FUTURE CHALLENGES FOR STRUCTURAL POWER COMPOSITES

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Going beyond Smart Materials....

• Conventional *reductionalist* approach to design - maximise efficiency of individual subcomponents.
  ⇒ Difficult compromises;
  ⇒ Limiting technological advance and stifling innovative design.

• Different *holistic* approach; structures & materials which simultaneously perform more than one function.

**Smart (Multifunctional Structures)....**

*Implanting of secondary materials or devices within a parent laminate to imbue additional functionality...*
  ⇒ e.g. embedding devices within structural materials

**Multifunctional Materials....**

*Constituents synergistically and holistically perform two very different roles....*
  ⇒ e.g. a nanostructured carbon lattice carrying mechanical load whilst storing electrochemical energy.
We can now tailor composite properties beyond purely the mechanical perspective.

⇒ New and diverse functionalities being added.

Multifunctional composite materials has potential to revolutionize transportation, portable electronics and infrastructure.

Focus of this presentation is structural supercapacitors:

⇒ Carry mechanical loads whilst storing and delivering electrical energy.

Objectives:

⇒ Overview of the structural supercapacitor research at Imperial College London;
⇒ Outline the near and medium-term challenges for these new materials;
⇒ Suggest industrial adoption strategies.
International Landscape

Complied list for papers on “Multifunctional composite materials for energy storage, harvesting and sensing,”
157 journal papers since 2000 (WoS)

(VOS Viewer)

- **Dot size** relates to number of publications by organisation.
- **Dot position** relates to frequency of citation by others.
Structural Supercapacitors – Imperial College Research
Supercapacitor Device

Conventional Supercapacitor

Ion permeable Separator (Insulator)
Current collector (Electrode)
Electrolyte

Electrolyte: Ionic Liquid + Epoxy
Separator: Spread tow GF or polymeric non-woven

Structural Supercapacitor

Electrodes: Carbon Aerogel/CF Spread tow
Research Streams

- **Structural Supercapacitors**
  - Constituent development
  - Electrical & mechanical characterisation
  - Device fabrication & demonstration
  - Multifunctional Design & Modelling

- **Automotive demonstration**
- **Aerospace demonstration**
- **Carbon aerogel reinforced CFs**
- **Biphasic multifunctional matrices**
- **Electrochemical characterisation**
  - 2.05 kW/kg
  - 3.73 kW/kg
  - 1.75 Wh/kg
  - 1.77 Wh/kg
- **Mechanical characterisation**
- **Microstructure topology optimisation**
- **Consolidation modelling**
- **Electrochemical modelling**
- **Consolidation modelling**
- **Autoimmune/ multifunctional boundaries**
- **New architectures**
## Summary of semi-structural & MF cell performance

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Separator</th>
<th>Electrolyte</th>
<th>C (F)</th>
<th>m (g)</th>
<th>V (V)</th>
<th>ESR (Ω)</th>
<th>C* (F/g)</th>
<th>E* (Wh/kg)</th>
<th>P* (kW/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAG CF 43 gsm</td>
<td>Woven GF (242 µm)</td>
<td>EMI-TFSI</td>
<td>0.68</td>
<td>0.91</td>
<td>2.7</td>
<td>2.66</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>CAG CF 43 gsm</td>
<td>PET/ceramic (23 µm)</td>
<td>EMI-TFSI</td>
<td>1.01</td>
<td>0.36</td>
<td>2.7</td>
<td>1.49</td>
<td>3.1</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>CAG CF 43 gsm</td>
<td>Woven GF (50 µm)</td>
<td>MF (40%)</td>
<td>0.34</td>
<td>0.39</td>
<td>2.7</td>
<td>7.45</td>
<td>0.9</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>CAG CF 43 gsm</td>
<td>PET/ceramic (23 µm)</td>
<td>MF (40%)</td>
<td>0.51</td>
<td>0.36</td>
<td>2.7</td>
<td>4.80</td>
<td>1.4</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Maxwell BCAP0150&lt;sup&gt;1&lt;/sup&gt;, length = 50 mm, dia. = 25 mm</td>
<td></td>
<td></td>
<td>150</td>
<td>32</td>
<td>2.7</td>
<td>14 mΩ</td>
<td>4.7</td>
<td>4.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>

