LICENTIATE THESIS

Multi-functional Composite Materials – CFRP Thin Film Capacitors

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ABSTRACT

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. A route to achieve this could be to combine more than one primary function in a material or component to create multi-functionality, thus reducing the number of components and ultimately the overall weight. This thesis presents an approach towards realising novel multi-functional polymer composites. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested.

In **papers I** and **II**, capacitors have been manufactured using different papers and polymer films as dielectric separator employing carbon fibre/epoxy pre-pregs as structural electrodes. Plasma treatment was used as a route for improved epoxy/polymer film adhesion. The manufactured materials were evaluated for mechanical performance by ILSS and tearing tests and electrical performance by measuring capacitance and dielectric breakdown voltage.

In **paper III** the concept was extended in a parametric study using the most promising approach with a polymer film as dielectric separator. Three thicknesses of PET (50, 75 and 125 μm) were used as dielectric separator with carbon fibre/epoxy pre-pregs as structural electrodes. PET was chosen due to availability in different thicknesses as well as the frequent use in ordinary capacitors making it a suitable candidate. As in **paper I** and **II**, plasma treatment was used to improve the PET/epoxy adhesion. The capacitor materials were evaluated for mechanical performance by tensile tests and ILSS and for electrical performance by measuring capacitance and dielectric breakdown voltage.

The multifunctional materials shows good potential for replacing steel and other materials with lower specific mechanical properties but cannot match the high specific mechanical performance of mono-functional materials. Both mechanical and electrical performance could have large benefits from developing new separator materials adapted for use in multifunctional applications and could be an interesting field for extended research.

PREFACE

The work presented in this licentiate thesis has been carried out at Swerea SICOMP AB in Mölndal, Sweden between January 2009 and December 2011. The financial support for my Ph.D. project is provided by the European Commission via the FP7 project grant no. 234236, StorAge.

First of all I would like to thank my supervisor Professor Leif Asp for his guidance and his never ending optimism. A born pessimist needs a counterpart like him. Also, without him there would not have been any funding for the work continuing where my master thesis ended. We have been through some interesting episodes and I will never forget our little road trip from Piteå to Göteborg in the aftermath of Mother Nature's wrath.

I would also like to thank Dr Maciej Wysocki for initiating the first ideas of multi-functional composite materials at Swerea SICOMP AB. He was a great inspiration during those months as my supervisor for my Master thesis work and are still visionary as I can only hope to be one day.

Big thanks to Professor Janis Varna for accepting me as a Ph.D. student at his division at Luleå University of Technology.

Professor Stanislav Gubanski and his Ph.D. students at High Voltage Enginering, Materials and Manufacturing Technology, Chalmers University of Technology are gratefully acknowledged for their assistance with capacitance, tanδ and dielectric breakdown measurements.

I would also like to thank all my colleagues at Swerea SICOMP AB for their support and help, and all the interesting, far out, discussions at the daily coffee breaks. You enlighten my days.

Thank you mom and dad for all support during the years, you have helped me lay the foundation for where I am today.

Last but not least I would like to thank my wonderful wife Louise for her support and understanding through sickness and health. We have been at each other's side for 11 years now and I know you make me a better person.

There are probably more people that should be acknowledged but I have to put an end somewhere and here seems to be good enough.

It has been an interesting journey so far and this is only the beginning...

"The biggest room in the world is the room for improvement"

- Unknown author

Mölndal, December 2011

Tony Carlson

LIST OF APPENDED PAPERS

Paper I

T. Carlson, D. Ordéus, M. Wysocki, L.E. Asp: "Structural capacitor materials made from carbon fibre epoxy composites" Composite Science and Technology, 70(7), pp 1135-1140, 2010.

Paper II

T. Carlson, D. Ordéus, M. Wysocki, L.E. Asp: "CFRP structural capacitor materials for automotive applications, Plastics, Rubbers and Composites" Plastics, Rubber and Composites, 40(6-7) pp 311-316, 2011.

Paper III

T. Carlson, L.E. Asp: "Multifunctional materials - capacitors made from structural carbon fibre composites", To be submitted.

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INTRODUCTION

MULTI-FUNCTIONAL MATERIALS

Environmental concerns along with the forecast of crude oil shortage have started recent trends towards electrification of ground vehicles. To realise electric vehicles the mobile platforms must carry increasingly larger masses and volume of energy storage components such as capacitors, supercapacitors and batteries. This development counteracts the realisation of efficient electric vehicles, for which low weight is essential. One route to address this problem could be the development of multifunctional materials, in this case, materials that could store electrical energy and withstand mechanical loading.

More than a decade ago Chung and Wang [1] presented the idea of using the semi-conductive nature of the carbon fibre in “structural electronics”, making electric devices, e.g. diodes, detectors, transistors, etc. Following this they were first to propose the use of a high dielectric constant material as an interface between CFRP laminas to make a structural parallel-plate capacitor. By this approach truly multifunctional materials, i.e. a material that can perform more than one function, emerge. In a follow-on study Luo and Chung demonstrated structural capacitor materials for the first time [2]. Lou and Chung made thin structural capacitors from single unidirectional carbon fibre epoxy pre-preg layers separated by different paper dielectrics.

More recently, another approach for making structural capacitors was suggested by Baechle et al. [3]. To achieve high energy density of the capacitor Baechle and co-workers made structural capacitors employing glass fibre/epoxy pre-preg as the dielectric with metalized polymer films as electrodes. By this approach Baechle and colleagues utilise the dielectric layer for structural performance.

This work has been focused on the approached suggested by Lou and Chung [2] and have utilized carbon fibre pre-pregs as structural electrodes along with a large set of different separator materials.

MATERIALS AND MANUFACTURING

Structural capacitors were made from carbon fibre epoxy composites to facilitate high performance mechanical electrodes. The electrode layers (laminas) were made from 0/90º twill weave, MTM57/CF3200-42% RW, pre-preg supplied by the Advanced Composites Group, UK.

In **papers I** and **II** a set of different papers and polymer films where used as separators while in **paper III** a parametric study was performed with three different thicknesses of Mylar-A (PET) film separator. Adhesion between polymer films and epoxy could be an issue and in addition to the neat polymer films, plasma treated polymer-films were prepared in all papers.

Manufacturing of all laminates were done according to the same principle. Prior to manufacturing the laminates the pre-preg roll was taken from the freezer and laminas were cut to required size. The laminas were allowed to reach room temperature before putting them in a vacuum chamber for 30 min to evaporate any leftover condensation. During manufacture the pre-preg layers were stacked along with the separators 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 mould was sealed with butyl tape and a vacuum bag. A schematic of the bagged layup is shown in Figure 1. Vacuum was applied and debulking without heat for 30 min was performed. The mould was then placed in an oven and heated according to the supplier's recommendations (120ºC for 30 minutes) to achieve fully cured laminates.

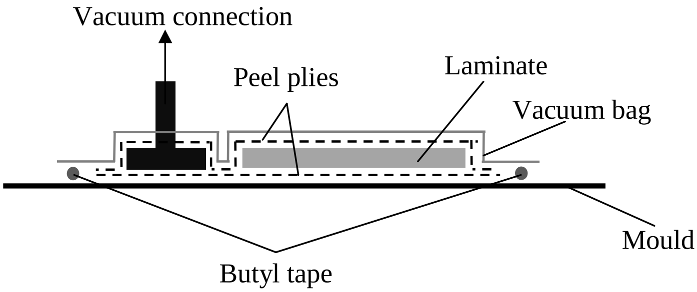

Fig. 1. Manufacture of the structural capacitor laminates.

A copper mesh was used as electrical connection on laminates for electrical characterisation. A laminate for electrical testing is depicted in Figure 2.

Fig. 2. A single dielectric layer structural capacitor for electric characterisation.

Specimens for mechanical characterisation were made to closely match the requirements set by the standards for respective test, ASTM standard D2344/2344M [4] for ILSS testing and D3039/D3039M [5] for tensile testing. The tearing tests in **paper II** were performed using a tearing test developed at Swerea SICOMP AB for simulating a tearing failure [6] and the specimens were manufactured to give enough material around the tearing affected area to avoid edge effects.

EXPERIMENTAL CHARACTERISATION

The multifunctional materials properties were determined experimentally for both electrical and mechanical properties.

Two electrical tests were performed on the multifunctional capacitor materials.The materials capacitance was measured by sweeping through 0.1-1000Hz while recording the electrical response, providing capacitance and tanδ.

Dielectric breakdown voltage (dielectric strength), of the capacitors was measured using the ASTM D3755 standard for direct current measurement of dielectric breakdown [7], as suggested by Baechle et al. [8]. The specimens were submerged in mineral oil to avoid any edge effects that may disturb the measurements.

Evaluation of specific energy allows comparison between the different capacitor devices. Use of thin film dielectric separators usually results in capacitors with high capacitance but low breakdown voltage [8]. The specific energy is given by

$$\overline{\Gamma}_{sc} = \frac{\frac{1}{2}CV^2}{m_{sc}}, \tag{1}$$

where $\overline{\Gamma}_{sc}$ is the specific energy of the structural capacitor, C the capacitance, V the voltage at dielectric breakdown and m_{sc} the mass of the structural capacitor.

