**Core Project Final Report**

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**Core Project (CP) Title** Manufacturing Multifunctional Composites

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## Executive Summary

Multifunctional composite materials have a key role in meeting the challenges of the climate emergency, driving innovation and sustainability of composites. These materials impact on a wide range of applications including portable electronics, electric transportation and infrastructure. One focus of this three-year project was multifunctional structural power composites which are load-bearing materials that can store electrical energy. The other focus of the project was on manufacturability of electrically conductive composites. Industrial adoption of such multifunctional composites offers a route addressing the societal issues associated with both lightweighting and energy storage. Electrical properties also enable a wide range of applications such as sensing, current collection, and more efficient manufacturing processes. However, the benefits remain constrained by issues associated with manufacture and design with these composites. The focus of this project was to address such challenges and advance transitioning this technology to industry, with the following having been achieved.

For structural power materials, scale-up and optimisation of the manufacture of the electrodes (carbon fibre fabric reinforced by carbon aerogel) was achieved, with active material ($MnO_2$) successfully introduced to enhance the electrochemical performance. We have also refined the device manufacturing process, including separator selection, the influence of manufacturing parameters on electrochemical performance and encapsulation strategies. Close collaboration between University of Bristol and Imperial successfully demonstrated additive manufacturing methods to zone monofunctional and multifunctional domains in components, and a strategy for the manufacture of curved components. This manufacturing concept, enabling creating continuously reinforced multi-matrix composites, reconciles the requirements of formability and functionality in applications such as repair, joining, and reuse. Other explored manufacturing concepts for functioning included hybrid sub-reinforcement and local incorporation of micro-additives. This culminated in the manufacture of an aerospace fuselage beam demonstrator, which powered an aircraft door (www.youtube.com/watch?v=yxa-BOpuDIs). We have also delivered modelling and design tools for structural power materials, including models to predict compaction of the dry laminates during fabrication, prediction of elastic behaviour and optimisation of current collection to minimise resistive losses, the latter being key to scale-up of these devices. The newly developed design tools also examine implications of

functional domains on forming. From the design perspective, we have developed and delivered a multifunctional design methodology, and undertaken analysis of adoption strategies for various vehicles, such as an aircraft cabin, fully electric airliner and an electric airtaxi.

## Background

The development of composite materials has focussed on structural performance, with any attempt to include functionality generally using multifunctional structures rather than multifunctional materials. Use of functionality within a composite structure to replace systems such as power systems or wiring could significantly reduce the complexity and weight of structures. The overarching aims of this project were to create a set of tools that would be applicable to facilitate design and manufacture of parts using multifunctional materials, many of which share challenges such as low formability, and provide a holistic methodology which allows all the pros and cons of the new and conventional systems to be compared. These were to be delivered while investigating one specific application - the development of structural supercapacitors through embedding structural carbon fibres in a carbon aerogel (CAG). CAGs are not suitable for structural applications alone, but when combined with structural carbon fibres act as a supporting scaffold. This project built on previous materials R&D, and investigated and addressed the design and manufacturing issues associated with these CAG-based multifunctional composites to facilitate industrial manufacture of multifunctional parts. This had been split into two objectives: (i) Explore the manufacturing issues associated with the creation of structural supercapacitors formed into complex geometries, which simultaneously store and deliver electrical energy, whilst carrying mechanical loads and (ii) Explore manufacturing and design of multi-matrix and multi-fibre graded composites to tailor heat and electrical conduction.

Functionalization of composites, e.g. making them more electrically conductive for advancing processing or performance characteristics, is associated with a number of common challenges. For instance, the incorporation of functional elements makes the composite less formable, the volume of additives (and hence functional capacity) is limited by the viscosity of resin suspension and the fabric filtration mechanisms, the processing window is substantially reduced, composite precursors become more prone to defects, and the presence of functional materials negatively impacts upon structural properties. As a result, the incorporation of these materials in complex-shape structures becomes unfeasible for many applications. The manufacturing paradigm deployed in this project was the locality of functionalisation. The allocation of local domains permits resolving of the compatibility issues between various materials whilst preserving the continuity of mechanical load. The locality of additives integration addresses the flow issues of enhanced resin suspension. Local tufting patterns can be tailored to the requirements of sensing, processing and formability. Hence, manufacturing multi-domain materials has the potential to address a whole raft of characteristic problems for functionalised composites.

