STRUCTURAL POWER PERFORMANCE REQUIREMENTS FOR FUTURE AIRCRAFT INTEGRATION

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Keywords: Multifunctional design, Structural power, Aircraft

ABSTRACT

This paper investigates the use of structural power composites in Airbus A220-100 aircraft cabins by integrating floor panels with face sheets made of structural power composites to power the in-flight entertainment system. This application requires a minimum specific energy of 305 Wh/kg and a minimum specific power of 0.610 kW/kg. The static and dynamic loads for which the floor panels must be certified require an in-plane Young's modulus of 50 GPa, a compressive strength of 225 MPa and a tensile strength of 119 MPa. Structural power composite floor panels are predicted to yield mass savings of 324 kg, annual cost savings of £85,000 per aircraft and annual reductions in CO_2 and NO_x emissions of 343 tonnes and 1.4 tonnes respectively. However, addressing challenges such as fire-resistance, long term cycling performance and public perception of structural power composites are necessary to enable widespread use of such materials on-board airliners.

1 INTRODUCTION

The development of multifunctional composites holds prodigious promise in enabling the realization of far lighter components, vehicles and other devices. As well as the benefits in terms of mass and volume savings, multifunctional materials also present exciting opportunities to design vehicles and products in ways which are currently unachievable using conventional monofunctional materials. Akin to the step change in design philosophy needed to optimize a design using composites rather than metals, a similar transformation in the mind-set of the engineer is required to fully exploit the potential benefits offered by multifunctional materials. The development of a universally agreed methodology with which to design using multifunctional materials in a manner that optimizes mass or volume savings is a key step towards the uptake of such materials in industrial applications.

The objectives of this paper are to understand how multifunctional materials can offer benefits over conventional systems, what performance levels are needed to provide benefits, and how best to integrate multifunctional materials in the conceptual design phase. The specific focus here will be the application of structural power composites (SPCs) [1] in the cabin of regional aircraft. The outcome of the current research is an analysis and modelling approach which enables calculation of the structural and specific energy and power requirements for a structural power composite to drive selected electrical systems by replacing purely structural components. This analysis can steer multifunctional material development by quantifying the required balance between structural and electrochemical performance characteristics.

The increasing electrification of aircraft systems together with the vast potential increases in flight range [2] that can be achieved by reducing the mass of electric aircraft makes a compelling case to explore multifunctional design using structural power composites as an example application. In the case of aircraft systems, the high energy and power requirements for propulsion mean that, in the near term, structural power materials would not replace, but instead supplement existing power sources. This paper investigates the potential use of SPCs in aircraft cabins, since this application has advantages in ease of access for inspections and maintenance, a controlled environment (temperature and pressure ranges) and the locality of devices which could use the electrical energy stored. Using accurate estimates of the electrical demands that the SPCs will need to meet, specific energy and specific power requirements can be obtained.

2 ELECTRICAL REQUIREMENTS

The regional aircraft sector is predicted to be a fast-growing market segment and the modest range makes the power and energy requirements significantly more viable to attain than those for long haul flights. To obtain accurate and relevant results, the investigation should be based on an existing aircraft, from which data can be obtained on system power usage, certification requirements, etc. Additionally, the type of aircraft used should be chosen carefully: it is unlikely that certification authorities permit new and relatively immature materials on-board 15-hour flights crossing oceans, which makes narrow body, regional aircraft the preferred platform. The Airbus A220-100 was chosen as test-bed for this investigation, as it is the latest narrow-body aircraft currently flying and so adopts numerous ‘More Electric Aircraft’ designs, including the very first electric braking system as standard, and extensive use of composite materials.

In its standard high density, all-economy, configuration, the Airbus A220-100 carries 125 passengers, in a 3-2 seating configuration. All passengers have access to a seat-back screen and three power sockets per row (in between the seats). This high-density configuration is chosen as it provides an upper limit to the electrical requirements. To ensure conservative results, it is assumed that the flight operates such that all seats are occupied. This is likely to result in a flight operating near the maximum payload point, which affects the range (down to 3700 km [3], from the maximum 5500 km) and endurance of the aircraft (just over four hours at M0.82). A four-hour-long flight is assumed, noting that Delta Airlines’ aircraft regularly fly more than three hours on their New York to Dallas route.