Three types of mechanical testing were performed in **papers I**, **II** and **III**.

Interlaminar shear strength was evaluated at room temperature using the short beam three-point bending test according to the ASTM D2344/D2344 M standard [4] to expose any negative or positive effects of the dielectric, at mid-thickness, on the mechanical performance of the composite. It is well known that the short beam three-point bend test does not provide very accurate ILSS values due to the non-uniformity of the stress field [9]. However, the test is useful to monitor difference in interlaminar shear strength between materials and therefore provides a useful tool for assessment of the relative performance of the individual structural capacitor materials developed in the current study.

In **paper II** a tearing test was chosen to evaluate the structural capacitors use in a crash situation that could be found in e.g. an automotive application. The tearing force was evaluated using a tearing test developed for simulating a tearing failure [6]. The test is easily performed in an ordinary tensile tester with purpose made fixture and requires very little specimen preparation making it very fast and robust.

In **paper III** tensile testing was performed to characterise the tensile properties of the structural capacitor materials. Output from the test was Young´s modulus and ultimate tensile strength of the laminates. The tests were performed at room temperature according to the ASTM standard D3039/D3039 M [5].

MULTI-FUNCTIONAL EVALUATION

Multifunctional performance is evaluated by assessment of measured specific electrical energy vs. specific mechanical properties. Employing specific electrical energy as the parameter to assess multifunctional performance allows for comparison between different structural capacitor designs and their applicability in a structural system with respect to their potential to reduce system weight. This is important as though the multifunctional element exhibits specific energy and strength and/or stiffness that are lower than those of the best monofunctional materials, at a system level the multifunctional material may still enable an overall mass saving. In the paper by O’Brien et al. [8] a procedure to evaluate multifunctional capacitor designs, following an approach suggested by Wetzel [10] is presented. O'Brien and co-workers [8] define a total system mass M equal to the sum of the mass of the capacitors m_c and the mass of the structure m_s. The design metric for capacitor performance is specific energy $\overline{\Gamma}$ (in J/kg) with overall system energy storage defined as $\Gamma = \overline{\Gamma} m_c$. Similarly, the mechanical performance, e.g. specific modulus or ILSS (J/kg), can be defined as $\overline{E}$ and $\overline{\tau}$. From these, the electrical energy density and specific mechanical properties of the structural capacitors can be found as $\sigma^e \overline{\Gamma}$, $\sigma^s \overline{E}$ and $\sigma^s \overline{\tau}$. σ^e and σ^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

$$\sigma^{mf} \equiv \sigma^e + \sigma^s > 1 . \qquad (2)$$

OBJECTIVE

The objective of this work has been to develop high performance multifunctional polymer composite capacitor materials. A method for manufacturing the laminates was developed and the materials were tested electrically and mechanically. The results were used to evaluate the resulting materials multi-functional efficiency.

SUMMARY OF PAPERS

Paper I

In this paper an approach towards realising novel multifunctional polymer composites is presented. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven laminae separated by a paper or polymer film dielectric separator. The structural capacitor multifunctional performance was characterised measuring capacitance, dielectric strength and interlaminar shear strength. The developed structural CFRP capacitor designs employing polymer film dielectrics (PA, PC and PET) offer remarkable multifunctional potential.

Paper II

In this paper an approach towards realising novel multifunctional polymer composites is presented. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven lamina separated by a polymer film dielectric separator. The structural capacitor multifunctional performance was characterised measuring capacitance, dielectric strength and tearing force. The developed structural

CFRP capacitor designs employing polymer film dielectrics (PA, PC and PET) offer remarkable multifunctional potential.

Paper III

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. The capacitors where made using three thicknesses of DuPont Mylar A thermoplastic PET as dielectric separator employing carbon fibre/epoxy pre-pregs as structural electrodes. Plasma treatment was used as a route for improved epoxy/PET adhesion. The manufactured materials were mechanically and electrically tested to evaluate their multifunctional efficiency.

The multifunctional materials show good potential for replacing steel and other materials with lower specific mechanical properties but cannot match the high specific mechanical performance of mono-functional composites.

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PAPER I

Structural capacitor materials made from carbon fibre epoxy composites

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ABSTRACT

In this paper an approach towards realising novel multifunctional polymer composites is presented. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven laminae separated by a paper or polymer film dielectric separator. The structural capacitor multifunctional performance was characterised measuring capacitance, dielectric strength and interlaminar shear strength. The developed structural CFRP capacitor designs employing polymer film dielectrics (PA, PC and PET) offer remarkable multifunctional potential.

Keywords: A: Functional composites, A: Layered structures, B: Electrical properties, B: Interfacial strength

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 transportation modes. To facilitate development of such products, a step change towards electrification to urban mobility and transport is imminent, further requiring yet lighter vehicles. The immediate need for electrical vehicles is driven by the forecasted shortage of crude oil based energy carriers together with the necessity to reduce greenhouse gas emissions.

To realise electric vehicles, and to keep up with the power requirements of new and emerging technologies, the mobile platforms 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 vehicles, for which low weight is essential. A decade ago Chung and Wang [1] presented the idea of using carbon fibre reinforced polymers (CFRP) in “structural electronics”. They suggested that the semi-conductive nature of carbon fibre composites could be used to make electric devices, e.g. diodes, detectors, transistors, etc. In this spirit they were first to propose use of a high dielectric constant material as an interface between CFRP laminae to provide a capacitor material, i.e. a structural parallel-plate capacitor. By this approach truly multifunctional material, i.e. a material that can perform more than one function, emerge. In the case of a structural capacitor, the material is stiff and strong to sustain mechanical loading and at the same time is able to store electric energy. In a follow-on study Luo and Chung demonstrated structural capacitor materials for the first time [2]. Lou and Chang made thin structural capacitors from single unidirectional carbon fibre epoxy pre-preg layers separated by different paper dielectrics. For these materials dynamic capacitance up to 1200 nF/m^2 at 2 MHz was demonstrated, however no mechanical characterisation was performed. More recently, another approach for making structural capacitors was suggested by Baechle et al. [3]. To achieve high energy density of the capacitor for maximised multifunctional efficiency Baechle and co-workers made structural capacitors from dielectric glass/epoxy pre-preg with thin metal electrodes. By this approach Baechle and colleagues utilise the dielectric layer for structural performance.

Since Chung and Wang [1] first suggested the use of structural electronics development of such materials has been reported in the open literature and a new research area has emerged – that of "composite structural power storage materials". Recently, concepts for structural polymer composite batteries [4, 5] and supercapacitors [6] have been presented. All these materials are developed with a desire to reduce vehicle weight permitting replacement of structural components (e.g. car floor panels) and energy storage devices (e.g. batteries). The work presented here was enthused by the ambition to develop a truly multifunctional composite material that may boost the development of future ultra-light electric vehicles.

The objective of this study is to develop high performance multifunctional polymer composite capacitor materials. These capacitor materials are developed in the spirit of Luo and Chung [2], employing carbon fibre pre-preg lamina separated by a dielectric material. In this study, papers and polymer films are utilised as dielectric separator layers. The electric and mechanical performance is characterised for each dielectric material employed and its overall multifunctional performance is assessed.

2 Experimental

2.1 Materials

Structural capacitors were made from carbon fibre epoxy composites to facilitate high performance mechanical electrodes. The electrode layers (laminae) were made from 0.125 mm thick pre-preg weaves. The pre-preg was a 245 g/m^2 2x2 Twill HS (3K) 0º/90º configuration, MTM57/CF3200-42% RW, supplied by the Advanced Composite Group, UK. The resulting CFRP composite had a fibre volume fraction of 52%. A dielectric layer in a composite laminate separated the electrode layers. A number of materials were employed as separator. The dielectric materials employed in this study, and their nominal thicknesses, are listed in Table 1. The papers were regular printing paper of different surface weights, which with the epoxy provide a separator layer. The Polyamide film brand was Airtech Wrightlon 5400. The Polyester film was DuPont Teijin Films Mylinex 301 Bondable Film. Finally, the polycarbonate film was a 0.15 mm thick PC quality supplied by Andren & söner, Sweden. Stacking two electrode layers separated by the dielectric layer made the structural capacitors. To facilitate mechanical testing thicker laminates were manufactured. Here, the electrode laminas were each made from a stack of 20 pre-preg weaves, separated by the dielectric layer, resulting in a laminate with a nominal thickness of 5 mm. The dielectric materials selection as well as the choice of pre-preg carbon fibre epoxy weaves was done after an extensive pre-study of dielectrics, composite materials and manufacturing techniques [7].

In addition to the dielectrics reported in Table 1 dielectrics were employed to study effects of surface treatment of the polymer dielectric films on structural performance. For this purpose, composite material capacitors utilising plasma treated (using a Technics Plasma

440G equipment) PA- and PET-films were manufactured. In the plasma treatment the surface of a substrate is exposed to plasma, i.e. excited in a gas e.g. N_2, as used in these experiments. The treatment is done to increase the adhesion between the dielectric film and matrix of a composite as chemical bonds in the film surface are broken and reactive positions are generated [7]. These reactive sites react with N creating polar groups at the surface. The advantage of this process is that no thermal or mechanical strains are introduced into the specimen. The treatment was performed during 15 seconds.

