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STRUCTURAL SUPERCAPACITOR COMPOSITE TECHNOLOGY DEMONSTRATOR

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Abstract: *Structural power composites, a class of multifunctional materials, have significant potential to facilitate lightweighting and accelerate widespread electrification in sustainable transportation. In civil aircraft, a bank of supercapacitors can provide power to open the doors in an emergency. Structural power composite fuselage components near the doors could provide this power and eliminate the mass and volume needed for the supercapacitors. To demonstrate this concept, we designed and manufactured a multifunctional component representative of a fuselage rib, which powered the opening and closing of a desktop scale composite aircraft door. This paper provides information about structural supercapacitor technology demonstrators, discusses the fabrication of this demonstrator and concludes by providing an insight into the future challenges that need to be addressed to realise structural power composite components.*

Keywords: structural; supercapacitor; composite; demonstrator

1. Introduction

Structural power composites (SPCs) [1] can significantly reduce the parasitic mass associated with conventional energy storage devices [2] and facilitate widespread electrification in sustainable transportation [3]. These emerging multifunctional materials can store and deliver electrical energy as well as support mechanical loads. Structural supercapacitors provide lower energy densities but greater power densities than structural batteries and have potential applications for electrical load levelling, buffering and high power delivery. Despite growing interest in structural batteries and supercapacitors, much of the research to date has focused on developing the multifunctional constituents (i.e., the electrodes/reinforcements and/or the structural electrolyte) rather than assembly, scale-up and demonstration through multicell assembly; the latter aspects are the focus of this paper.

The aim of this study was to develop a physical embodiment of structural supercapacitor technology to (a) aid researchers, stakeholders and the general public to readily grasp the concept of energy-storing structural materials; (b) demonstrate the elevation of the technology readiness level of SPCs and (c) gain an improved understanding of the engineering issues associated with scaling up from small lab-scale single-cell devices to larger multi-cell structural components. For these purposes, the structural requirements were chosen to meet those needed to ensure durability for handling and transportation, rather than those needed to carry the structural loads for the intended industrial application.

To date, more large-scale structural power demonstrators have been reported for structural supercapacitors than for structural batteries due to the higher level of maturity of the former type of device and the greater complexity associated with battery chemistry and scale-up. The electrical performance requirements have been fairly modest and representative of low power and energy applications such as lighting systems. Structural components for demonstration were selected to be easy identifiable to all target groups and not necessarily on the basis of optimal system weight saving considerations. Other considerations for selection were the ease of access for replacement, similar stiffness demands to those achievable by the SPCs developed in the corresponding research projects and space to allow for thicker laminates and additional wiring. In all of the demonstrators developed so far, the approach has primarily involved direct replacement of the existing structural components. The geometries were kept the same as the original parts and only the thickness of the component differed from the originals. In some cases, finite element modelling was carried out to design the multifunctional component to meet the specific structural requirements of the application. Examples of previous structural supercapacitor demonstrators and their characteristics are shown in Figure 1 and Table 1.

Figure 1 Desktop scale (approximately 30 cm long) structural supercapacitor composite demonstrators in the form of automotive exterior panels able to power LED lights [1]

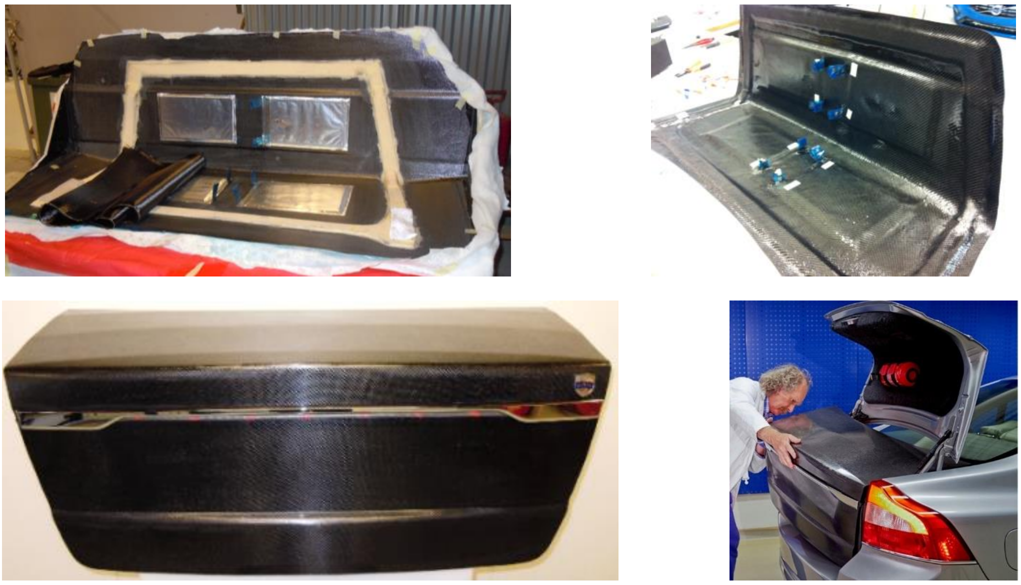

Figure 2 Full scale Volvo S80 boot lid demonstrator with integrated structural supercapacitors to power external lights [1]