Finally, to minimise the impact of using SPCs on-board, the charge time of the system should be as short as possible. Analysis of typical on-ground time of several A220-100 aircraft, and the Airport Planning Publication for the aircraft type [3] revealed most turn-arounds are under one hour, with the shortest seen at 40 mins. The charge time is chosen to be 30 mins, to allow enough flexibility for other turnaround operations.

The electrical system in the cabin (ATA 44), which comprises the in-flight entertainment (IFE) system and power sockets, also represents a significant share of non-essential total electrical consumption, up to 33% [4]. Unlike the galleys however, the ATA 44 electrical load is distributed throughout the cabin, with a seat-back screen and power socket available for every passenger. This has two clear benefits: redundancy, as each SPC component powers only part of the ATA 44 system, and mass savings on wiring [5]. The ATA 44 system accounts for a large part of the non-safety-critical energy consumption and is a well spatially distributed electrical load. It is therefore a prime candidate to receive electrical power from SPCs located in the cabin. The entire IFE system on-board a wide-body airliner can weigh up to 5000 kg [6].

The IFE system can be divided in two parts (Fig. 1): the power system and the data system. The former takes care of providing electrical power to the individual screens, while the latter provides media content, from live TV to music and movies (through the IFE centre, IFEC). IFE screens typically run on 28 VDC, which requires converters and other electronics to be adapted from the aircraft’s 115 VAC system [7]. Additionally, to improve reliability, manufacturers have decentralised IFE systems, relying on numerous electronics boxes spread around the cabin: secondary power distribution boxes (SPDBs), floor disconnect boxes (FDBs), seat electronics boxes (SEBs), in-seat power supply (ISPS) etc. On wide-body airliners, this can result in hundreds of electronic components, which often impinge on passenger foot space, resulting in lowered satisfaction.

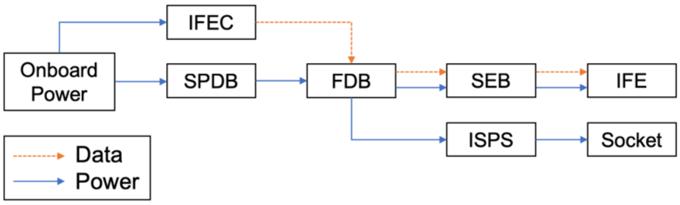

Figure 1: Conventional IFE system.

SPDBs can provide power for up to 15 seats, assuming an architecture like the Boeing 787's (21 SPDBs for 300 passengers [8]). They then distribute power to FDBs (one per group of seats), which feed the SEB and the ISPS (one per group of seats for both). The masses of each component can be found in Table 1.

Component	Mass (kg)
SPDB	6.36
FDB	1.50
SEB	1.20
ISPS	0.90

Table 1: In-flight entertainment system component masses.

For this study, passenger surveys and airlines statistics are used to estimate the number of passengers using the IFE, power sockets etc. According to the British department for transport, on average 20% of passengers flying in the UK do so for business [9]. It is assumed that business passengers require using their laptops, and therefore keep them plugged in throughout the flight. The remaining passengers, according to surveys, either access content through the built-in IFE system (44%), use their personal electronic devices (PEDs) (e.g. smartphones, tablets, 46%) or switch between the two (10%) [10]. Passengers using their PEDs are assumed to 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 typically around 70 W [11]. Similarly, PEDs require anywhere from 5 W for an iPod, to 18 W for the iPad Pro. To ensure enough energy and power for all passengers, the upper end of 18 W is chosen. It is also important to note that the ISPS require 110 VAC. 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. With regards to data, a seat-centric RAVE 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 is assumed that every unit draws 15 W for the duration of the flight, regardless of whether the passenger is using it or not. Table 2 shows the individual and total electrical demand.

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

Table 2: ATA 44 system electrical loads.

In addition, to ensure adequate margins and avoid under-capacity, a safety factor should be applied to the total electrical power calculated above. A safety factor of 15% ensures more than 99% availability [12]. Hence, the final ATA 44 power requirement is 5.2 kW, or 42 W per passenger. Remembering the maximum flight time of four hours, the SPC components must be able to provide energy for the entire flight, that is 20.9 kWh. Finally, enforcing the requirement that a full charge must be achieved in 30 mins, the charging power requirement becomes 41.8 kW. This does not take losses into account.

