voltage of 2.7 V DC (Fig. 5). The two fore and aft sections may be located at the galleys, and therefore not close to seats and the associated electrical loads of the IFE. These sections would act as storage-only: they are charged on the ground and feed power back to the PMEB in flight, which redistributes power wherever necessary. Those two sections would therefore be equipped with a primary converter unit (CU1) capable of converting ground voltage to panel working voltage and back. The other eight sections have secondary converter units (CU2). These CU2s not only convert ground voltage to panel working voltage, but also convert the panel working voltage to either IFE voltage (28 V DC) or ISPS voltage (110 V AC). To provide as much flexibility as possible, the CU2s can also convert panel working voltage to ground voltage to feed the other sections (Fig. 5).

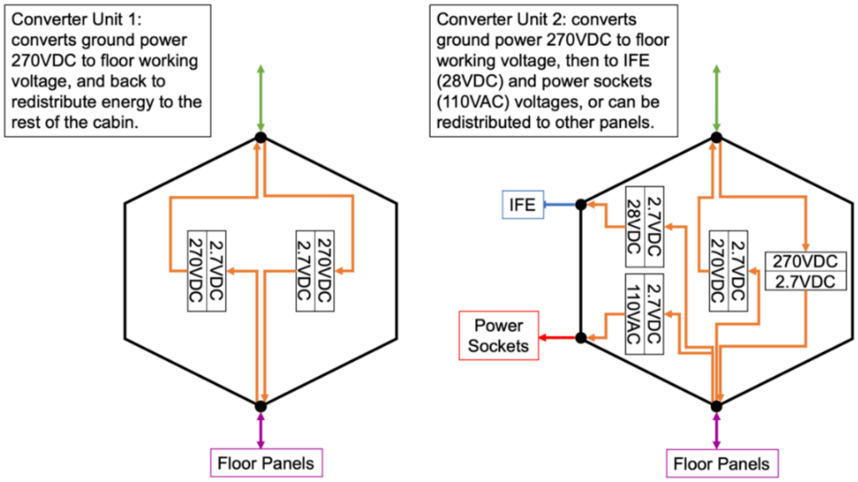


Fig. 5 Schematics of the primary and secondary converter units.

To estimate the system losses due to the converter efficiencies, average efficiencies have been adopted here (Table 6). These data were used to calculate the overall efficiency of the system and to amend the power and energy targets to account for such losses. Some power would first be stored in the foremost or aft-most panels prior to being redistributed elsewhere in the cabin. The revised power and energy demands, accounting for losses, increased the total electrical consumption by 25%.[1] Including these power losses yielded a total discharge power demand of 6.5 kW, a total charge power demand of 52 kW and a total stored energy demand of 26 kWh.

Table 6 Efficiency and power density of electrical power conversion devices

Device type	Efficiency, %	Mass/power for $P < 5$ kW, kg/kW	Mass/power for $P > 5$ kW, kg/kW
DC / DC	93 [35]	1	0.2
DC / AC	97 [36]	6	1.0
AC / AC	96 [37]	12	1.4
AC / DC	97 [38]	7	0.1

Results and discussion

In addition to providing minimum mechanical and electrical requirements for SPCs in aircraft cabin applications, it is important to identify the key advantages of using such technology on-board. The results presented in this section

---

[1] For comparison, the losses in a conventional aircraft power distribution system due to the resistance of the cables alone was estimated to be 8.8% assuming transmission line losses of 29.43 W/m [59].

combine the advantages of seat-centric IFE technology with SPC floor panels, as the two operate in conjunction to optimise the cabin electrical system.

Performance requirements

The deflection and mechanical load requirements would be met if both the mechanical properties and thickness of the face sheets and panel matched those of the conventional panels, since the maximum deflection and buckling load are primarily governed by the elastic properties of the face sheets [24]. A conservative requirement assumes that $E_{SPC} > E_{conv}$. From experimental data for unidirectional (UD) GFRP laminates, $E = 48$ GPa [39], and for a woven GFRP laminate, $E = 31$ GPa [40]. The higher value of 48 GPa was selected to provide a conservative requirement. Since the SPC face sheet thickness (1.32 mm) is almost twice that of the top face sheet (0.76 mm) for the thickest conventional panel, the requirement that $E_{SPC} > 28$ GPa was determined. The compressive strengths for UD and woven GFRP laminates have been measured as 380 MPa [41] and 153 MPa [42]. The higher value of 380 MPa was regarded as a conservative compressive strength requirement, which led to $X_{C,\,SPC} > 219$ MPa. The tensile strength requirement was taken to be the same as the compressive strength requirement, since a compressive stress in one region of the panel (e.g. in front of the seats) implies an equal tensile stress in another region (e.g. behind the seats). Both the elastic and strength requirements were considered attainable using state-of-the-art SPCs [29,43] based on UD or woven carbon fibre reinforcements.

The overall panel thickness and areal mass were 12.6 mm and 2.91 kg/m^2 respectively. The total masses of the SPC face sheets, Nomex core and cabin floor panels were 226 kg, 37 kg and 263 kg, respectively. For comparison, the conventional GFRP/Al honeycomb floor weighs 287 kg. Using SPC panels resulted in a mass saving because of the lighter, carbon fibre-based SPC face sheets.

