1 Introduction
The use of lightweight materials in structural applications is ever increasing. Today, lightweight engineering materials are needed to realise greener, safer and more competitive products in all technological fields. Especially, a change towards electrification for urban mobility and transport is driven by the forecasted shortage of crude oil based energy carriers together with the necessity to reduce greenhouse gas emissions. But also other consumer products, such as mobile phones and laptops can benefit from the solutions developed.

To keep up with the power requirements of new and emerging technologies, products must carry increasingly larger masses and volume of energy storage components such as capacitors, supercapacitors and batteries. This development works against realisation of efficient electric energy storage, for which low weight is essential.

This paper presents an approach towards realising novel multifunctional polymer composites. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested. This work is a part of a research campaign at Swerea SICOMP to develop structural capacitor and structural battery materials from polymer composites. The structural capacitors developed here are improvements of the capacitors developed in previous studies [1, 2].

2 Materials
The structural capacitor materials were made from carbon fibre epoxy pre-preg woven lamina (245 g/m² 2x2 Twill HS (3K) 0º/90º configuration, MTM57/CF3200-42% RW, supplied by the Advanced Composite Group, UK) separated by a thermoplastic polyester (PET) film (DuPont Mylar A, supplied by Trafomo AB) dielectric separator. A systematic set of three film thicknesses (50, 75 and 125μm) were employed for evaluating separator thickness influences on multifunctional performance. Further, plasma treatment (PT) was used for evaluating the potential of increased bond strength between separator film and epoxy matrix.

3 Composites manufacture
Specimen manufacture was performed by stacking pre-preg layers in a release agent coated mould. To achieve equal surface properties on both sides of the laminate the structural capacitor laminates were manufactured using peel plies on both top and bottom surfaces. The specimens for electrical measurements were fitted with strips of a fine copper mesh as connectors. The mould was sealed with butyl tape and a vacuum bag. A schematic of the bagged lay up is shown in Fig. 1. Vacuum was applied and debulking without heat was performed. The mould was then placed in an oven and heated according to the supplier’s recommendations (120°C for 30 minutes) to achieve fully cured laminates. A structural capacitor specimen is shown in Fig. 2.

Fig. 1. Manufacture of structural capacitor laminates
4 Experimental characterisation

To evaluate the multifunctional performance of the structural capacitors, electrical properties were characterised by measuring capacitance by sweeping trough 0.1-100Hz at 1V and dielectric strength measurements were based on the ASTM standard D3755-97 [3] while mechanical performance was characterised by tensile tests according to ASTM D3039/D3039M [4] and ILSS using short beam three point bending tests according to ASTM D2344/2344M [5]. The developed structural CFRP capacitor designs were evaluated for their multifunctional potential with respect to weight reduction of composite materials components for structural applications. Multifunctional properties considered are in-plane stiffness and strength as well as interlaminar shear strength, on the mechanical properties side, and energy density and capacitance on the electric properties side. The energy density is calculated from the measured values of capacitance and dielectric strength through equation 1 [6].

\[
\bar{\Gamma}_{sc} = \frac{1}{2} \frac{CV^2}{m_{sc}},
\]

where \(\bar{\Gamma}_{sc}\) is the energy density of the structural capacitor, \(C\) the capacitance, \(V\) the voltage at dielectric breakdown and \(m_{sc}\) the mass of the structural capacitor.

Results from electrical measurements are shown in table 1 and results from mechanical measurements are shown in table 2.

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Capacitance * [nF/m(^2)]</th>
<th>Dielectric strength [kV]</th>
<th>Specific energy [J/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET-film 50μm</td>
<td>447±4</td>
<td>14.6±2</td>
<td>0.06±0.02</td>
</tr>
<tr>
<td>PET-film 50μm PT</td>
<td>442±3</td>
<td>15.4±2</td>
<td>0.06±0.01</td>
</tr>
<tr>
<td>PET-film 75μm</td>
<td>300±3</td>
<td>22.4±2</td>
<td>0.08±0.03</td>
</tr>
<tr>
<td>PET-film 75μm PT</td>
<td>300±4</td>
<td>20.8±2</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>PET-film 125μm</td>
<td>193±5</td>
<td>29.4±4</td>
<td>0.09±0.02</td>
</tr>
<tr>
<td>PET-film 125μm PT</td>
<td>195±2</td>
<td>29.8±5</td>
<td>0.09±0.03</td>
</tr>
</tbody>
</table>