One crucial aspect of the introduction of SPC on-board aircraft is charging. However, to obtain results as accurate as possible for the floor panels, a charging solution must be introduced and developed. It is also necessary to estimate the system losses and to cater for those. In this study, it was decided to charge the system on the ground. This solution was chosen for the weight savings it offers, primarily in terms of wiring and generator mass. Charging through the engine generators could also be an issue if the aircraft lands with minimal energy left in the floor panels and no way to charge on the ground. Until the aircraft is back in the air and the system is charged enough, the ATA 44 system would be inoperable. Therefore, it is preferable to charge the SPC panels directly on the ground, through conventional DC ground power units (GPUs).

It is necessary to estimate the losses associated with the transfer of energy from ground to panels and then to the ATA 44 system. The proposed layout (Fig. 2) is composed of ten sections, each made of six 2.5 m × 0.5 m SPC panels. Large panels are preferred as they reduce the amount of wiring required. However, they create large internal resistance; the internal resistance losses are neglected for now. To better distribute power throughout the cabin and enable efficient charging, the aircraft is equipped with two ground sockets, one fore and one aft. When the GPUs 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. 2).

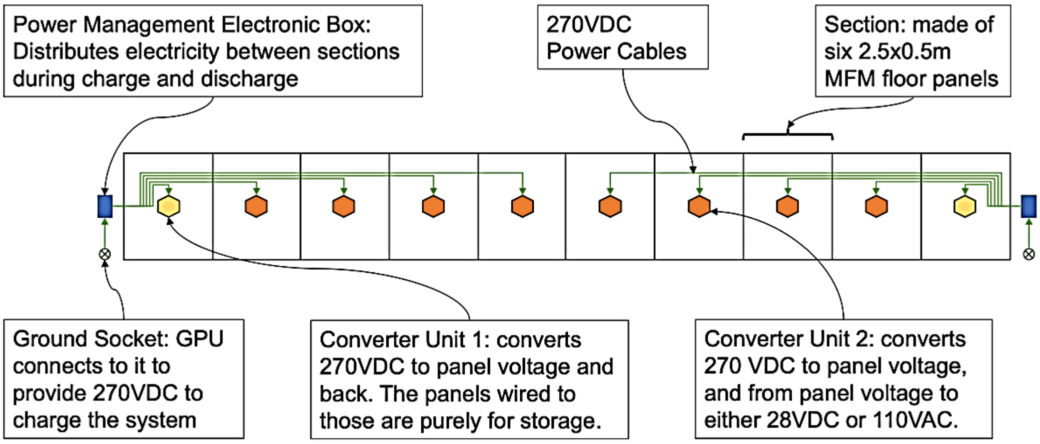

Figure 2: Diagram of the power distribution system.

Two sections, fore and aft, are located at the galleys, and therefore are not close to seats and the associated electrical loads of the ATA 44 system. These sections 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 are therefore equipped with a converter unit (CU1) capable of converting ground voltage to panel working voltage and back. The other eight sections have more elaborate converter units (CU2). These CU2s can not only convert ground voltage to panel working voltage, but also convert the panel working voltage to either IFE voltage (28 VDC) or ISPS voltage (110 VAC). To provide as much flexibility as possible, CU2s can also convert panel working voltage to ground voltage to feed other sections (Fig. 3).

It is now possible to estimate the system losses due to the converters' efficiencies. Converter efficiency varies from device to device; however, averages can be used for the moment (Table 3). This data is used to calculate the overall efficiency of the system and to amend the power and energy targets to account for the losses. It must also be considered that some power will first be stored in the foremost or aft-most panels before being redistributed elsewhere in the cabin. The new values can be found in Table 4. Accounting for losses increase the total electrical consumption by 25%.

Device type	Efficiency	Mass/power ($P < 5$ kW) (kg/kW) [112]	Mass/power ($P > 5$ kW) (kg/kW) [13]
DC / DC	93% [14]	1	0.2
DC / AC	97% [15]	6	1.0
AC / AC	96% [16]	12	1.4
AC / DC	97% [17]	7	0.1

Table 3: Efficiency and power density of electrical power conversion devices.