By combining and dividing the electrical requirements (including losses) by the total mass of the SPC face sheets, the required E^* and P^* for the SPC floor panels were calculated to be 115 Wh/kg and 0.23 kW/kg respectively. Comparing these results with existing state-of-the-art SPCs suggested that E^* could be attained with laminated structural batteries [43], and P^* was within reach of current structural supercapacitors [29] provided their performance values determined at lab scale can be achieved at larger component scales. These E^* and P^* requirements were calculated assuming that the device can be fully discharged. However, a low state of charge is considered harmful for Li-ion batteries, which should always maintain a state of charge above 20% [44]. For supercapacitors, the voltage drops during discharge and the voltage needs to remain above that required for the electrical module to operate. Since the specific energy target is too high for a supercapacitor, either structural or conventional, a structural battery or hybrid solution is more realistic. Therefore, the minimum state of charge requirement is expected to be necessary. If this minimum state of charge is considered, E^* and P^* would correspondingly rise by 25%, to 144 Wh/kg and 0.29 kW/kg, respectively.

Mass and volume savings

The use of the proposed SPC cabin floor panels was calculated to offer several major weight and volume savings (Table 7). The overall mass saving of 261 kg represents ca. 2% of the maximum payload mass on the A220-100, or the equivalent of three extra passengers and their luggage. To estimate approximate volume savings, an average density for each component was assumed where applicable. For example, the density of aluminium (2.7 kg/l) was used to estimate the volume of aluminium wiring whilst the wire insulating material volume was neglected. For the electronic boxes and IFE data system, dimensions and masses were taken from manufacturer data sheets [45]. To estimate the additional volume of the new convertor units, the masses of CU1 and CU2 were divided by the effective density of an electronic box of similar function, the in-seat power supply [46].

The mass savings due to the complete removal of all IFE data servers and wiring were calculated based on data from a retrofit of the seat-centric IFE system on their Airbus A330s [10] (200 economy seats). The total mass saving was 600 kg, of which 185 kg could be directly attributed to the data system. Scaling this mass saving to the A220-100 (125 economy seats) would instead provide a 115 kg mass saving. The generator mass savings arise from the lowered electrical loads due to the presence of the SPC floor panels: the generators do not have to generate the 5.4 kW now supplied by the panels. Narrow-body aircraft generators have a mass to power ratio of around 0.67 kg/kW [22], and therefore the total mass of the generators decreased by 3.6 kg. The fuel saved by not generating electricity through the generators should also be calculated: since the efficiency of a turbofan is roughly 53% [22] and the energy density of Jet A fuel is 11.9 kWh/kg, 3.4 kg of Jet A fuel can therefore be spared per flight.

Table 7 Estimated weight and volume savings achievable by adopting SPC floor panels

Component	Old mass, kg	New mass, kg	Mass saving, kg	Volume saving, l
Electronic boxes	238	39	199	363
IFE data system	115	0.0	115	172
Floor panels	287	263	24	0
Generators	108	104	3.6	0.6
Fuel	3.4	0.0	3.4	4.2
Wiring	23	107	-84	-31
Total			261	509

In the longer term, as SPCs improve in performance, the overall mass saving could be increased by selecting designs with higher performance requirements. For example, the mass of the SPC face sheets could simply be reduced by reducing the number of cells. The corresponding reduction in the thickness of the face sheets would increase the specific electrochemical and mechanical requirements. However, since the floor panels themselves only account for a fraction of the total mass saving, the overall mass savings do not scale linearly with the increase in SPC performance requirements; there are diminishing returns. To mitigate the increase in performance requirements, one option would be to modify the allowable flight time, currently fixed at four hours; for example, only allow aircraft used for shorter flights to be equipped with SPC floor panels. Using lighter two-cell face sheets, but restricting to only two-hour flights for instance, would maintain the specific energy targets at the same values calculated earlier, whilst achieving a mass saving of 366 kg (40% improvement). Many other parameters could be changed (such as on-board usage, ground charging time, etc.) which could further modify the performance targets to keep them at feasible levels and still achieve high mass savings. For the longer flights needing relatively high E^* and P^*, one approach would be to develop hybrid SPCs, which combine Faradaic energy storage with double-layer capacitance.

Economic, environmental and technological benefits

This sub-section quantifies how the mass savings calculated would affect the fuel burn, associated cost savings, sustainability and other multifunctional system benefits. It has been estimated that the cost of carrying one extra kilogram on-board is £242 every 500 flight hours (FH), or 0.092 kg of fuel/FH [22]. Assuming a daily usage of 10 hours (the average utilisation rate in the US [10]) results in annual fuel savings of 88 tonnes per aircraft. To this figure can be added the fuel saved from not using the generators (at a rate of 3.4 kg for a four-hour flight), which totals an additional 3 tonnes a year. At £0.62/*l* [22], this rate yields annual cost savings of £70k per aircraft.