Dielectric material	Thickness [mm]
Paper 40g/m^2	0.08
Paper 80g/m^2	0.10
Paper 150g/m^2	0.19
PA-film	0.05
PET-film	0.02
PC-film	0.17

Table 1. Dielectrics and their nominal thickness.

2.2 Composite manufacture and characterisation

During manufacture pre-preg layers were stacked 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 mould was sealed with butyl tape and a vacuum bag. A schematic of the bagged lay up is shown in Figure 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 (120ºC for 30 minutes) to achieve fully cured laminates. The vacuum was necessary to achieve void free, high quality composite laminates. Voids must be to be kept to minimum. Air has a lower dielectric constant then the tested dielectrics. Presence of voids will therefore locally reduce the isolative properties of the dielectric, also mechanical properties are lowered.

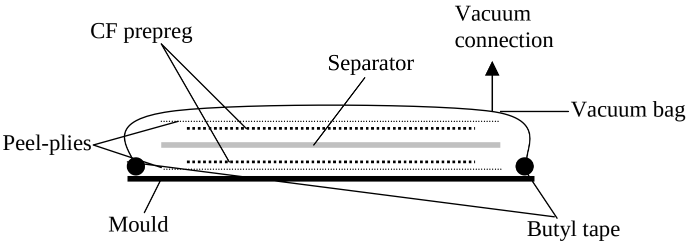


Figure 1. Manufacture of the structural capacitor laminates.

In total six types of structural capacitor laminates were manufactured for electrical characterisation. For each type of material a set of five specimens was manufactured. The specimen designed for electrical (capacitance) characterisation is depicted in Figure 2. The specimen had a total area of 0.010 m^2 and had a nominal thickness between 0.25-0.45 mm, depending on the dielectric material employed. The square shape was chosen because it is easy to control size and placement, though a circular shape would be better from electrical point of view, since corners concentrate charge. The dielectric material has an excess of approximately 10 mm around carbon fibre plies to avoid edge effects. A copper mesh was used as electrical connection due to good electrical conductivity and compatibility to most matrices, as well as flexibility.

Eight structural capacitor materials were manufactured for mechanical characterisation. In addition to the six capacitor materials made for electrical characterisation capacitors employing the plasma treated PA and PET separator films, PA-PT and PET-PT respectively were manufactured. Note that no capacitance measurements were performed on capacitors using plasma treated dielectrics. The reason for this is that plasma treatment alters only the surface properties of the polymer film and not its intrinsic properties, nor its thickness. It is therefore assumed that plasma treatment of the dielectric will have negligible influence on the capacitance of the structural capacitor.

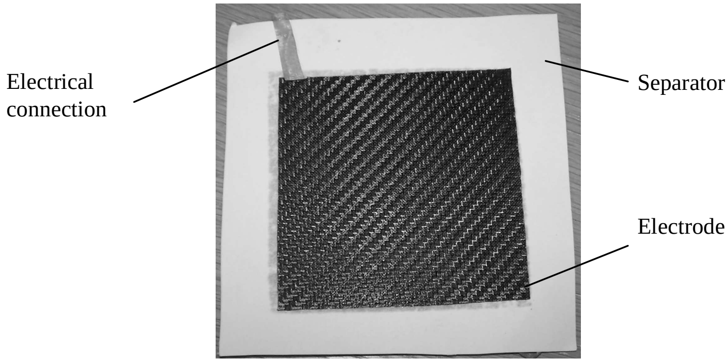


Figure 2. A single layer structural capacitor for electric characterisation.

Specimens for ILSS characterisation using the short beam 3-point bending test [8] were manufactured. The specimens were grinded and polished to the nominal dimensions: thickness 5 mm, width 10 mm and length 40 mm.

2.3 Experimental characterisation

2.3.1 Capacitance

Capacitance measurements were carried out on in total 30 specimens, five for each type of dielectric. Measurements were performed as follows: The capacitor was charged repeatedly to an increasing voltage (*V*) until the structural capacitor was short-circuited. For each voltage the structural capacitor was discharged and the charge (*Q*), in Coulombs, giving the capacitance as

$$C = \frac{Q}{V}. \tag{1}$$

The voltage to which the capacitor was charged was measured using a Voltmeter, Eltex EMF 58. The charge during discharge was measured employing a Coulomb meter, Keithley Instruments 602 Solid state electrometer.

To further characterise the electric properties of the structural capacitors measurements of dynamic capacitance and losses were performed. The tests were run in a dynamic electric test equipment, General Electric Programma IDA 200. In these tests the impedance was measured over the frequency range 0.1 Hz - 1 kHz. Tests were only performed on one randomly selected sample of each capacitor material.

2.3.2 Dielectric breakdown voltage

Dielectric breakdown voltage (dielectric strength), of the capacitors was measured using the ASTM standard for direct current measurement of dielectric breakdown [11] as done by Baechle et al. [12]. Voltage was applied with a rate of 100V/s with the specimen submerged in mineral oil. Breakdown tests were performed on three structural capacitors of each type, in total 18 measurements. The equipment used was a Spellman SR6 High Voltage Supply controlled by PCI GPIB and a HP 33120A Function Waveform Generator, with a maximum voltage of 28,3 kV. A PCI NI-6023E (DAQ) with a BNC-2111 connector block was used to record the results from the tests. Voltage was applied until failure was evident by a large drop in voltage.

2.3.3 Interlaminar shear strength

The mechanical characterisation was limited to measurement of the interlaminar shear strength (ILSS) of the structural capacitor to expose any negative or positive effects of the dielectric, at mid-thickness, on the mechanical performance of the composite. This is motivated, as the fibre-dominated in-plane properties are almost unaffected by the introduction of a soft and weak dielectric layer, whereas the matrix-dominated out-of-plane properties are, in particular the ILSS. No significant effect of the dielectric on the matrix-dominated in-plane mechanical properties, e.g. transverse strength, is expected.

The interlaminar shear strength was evaluated using the short beam three-point bending test according to the ASTM D2344 standard [8]. The test set-up is shown in Figure 3. In the test, the specimen rested on two support rollers. The displacement was applied at the centre of the specimen at a rate of 1.0 mm/min. As a result, maximum shear stresses appear at the specimen mid-thickness, i.e. at the position of the dielectric. Hence, the ILSS of the dielectric/CFRP interface was measured in the test. In total, 40 specimens were tested, five for each capacitor material, including the structural capacitor materials with the plasma treated dielectrics. In addition, ILSS for the CFRP was measured on five samples.

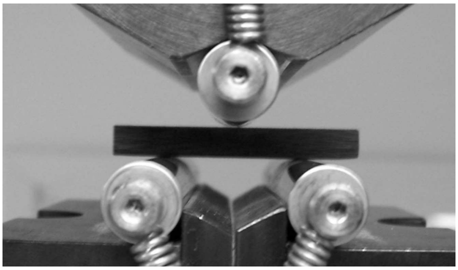


Figure 3. Short beam 3-point bending set up.

Due to design of the test rig, the ILSS test set-up was modified somewhat compared to ASTM D2344 standard [8]. The employed rig had a minimum span of 22.7 mm with rollers 10 mm in diameter.

During the ILSS tests load and crosshead displacement were recorded. The load was applied until either of three conditions occurred; a load drop of 30 %, the cross head displacement exceeded the specimen nominal thickness or specimen fracture. The interlaminar shear strength was calculated according to the standard [8].

It is well known that the short beam three-point bend test does not provide very accurate ILSS values due non-uniformity of the stress field [9]. However, the test is useful to monitor difference in interlaminar shear strength between materials and therefore provides a useful tool for assessment of the relative performance of the individual structural capacitor materials developed here. The method is selected in this study being a very easy to perform and robust test.

2.4 Energy density

Evaluation of energy density allows comparison between the different capacitor devices. Use of thin film dielectric separators usually results in capacitors with high capacitance but low breakdown voltage [12]. The energy density is given by

$$\overline{\Gamma}_{sc} = \frac{\frac{1}{2}CV^2}{m_{sc}}, \qquad (2)$$

where $\overline{\Gamma}_{sc}$ 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. It should be pointed out that the energy density of a single dielectric layer capacitor, like the ones assessed here, will be lower than that of a conventional multilayer capacitor. This is due to the more effective use of electrodes in a multilayer capacitor. A single layer capacitor has two electrodes and one dielectric layer. Generally a n-layer capacitor will have n+1 electrodes and n dielectric layers. Here the energy density will be used to evaluate the multifunctional efficiency of the structural capacitors.

3 Results and discussion

3.1 Electrical properties

Dielectric	Thickness [μm]	Capacitance [nF/m^2]	Dielectric strength [kV]	Average energy density [J/g]
Paper 40g/m^2	71±4	712±118	0.55±0,08	0.00013
Paper 80g/m^2	89±3	2466±1007	0.78±0,05	0.00088
Paper 150g/m^2	173±5	766±286	1.69±0,08	0.0012
PA-film	50±3	868±198	7.80±1,03	0.034
PET-film	19±1	1860±1024	6.40±0,66	0.052
PC-film	155±8	206±11	28.3*	0.089*

*The capacitors had not failed at maximum voltage in the breakdown voltage tests.