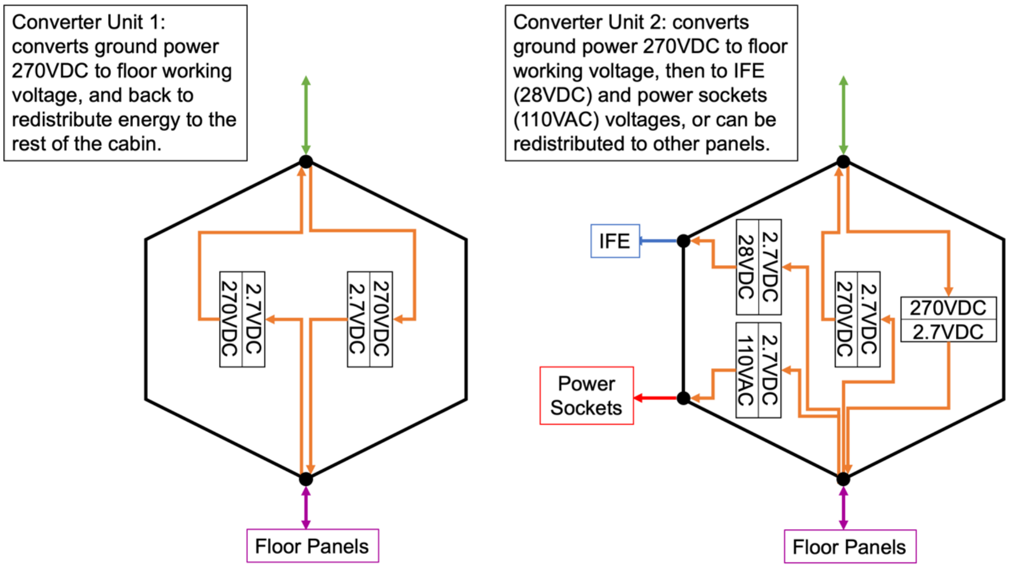

Figure 3: Diagrams of the converter units

Total discharge power (kW)	6.5
Total stored energy (kWh)	26.1
Total charge power (kW)	52.1

Table 4: Energy and power demands accounting for losses.

3 STRUCTURAL REQUIREMENTS

The design of cabin floor panels must meet several static and dynamic requirements. The static requirements are typically specified by the aircraft manufacturer, whilst the dynamic requirements come from certification documentation. The static requirements are: 300 lbs on any 1 ft^2 in non-seat areas under all certified dynamic conditions without permanent deformation; 170 lbs on any 1 ft^2 in seat areas under all certified dynamic conditions without permanent deformation; and 200 lbf on any 0.5-inch diameter circular area without appreciable deformation. In addition, the floor panels must survive the dynamic crashworthiness criteria [18]: downward at 6 g and forward at 9 g.

The underfloor structure on which the floor panels are fixed is effectively a 0.5 m × 0.5 m grid, made up from light frames and seat tracks. The floor panels are typically screwed onto those frames. For this analysis, it is assumed that each panel is a 0.5 m × 0.5 m fully clamped sandwich plate. The fully clamped method is thought to be a more accurate representation than simply supported. However, it creates a layer of complication, as fully clamped sandwich structures have not been the subject of much research. Point loads on rectangular fully clamped sandwich panels do not have published closed-form solutions for instance, which limits the range of this study. In the mass estimation process, it was decided to use an Young’s modulus of 33 GPa [19]. It must now be checked that a panel with this Young’s modulus can sustain all required loads.

300 lbs/ft^2 *at 9 g forwards*: Lopatin’s method for the buckling of fully clamped rectangular sandwich plates [20] was used to determine the critical buckling load as a function of the face sheets’ Young’s modulus. The next step was to determine the Young’s modulus needed to ensure the floor panels would not buckle under the maximum dynamic load. The minimum Young’s modulus for the SPC material was therefore found to be 50 GPa (in both longitudinal and transverse directions). Immediately before buckling, the compressive stress in the face sheets reaches 225 MPa, which becomes a compressive strength requirement. As the Young’s modulus is higher than the previously assumed 33 GPa used for the mass estimation, another iteration (at least) would be required to ensure all properties and results converge. However, at this point, it is preferable to slightly over-design the floor panels to ensure they meet or exceed all the requirements.