This project objectives include the development a platform for local functionalisation that can be used both in application to structural supercapacitors and other relevant applications, such as sensing, current collection and efficient processing. The project addresses the processing aspects of domain allocation in continuously reinforced preforms, developing design tools for domain assignment and defect mitigation in functionalised preforms, optimisation of out-of-bag incorporation of functionalised resin suspension, the development of novel hybrid sub-reinforcements, the examination of functional properties of the obtained composites in experiments for sensing and inductive curing.

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## Results/Deliverables/Outcomes

Two aspects of structural supercapacitors were considered: *manufacture* and *design*. Regarding the former (Manufacture), the main effort focussed on delivery of a viable method to manufacture with complex geometries. Novel printing processes developed at University of Bristol have allowed creation of domains the rigid load bearing supercapacitors integral to formable textiles allowing production of complex shaped composites parts containing multifunctional structural supercapacitors. We have demonstrated a method to mask/barrier multifunctional/monofunctional domains in the CAGed lamina facilitating complex part production **(*Deliverable D2*)**. Validated simulation tools have been created that allow functional and stabilising elements to be placed to control forming deformation and mitigate against defects. The process for manufacturing carbon aerogel-reinforced structural power devices has also been scaled up to about 1 m² per batch. Current collection efficiency and CAG production have been identified as limiting factors to scale up, and solutions to these issues have been studied. The use of electrochemical deposition to decorate the carbon aerogel with active elements to enhance the electrochemical performance, along with use of new separator materials, has allowed small-scale multifunctional devices to be made and tested, demonstrating energy and power performance (1.4 Wh/kg and 1.1 kW/ kg) that exceeded the original aspirations. Separator and current collection solutions have been identified and validated, but the issue of encapsulation is still outstanding and a suitable candidate that can provide a light-weight, impervious (and insulating) barrier whilst still transmitting mechanical load across the multifunctional/monofunctional interface, is yet to be identified. This is the subject of a joint ICL/UoB/DU proposal submitted to EPSRC last year. Finally, a multicell structural beam has been manufactured, containing eight cells, stacking in two stacks of four. The total mass of the beam is 2.6 kg, whilst the total cell mass is 268g (i.e. 10% of component mass). The cells have been demonstrated to power a servomotor in a door, as demonstrated in this video (https://youtu.be/20HMFKRxwR0) (*Deliverable D9*).

Regarding Design, models to predict the consolidation of dry CAGed lamina when assembled into a device were delivered [**Error! Reference source not found.**] (***Deliverable D1***). These predicted the fibre volume fraction of the final device and the resulting microstructure. This included phenomena such as nesting of the carbon and glass tows in the laminate. These models were then utilised to predict the mechanical performance (elastic behaviour) of the devices under tensile and in-plane shear loadings. To a limited extent, these models were able to capture the influence of manufacturing defects on the mechanical performance, although further work is required in this area [**Error! Reference source not found.**,**Error! Reference source not found.**] (***Deliverable D4***). Finally, current collection models were developed to formulate strategies to minimise the resistive losses associated with device scale-up [**Error! Reference source not found.**] (***Deliverable D8***). These models quantified the relative contributions from the in-plane, through-thickness and contact resistances, and hence indicated how best to minimise resistive losses for minimal mass: it should be noted that in conventional energy storage devices, the current collectors can account for as much as 25% of the device mass. For multifunctional design we have developed a means to compare between a multifunctional component and a current off-the-shelf assembly of power source and structure. This methodology will permit end-users to quantify the gains in adoption of structural power materials (such as weight or volume saving) over conventional systems. We have undertaken studies for different platforms as to the potential benefits of using structural power materials: in particular, structural power floor panels in the aircraft cabin to power the seat-back entertainment units and power sockets.