Table 1: Structural supercapacitor technology demonstrators manufactured to date [1,2]

Structural component	Electrical system powered	Cells	Voltage [V]
Small scale car body shell	LED lights	1	3
Small scale Volvo car roof	LED lights	2	6
Aircraft electronics box casing	Power spike buffer	15	30
Volvo S80 boot lid	External rear lighting	16	12

2. Demonstrator

In this study, a demonstrator was fabricated to illustrate the concept of a multifunctional fuselage component which can open aircraft passenger doors in an emergency and eliminate the mass and volume needed for conventional supercapacitors. The structural and electrical components selected were representative of a fuselage C-section rib (Figure 3a) and a bank of conventional supercapacitors (Figure 3b) located on the door (Figure 3c). The supercapacitors produce the torque to open the door as a backup power source. The multifunctional beam (Figure 3d) was to be a representative element which stores energy in the web region (blue) rather than in the whole beam. The potential mass saving if SPCs were used to power all sixteen passenger doors is approximately equal to the mass of sixteen supercapacitor banks. The potential volume saving if SPCs were used for all doors could reach the volume of 16 supercapacitor banks. Both of these benefits are conditional on the SPC being able to completely fulfil both the structural and power requirements provided by the existing ribs and conventional supercapacitor banks without significant changes in mass or volume compared to the original ribs.

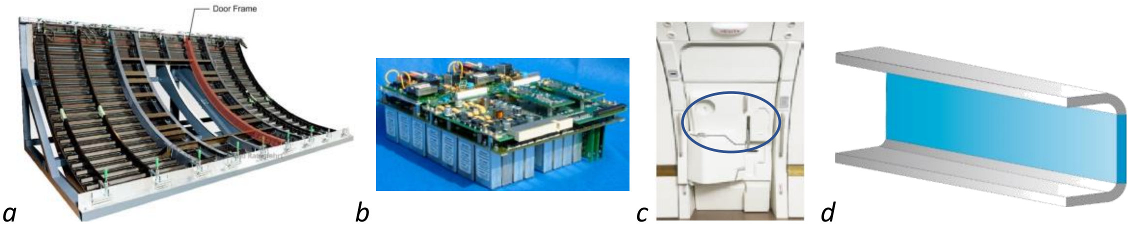

Figure 3 (a) Location of the actual curved fuselage rib shown in red (b) supercapacitor bank and circuit board (c) passenger door showing the location of the supercapacitor bank circled (d) proposed multifunctional web of the C-section beam

An 80 cm long × 20 cm wide × 7 mm thick C-section beam containing two stacks of four 30 cm × 15 cm × 0.5 mm structural supercapacitor cells (Figures 4 and 5) within the web region was manufactured. These structural supercapacitors comprise Oxeon spread tow carbon fibre fabric electrodes reinforced with high surface area carbon aerogel [4] to provide high capacitance and structural rigidity. A polymeric separator was bonded between the electrodes using patterned structural epoxy, and the whole laminate was infused with an electrolyte and packaged with protruding current collector tapes. A computer aided design (CAD) model (Figure 6) of an aircraft fuselage and passenger door assembly (approximately A3 size) was generated and this assembly was manufactured. The majority of the parts were 3D printed using ABS and the fuselage, door and floor panel (Figure 7) were made from a low temperature cure prepreg as used for the C-beam structural plies.