300 lbs/ft^2 at 6 g downwards: This requirement was used to determine the minimum tensile and compressive strength of the material. For the calculation of moments and forces, a simplification was made, which assumed the plate behaved like a beam along its centreline. The maximum stress occurs at the centre of the plate, culminating in a stress of 119 MPa, which is taken as the minimum tensile strength. As the compressive stress determined earlier is greater than the stress calculated here, the higher stress is retained as the minimum compressive strength requirement for the floor panels.

200 lbf over a 0.5-inch diameter circular area: This final requirement was more difficult to determine, as there is no published method on the deformation of rectangular fully clamped sandwich plates under point load. However, Zenkert has published a closed-form solution for a circular fully clamped sandwich plate. Acknowledging that a circular plate having a diameter equal to the diagonal length of a square 0.5 m × 0.5 m plate, will have a larger displacement than the square plate, the circular plate provides a valuable upper bound. Using 50 GPa as the Young's modulus, this yields a displacement of 0.55 mm, which satisfies the 'without appreciable deformation' criterion.

4 MASS ANALYSIS

Floor panels typically have a sandwich construction. Historically, the face sheets were made of glass fibre reinforced polymer (GFRP) with an aluminium honeycomb core, which was preferred for its good corrosion resistance. Recently however, the materials have changed to CFRP/GFRP for the face sheets and a Nomex honeycomb core, to make the panels lighter. Since CFRP is already used in this application, this should facilitate certification of SPC floor panels.

In most modern aircraft, there are various types of floor panels depending on the location in the cabin. At the galleys, the face sheets are thicker to provide improved bending resistance against the heavy passenger and galley cart loads. Under the seats, the lighter loads require thinner face sheets, but the overall thickness of the panels remains constant to provide a flat floor (Fig. 4 and Table 5).

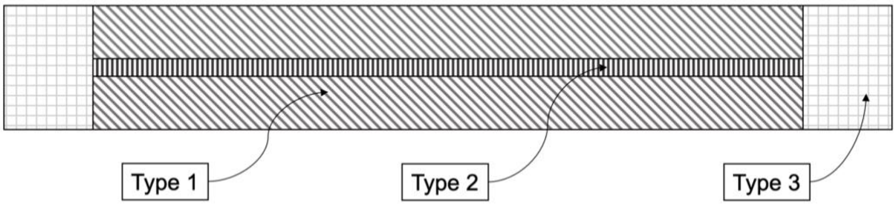

Figure 4: Floor panel types.

Floor panel type	Type 1	Type 2	Type 3
Location	Under seat	Aisles	Galleys
Face sheet thickness (mm)	0.381	0.457	0.559
Total thickness (mm)	10	10	10
Areal weight (kg/m^2)	2.59	3.03	3.51

Table 5: Floor panel types and specifications [21].

The primary purpose of floor panels is to sustain the weight of passengers, galley carts and other loads, with limited bending. Therefore, the SPC panels are designed to have the same flexural rigidity as conventional panels, such that

$$(EI)_{SPC} = (EI)_{Conv.} \tag{1}$$

For a sandwich construction, the flexural rigidity is defined as [22]

$$(EI)_{Sandwich} = \frac{E_f t_f}{2(1-\upsilon^2)}\left[\frac{t_f^2}{3} + \left(t_c + t_f\right)^2\right] + \frac{E_c}{1-\upsilon^2}\frac{t_c^3}{12}. \tag{2}$$

where E_f and t_f are the Young's modulus and thickness of the face sheets respectively, E_c and t_c are the Young's modulus and thickness of the core respectively, and v is the panel's Poisson's ratio. For the

Young's modulus of the face sheets, an experimental value of 33 GPa [19] for a structural supercapacitor is therefore used.