Table 2. Summary of results for various structural capacitors

The results from the discharge and dielectric strength experiments are presented in Table 2. The results are measured average capacitance and dielectric strength with standard deviations, for respective dielectric.

3.1.1 Capacitance

The 80 g/m^2 paper capacitor gives the highest capacitance. This is unexpected since the thinner 40 g/m^2 paper dielectric should give a higher capacitance as capacitance is proportional to the inverse of the thickness of the dielectric. One plausible reason for the lower capacitance of the 40 g/m^2 paper capacitor could be migration of carbon dust into the porous surface of the paper. Such effects were observed in an earlier study for other thin porous dielectrics [7] and also found by Luo and Chung [2] for thin paper dielectrics.

For the polymer films, thickness is the main variable controlling capacitance. This is evident for the PC film, which has the largest thickness and consequently the lowest capacitance. An explanation for the noticeably high standard deviation for 80 g/m^2 and PET could be test equipment limitations. The capacitors with high capacitance required low voltage in order to be measured, affecting accuracy of measurements.

The reported capacitances for all structural CFRP electrode capacitor designs studied here were significantly higher than those found for capacitors employing structural dielectric layers [3, 12]. The highest capacitance reported for those materials was approximately 150 nF/m^2 [12], c.f. Table 2. No experimental comparison with capacitance of a conventional capacitor material was possible. Nevertheless, a comparison with theoretical capacitance of conventional film capacitors (80 μm thick PET film covered by 4 μm copper on both sides) suggests that the structural capacitors developed in this study match the conventional capacitors considering capacitance. The theoretical capacitance for such a conventional film capacitor is 365 nF/m^2 to be compared with the 1860 nF/m^2 for the PET-film structural capacitor developed here. As discussed by Luo and Chung [2], the carbon fibres in the structural capacitor electrodes provide an increased surface area, and therefore promote an increase in capacity compared to conventional film electrode capacitors.

Dielectric	Dynamic capacitance [nF/m^2]	Tan δ
Paper 40g/m^2	783	0.486
Paper 80g/m^2	2450	2.449
Paper 150g/m^2	924	1.178
PA-film	2461	0.635
PET-film	1144	0.022
PC-film	157	0.003

Table 3. Dynamic capacitance and electric loss at 0.1 Hz.

Results from the dynamic capacitance and loss measurements at 0,1 Hz are presented in Table 3. The 80 g/m^2 paper capacitor along with PA and PET ones exhibit the highest values of dynamic capacitance. Complete data from the dynamic tests are found in ref. [7].

3.1.2 Dielectric strength

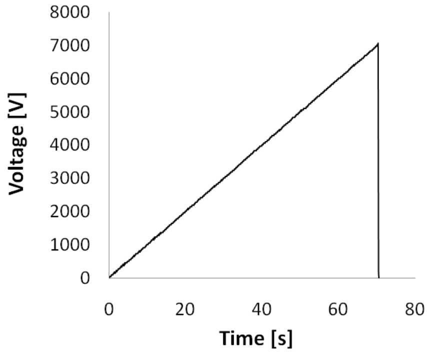


Figure 4. Voltage history of a typical dielectric strength test.

In Figure 4 the voltage history for a typical dielectric strength test series is depicted. Note the absence of clearing reported in tests on capacitors employing structural dielectric separators [12]. Results from the dielectric breakdown voltage measurements are presented in Table 2. The results show superior performance of the polymer films to that of impregnated paper dielectrics. The dielectric strength of the polymer film capacitors was at least one order of magnitude higher than that for capacitors with paper dielectric separators. The performance of the PC-film capacitor was outstanding, and did not breakdown before maximum voltage was reached. Hence is should be recognized that maximum energy density for the PC-film capacitor could not be measured with the current test set-up.

The average static capacitance, average breakdown voltage and average weight were used to calculate the energy density according to Equation (2). The calculated energy densities are presented in Table 2.

The achieved energy densities for the capacitors with polymer film dielectric separators are significantly higher than those from paper dielectrics. This is explained by the superior dielectric strengths of these capacitors. The energy density for PC-film capacitor was particularly good. All PC-film capacitors exceeded an energy density of 0.089 J/g. This value is lower than the 0.28 J/g reported for structural dielectric separator capacitors developed by O'Brien et al. [12]. However, the breakdown voltage was not reached for the PD-film dielectric capacitor studied here. As the energy density is proportional to the breakdown voltage squared, even a moderate increase in measured dielectric strength will result in a significant increase in energy density.

3.2 Mechanical properties –ILSS

Dielectric	ILSS [MPa]
Paper 40g/m^2	9.54±0.19
Paper 80g/m^2	21.76±1.08
Paper 150g/m^2	36.61±2.34
PA-film	22.12±3.50
PA-film, plasma treated	65.26±1.19
PET-film	20.31±0.58
PET-film, plasma treated	29.78±2.22
PC-film	10.19±1.04
CFRP	23.28±2.88

Table 4. Interlaminar shear strength for the structural capacitors.

The interlaminar shear strength (ILSS) results from the short beam three-point bending tests are summarised in Table 4. ILSS tests were also performed on the carbon fibre epoxy laminate without any dielectric (i.e. the monofunctional structural composite material). The average ILSS for the five CFRP specimens was 23.28 MPa.

A clear trend is observed for the paper capacitors: the thicker paper the higher interlaminar shear strength. The 150 g/m^2 paper dielectric capacitor out-performs the conventional CFRP laminate by approximately 50%! All untreated plastic film capacitors show lower values than the 150 g/m^2 paper capacitor. However, both the PA-film and PET-film capacitors perform as good as the CFRP laminate, all exceeding ILSS of 20 MPa. This is also the case for the 80 g/m^2 paper capacitor. Among the polymer film dielectrics the PC-film capacitors perform less good. Its ILSS is less than half of that of the CFRP. Although not generally observed here, improved delamination resistance is expected by interleaving CFRP with thermoplastic films, see e.g. [13]. To reach such improvements, however, excellent film/composite adhesion is required. Consequently, the results for plasma treated films reveal a tremendous effect of plasma treatment of the polymer film dielectrics on the ILSS of the structural capacitor materials. Plasma treatment of the PA-film dielectric results in an increase from 22.12 MPa to 65.26 MPa for the composite capacitor material. That is an increase in ILSS by almost 200%! Also for the PET-film capacitor a very large improvement of the interlaminar shear strength was found (almost 50%).

An ocular inspection of the fractured specimens was done immediately after testing. The visual inspection showed that all specimens fractured at the middle interface, i.e. at the position of the dielectric separator. The specimens were split open and the fracture surfaces were inspected in an optical microscope. For the capacitors with paper dielectrics cohesive failure in the impregnated paper was observed, leaving residue paper on both fracture surfaces. For the plastic film structural capacitors adhesive failure at the separator/composite interface with, some evidence of improved adhesion for the plasma treated films was observed.

3.3 Multifunctional performance

Multifunctional performance is evaluated by assessment of measured energy density vs. specific interlaminar shear strength and calculated specific in plane stiffness. Here, the in plane stiffness was calculated by rule of mixture using the stiffness data for the CFRP and the polymer films provided by the material suppliers. Although capacitance and dielectric strength are important properties for the performance of a capacitor, use of these properties individually to assess multifunctional performance of a structural capacitor will produce contradicting results. For example, if one was to assess multifunctional performance with respect to capacitance alone, the 80 g/m^2 paper and PET-film would be found most suitable to achieve structural capacitor materials, whereas the PC-film capacitor would be found worse. In contrast, if only dielectric strength was to be considered, the PC- and PET-film capacitors would be ranked highest and the all paper dielectric capacitors would be found inferior.

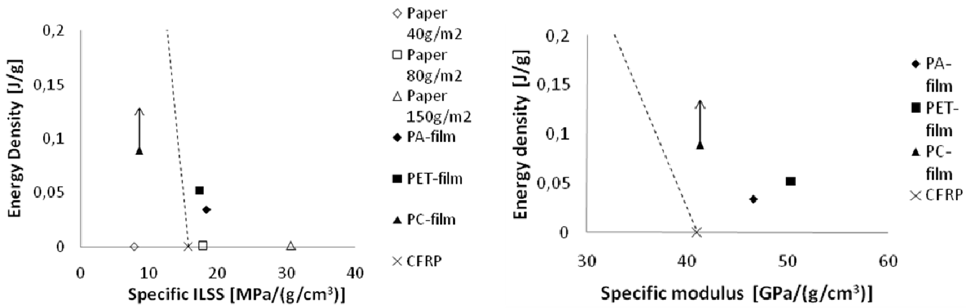
Employing energy density as the parameter to assess multifunctional performance allows us to compare the different structural capacitor designs for their applicability in a structural system, where energy needs to be stored, with respect to their potential to reduce system weight. Consequently, this approach allows us to evaluate the structural capacitors influence on system weight, as described by O'Brien et al. [12]. This is important as even though the multifunctional element exhibits energy density and strength and/or stiffness that usually are lower than the best monofunctional materials, at a system level the multifunctional material enables an overall mass saving. In the paper by O'Brien et al. [12] a procedure to evaluate multifunctional capacitor designs, following an approach suggested by Wetzel [14] is presented. O'Brien and co-workers [12] define a total system mass M equal to the sum of the mass of the capacitors m_c and the mass of the structure m_s. The design metric for capacitor performance is energy density $\overline{\Gamma}$ (in J/kg) with overall system energy storage defined as $\Gamma = \overline{\Gamma} m_c$. Similarly, the mechanical performance, e.g. specific modulus or ILSS (J/kg), can be defined as $\overline{E}$ and $\overline{\tau}$. From these, the energy density and specific mechanical properties of the structural capacitors can be found as $\sigma^e \overline{\Gamma}$, $\sigma^s \overline{E}$ and