Figure 4 Structural supercapacitor composite cells integrated into the 80 cm long beam

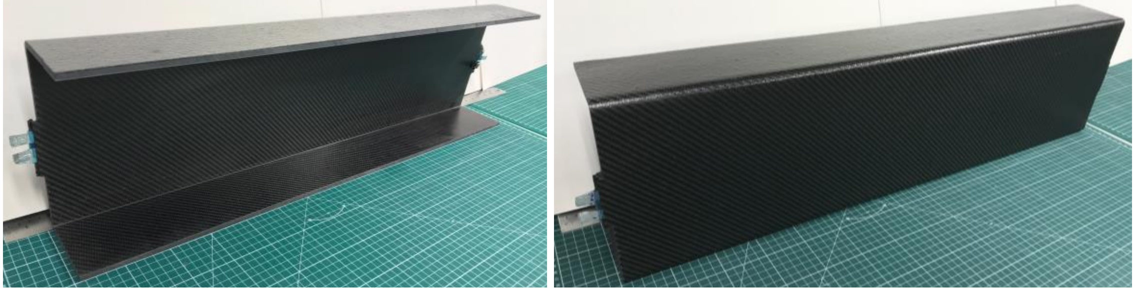

Figure 5 Inner and outer surfaces of structural supercapacitor composite beam

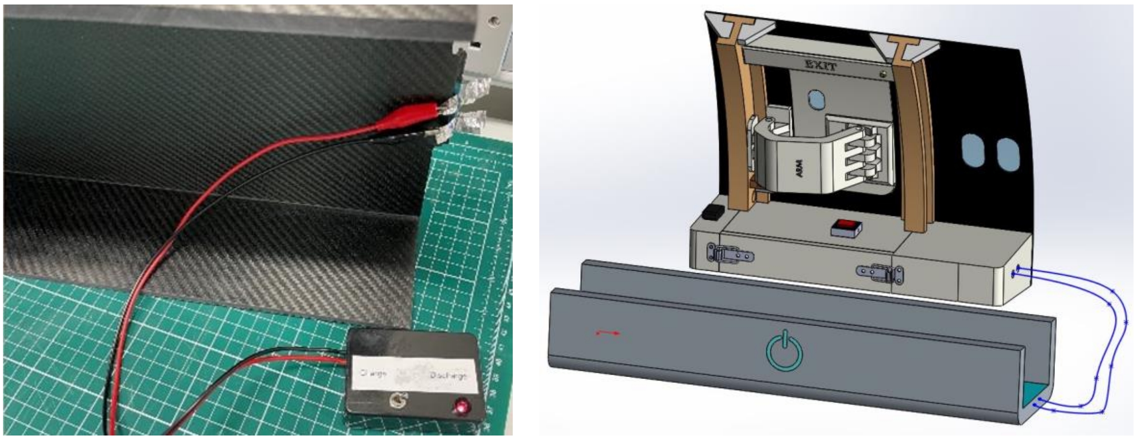

Figure 6 LED indicator to check operation and CAD model showing the scaled fuselage door assembly and structural supercapacitor composite beam

Prior to integrating the cells into the beam, charging four of the structural supercapacitor cells connected in series to 6 V for 10 s could power the door mechanism (Figure 7) to open and close three times. However, after integrating the cells into the beam, some loss in electrochemical performance was observed such that a longer charge time of 30 s was needed to achieve the same door mechanism operating performance. (A video showing the operation can be viewed at https://www.youtube.com/watch?v=yxa-BOpuDls&t=17s). A major contributor to the loss in performance was considered to be the lack of through-thickness pressure on the structural supercapacitors after consolidation and curing. Measurements indicated that greater through-thickness pressure reduced the internal resistance by enhancing the electrical contact between the aluminium tape current collector material and the active electrode material.