* @ 1V and 0.1Hz

Table 1. Summary of electrical properties for various structural capacitors. PT refers to plasma treated film separators

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>E [GPa]</th>
<th>σ(\text{ult}) [MPa]</th>
<th>ILSS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET-film 50μm</td>
<td>42.7±3.0</td>
<td>354±66</td>
<td>29.5±1.3</td>
</tr>
<tr>
<td>PET-film 50μm PT</td>
<td>42.5±2.1</td>
<td>320±47</td>
<td>32.0±1.1</td>
</tr>
<tr>
<td>PET-film 75μm</td>
<td>44.6±0.8</td>
<td>377±15</td>
<td>30.6±1.7</td>
</tr>
<tr>
<td>PET-film 75μm PT</td>
<td>41.7±5.2</td>
<td>344±35</td>
<td>30.7±2.0</td>
</tr>
<tr>
<td>PET-film 125μm</td>
<td>36.5±1.9</td>
<td>317±36</td>
<td>32.5±1.4</td>
</tr>
<tr>
<td>PET-film 125μm PT</td>
<td>37.8±4.3</td>
<td>339±35</td>
<td>31.8±1.1</td>
</tr>
<tr>
<td>CF Ref.</td>
<td>56.1±1.7</td>
<td>631±73</td>
<td>54.4±1.5</td>
</tr>
</tbody>
</table>

Table 2. Summary of mechanical properties for various structural capacitors and the CFRP reference. PT refers to plasma treated film separators

5 Multi-functionality

A method to evaluate multi-functionality developed by O’Brien et al. [6], following an approach suggested by Wetzel [7] is to be employed. O’Brien and co-workers [6] defined a total system mass \(M\) equal to the sum of the mass of the capacitors \(m\) and the mass of the structure \(m_s\). The design metric for capacitor performance is energy density \(\bar{\Gamma}\) (in J/kg) with overall system energy storage defined as
Carbon fibre composites capacitors for short term electric energy storage in structural applications

\[ \Gamma = \bar{\Gamma} m_c. \] Similarly, the mechanical performance, e.g. specific modulus or ILSS, can be defined as \( E \) and \( \tau \). From these, the energy density and specific mechanical properties of the structural capacitors can be found as \( \sigma^e \bar{E} \), \( \sigma^s \bar{E} \) and \( \sigma^e \bar{\tau} \). \( \sigma^e \) and \( \sigma^s \) are the structural capacitor’s energy and structural efficiencies, respectively. An improved multifunctional design would maintain the same overall system energy and mechanical performance but reduce the total system weight. However, a structural capacitor will only enable such system level mass savings if

\[ \sigma^{mf} = \sigma^e + \sigma^s > 1. \] (2)

The results from the multi-functionality analysis of the structural capacitor materials are shown in figures 3a, b and c.

The dotted line represents a multi-functionality of one, all according to equation 2, where the energy density for a pure capacitor is assumed to be 0.5 J/g, as found in literature [8] as a maximum for an electric field energy storage device, such as the multifunctional materials in this study. The reference carbon fibre composite is used as benchmark for mechanical properties. The solid line provides a reference with specific mechanical properties for steel, a likely candidate to be replaced by a multifunctional material. Values chosen are specific stiffness 25 GPa/(g/cm\(^3\)) [9], and specific strength 150MPa/(g/cm\(^3\)) [9].

6 Discussions

A seen in figures 3a, b, and c, no capacitor material provides a multi-functional material with potential to reduce system weight when considering the measured data compared to the composite mechanical reference.

The main reason for this result is the significant knock down in performance for the capacitor materials compared to the carbon fibre reference as seen in table 2.

However, if multifunctional performance of the composite materials were to be compared to the mechanical performance of steel as reference, system weight savings would be possible to realize.
This is illustrated by the fact that the multifunctional materials provides specific stiffness and strength values to the right of the solid line in figures 3a and 3b.

In further work there are several ways to improve the performance, the easiest one being replacing the PET-film with a higher dielectric constant and higher dielectric strength material, hence increasing the amount of energy stored.

The other approach would be to further analyze the failed mechanical specimens by e.g. fractography to find the reason for the large drop in mechanical properties and try to overcome this.

In the long run both approaches suggested above will probably be needed to manufacture a highly multifunctional material that stores enough energy and provided sufficient mechanical properties to be a competitor to mono-functional materials.

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References