$\sigma^s \bar{\tau}$. σ^e and σ^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

$$\sigma^{mf} \equiv \sigma^e + \sigma^s > 1 . \qquad (3)$$

Multifunctional performance is depicted in Figure 5. In Figure 5a energy density is plotted as function of specific interlaminar shear strength. In the Figure, a dashed line, representing Equation (3) is introduced to indicate multifunctional efficiency, σ^{mf}, of the structural capacitors, with respect to ILSS. Data points located to the right of the dashed line exhibit a multifunctional efficiency greater than unity. Here, the reference energy density for a state of the art capacitor material has been assumed to 1 J/g [12], whereas the ILSS for the CFRP is used as benchmark for the strength. From the graph it is evident that the PA- and PET-film capacitors exhibit multifunctional efficiencies exceeding unity. Note that these data refer to the tests on untreated films. When plasma treated, the ILSS increased substantially, by which both capacitors should achieve multifunctional efficiencies exceeding unity by a large margin. Also, the 150 g/m^2 paper exhibits multifunctional efficiency larger than unity. This is however solely due to the high specific ILSS of the capacitor material exceeding that of the CFRP. Consequently, based on these results use of the paper dielectric capacitors cannot be recommended.

Results for multifunctional efficiency with respect to specific in plane stiffness are plotted in Figure 5b. Again a dashed line indicating multifunctional efficiency of unity, according to Equation (3) is introduced, where energy density of 1 J/g and specific modulus of 40.93 GPa/(g/cm^3) are used for the monofunctional materials. Consequently, the stiffness offered by the CFRP structural capacitor electrodes greatly exceeds that resulting from use of GFRP dielectrics developed by O'Brien et al. [12]. Here, data for polymer films only are presented, as the energy densities in the paper-separated capacitors are too low to be of interest. For this case, a multifunctional efficiency higher than unity is achieved for all polymer-film capacitor materials. Note that in both Figure 5a and 5b, the energy density plotted for the PC-film capacitor is a lower than the maximum energy density, which remains unknown at this stage.



a) b)

Figure 5. a) Energy density versus specific ILSS for the structural capacitors b) Energy density versus calculated specific stiffness for plastic film structural capacitors.

4 Conclusions

A series of structural capacitor materials made from carbon fibre reinforced polymers electrodes have been manufactured and evaluated for their mechanical, electric and multifunctional performance. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven lamina as electrodes separated by a dielectric material. The dielectric materials employed in this study were three different surface weights of paper and three different polymer films (PA, PET and PC).

Multifunctional efficiency of the developed structural capacitors was evaluated on the basis of achieved energy density and interlaminar shear strength as well as in plane stiffness. All capacitors employing a polymer film dielectric separator investigated indicate potential for high multifunctional efficiency. Depending on film thickness and surface plasma treatment significantly improved multifunctional designs with overall weight savings can be achieved. In particular, use of CFRP in the capacitor electrodes will result in significantly higher in plane stiffness of the multifunctional component than will use of GFRP structural dielectric separators. Nevertheless, further research is needed to identify best choice of polymer film and film thickness as well as best practice for surface treatment.

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PAPER II

CFRP structural capacitor materials for automotive applications

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ABSTRACT

In this paper an approach towards realising novel multifunctional polymer composites is presented. A series of structural capacitor materials made from carbon fibre reinforced polymers have been developed, manufactured and tested. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven lamina separated by a polymer film dielectric separator. The structural capacitor multifunctional performance was characterised measuring capacitance, dielectric strength and tearing force. The developed structural CFRP capacitor designs employing polymer film dielectrics (PA, PC and PET) offer remarkable multifunctional potential.

Keywords: Multifunctional, Electrical properties, Mechanical properties, Carbon fibre

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 transportation modes. To facilitate development of such products, a step change towards electrification to urban mobility and transport is imminent, further requiring yet lighter vehicles. The immediate need for electrical vehicles is driven by the forecasted shortage of crude oil based energy carriers together with the necessity to reduce greenhouse gas emissions.

To realise electric vehicles, and to keep up with the power requirements of new and emerging technologies, the mobile platforms 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 vehicles, for which low weight is essential. A decade ago Chung and Wang [1] presented the idea of using carbon fibre reinforced polymers (CFRP) in “structural electronics”. They suggested that the semi-conductive nature of carbon fibre composites could be used to make electric devices, e.g. diodes, detectors, transistors, etc. In this spirit they were first to propose use of a high dielectric constant material as an interface between CFRP lamina to provide a capacitor material, i.e. a structural parallel-plate capacitor. By this approach truly multifunctional material, i.e. a material that can perform more than one function, emerge. In the case of a structural capacitor, the material is stiff and strong to sustain mechanical loading and at the same time is able to store electric energy. In a follow-on study Luo and Chung demonstrated structural capacitor materials for the first time [2]. Lou and Chang made thin structural capacitors from single unidirectional carbon fibre epoxy pre-preg layers separated by different paper dielectrics. For these materials dynamic capacitance up to 1200 nF/m^2 at 2 MHz was demonstrated, however no mechanical characterisation was performed. More recently, another approach for making structural capacitors was suggested by Baechle et al. [3]. To achieve high energy density of the capacitor for maximised multifunctional efficiency Baechle and co-workers made structural capacitors from dielectric glass/epoxy pre-preg with thin metal electrodes. By this approach Baechle and colleagues utilise the dielectric layer for structural performance.

Since Chung and Wang [1] first suggested the use of structural electronics development of such materials has been reported in the open literature and a new research area has emerged – that of “composite structural power storage materials”. Recently, concepts for structural polymer composite batteries [4, 5] and supercapacitors [6] have been presented. All these materials are developed with a desire to reduce vehicle weight permitting replacement of structural components (e.g. car floor panels) and energy storage devices (e.g. batteries). The work presented here was enthused by the ambition to develop a truly multifunctional composite material that may boost the development of future ultra-light electric vehicles.

The objective of this study is to develop high performance multifunctional polymer composite capacitor materials. These capacitor materials are developed in the spirit of Luo and Chung [2], employing carbon fibre pre-preg lamina separated by a dielectric material. In this study polymer films are utilised as dielectric separator layers. The electric and mechanical performance is characterised for each dielectric material employed and its overall multifunctional performance is assessed.

2 Experimental

2.1 Materials

Structural capacitors were made from carbon fibre epoxy composites to facilitate high performance mechanical electrodes. The electrode layers (laminae) were made from 0.125 mm thick pre-preg weaves. The pre-preg was a 245 g/m^2 2x2 Twill HS (3K) 0º/90º configuration, MTM57/CF3200-42% RW, supplied by the Advanced Composite Group, UK. The resulting CFRP composite had a fibre volume fraction of 52%. A dielectric layer in a composite laminate separated the electrode layers. A selection of materials was employed as separator. The dielectric materials employed in this study, and their nominal thicknesses, are listed in Table 1. The Polyamide film brand was Airtech Wrightlon 5400. The Polyester film was DuPont Teijin Films Mylinex 301 Bondable Film. Finally, the polycarbonate film was a 0.15 mm thick PC quality supplied by Andren & söner, Sweden. Stacking two electrode layers separated by the dielectric layer made the structural capacitors. To facilitate mechanical testing thicker laminates were manufactured. Here, the specimens were made from six layers of pre-preg weaves alternated with five dielectric layers, resulting in a laminate with a nominal thickness of 2 mm.

In addition to the dielectrics reported in Table 1 dielectrics were employed to study effects of surface treatment of the polymer dielectric films on structural performance. For this purpose, composite material capacitors utilising plasma treated (using a Technics Plasma 440G equipment) PA- and PET-films were manufactured. In the plasma treatment the surface of a substrate is exposed to plasma, i.e. excited in a gas e.g. N_2, as used in these experiments. The treatment is done to increase the adhesion between the dielectric film and matrix of a composite as chemical bonds in the film surface are broken and reactive positions are generated [7]. These reactive sites react with nitrogen creating polar groups at the surface. The advantage of this process is that no thermal or mechanical strains are introduced into the specimen. The treatment was performed during 15 seconds.

Dielectric material	Thickness [mm]
PA-film	0.05
PET-film	0.02
PC-film	0.17

Table 1. Dielectrics and their nominal thickness.

2.2 Composite manufacture and characterisation

During manufacture pre-preg layers were stacked 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 mould was sealed with butyl tape and a vacuum bag. A schematic of the bagged layup is shown in Figure 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 (120ºC for 30 minutes) to achieve fully cured laminates. The vacuum was necessary to achieve void free, high quality composite laminates. Voids must be to be kept to minimum. Air has a lower dielectric constant then the tested dielectrics. Presence of voids will therefore locally reduce the isolative properties of the dielectric, also mechanical properties are lowered.