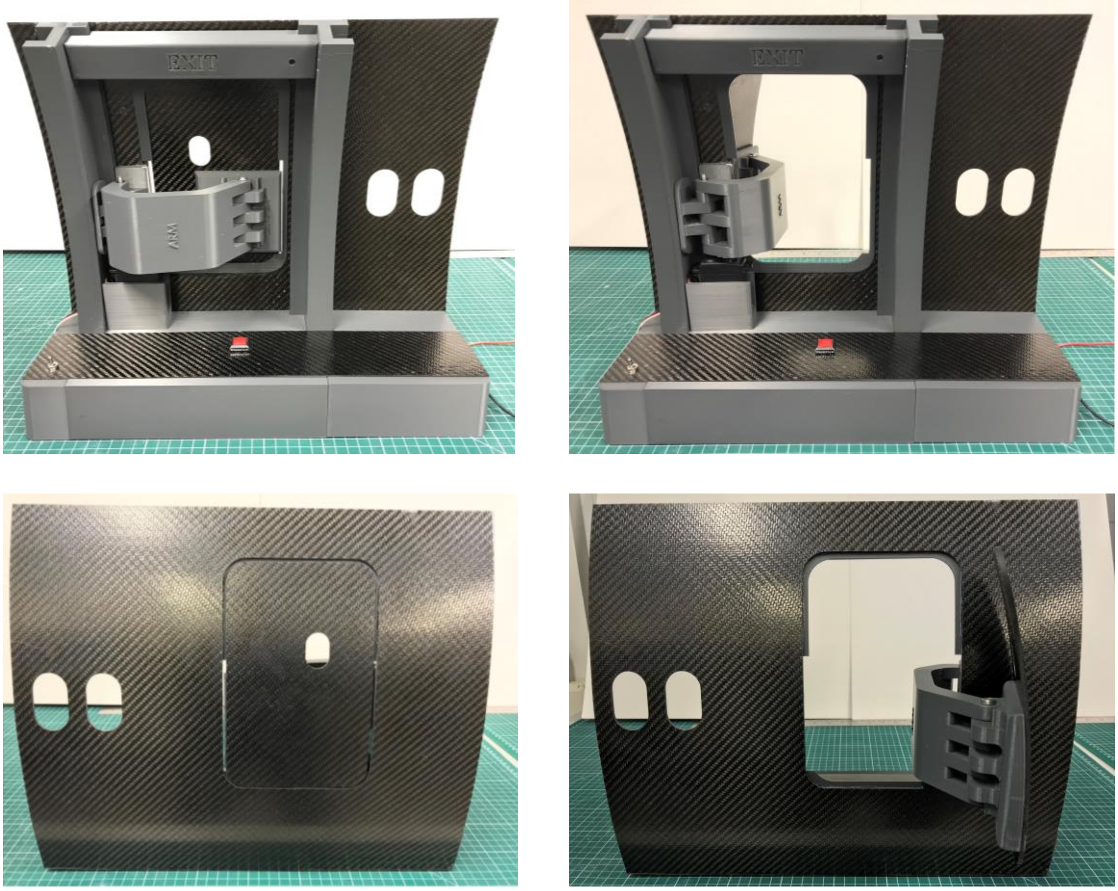

Figure 7 Desktop scale aircraft fuselage and door opening and closing powered by the beam

3. Challenges

A number of challenges arise when manufacturing large scale multifunctional components for demonstrators that are not encountered when manufacturing single-cell lab-scale devices. The key issues are current collection, encapsulation / packaging, reproducible manufacturing and multicell power management. The relatively low electrical conductivity of carbon fibres as compared to metals can lead to large power losses due to internal resistance for thin devices with large areas. One way of addressing this issue has been to use carbon nanotube fibre veils that act as corrosion-resistant current collectors as well as the active electrodes [5]. Another approach has been to incorporate a copper mesh (lightning strike protection) coated with a conductive carbon ink for passivation outside each electrode [6].

A second issue is that most applications require multiple cells to meet the operating voltage requirements. Efficient structural configurations rely on continuous load paths throughout the structure, which is contradictory to the arrangement of most power sources that consist of stacks or cylindrical configurations of small cells. The packaging arrangement for such cells requires greater consideration than that for a single cell to optimise mechanical and electrochemical efficiency and efficacy. Two main configurations have been utilised, and the demonstrator reported here used both configurations together. The first configuration involves stacking cells on top of each other and the second is placing cells adjacent to each other in the same plane. Where cells are stacked, the relative proportion of packaging mass (for encapsulation and conventional structural plies) can be reduced as compared to single cell devices. For planar cell arrangements, the space in between cells present potential structural weaknesses as well as regions where defects in composite manufacturing such as ply wrinkles or resin rich regions in the surrounding structural composite plies may manifest.

A third issue that becomes much more pronounced for multicell structural power components is the issue of manufacturing both from a structural perspective and from an electrochemical perspective. The manufacturing process is more difficult than for a conventional composite. The relatively small-scale fabrication processes of structural power materials used to date have typically not ensured a high degree of reproducibility in the performance from one cell to another. This can lead to inherent variability in the capacitance and resistance across a set of cells and an uneven voltage distribution across the cells. Furthermore, high performance electrochemical device materials, especially for the separator, are very thin and it is thus often difficult to handle large sheets manually without introducing wrinkles or other such defects. Manufacturing in a moisture-free environment to permit high voltage operation without electrochemical degradation requires fabrication in a glove box, which adds difficulties associated with the size of the glove box airlock, reduced manual dexterity and being able to use conventional composites manufacturing equipment. For this reason, most demonstrators have instead opted to use vacuum sealing to encapsulate devices immediately after manufacture outside a glovebox.

Translation of structural power composite technology from the lab to larger scale components that are relevant to industry requires further research to address all of these technical hurdles. In particular, there is a need for more studies to investigate scale-up issues and demonstration using multicell assemblies and complex geometry structural components. Solutions to the aforementioned technical challenges would enable structural power composites to revolutionise future structural and electrical engineering applications.

Acknowledgements

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