*Normalised to active mass

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Conventional supercapacitor

\[ J = 4.7 \text{Wh/kg} \text{ & } P = 4.1 \text{kW/kg} \]

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**EPSRC**

Engineering and Physical Sciences Research Council

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Carbon fabrics 138 mg
Aerogel 62 mg
Separator (PC) 53 mg
Electrolyte 107 mg
Future Challenges
Future Challenges – Multifunctional Design

- Conventional design approach
  - Implement new properties and then characterize how the improved performance compares to that of the COTS (Current Off The Shelf) for the same function.
- However, structural power material cannot...
  - Offer better mechanical load-carrying capability than a fully optimized conventional structural material
  - Offer better electrochemical performance than a conventional battery or supercapacitor.
- **Taking a holistic view during design is vital**
  - Structural power materials partially undertake the role of both the structural components (e.g. spars or skins) and the energy storage (e.g. battery, supercapacitor, etc.);
  - Hence a system approach to design, rather than the conventional compartmentalized approach, should be followed.
- Structural Power Materials also offer
  - Localization of power sources (i.e. reducing wiring)
  - Opportunities to tailor mass distribution across a platform.
- **Need to capture this within a new design methodology**
Future Challenges – Fabrication

- Fabrication methodologies for structural power materials very different to conventional approaches.
- Melding of polymer composite manufacture and electrochemical device fabrication.
  - Any exposure of the matrix/electrolyte to ambient moisture is critical to electrochemical performance.
  - ‘Moisture-free’ composite fabrication required
- Fabrication of curved components present additional challenges:
  - Currently being addressed with University of Bristol through the development of masking of fold lines/barriers, to permit monofunctional and multifunctional domains.
  - Investigating as a route to achieve continuity of carbon-fibres across monofunctional/multifunctional boundaries.

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*Fabrication demonstration using barriers*

*Carbon fibre fabric*

*Carbon fibre fabric infused with carbon aerogel*

*Carbonised Epoxy barrier*

*Multifunctional web and cap*

*Monofunctional fold-lines*

*Continuity across monofunctional loading pads*
Critical near-term challenge is how to encapsulate the structural power material.

Isolate from the surrounding systems, conventional structure, and ultimately the environment, whilst still transferring mechanical load across the monofunctional/multifunctional interfaces.

Conventional energy storage devices are encased in inert, insulating sheaths.

Electrolyte phase (Ionic liquid) is leached out by the uncured epoxy, leading to considerable loss of electrical performance.
Future Challenges – Current Collection / Scale-up

10 mm
Electrolyte: EMIM TFSI
Area of electrodes: 0.785 cm$^2$
Area of separator: 1.13 cm$^2$

All values normalised by device mass
(CAG/C-weave + GF separator + IL to fill all pores)

Swagelok cell (1 cm diameter)

Swagelok (m = 51 mg)
C* = 1.73 F/g
E$^{\text{max}}$ = 1.75 Wh/kg
P$^{\text{max}}$ = 2.05 kW/kg

Lab scale (16 cm$^2$)

Plain
0/90 A4 (m = 32 g)
C* = 0.82 F/g
E$^{\text{max}}$ = 0.83 Wh/kg
P$^{\text{max}}$ = 0.027 kW/kg

Cu Mesh
0/90 A4 (m = 40 g)
C* = 1.3 F/g
E$^{\text{max}}$ = 1.3 Wh/kg
P$^{\text{max}}$ = 0.066 kW/kg

Component scale (446 cm$^2$)
Future Challenges – Multifunctional Material Design

- Ionic transport
- Thermal transport
- Energy storage
- Energy harvesting
- Shock absorption