It is important to realise that for laminate structural batteries and structural supercapacitors, the term t_f is discrete: a cell has a fixed thickness. For the case of structural supercapacitors, Table 6 Table 6 presents the thickness and areal mass for a given number of cells. Note that a two-cell device is thinner than two one-cell devices put together, due to optimised packing and stacking sequences.

Number of cells	1	2	3	4
Device thickness (mm)	0.361	0.681	1.001	1.321
Device areal mass (kg/m^2)	0.311	0.571	0.830	1.090

Table 6: Structural supercapacitor thickness and mass for given cell number.

Because more data related to thickness, mass, constitutive properties and stacking sequence is available for structural supercapacitors, the entire analysis presented here is based on using structural supercapacitors. However, this method can easily be modified for laminate or 3D structural batteries, by altering device thicknesses and areal masses. A Matlab script was written to obtain the mass of the floor panels as a function of the total panel thickness containing a Nomex core (density 48 kg/m^3 [23]) and two SPC face sheets. The total panel thickness was progressively decreased, which caused the face sheet thickness to increase to maintain Equation 1. The results (Fig. 5) show the trend between overall panel thickness and cabin floor mass. The numbers in parenthesis indicate the number of cells in the face sheets required for stiffness in Type 1, 2 and 3 panels respectively. The discontinuities arise from the discrete thickness of the face sheets, as well as the various types of conventional panels. For comparison, a conventional GFRP/Aluminium honeycomb floor weighs 212 kg. Using SPC panels results in a mass saving because of the lighter CFRP material. Unfortunately, a lack of reliable data for modern CFRP/Nomex floor panels did not allow for a direct comparison of those with the SPC panels.

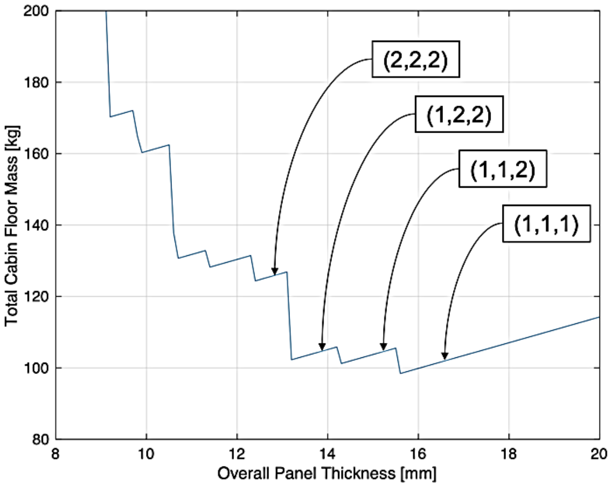

Figure 5: Cabin floor mass as a function of floor panel thickness.

To simplify manufacturing and maintenance, it was decided to use the same panel throughout the cabin. Whilst this might have a negative effect on mass savings, it is deemed appropriate to be conservative when working with an immature technology. It is also chosen to use a two-cell device as face sheets, for two reasons: improved bending resistance as the flexural rigidity of the sandwich is increased, and a lower electrical performance requirement from almost doubling the SPC mass. Table 7 presents the resulting geometry of the floor panels. To obtain a comprehensive 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 can be determined from Table 3, and is presented in Table 8.

Parameter	Value	Units
Panel thickness	12.4	mm
Panel areal mass	1.7	kg/m^2
SPC mass	85.7	kg
Nomex core mass	39.7	kg
Total floor mass	125.4	kg

Table 7: SPC floor panel specifications

Device	Conversion (V)	Power (W)	Mass (kg)	Total mass (kg)
CU1	270 DC / 2.7 DC	5210	0.9	1.8
	2.7 DC / 270 DC	5210	0.9	
CU2	270 DC / 2.7 DC	5210	0.9	4.4
	2.7 DC / 270 DC	5210	0.9	
	2.7 DC / 28 DC	270	0.3	
	2.7 DC / 110 AC	384	2.3	

Table 8: Converter unit mass estimation.

Estimating wiring mass involved obtaining approximate lengths of cables as well as amperage to determine which wire gauge to use. Copper wires have been largely phased out on-board airliners and replaced by lighter aluminium wires; the latter type is used for this study. The proposed wiring within a section provides an estimate of the length of each cable (Fig. 6). Note that wires to seat-back screens must run 1.5 m up and 0.5 m up for power sockets. The breakdown of the total cabin wiring mass can be found in Table 9, and Table 10 provides a summary of the mass estimate of the entire electrical setup.