The annual electricity usage (23.8 MWh) to charge a single aircraft on the ground at a price of £65/MWh [22] would cost £1550/yr. Therefore, the cost savings from fuel and mass far exceed the additional cost of ground-sourced electricity. To put this in perspective, at the same utilisation rate, the yearly fuel bill for an A220-100 is close to £8.3M, and therefore the fuel cost savings would be 0.84% of the total fuel expenditure. Additionally, by reducing the number of electronic boxes, removing the IFE data system and installing the same type of floor panels throughout the cabin, it is reasonable to expect that maintenance and associated costs could potentially be reduced.

Having determined that SPC floor panels could save 91 tonnes of fuel per year, the reduction in gas emissions was estimated using background information that 1.00 kg of jet fuel reacts with oxygen to create 3.16 kg of CO_2 and 12.90 g of NO_x [47]. The resulting mass and fuel savings from the installation of SPC floor panels could result in a reduction of 288 tonnes of CO_2, and 1.2 tonnes of NO_x per aircraft per year if the electricity used to charge the floor panels comes from renewable energy generation. The emissions from the production of electricity on the ground were determined to be 4.4 tonnes of CO_2, and 0.71 kg of NO_x per aircraft per year. This calculation was based on natural gas being the most common electricity generation fuel in the UK, accounting for over 40% [22]. Furthermore, closed-cycle gas turbines are the only type of power plant using natural gas in the UK and emit 184 kg of CO_2/MWh [22] and 30 g of NO_x/MWh. These emissions values resulted in net reductions of 284 tonnes of CO_2 and 1.2 tonnes of NO_x per aircraft per year.

Generators on turbofans are connected to an accessory drive, which diverts mechanical power away from the engine to power hydraulic pumps, oil pumps, etc. Lowered generator loads would likely reduce the power diverted from the engine, and therefore improve the distance travelled for a given fuel consumption.

In completely new aircraft designs, the incorporation of SPC technology on-board could unlock much greater mass savings than are possible in a simple retrofit to existing systems. The landing gear for instance, is a component that largely depends on the empty weight of the aircraft, and is a heavy system itself, representing 6% of the aircraft's operating empty weight for a retractable system [22]. Since the mass savings determined here are not payload-related, the landing gear could be lighter. This reduction in turn would alleviate some of the stresses on the airframe and likely yield additional mass savings. This discussion shows the clear advantages of including SPCs early in new aircraft designs, to fully exploit their potential benefits.

Adaptability is also a valuable attribute of SPCs, and particularly when used in floor panels. If the aircraft in question were not equipped with IFE screens or power sockets, a simple rewiring and slight changes in the converter units would enable the panels to power other cabin loads, such as the lighting system and the electronics in the overhead passenger service unit.

As promising as structural power composite technology is to reduce cost, emissions and improve overall efficiency, many challenges remain before they can be fully adopted in aircraft. The subsequent paragraphs discuss the challenges specific to aircraft cabin applications, and not the larger obstacles in the development of such materials [29].

Flammability, smoke and toxicity (FST)

A critical set of requirements for structural materials or power sources on-board aircraft concerns their flammability, smoke and toxicity behaviour. Both the risks of the floor being a source of fire and burning as a result of an unconnected source of ignition need to be recognised and mitigated. Various fire incidents have plagued the Boeing 787 and its Li-ion batteries during its early years of service. Since then, Boeing has identified a means to contain (but not prevent) thermal runaway issues, by building a stainless-steel protective casing [22], adding substantial mass to that of the Li-ion batteries. It is therefore critical to ensure that SPCs meet strict Federal Aviation Administration (FAA) certification requirements [48] (or equivalent, such as European Union Aviation Safety Agency (EASA) CS25) which specify that for cabin materials, the "average burn length must not exceed 15 cm and the average flame time after removal of the flame may not exceed 15 seconds." In fires involving CFRP, it is typically the resin that vaporises and burns whilst the carbon fibres usually char upon burning, slowing down the burn rate, which can cause self-extinguishing [49]. When CFRP burns, small ablated fragments of the fibres can be released, which present a health risk [22]. However, since CFRP can be found in the cabin already, this risk is not an additional issue. Less is known about the burning characteristics of a multifunctional structural electrolyte matrix. Many systems combine epoxy resin with ionic liquid electrolytes. Ionic liquid electrolytes are non-volatile and have low flammability, high thermal stability with a high onset decomposition temperature (358 °C) [50] and have been shown to make electrolyte mixtures self-extinguishable [51]. Furthermore, many researchers have considered the addition of ionic liquids as fire retardants [52] and observed reductions in average heat release rates of 37% [53]. Further research is recommended to understand, assess and mitigate the risks associated with FST of SPCs and, more pertinently, accidental penetration / shorting, although initial experiments show a promisingly benign response [8]. Supercapacitor-based systems, with either ionic liquid [54] or aqueous electrolytes raise far fewer safety concerns than Li-based batteries, as they do not involve flammable volatile components or reactive metals. Future research could incorporate recently developed fire-proof solid polymer electrolytes [55] into SPCs.

Encapsulation and integration

Encapsulation refers to the way the SPCs are isolated from the surrounding environment, thereby providing protecting. Encapsulation is critical to prevent moisture, dust or other substances degrading the SPC and can also be used as containment, such as to prevent the spread of a fire from one cell to another for instance. The encapsulation therefore needs to be a robust, reliable safety barrier and provide mechanical load transfer between the cell and the surrounding structure.