Structural requirement

Multi-objective Structural Optimization

Optimized microstructure
Multifunctional polymer electrolyte
Multifunctional composite materials

Electrolyte: Structural epoxy/ionic Liquid
Separator: GF weave or PE veil
Electrodes: Carbon Fibre Weave

Numerical investigation

Structural evaluation (FEA)
Functional evaluation (RESNET)

Experimental investigation

Mechanical test
Functional test

3D printing

Structural test specimen
Functional test specimen

Outcome

Lee, C., et.al., Multifunctional Materials, v2, 2019
Future Challenges – Certification & Predictive Modelling

- Most significant hurdle is that of certification, particularly for aerospace applications.
  - Conventional structural materials are required to demonstrate airworthiness through the “Rouchon pyramid”.
- Structural power materials would not only have to be mechanically certified, but also electrochemically too.
  - Any mechanical/electrochemical interactions (e.g. mechanical cycling inducing damage that reduces the electrical performance) needs to be considered.
- Best addressed through developing predictive modelling
  - Development of finite element models which can predict both mechanical and electrochemical behavior, and any coupling interactions.
Future Challenges – Predictive Modelling Strategy

Consolidation modelling

Electrochemical Modelling

Mechanical Modelling

• Provide a framework to support certification of structural power devices
• Couple electrical and mechanical models
Future Challenges – In-service Conditions

- Range of in-service requirement and conditions to which structural power materials could be exposed, and would be required to tolerate.

- These include
  - Cycling (both mechanical and electrical)
  - Temperature extremes,
  - Fire resistance
  - Machining/Finishing
  - Impact and Damage Tolerance.
  - Inspection/Repair/Disposal

85% retention after 3000 CD cycles at 2.7V and 1 A/g

Local heating following penetrative impact

Drilling damage
Potential Adoption Routes

- Structural power is still a very immature technology.
- Performance is too low to replace existing propulsion (aerospace and automotive)
- More reasonable target is to replace auxiliary power sources, such as to reduce the electrical load on main power sources.
- Automotive
  ⇒ Utilize in secondary sources (stop/start battery, etc);
  ⇒ Focus on panels and non-safety critical applications.
- Aerospace
  ⇒ Cabin applications (benign temperature regime);
  ⇒ Powering seat-back personal displays, etc;
  ⇒ Local power sources for safety equipment;
  ⇒ Systems and electronics boxes.
- Other Sectors
  ⇒ Electric bicycles – energy recovery, etc;
  ⇒ Mobile electronics.

Volvo bootlid demonstrator from STORAGE project

Doorframe demonstrator from SORCERER
Conclusions

• Structural power composites is an exciting emerging technology for transportation and portable electronics.
• Current performance - c.f. conventional supercapacitor at device level (4.7Wh/kg & 4.1kW/kg)
  \[ \Rightarrow 3.2\text{Wh/kg} \& 3.4\text{kW/kg (semi-structural)}; \quad 1.4\text{Wh/kg} \& 1.1\text{kW/kg (structural)}. \]
• Still considerable technical hurdles to be addressed, but the outlook is promising.
  \[ \Rightarrow \text{Multifunctional Design} \]
  \[ \Rightarrow \text{Fabrication} \]
  \[ \Rightarrow \text{Encapsulation} \]
  \[ \Rightarrow \text{Current Collection / Scale-up} \]
  \[ \Rightarrow \text{Multifunctional Material Design} \]
  \[ \Rightarrow \text{Certification and Predictive Modelling} \]
  \[ \Rightarrow \text{In-service Conditions} \]
• Early adoption routes – auxiliary applications and power sources (aircraft cabin)
• My personal view – structural power, and the generic concept of truly multifunctional materials, is such an simple idea which will provide huge performance benefits and design freedom, it’s clearly a case of \textit{when} not \textit{if} it is widely adopted.

• \textit{In 50 years time, we won’t be using discrete monofunctional batteries, we will build structures from multifunctional materials with innate electrical energy storage.}
Acknowledgements

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