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This work demonstrated that using structural power materials at the performance levels expected to be reached in the next three years, will provide a mass saving of 260kg per aircraft for a 100 seat Airbus 220. This corresponds to an annual reduction of 28 tonnes of CO2 per aircraft [**Error! Reference source not found.**] (***Deliverable D7***). We have also undertaken studies into a fully electric airliner (220 seat aircraft) using a combination of conventional battery and structural power, demonstrating that structural power would be a critical enabler for fully electric aircraft by depressing the performance targets needed for conventional batteries [**Error! Reference source not found.**]. Finally, we have applied this methodology to other air vehicles, such as drones and air-taxis (four-seat vehicles). Our studies have demonstrated that using structural power in such vehicles has the potential to double the aircraft range. We anticipate publishing this work in the next couple of months.

Functional sub-reinforcement has been successfully incorporated using microbraiding and subsequent tufting of yarns containing metal filaments. Tailored matrix and reinforcement placement expands the number of added properties, such as electrical conductivity, providing potential solutions for current collection as well as enabling sensing, new approaches to heating and curing, and repairability. We have demonstrated sensing and accelerated heating using micro-braids and developed an approach to integrating functionalised resins into fabric without vacuum, achieving high local functional properties.

This project pioneered and proved the feasibility of allocating domains for forming deformations and domains for structural power in continuously-reinforced preform (*Deliverable D3*). This concept paved the way for incorporating non-formable functional areas in complex structures but demanded the tool for designing such systems. This project deployed high-fidelity forming simulations and complemented them with (a) the automatic assessment of defects and their magnitude enabling parametric optimisation, (b) the algorithms for placement of domains or stabilising patches to minimise defect risks and intensity. In contrast to the conventional approach, the algorithms examine the rotation of the material leading to wrinkling rather than shear angle. The numerical tool also examines the possibility to mitigate against forming defects by placing stabilising patches that can be used in conjunction with functional domain or as an independent tool. The potential for such defect optimisation strategy was proven experimentally [**Error! Reference source not found.**]. The allocation of functional domains in numerical simulations requires knowledge of their properties which can be challenging to measure in isolation from hosting preforms. A new methodology for testing heterogenous samples with dissimilar regions has been developed in this project (***Deliverable D6***). It allows assessing viscous and non-linear elastic properties of functional domains hosted in the dry preform. The concept has been validated both in the virtual environment and manufacturing trials with PLA and epoxy patches deposited on the preform surface [**Error! Reference source not found.**]. Deposition of functional resin is associated with difficulties related to high viscosity additive-rich resin suspension and filtration issues. Local resin deposition, such as liquid resin print, resolved this problem and allows an increase the additives content. However, these manufacturing methods are an out-of vacuum bag process which creates problems with voidage control. The new approach has been developed to create void free patches (***Deliverable D5***), based on thermal conditioning of the resin, close monitoring of resin state using model-based rheo sensors, and elimination of voidage in the consolidation process [**Error! Reference source not found.**,**Error! Reference source not found.**].

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Tufting using hybrid metal-carbon microbraids was investigated as a prospective route to create materials with high functional properties (***Deliverable D11***). The presence of metal fasteners not only enhances structural (through-thickness) properties of composite but also enables characterisation of structural integrity by monitoring the evolution of electrical conductivity. Electrical properties of the new materials were assessed in various tests: braided threads in the process of tensioning, tufted samples in the DCB tests, and macro-scale T-section subjected to the separation of tufted web and flanges. It has been confirmed that incorporation of the tufts makes the material much more responsive to monitoring, though positioning of the braid in macrostructures needs to be carefully chosen to respond to the anticipated failure mode [**Error! Reference source not found.**]. Functional braiding has proven to have large design space – it permits the combination of various materials, patterns, yarn densities. All these factors have implications on manufacturability, electrical and structural properties. Hybrid tufted braid has a complex architecture and there were no readily available tools for detailed assessment of their properties prior to manufacturing: a such tool has been created (***Deliverable D12***). It deployed an established tool for modelling flat textiles (WiseTex) and then used geometrical operations to roll an initial material form into a braided thread. The results structure is then created in standard FEA software (Abaqus), where its electrical conductivity is assessed. The results of the calculation of effective electrical conductivities were compared with both measurements of electrical conductivity on individual threads and local domains of tufted composite. It has been shown that tufting imbues a substantial boost of electrical conductivity, although the potential is not fully realised by the available manufacturing processes due to wire damage in the process of tufting. The results were presented in the paper O'Keeffe et al [**Error! Reference source not found.**].