Integration of the SPC floor panels into the cabin also must be considered. In addition to the placement of wiring and converter units, how to mount the floor panels on the substructure needs to be investigated. With conventional floor panels, screws are generally used to facilitate maintenance and replacement. The holes in the sandwich panels are typically fitted with metal inserts to distribute the stresses associated with the screw head. A similar solution, possibly using insulating PTFE inserts, may be used for SPC panels. Since the mass of energy storing SPC would decrease due to the holes, the electrical requirements might rise slightly. Drilling holes might raise other concerns about shorting the devices due to machining damage or debris. However, previous research found that the capacitance of structural supercapacitors was retained when holes were drilled under carefully controlled conditions [56]. Additional research is, therefore, needed to achieve robust encapsulation of the SPC cells, while allowing for electrical connectors [8], drill holes and fasteners. This research is essential to ensure the safety of passengers, while allowing quick access for maintenance or replacement.

The effects of mechanical impact forces on SPC floor panels would need to be studied to obtain a comprehensive understanding of the structural and electrical performance implications. An object falling onto a SPC panel could potentially cause short-circuits (if the two electrodes come into contact) or affect the long-term performance of the panel. Such impacts could have further implications on the maintenance requirements of the panels and their service life.

Reliability and maintenance

Maintenance on-board aircraft is categorised in two types: scheduled and unscheduled. The first refers to regular maintenance intervals, which are:

- *A-check:* every 850 flight hours, general inspection of interior and exterior, typically overnight [22],
- *C-check:* every 8500 flight hours, structural inspections and functional system checks, usually one to two weeks long [22].

Unscheduled maintenance by contrast is any maintenance caused by a failure during flight operations. These can be as simple as changing a wheel, but sometimes require more time, when damage is beyond allowable limits as per aircraft documentation. In the latter, the incident is of aircraft-on-ground type, in which the aircraft cannot become airborne until repairs are conducted.

To ensure minimal impact from the installation of SPC floor panels, their reliability, inspection intervals and service life should all be linked to existing maintenance intervals. For instance, the service life (and therefore long-term cycling performance) of the SPC could be based on the C-check interval of 8500 flight hours and ensure that the panels can meet this requirement without failure. A full analysis of the failure probability would be required to gather a good understanding of the behaviour of the material and plan preventive maintenance around it. Additionally, positioning the converter units under the aisle floor panels would make accessing them and performing inspections and repairs easier. This approach would not require the removal of any seats and would minimise downtime. Finally, the lifetime of the SPC would dictate the timescale for replacement of the structure. One approach to servicing would be to ensure the scheduled floor panel replacement does not exceed the SPC lifetime.

Cost analysis

The cost saving during operation showed a 50% reduction in recurring costs to power the IFE system. The costs to produce SPC floor panels was evaluated assuming a panel made of two-cell face sheets with a Nomex core (Table 8). This cost analysis accounts for processing costs in addition to material costs by assuming that, as for conventional batteries [37], the processing costs account for 45% of the total costs. A similar analysis for a modern CFRP sandwich panel yields £722/m^2, making SPC floor panels 70% more expensive. However, keeping in mind the cost savings experienced during the service life of the aircraft, break-even for the A220-100 would be achieved in just six months. In addition to the floor panels, the converter units would have to be designed, developed and manufactured, adding significant costs. However, there would be cost savings associated with removing IFE system components, seat electronic boxes and wiring. Further studies would help to quantify the cost breakdown for these electronic components.

Table 8 SPC floor panel cost estimation based on a structural supercapacitor configuration [10, 37]

Item	Cost [£/m^2]
Carbon fibre fabric	156
Current collector	116
Ionic liquid	14
Resin	2
Separator	14
Nomex	61
Overheads/processing	544
Total	1210

Airport electrical demands

First order estimates of the total energy and power demands at airports for charging SPC floor panels were made using data from London Heathrow Airport [22] where at peak time, from 08:30 to 09:30, a total of 47 narrow-body aircraft need to charge. Considering the staggering of departures, and if all narrow-body flights were equipped with SPC floor panels and seat 180 passengers (based on an A320, which brings the power requirement to 75 kW per aircraft), the maximum power demand would be 1.5 MW.

The annual energy requirement was calculated using the same assumptions and taking 423 narrow-body flights per day on average (based on monthly flight logs [22]). This yielded a total of 5.8 GWh of electricity per year. For comparison, London Heathrow Airport predicts a yearly electrical consumption of 550 GWh in 2020 [22]. The added demand from SPC panels would therefore represent just over 1% of the total consumption. This requirement is significantly lower and more achievable than the 1.93 TWh that London Heathrow Airport would consume if all short-haul flights were fully electric [58].

Passenger perception

One potential hurdle to the introduction of SPCs in aircraft cabins is the reaction of the passengers. A sense of concern could be exacerbated by the battery issues that the Boeing 787 was confronted with during its early service. At the time of the incidents, a survey of frequent flyers revealed that 32% of respondents refused to fly on the B787, while 35% avoided it if possible [10]. In another survey, 46% of respondents said they would wait a year or two before flying on a B787 [22].