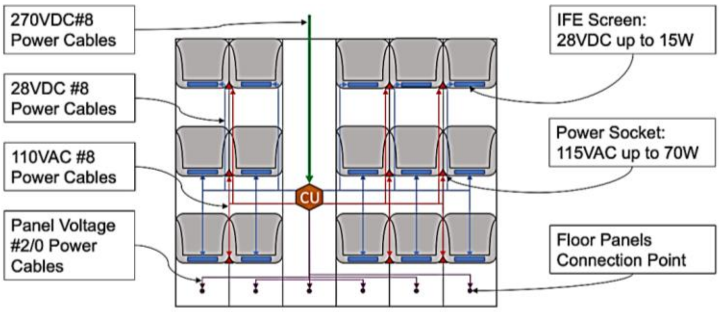

Figure 6: Diagram of a section, showing wiring and converter unit.

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

Table 9: Total cabin wiring mass estimation.

Component	Quantity	Mass (kg)
CU1	2	1.8
CU2	8	4.4
Wiring	All	106.9
Total		145.7

Table 10: Summary of the electrical system mass.

5 PERFORMANCE TARGETS

By combining the data from Tables 4 and 7, the specific energy and specific power requirements for the SPC floor panels were calculated as 305 Wh/kg and 0.610 kW/kg respectively. Comparing these results with existing state-of-the-art SPCs shows that the specific energy requirement is at the upper end of current battery technology, conventional or structural. The specific power requirement is within reach of current structural supercapacitors. The problem lies in the combination of high specific energy and high specific power. An instinctive solution would be to combine a structural battery with a structural supercapacitor to exploit the best properties of both. Since charging constrains the specific power requirement, a potential solution could be to use the structural supercapacitor as a buffer, accumulating energy at high power to reduce charge time, which then feeds into a structural battery. However, assuming the structural supercapacitor can store 25 Wh/kg (current state-of-the-art), the structural battery would need a specific power of at least 1.28 kW/kg to satisfy a half hour charge, which is far above current capabilities. Inversely, if the structural battery is capable of 0.3 kW/kg (again, state-of-the-art), the structural supercapacitor must store at least 223 Wh/kg, which is ten times more than current technology can store. Clearly, this solution is not adequate. Instead, research should focus on emerging hybrid SPCs, which combine faradaic energy storage with double-layer capacitance. This technology could be the breakthrough needed to provide both high power and high energy.

In the near term, there are simple methods to reduce the performance requirements, albeit while compromising on other aspects. Firstly, the mass of SPC could simply be increased. Whilst this would negate some of the mass savings of the lighter CFRP technology, it would undeniably cut down specific electrochemical requirements. Another way would be to modify the allowable flight time, currently fixed at four hours; for example, only allow shorter flights to be equipped with SPC floor panels. A one-hour flight for instance, would lower the specific energy target to 77 Wh/kg and the specific power target to 0.153 kW/kg. Many other parameters could be changed (such as on-board usage, charging time, etc.) which could further modify the performance targets. It is also important to note that the values for specific energy and specific power presented above assume that the device can be brought to a zero percent state of charge. In effect, this means assuming the SPC is a supercapacitor, as it is considered very harmful for batteries to be completely drained. Batteries should always be kept at a state of charge above 20%. If this is considered, the specific energy and specific power targets would correspondingly rise by 25%, to 381 Wh/kg and 0.763 kW/kg.

In addition to providing minimum electrical and mechanical requirements for SPCs in aircraft cabin applications, it is important to identify the key advantages of using such technology on-board. The analysis presented below combines the advantages of seat-centric IFE technology with SPC floor panels, as the two operate in conjunction to streamline the ATA 44 system. The increasing use of composite materials in aircraft design has had one primary aim: shedding mass on-board. Indeed, carrying extra structural mass implies the need for extra fuel to fly the same distance. It is therefore increasingly important to minimise weight on-board. The use of SPCs for cabin floor panels unlocks several major weight savings, which are summarised in Table 11.