Enhancing electrical conductivity opens the possibility for more efficient processing. For instance, induction heating allows for faster, less energy demanding heating/curing with more compact heating tooling. This has a great potential for repair, bonding, and joining operations. The manufacturing trials with the functionalised materials proved the feasibility of induction curing, including those based on the glass preforms tufted in an intersecting pattern. More traditional linear patterns showed less energy supply than for a reference preform. The hypothesis, partly corroborated with numerical simulations, is that the metal wires in the current configuration of braided preforms are too fine to be susceptible for EM waves. Modelling tools have been developed to assess various pattern of the tufts as well as the optimisation of many other process parameters (frequency, current, laminate parameters, distance of the coil) (***Deliverable D13***). The local processing resulted in new manufacturing concept allowing local melting of current collectors for better fibre contacts.

Manufacturing trials on segmentation of formable/functional areas have been successfully conducted using two manufacturing approaches (***Deliverable D3***). The first one is masking of the formable area with PLA film, infusion with functional precursor into remaining domain, with subsequent pyrolysis, removing the films, and creating the CAG in one go. The second approach is to create separate domains by integrating barriers into the preform that would divide the preform during the infusion of the precursors. Various parameters of barrier integration – shape, sizes, and materials have been trialled. The infusions strategies were successfully managed the concept was proven feasible. One of the identified challenges was the deterioration of formable domain caused in the process of pyrolysis. The optimisation of the pyrolysis parameters has helped to address the issue.

**Future Direction/Impact**

Regarding structural supercapacitors, there are a number of issues which need to be addressed. Most pressing is the development of structural encapsulation of the devices, to ensure load transfer across the monofunctional/multifunctional domain interfaces. Similarly, the current collection models developed here need to be validated against experimental studies. From the perspective of design, electrochemical models of structural supercapacitors need to be advanced, and in particular, model coupling between mechanical damage and residual electrochemical performance. Finally, given the emerging nature of this technology, there is a strong need to standardise mechanical, electrochemical and combined multifunctional characterisation techniques. To exploit the full potential of locality in manufacturing, several further challenges require attention. The implications of creating fibre-bridged interfaces in multi-matrix composites need to be examined. The yarn and ply architecture of micro fasteners require further optimisation to boost inductive heat supply and demand application-specific positioning for sensing.

## Synergy with other Hub projects

There have been linkages with ten other Hub projects. This includes investigating the use of eddy current for inspection with the Feasibility study 'Evaluating in-process eddy-current testing of composite structures'.

- The Core Project 'Optimise' is providing support to this project through provision of knowledge and braided fabrics
- The Feasibility Study 'Can a composite forming limit diagram be constructed?' which became Core Project 'Design simulation tools and process improvements for NCF preforming' has similar goals in terms of understanding wrinkle forming, so best practice is being shared.
- Sharing good practice in inkjet printing with Platform Fellowship 'Local Resin Printing for preform stabilisation'.
- Support around local preform stabilisation is being provided into the Feasibility study and Core project 'Layer by Layer'.
- The use of algorithms developed by the Feasibility study and new Core Project 'Active RTM' was investigated, although not used.
- Initial discussions have taken place around sharing of through-thickness know-how from Feasibility Study 'Controlled Micro Integration of Through Thickness Polymeric Yarns' to facilitate multifunctionality.
- Forming modelling tools have been shared with the core project "Technologies framework for Automated Dry Fibre Placement"