The automobile industry provides valuable insight on the adoption of new electric technology in vehicles. Research to identify the main safety concerns of new electric vehicle (EV) drivers found that battery failure accounted for 20% of safety concerns. As for aircraft, these concerns been fuelled by several incidents on EVs, some of which caught fire following crash tests; others when the battery pack was hit by debris. It may be necessary to inform and reassure the public about the safety and reliability of SPCs before the technology enters service.

One advantage that SPC floor panels offers passengers comes from removing SEBs. On modern airliners, there is one SEB per group of seats (two per row in the A220), which limits foot space for passengers. With ever higher requirements on the IFE system, SEBs have grown over time and many passengers would experience greater comfort following the removal of SEBs.

Conclusions

This study investigated the potential integration of structural power composites in cabin applications on-board the A220-100 narrow-body aircraft. One feasible application within the aircraft cabin was investigated in depth: structural power floor panels that power the in-flight entertainment system. This application was considered highly suitable for SPC integration because cabin floor panels are easily accessible for maintenance, have a simple flat geometry and are close to the cabin electrical loads.

The mechanical requirements were determined by assuming four-cell SPC face sheets for the floor sandwich panels with mechanical properties exceeding those of the conventional floor panel face sheets. This configuration yielded minimum requirements of 28 GPa for the elastic modulus and 219 MPa for the tensile and compressive strengths. The specific energy and specific power targets were determined to be 144 Wh/kg and 0.29 kW/kg respectively, accounting for all losses in the electrical distribution system and a 20% minimum state of charge.

Mass and volume savings, in conjunction with new seat-centric IFE technology, were determined to be 261 kg and 510 *l* respectively. The mass savings could directly translate into significant annual fuel and cost savings well above the cost of electricity used to charge the panels. Annual CO_2 and NO_x emissions could also be reduced by 284 and 1.2 tonnes respectively per aircraft. Overall engine efficiency could also improve due to the reduced power drawn from the generators. A blank-sheet aircraft system design could maximise the benefits by exploiting further mass savings on many structures that are sized according to the aircraft empty operating weight.

To achieve the potential weight and volume savings estimated, several key topics regarding the adoption of SPCs in the cabin need further research; the most paramount are related to addressing FST- and encapsulation-related safety concerns and validation of the multifunctional design methodology. Other research topics that warrant investigation include impact resistance, long-term cycling performance and public perception. Passengers may be concerned of new technologies on-board, and appropriate reassurance of the safety of SPCs may be required.

Ultimately, it is necessary to develop a *multifunctional design* methodology to facilitate adoption of structural power, such that the practical implementation fully exploits the capabilities of multifunctional materials. The outcome of the current research is an analysis approach which enables calculation of the structural and specific energy and power requirements for a structural power composite to perform the functions that conventional structural components and power sources would perform. This analysis can steer SPC development by quantifying the relative balance needed between structural and electrochemical performance characteristics. In addition, this study identified the main advantages of using SPCs in aircraft cabins and highlighted the challenges to be addressed for SPCs to meet airworthiness standards. The methodology presented here to determine performance targets and benefits for structural power may be extended to many other multifunctional materials for applications in a wide range of industry sectors.

Funding Sources

The authors would like to acknowledge the funding provided by the EPSRC Future Composites Research Manufacturing Hub (EP/P006701/1), the EPSRC Beyond Structural project (EP/P007465/1), the European Office of Aerospace Research and Development (IOE Grant FA9550-17-1-0251), EU Clean Sky 2 (SORCERER Project #738085) and the Royal Academy of Engineering (Chair in Emerging Technologies).

References

[1] Asp, L. E., and Greenhalgh, E. S. “Structural Power Composites.” *Composites Science and Technology*, Vol. 101, No. Sep., 2014, pp. 41–61. https://doi.org/10.1016/j.compscitech.2014.06.020.

[2] Schwingshackl, C. W., Aglietti, G. S., and Cunningham, P. R. “Experimental Determination of the Dynamic Behavior of a Multifunctional Power Structure.” *AIAA Journal*, Vol. 45, No. 2, 2007, pp. 491–496. https://doi.org/10.2514/1.23894.

[3] Anton, S. R., Erturk, A., and Inman, D. J. “Multifunctional Unmanned Aerial Vehicle Wing Spar for Low-Power Generation and Storage.” *Journal of Aircraft*, Vol. 49, No. 1, 2012, pp. 292–301. https://doi.org/10.2514/1.C031542.

[4] Carlstedt, D., and Asp, L. E. “Performance Analysis Framework for Structural Battery Composites in Electric Vehicles.” *Composites Part B: Engineering*, Vol. 186, No. Apr., 2020, p. 107822. https://doi.org/10.1016/j.compositesb.2020.107822.

[5] Johannisson, W., Zerkert, D., Lindbergh, G., Zenkert, D., and Lindbergh, G. “Model of a Structural Battery and Its Potential for System Level Mass Savings.” *Multifunctional Materials*, Vol. 2, No. 3, 2019, p. 035002. https://doi.org/10.1088/2399-7532/ab3bdd.