Traditional ATA 44 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. Since the A220-100 requires 9 SPDBs (one per 15 seats) and 50 FDBs, 50 SEBs and 50 ISPSs (one per seat group each), this amounts to 238 kg of electronic boxes. The mass savings due to the complete removal of all IFE data servers and wiring is calculated based on data acquired by Lufthansa as they performed retrofit of the RAVE system on their Airbus A330s [24] (200 economy seats). The total mass savings was 600 kg, of which 185 kg could be directly attributed to the data system. Scaling this to the A220-100 (125 economy seats) provides an additional 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 [25], and therefore the total mass of the generators decreases 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 $\eta = 53\%$ [26] and the energy density of Jet A fuel is 11.9 kWh/kg, 3.4 kg of Jet A fuel can therefore be spared.

Component	Old mass (kg)	New mass (kg)	Saving (kg)
Floor panels	212.5	125.4	87.1
Electronic boxes	238.0	38.8	199.2
IFE data system	115.0	-	115.0
Wiring	22.5	106.9	-84.4
Generators	108.0	104.4	3.6
Generator fuel	3.4	-	3.4
		Total	323.9

Table 11: Summary of the weight savings due to SPC floor panels.

A mass saving of 324 kg represents over 2% of the maximum payload mass on the A220-100, or the equivalent of three extra passengers and their luggage. It is equally interesting however to identify how this mass saving would affect the fuel burn of the aircraft, associated cost savings and benefits to the environment. Greenhouse gas emissions are also reduced by 343 tonnes for CO_2 and 1.4 tonnes for NO_x. Overall engine efficiency is also likely to improve from the reduced generator load. A blank-sheet design would however benefit most from the use of SPCs on-board, leading to large mass savings on many structures.

To achieve the potential weight savings discussed, several key challenges to using SPCs in the cabin need to be addressed; the most paramount are related to safety and fire resistance. However, other obstacles remain, such as impact behaviour, cyclability and importantly, public perception. It was noted that passengers are concerned of new technologies on-board, and appropriate reassurance of the safety of SPCs would be required. Whilst this study has highlighted keys aspects of the use of SPCs on-board, more research is required in this field. The concept of hybrid structural battery-supercapacitors could help address the high-power-high-energy requirements. The impact behaviour, cost analysis and reliability evaluation must all be studied in more detail.

6 CONCLUSIONS

This study aimed to provide a comprehensive investigation of the potential integration of structural power composites in aircraft design. Research has so far focused on the applications of SPCs at a large-scale structure level, however it has been made clear that the prospect of long range all-electric aircraft is still a distant prospect [27], and that the use of SPCs as primary airframe materials would require major development and technology maturity. Instead, this study focused on smaller, cabin applications, on-board the A220-100 narrow-body aircraft.

This research presented one feasible application within the aircraft cabin: floor panels to power the in-flight entertainment system; they appear to be the ideal first application for a new SPC material: easily accessible for maintenance, simple flat geometry and close to the electrical loads. Following detailed estimates of the electrical demands to power the in-flight entertainment system, specific energy and specific power targets were calculated. For the SPC floor panels, they were 305 Wh/kg and 0.610 kW/kg respectively, accounting for all losses in the electrical distribution system. The mechanical requirements were also defined, based on certification and other static and dynamic load cases. They yielded minimum requirements of 50 GPa for the Young’s modulus, 225 MPa for the compressive strength and 119 MPa for the tensile strength.

A large part of this study was also dedicated to identifying the advantages of the use of SPCs in cabin applications. Mass savings were evaluated at 324 kg for the A220-100 (in conjunction with the new seat-centric IFE technology), which directly translate into £85,000 a year of fuel saved, accounting for the cost of charging the panels.

Ultimately, it is necessary to develop a road-map to facilitate adoption structural power, such that the practical implementation aligns with the capabilities of the material. Beyond this study focused on structural power applications, it is envisaged that the general multifunctional design methodology presented here to determine material performance targets and benefits can be later extended to many other multifunctional materials, such as those which provide sensing, actuation and energy harvesting.

ACKNOWLEDGEMENTS

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) and EU Clean Sky 2 (SORCERER Project #738085).

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