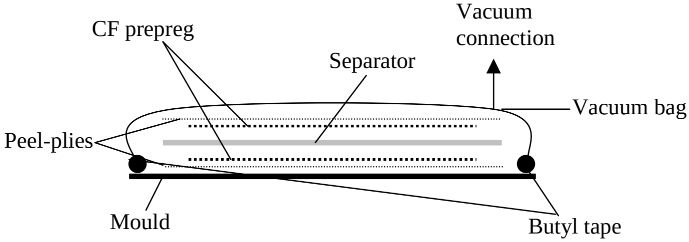


Figure 1. Manufacture of the structural capacitor laminates.

In total three types of structural capacitor laminates were manufactured for electrical characterisation. For each type of material a set of five specimens was manufactured. The specimen designed for electrical (capacitance) characterisation is depicted in Figure 2. The specimen had a total area of 0.010 m^2 and had a nominal thickness between 0.27-0.42 mm, depending on the dielectric material employed. The square shape was chosen because it is easy to control size and placement, though a circular shape would be better from electrical point of view, since corners concentrate charge. The dielectric material has an excess of approximately 10 mm around carbon fibre plies to avoid edge effects. A copper mesh was used as electrical connection due to good electrical conductivity and compatibility to most matrices, as well as flexibility.

Two structural capacitor materials were manufactured for mechanical characterisation. In addition to the three capacitor materials made for electrical characterisation capacitors employing the plasma treated PA and PET separator films, PA-PT and PET-PT respectively were manufactured. Note that no capacitance measurements were performed on capacitors using plasma treated dielectrics. The reason for this is that plasma treatment alters only the surface properties of the polymer film and not its intrinsic properties, nor its thickness. It is therefore assumed that plasma treatment of the dielectric will have negligible influence on the capacitance of the structural capacitor.

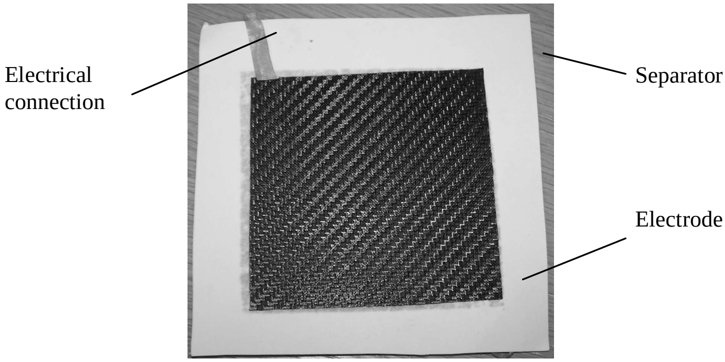


Figure 2. A single layer structural capacitor for electric characterisation.

Specimens for tearing were manufactured; specimens were cut and grinded to the nominal dimensions: thickness 2 mm, width 30 mm and length 150 mm and a hole with diameter 5 mm was drilled.

2.3 Experimental characterisation

2.3.1 Capacitance

Capacitance measurements were carried out on in total 15 specimens, five for each type of dielectric. Measurements were performed as follows: The capacitor was charged repeatedly to an increasing voltage (V) until the structural capacitor was short-circuited. For each voltage the structural capacitor was discharged and the charge (Q), in Coulombs, giving the capacitance as

$$C = \frac{Q}{V} \tag{1}$$

The voltage to which the capacitor was charged was measured using a Voltmeter, Eltex EMF 58. The charge during discharge was measured employing a Coulomb meter, Keithley Instruments 602 Solid state electrometer.

2.3.2 Dielectric breakdown voltage

Dielectric breakdown voltage (dielectric strength), of the capacitors was measured using the ASTM standard for direct current measurement of dielectric breakdown [8] as done by Baechle et al. [9]. Voltage was applied with a rate of 100V/s with the specimen submerged in mineral oil. Breakdown tests were performed on three structural capacitors of each type, in total 18 measurements. The equipment used was a Spellman SR6 High Voltage Supply controlled by PCI GPIB and a HP 33120A Function Waveform Generator, with a maximum voltage of 28.3 kV. A PCI NI-6023E (DAQ) with a BNC-2111 connector block was used to record the results from the tests. Voltage was applied until failure was evident by a large drop in voltage.

2.3.3 Tearing

A tearing test was chosen to evaluate the structural capacitors use in a crash situation that could be found in e.g. an automotive application. The tearing force was evaluated using a tearing test developed for simulating a tearing failure [10]. The test is easily performed and requires very little specimen preparation making it very fast and robust. The test was performed in an ordinary tensile tester utilizing a purpose made fixture. The specimen was clamped at end and a bolt was put though the predrilled hole.

When performing the test a fixed cross head speed of 50 mm/min and a tearing distance of 70 mm were used. The force was measured continuously throughout the test. The structural capacitor materials have different thicknesses. Consequently to allow comparison of tearing force the measured force is normalized with bolt diameter and laminate thickness, expressed in equation 2 as

$$F_{norm} = \frac{\overline{F}}{t * d}. \quad (2)$$

Where $\overline{F}$ is the average tearing force, t is the thickness of the sample and d is the diameter of the bolt (4.88 mm for the test equipment used here).

Due to the nature of this test being a process measuring over a bulk of material it was considered sufficient to use only two specimens of each type.

2.4 Electrical energy density

Evaluation of electrical energy density allows comparison between the different capacitor devices. Use of thin film dielectric separators usually results in capacitors with high capacitance but low breakdown voltage [9]. The energy density is given by

$$\overline{\Gamma}_{sc} = \frac{\frac{1}{2} C V^2}{m_{sc}} \quad (3)$$

Where $\overline{\Gamma}_{sc}$ 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.

3 Results and discussion

3.1 Electrical properties

Dielectric	Thickness [μm]	Capacitance [nF/m^2]	Dielectric strength [kV]	Average electrical energy density [J/g]
PA-film	50±3	868±198	7.80±1,03	0.034
PET-film	19±1	1860±1024	6.40±0,66	0.052
PC-film	155±8	206±11	28.3*	0.089*

*The capacitors had not failed at maximum voltage in the breakdown voltage tests.

Table 2. Summary of results for various structural capacitors

The results from the discharge and dielectric strength experiments are presented in Table 2. The results are measured average capacitance and dielectric strength with standard deviations, for respective dielectric.

3.1.1 Capacitance

For the polymer films, thickness is the main variable controlling capacitance. This is evident for the PC film, which has the largest thickness and consequently the lowest capacitance. An explanation for the noticeably high standard deviation for the PET-film capacitor could be test equipment limitations. The capacitors with high capacitance required low voltage in order to be measured, affecting accuracy of measurements.

The reported capacitances for all structural CFRP electrode capacitor designs studied here were significantly higher than those found for capacitors employing structural dielectric layers [3, 9]. The highest capacitance reported for those materials was approximately 150 nF/m^2 [9], c.f. Table 2. No experimental comparison with capacitance of a conventional capacitor material was possible. Nevertheless, a comparison with theoretical capacitance of conventional film capacitors (80 µm thick PET-film covered by 4 µm copper on both sides) suggests that the structural capacitors developed in this study match the conventional capacitors considering capacitance. The theoretical capacitance for such a conventional film capacitor is 1460 nF/m^2 to be compared with the 1860 nF/m^2 for the PET-film structural capacitor developed here. As discussed by Luo and Chung [2], the carbon fibres in the structural capacitor electrodes provide an increased surface area, and therefore promote an increase in capacity compared to conventional film electrode capacitors.

3.1.2 Dielectric strength

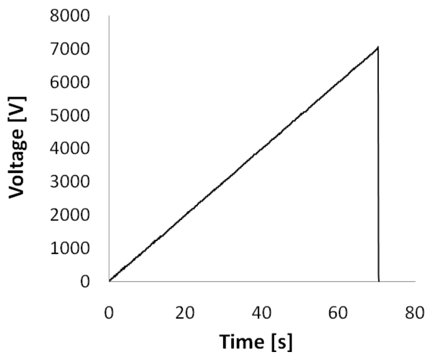


Figure 3. Voltage history of a typical dielectric strength test.

In Figure 3 the voltage history for a typical dielectric strength test series is depicted. Note the absence of clearing reported in tests on capacitors employing structural dielectric separators [9]. Results from the dielectric breakdown voltage measurements are presented in Table 2. The PA and PET films performance are in the same region but the lower thickness of the PET film makes it favourable as an insulator in a structural capacitor. The performance of the PC-film capacitor was outstanding, and did not breakdown before maximum voltage was reached. Hence is should be recognized that maximum electrical energy density for the PC-film capacitor could not be measured with the current test set-up.

The average static capacitance, average breakdown voltage and average weight were used to calculate the electrical energy density according to Equation (3). The calculated energy densities are presented in Table 2.