[6] Tsushima, N., and Su, W. “Modeling of Highly Flexible Multifunctional Wings for Energy Harvesting.” *Journal of Aircraft*, Vol. 53, No. 4, 2016, pp. 1033–1044. https://doi.org/10.2514/1.C033496.

[7] Tsushima, N., and Su, W. “Concurrent Active Piezoelectric Control and Energy Harvesting of Highly Flexible Multifunctional Wings.” *Journal of Aircraft*, Vol. 54, No. 2, 2016, pp. 724–736. https://doi.org/10.2514/1.C033846.

[8] Greenhalgh, E. S., and Asp, L. E. *STORAGE (Composite Structural Power Storage for Hybrid Vehicles) Final Publishable Summary Report, STORAGE/WP1/ICL/M1-42*. 2013.

[9] Adam, T. J., Liao, G., Petersen, J., Geier, S., Finke, B., Wierach, P., Kwade, A., Wiedemann, M., Adam, J. T., Liao, G.,

Petersen, J., Geier, S., Finke, B., Wierach, P., Kwade, A., and Wiedemann, M. “Multifunctional Composites for Future Energy Storage in Aerospace Structures.” *Energies*, Vol. 11, No. 2, 2018, p. 335. https://doi.org/10.3390/en11020335.

[10] Friedrich, C., and Robertson, P. A. “Hybrid-Electric Propulsion for Aircraft.” *Journal of Aircraft*, Vol. 52, No. 1, 2014, pp. 176–189. https://doi.org/10.2514/1.C032660.

[11] Epstein, A. H., and O’Flarity, S. M. “Considerations for Reducing Aviation’s CO2 with Aircraft Electric Propulsion.” *Journal of Propulsion and Power*, Vol. 35, No. 3, 2019, pp. 572–582. https://doi.org/10.2514/1.B37015.

[12] Finger, D. F., Bil, C., and Braun, C. “Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft.” *Journal of Aircraft*, Vol. 57, No. 2, 2019, pp. 245–255. https://doi.org/10.2514/1.C035428.

[13] Ng, W., and Datta, A. “Hydrogen Fuel Cells and Batteries for Electric-Vertical Takeoff and Landing Aircraft.” *Journal of Aircraft*, Vol. 56, No. 5, 2019, pp. 1765–1782. https://doi.org/10.2514/1.C035218.

[14] Scholz, A., Hermanutz, A., and Hornung, M. Feasibility Analysis and Comparative Assessment of Structural Power Technology in All-Electric Composite Aircraft, Deutscher Luft- Und Raumfahrtkongress, Friedrichshafen, Germany, 2018, pp. 1-12. 2018.

[15] Dean, T. S., Wroblewski, G. E., and Ansell, P. J. “Mission Analysis and Component-Level Sensitivity Study of Hybrid-Electric General-Aviation Propulsion Systems.” *Journal of Aircraft*, Vol. 55, No. 6, 2018, pp. 2454–2465. https://doi.org/10.2514/1.C034635.

[16] Finger, D. F., Braun, C., and Bil, C. “Comparative Assessment of Parallel-Hybrid-Electric Propulsion Systems for Four Different Aircraft.” *Journal of Aircraft*, 2020, pp. 1–11. https://doi.org/10.2514/1.C035897.

[17] de Vries, R., Brown, M., and Vos, R. “Preliminary Sizing Method for Hybrid-Electric Distributed-Propulsion Aircraft.” *Journal of Aircraft*, Vol. 56, No. 6, 2019, pp. 2172–2188. https://doi.org/10.2514/1.C035388.

[18] Ma, Y., Zhang, W., Zhang, Y., Zhang, X., and Zhong, Y. “Sizing Method and Sensitivity Analysis for Distributed Electric Propulsion Aircraft.” *Journal of Aircraft*, Vol. 57, No. 4, 2020, pp. 730–741. https://doi.org/10.2514/1.C035581.

[19] Bradley, M. K., and Droney, C. K. *Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development*. NASA/CR-2012-217556, 2012.

[20] Bradley, M. K., and Droney, C. K. *Subsonic Ultra Green Aircraft Research: Phase II – Volume II – Hybrid Electric Design Exploration*. NASA/CR-2015-218704/Volume II, 2015.

[21] Airbus. *Global Market Forecast, Cities, Airports and Aircraft 2019-2038*. 2019.

[22] Nguyen, S. N., Millereux, A., Pouyat, A., Greenhalgh, E. S., P, M. S., Shaffer, Kucernak, A. R. J., and Linde, P. Structural Power Performance Requirements for Future Aircraft Integration, ICCM22, Melbourne, Australia, 11-16 August. 2019.

[23] Schroeter, T. *Power Management on Aircraft*. VDE Verlag GmbH, Berlin, 2013.

[24] Zenkert, D. *An Introduction to Sandwich Construction*. Engineering Materials Advisory Services Ltd, London, 1995.

[25] Nunes, J. P., and Silva, J. F. *Advanced Composite Materials for Aerospace Engineering: Processing, Properties and Applications, Chapter 5, p 151*. Woodhead Publishing, Cambridge, MA, 2016.

[26] Daniel, I. M., Gdoutos, E. E., and Rajapakse, Y. D. S., Eds. *Major Accomplishments in Composite Materials and Sandwich Structures*. Springer Netherlands, Dordrecht, 2009.

[27] Federal Aviation Administration. *14 CFR § 25.561*. 2002.

[28] Greenhalgh, E. S., Ankersen, J., Asp, L. E., Bismarck, A., Fontana, Q., Houlle, M., Kalinka, G., Kucernak, A., Mistry, M., Nguyen, S., Qian, H., Shaffer, M., Shirshova, N., Steinke, J., and Wienrich, M. "Mechanical, Electrical and Microstructural Characterisation of Multifunctional Structural Power Composites." *Journal of Composite Materials*, Vol. 49, No. 15, 2015. https://doi.org/10.1177/0021998314554125.

[29] Greenhalgh, E. S., Shaffer, M. S. P., Kucernak, A. R., Anthony, D. B., Senokos, E., Nguyen, S. N., Pernice, F., Zhang, G., Qi, G., Balaskandan, K., and Valkova, M. Future Challenges and Industrial Adoption Strategies for Structural Supercapacitors. 2019.

[30] Asp, L. E., Bouton, K., Carlstedt, D., Duan, S., Harnden, R., Johannisson, W., Johansen, M., Johansson, M. K. G., Lindbergh, G., Liu, F., Peuvot, K., Schneider, L. M., Xu, J., and Zenkert, D. "A Structural Battery and Its Multifunctional Performance." *Advanced Energy and Sustainability Research*, Vol. n/a, No. n/a, 2021, p. 2000093. https://doi.org/https://doi.org/10.1002/aesr.202000093.

[31] Johannisson, W., Ihrner, N., Zenkert, D., Johansson, M., Carlstedt, D., Asp, L. E., and Sieland, F. "Multifunctional Performance of a Carbon Fiber UD Lamina Electrode for Structural Batteries." *Composites Science and Technology*, Vol. 168, No. March, 2018, pp. 81–87. https://doi.org/10.1016/j.compscitech.2018.08.044.

[32] Carlstedt, D., Marklund, E., and Asp, L. E. "Effects of State of Charge on Elastic Properties of 3D Structural Battery Composites." *Composites Science and Technology*, Vol. 169, No. Jan., 2019, pp. 26–33. https://doi.org/10.1016/J.COMPSCITECH.2018.10.033.

[33] Seemann, R., and Krause, D. Numerical Modelling of Nomex Honeycomb Cores for Detailed Analyses of Sandwich Panel Joints, 11th World Congress on Computational Mechanics, Hamburg, Germany, 2015, Pp. 1-12.

[34] Maxwell. *2.7V 1F/100F/150F Cell Datasheet, Document Number: 3001959-EN.3*. 2018.

[35] Duan, C., Bai, H., Guo, W., and Nie, Z. "Design of a 2.5-KW 400/12-V High-Efficiency DC/DC Converter Using a Novel Synchronous Rectification Control for Electric Vehicles." *IEEE Transactions on Transportation Electrification*, Vol. 1, No. 1, 2015, pp. 106–114. https://doi.org/10.1109/TTE.2015.2426506.

[36] Pittini, R., Anthon, A., Zhang, Z., and Andersen, M. A. E. Analysis and Comparison of Si and SiC Power Devices on a Grid-Tie Fuel Cell Energy Storage System, International Power Electronics and Application Conference and Exposition, Shanghai, 2014, Pp. 296-301. 2014.

[37] Sarnago, H., Mediano, A., and Lucia, Ó. "High Efficiency AC–AC Power Electronic Converter Applied to Domestic Induction Heating." *IEEE Transactions on Power Electronics*, Vol. 27, No. 8, 2012, pp. 3676–3684. https://doi.org/10.1109/TPEL.2012.2185067.

[38] Mahesh, M., and Panda, A. K. "High-Power Factor Three-Phase Ac-Dc Soft-Switched Converter Incorporating Zero-Voltage Transition Topology in Modular Systems for High-Power Industry Applications." *IET Power Electronics*, Vol. 4, No. 9, 2011, pp. 1032–1042. https://doi.org/10.1049/iet-pel.2010.0409.

[39] Peters, S. T. *Handbook of Composites*. Springer, London, 1998.

[40] Gao, G., and Li, Y. "Mechanical Properties of Woven Glass-Fiber Reinforced Polymer Composites." *Emerging Materials Research*, Vol. 5, No. 2, 2016, pp. 201–208. https://doi.org/10.1680/jemmr.16.00018.

[41] Jin, H., Nelson, K., Nissen, A., Werner, B., and Briggs, T. *Mechanical Characterization of Woven Composites at Different Temperatures*. Report SAND2018-8563, Sandia National Labs, Livermore, CA, US, 2018.

[42] Leopold, C., Harder, S., Philipkowski, T., Liebig, W., and Fiedler, B. "Comparison of Analytical Approaches Predicting the Compressive Strength of Fibre Reinforced Polymers." *Materials*, Vol. 11, No. 12, 2018, p. 2517. https://doi.org/10.3390/ma11122517.