The electrical energy density for PC-film capacitor was particularly good. All PC-film capacitors exceeded an electrical energy density of 0.089 J/g. This value is lower than the 0.28 J/g reported for structural dielectric separator capacitors developed by O'Brien et al. [9]. However, the breakdown voltage was not reached for the PD-film dielectric capacitor studied here. As the energy density is proportional to the breakdown voltage squared, even a moderate increase in measured dielectric strength will result in a significant increase in electrical energy density

3.2 Mechanical properties – Tearing

A typical force measurement is depicted in Figure 5. The force used in the calculations is the average force in the steady state region of the tearing.

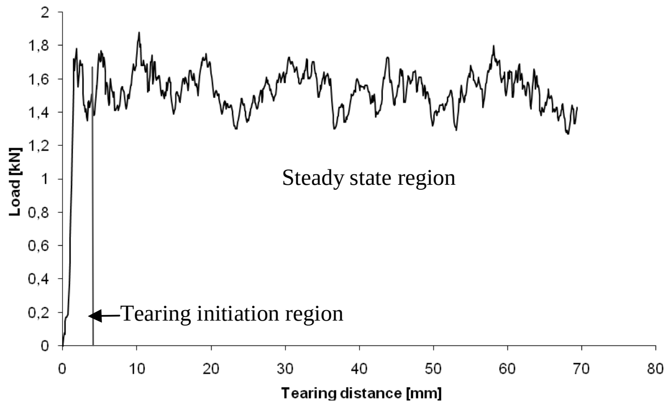


Figure 5. Typical tearing force measurement

Dielectric	Normalized tearing force [MPa]
PA-film	124.5 (11.4)
PA-film, plasma treated	171.0 (12.4)
PET-film	127.4 (16.0)
PET-film, plasma treated	121.9 (15.8)
PC-film	154.2 (14.8)
CFRP	202.8 (15.6)

Table 3. Average tearing force normalized by sample thickness and bolt diameter (Std. dev. within brackets)

The normalized tearing forces (see Eq. 2) are presented in table 3. As seen in the table no structural capacitor can compete with the pure CFRP laminate. Worth noting, however, is the great performance for the plasma treated PA-film capacitor material compared to the non-treated PA-film material. No such improvements from treatment noted for the PET-film, for which the plasma treated film shows slightly lower performance than that of the non-treated film material. The variation is quite small and could be due to natural variations within the samples.

3.3 Multifunctional performance

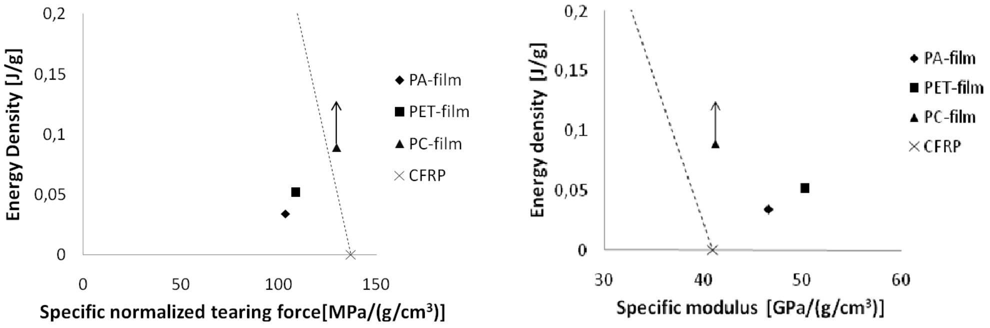
Multifunctional performance is evaluated by assessment of measured energy density vs. specific tearing force and calculated specific in plane stiffness. Here, the in plane stiffness was calculated by rule of mixture using the stiffness data for the CFRP and the polymer films provided by the material suppliers. Although capacitance and dielectric strength are important properties for the performance of a capacitor, use of these properties individually to assess multifunctional performance of a structural capacitor will produce contradicting results. For example, if one was to assess multifunctional performance with respect to capacitance alone, PET-film would be found most suitable to achieve structural capacitor materials, whereas the PC-film capacitor would be found worse. In contrast, if only tearing energy was to be considered none could match the pure CFRP but the best choice would be the PC-film capacitor.

Employing energy density as the parameter to assess multifunctional performance allows us to compare the different structural capacitor designs for their applicability in a structural system, where energy needs to be stored, with respect to their potential to reduce system weight. Consequently, this approach allows us to evaluate the structural capacitors influence on system weight, as described by O’Brien et al. [9]. This is important as even though the multifunctional element exhibits energy density and strength and/or stiffness that usually are lower than the best monofunctional materials, at a system level the multifunctional material enables an overall mass saving. In the paper by O'Brien et al. [9] a procedure to evaluate multifunctional capacitor designs, following an approach suggested by Wetzel [11] is presented. O'Brien and co-workers [9] define a total system mass M equal to the sum of the mass of the capacitors m_c and the mass of the structure m_s. The design metric for capacitor performance is energy density $\overline{\Gamma}$ (in J/kg) with overall system energy storage defined as $\Gamma = \overline{\Gamma} m_c$. Similarly, the mechanical performance, e.g. specific modulus or ILSS (J/kg), can be defined as $\overline{E}$ and $\overline{\tau}$. From these, the energy density and specific mechanical properties of the structural capacitors can be found as $\sigma^e \overline{\Gamma}$, $\sigma^s \overline{E}$ and $\sigma^s \overline{\tau}$. σ^e and σ^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

$$\sigma^{mf} \equiv \sigma^e + \sigma^s > 1 \qquad (4)$$

Multifunctional performance is depicted in Figure 6. In Figure 6a electrical energy density is plotted as function of specific normalized tearing force. In the Figure, a dashed line, representing Equation (4) is introduced to indicate multifunctional efficiency, σ^{mf}, of the structural capacitors, with respect to tearing force. Data points located to the right of the dashed line exhibit a multifunctional efficiency greater than unity. Here, the reference electrical energy density for a state of the art capacitor material has been assumed to 1 J/g [9], whereas the tearing force for the CFRP is used as benchmark for the strength. From the graph it is evident that only the PC-film capacitor exhibit multifunctional efficiencies exceeding unity. Note that these data refer to the tests on untreated films. When plasma treated, the tearing force increased substantially for the PA-film and would therefore achieve multifunctional efficiency exceeding unity by a large margin.

Results for multifunctional efficiency with respect to specific in plane stiffness are plotted in Figure 6b. Again a dashed line indicating multifunctional efficiency of unity, according to Equation (3) is introduced, where electrical energy density of 1 J/g and specific modulus of 40.93 GPa/(g/cm^3) are used for the monofunctional materials. Consequently, the stiffness offered by the CFRP structural capacitor electrodes greatly exceeds that resulting from use of GFRP dielectrics developed by O'Brien et al. [9]. In all cases a multifunctional efficiency higher than unity is achieved for all polymer-film capacitor materials. Note that in both Figure 5a and 5b, the energy density plotted for the PC-film capacitor is a lower than the maximum energy density, which remains unknown at this stage.



a) **b)**

Figure 6. a) Energy density versus specific specific normalized tearing force for the structural capacitors b)Energy density versus calculated specific stiffness for plastic film structural capacitors.

4 Conclusions

A series of structural capacitor materials made from carbon fibre reinforced polymers electrodes have been manufactured and evaluated for their mechanical, electric and multifunctional performance. The structural capacitor materials were made from carbon fibre epoxy pre-preg woven lamina as electrodes separated by a dielectric material. The dielectric materials employed in this study were three different polymer films (PA, PET and PC).

Multifunctional efficiency of the developed structural capacitors was evaluated on the basis of achieved electrical energy density and tearing force as well as in plane stiffness. All capacitors investigated indicate potential for high multifunctional efficiency. Depending on film thickness and surface plasma treatment significantly improved multifunctional designs with overall weight savings can be achieved. In particular, use of CFRP in the capacitor electrodes will result in significantly higher in plane stiffness of the multifunctional component than will use of GFRP structural dielectric separators. Nevertheless, further research is needed to identify best choice of polymer film and film thickness as well as best practice for surface treatment.

5 Acknowledgements

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PAPER III

Multifunctional materials – capacitors made from structural carbon fibre composites

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ABSTRACT

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. The capacitors where made using three thicknesses of DuPont Mylar A thermoplastic PET as dielectric separator employing carbon fibre/epoxy pre-pregs as structural electrodes. Plasma treatment was used as a route for improved epoxy/PET adhesion. The manufactured materials have been mechanically and electrically tested to evaluate their multifunctional efficiency.

The multifunctional materials shows good potential for replacing steel and other materials with lower specific mechanical properties but cannot match the high specific mechanical performance of mono-functional composites.

Keywords: A: Multi-functional composites, A: Layered structures, B: Electrical properties, B: Interfacial strength

1 Introduction

Environmental concerns along with the forecast of crude oil shortage have started recent trends towards electrification of ground vehicles. Hence, a step change towards electrification to urban mobility and transport is imminent.

To realise electric vehicles the mobile platforms must carry increasingly larger masses and volume of energy storage components such as capacitors, supercapacitors and batteries. This development counteracts the realisation of efficient electric vehicles, for which low weight is essential. One route to address this problem could be the development of multifunctional materials, in this case, materials that could store electrical energy and withstand mechanical loading.