[43] Asp, L. E., Johansson, M., Lindbergh, G., Xu, J., and Zenkert, D. "Structural Battery Composites: A Review." *Functional Composites and Structures*, Vol. 1, No. 4, 2019, p. 042001. https://doi.org/10.1088/2631-6331/ab5571.

[44] Spirit Energy. Battery Storage Knowledge Bank, Understanding Batteries. https://www.spiritenergy.co.uk/kb-batteries-understanding-batteries. Accessed Apr. 8, 2019.

[45] Ametek. AC Secondary Power Distribution. https://www.ametekpds.com/-/media/ametekpds/datasheets pdf/power distribution/ac spdu flyer.pdf. Accessed Mar. 23, 2020.

[46] TDI Power. Airborne In-Seat Power Supply - Model ACS1275. https://pdf.directindustry.com/pdf/tdi-transistor-devices/in-seat-power-supply/12691-406185.html. Accessed Mar. 23, 2020.

[47] Freeman, S. J. *Examining the Effects of Aviation NOx Emissions as a Short-Lived Climate-Forcer*. Ph.D. Dissertation, Faculty of Science and Engineering, Manchester Metropolitan University, Manchester, UK, 2017.

[48] Federal Aviation Administration. *Appendix F to Part 25 Test Criteria and Procedures for Showing Compliance with § 25.853, or § 25.855*. 2012.

[49] Federal Aviation Administration. *Flammability Properties of Aircraft Carbon-Fiber Structural Composite*. DOT/FAA/AR-07/57, NTIS, Springfield, Virginia 22161, 2007.

[50] An, Y., Zuo, P., Cheng, X., Liao, L., and Yin, G. "Preparation and Properties of Ionic-Liquid Mixed Solutions as a Safety Electrolyte for Lithium Ion Batteries." *International Journal of Electrochemical Science*, Vol. 6, No. 7, 2011, pp. 2398–2410.

[51] Vo, T. D., Nguyen, H. V, Nguyen, Q. D., Phung, Q., Tran, V. M., and Le, P. L. M. “Carbonate Solvents and Ionic Liquid Mixtures as an Electrolyte to Improve Cell Safety in Sodium-Ion Batteries.” *Journal of Chemistry*, Vol. 2019, No. Jul, 2019, pp. 1–10. https://doi.org/10.1155/2019/7980204.

[52] Sonnier, R., Dumazert, L., Livi, S., Nguyen, T. K. L., Duchet-Rumeau, J., Vahabi, H., and Laheurte, P. “Flame Retardancy of Phosphorus-Containing Ionic Liquid Based Epoxy Networks.” *Polymer Degradation and Stability*, Vol. 134, No. Dec., 2016, pp. 186–193. https://doi.org/10.1016/j.polymdegradstab.2016.10.009.

[53] Shi, Y. Q., Fu, T., Xu, Y. J., Li, D. F., Wang, X. L., and Wang, Y. Z. “Novel Phosphorus-Containing Halogen-Free Ionic Liquid toward Fire Safety Epoxy Resin with Well-Balanced Comprehensive Performance.” *Chemical Engineering Journal*, Vol. 354, No. Dec., 2018, pp. 208–219. https://doi.org/10.1016/j.cej.2018.08.023.

[54] Shirshova, N., Rogaume, T., Najmi, H., and Poisson, M. The Combustion Behaviour of Epoxy Based Multifunctional Electrolytes. *Fire and Materials*. 2021 (Not yet published).

[55] Cui, Y., Wan, J., Ye, Y., Liu, K., Chou, L.-Y., and Cui, Y. “A Fireproof, Lightweight, Polymer–Polymer Solid-State Electrolyte for Safe Lithium Batteries.” *Nano Letters*, Vol. 20, No. 3, 2020, pp. 1686–1692. https://doi.org/10.1021/acs.nanolett.9b04815.

[56] Ankersen, J., Mistry, M., Nguyen, S., Greenhalgh, E. S., and Kucernak, A. Addressing Engineering Issues for a Composite Structural Power Demonstrator, ICCM19 International Conference on Composite Materials, Montreal, Canada, 28 Jul - 2 Aug 2013, Pp. 1-10.

[57] Patry, G., Romagny, A., Martinet, S., and Froelich, D. “Cost Modeling of Lithium-Ion Battery Cells for Automotive Applications.” *Energy Science & Engineering*, Vol. 3, No. 1, 2015, pp. 71–82. https://doi.org/10.1002/ese3.47.

[58] Schäfer, A. W., Barrett, S. R. H., Doyme, K., Dray, L. M., Gnadt, A. R., Self, R., O’Sullivan, A., Synodinos, A. P., and Torija, A. J. “Technological, Economic and Environmental Prospects of All-Electric Aircraft.” *Nature Energy*, Vol. 4, No. 2, 2019, pp. 160–166. https://doi.org/10.1038/s41560-018-0294-x.

[59] Nya, B. H., Brombach, J., and Schulz, D. Benefits of Higher Voltage Levels in Aircraft Electrical Power Systems, Electrical Systems for Aircraft, Railway and Ship Propulsion Conference, Bologna, 2012, pp. 1-5. 2012.