More than a decade ago Chung and Wang [1] presented the idea of using the semi-conductive nature of the carbon fibre in “structural electronics”, making electric devices, e.g. diodes, detectors, transistors, etc. Following this they were first to propose the use of a high dielectric constant material as an interface between CFRP laminas to make a structural parallel-plate capacitor. By this approach truly multifunctional materials, i.e. a material that can perform more than one function, emerge. In a follow-on study Luo and Chung demonstrated structural capacitor materials for the first time [2]. Lou and Chung made thin structural capacitors from single unidirectional carbon fibre epoxy pre-preg layers separated by different paper dielectrics. For these materials dynamic capacitance up to 1200 nF/m^2 at 2 MHz was demonstrated, however no mechanical characterisation was performed. More recently, another approach for making structural capacitors was suggested by Baechle et al. [3]. To achieve high energy density of the capacitor Baechle and co-workers made structural capacitors employing glass fibre/epoxy pre-preg as the dielectric with metalized polymer films as electrodes. By this approach Baechle and colleagues utilise the dielectric layer for structural performance.

Previous work [4-6] performed at Swerea SICOMP AB has investigated the use of different surface weight printing papers and polymer films dielectric separator with carbon fibre prepreg electrodes in the spirit of Luo and Chung [2]. The concept of making capacitors with carbon fibre epoxy pre-preg electrodes separated by a thin polymer film was found to be most promising. This concept is further explored in this paper.

The objective of this follow-on study of previous work [4-6] has been to develop high performance multifunctional polymer composite capacitor materials. In this study thermoplastic PET-films of three different thicknesses, with and without surface treatment, are utilised as dielectric separator layers between carbon fibre epoxy pre-pregs. The electric and mechanical performance was characterised for each dielectric separator thickness and surface treatment employed and the overall multifunctional performance was assessed.

2 Experimental

2.1 Materials

Structural capacitors were made from carbon fibre epoxy composites to facilitate high performance mechanical electrodes. The electrode layers (laminas) were made from 0.268 mm thick pre-preg weaves. The pre-preg was a 245g/m^2 2x2 Twill HS (3K) 0º/90º configuration, MTM57/CF3200-42% RW, supplied by the Advanced Composites Group, UK. As dielectrics three thicknesses, 50, 75 and 125μm of DuPont Mylar A, thermoplastic polyester film supplied by Trafomo AB, Sweden, was used. The dielectric material selection, as well as the choice of pre-preg carbon fibre epoxy weaves, was done after an extensive pre-study of dielectrics, composite materials and manufacturing techniques [4-6]. PET is available in different thicknesses and is commonly used in capacitors, hence a logic choice for a parametric study.

However, adhesion between PET and epoxy could be an issue and in addition to the neat polymer films, plasma treated PET-films were prepared. The excited plasma gas breaks chemical bonds in the film surface generating active sites where chemical bonds can form for improved adhesion to the epoxy matrix [7]. Equipment used was a Technics Plasma 440G. The treatment was performed in N_2 gas for 15 seconds with 300W of power for all plasma treated specimens.

2.2 Composite manufacture and sample preparation

The pre-preg requires to be kept in a freezer to avoid premature curing. Therefore, prior to manufacturing the laminates the pre-preg roll was taken from the freezer and cut to required size laminas. The laminas were allowed to reach room temperature before putting them in a vacuum chamber for 30 min to evaporate any leftover condensation. During manufacture the pre-preg layers were stacked 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 mould was sealed with butyl tape and a vacuum bag. A schematic of the bagged layup is shown in Figure 1. Vacuum was applied and debulking without heat for 30 min was performed. The mould was then placed in an oven and heated according to the supplier's recommendations (120ºC for 30 minutes) to achieve fully cured laminates. Application of vacuum was necessary to achieve void free, high quality composite laminates. This is important as presence of voids lowers the mechanical properties (e.g. ILSS) as well as the isolative properties of the laminate. Thus present voids could cause premature dielectric breakdown in the electrical specimens.

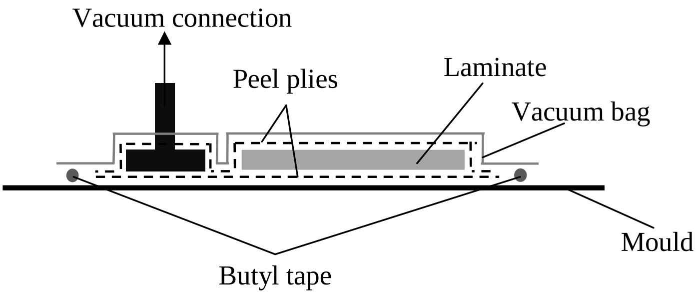


Figure 1. Manufacture of the structural capacitor laminates.

In total six types of structural capacitor laminates were manufactured for electrical characterisation, capacitance and dielectric breakdown. For each type of material a set of five specimens was manufactured. These structural capacitor laminates where made from two pre-preg plies separated by one PET film. A laminate for electrical testing is depicted in Figure 2. The specimen had a nominal electrode area of $0.010m^2$. The square shape was chosen because it is easy to control size and placement, although a circular shape would be better from an electrical point of view, since corners concentrate charge. The dielectric material has an excess of approximately 25mm around carbon fibre plies to avoid edge effects. A copper mesh was used as electrical connection due to good electrical conductivity and compatibility to most matrices, as well as flexibility.

Figure 2. A single dielectric layer structural capacitor for electric characterisation.

For mechanical characterisations materials for both tensile and interlaminar shear stress tests were manufactured. In total seven types, six analogous to the electrical specimens and a reference CFRP laminate, were manufactured for both mechanical tests. A set of five specimens per test was manufactured for each material.

Tensile test specimens were manufactured for testing according to ASTM standard D3039/D3039M [8] in an alternating layup of ten pre-preg plies and nine PET plies. The manufactured plates were cut to 25x250 mm pieces and fitted with grip tabs according to the standard. The thickness varied depending on the thickness of the PET-film used.

ILSS test specimens were manufactured, for testing according to ASTM standard D2344/2344M [9]. The laminates were manufactured from 20 pre-preg plies, 10 on each side of a single PET ply for testing the shear strength of the PET/epoxy bond. All specimens were cut according to the standard. However, the reference needed larger specimens to break in shear. Average dimension of the specimens are listed in table 1.

Dielectric	Thickness [mm]	Length [mm]	Width [mm]
50 µm	5.8	34.0	11.5
50 µm PT	5.7	33.3	11.3
75 µm	5.7	33.2	11.1
75 µm PT	5.8	34.0	11.4
125 µm	5.8	34.1	11.4
125 µm PT	5.8	33.6	11.4
Ref.	5.8	39.9	12.2

Table 1. ILSS specimen average dimensions

2.3 Experimental characterisation

2.3.1 Capacitance and tanδ

To characterise the structural capacitor materials the capacitance was measured by sweeping through 0.1-1000Hz at 1 and 10V while capacitance and tanδ was recorded. The equipment used was a General Electric Programma IDA200 with Keithley 8009 electrode fixtures.

2.3.2 Dielectric breakdown voltage

Dielectric breakdown voltage (dielectric strength), of the capacitors was measured using the ASTM D3755 standard for direct current measurement of dielectric breakdown [10], as suggested by Baechle et al. [11]. Voltage was applied with a rate of 500V/s according to the standard instead of 100V/s as done by Baechle and co-workers [11]. The specimens were submerged in mineral oil to avoid any edge effects that may disturb the measurements. The test was stopped when breakdown was apparent by the voltage over the capacitor sharply dropping to zero. Equipment used was an AC transformer with a half wave rectifier. The sample voltage was measured with a resistive voltage divider connected to a DAQ-card on a stationary computer.

2.3.3 Tensile testing

Two types of mechanical testing were performed. The first was tensile testing to characterise the tensile properties of the structural capacitor materials. Output from the test was Young´s modulus and ultimate tensile strength of the laminates. The tests were performed at room temperature according to the ASTM standard D3039/D3039 M [8]. The equipment used was an INSTRON 8501/H0162 with a 100kN load cell (INSTRON 2518-111). A constant crosshead speed of 2mm/min was used and strain was measured with a 25mm gauge length extensometer.

2.3.4 Interlaminar shear strength

Interlaminar shear strength (ILSS) of the structural capacitor configurations was also measured to expose any negative or positive effects of the dielectric, at mid-thickness, on the mechanical performance of the composite.

The interlaminar shear strength was evaluated at room temperature using the short beam three-point bending test according to the ASTM D2344/D2344 M standard [9]. The equipment used was a MTS 20/M with a 10kN load cell. A constant crosshead speed of 1mm/min was used.

It is well known that the short beam three-point bend test does not provide very accurate ILSS values due non-uniformity of the stress field [12]. However, the test is useful to monitor difference in interlaminar shear strength between materials and therefore provides a useful tool for assessment of the relative performance of the individual structural capacitor materials developed in the current study. The method is selected in this study since it is a robust and easily performed test.

2.4 Specific energy

Evaluation of specific energy allows comparison between the different capacitor devices. Use of thin film dielectric separators usually results in capacitors with high capacitance but low breakdown voltage [11]. The specific energy is given by

$$\overline{\Gamma}_{sc} = \frac{\frac{1}{2}CV^2}{m_{sc}}, \tag{1}$$

where $\overline{\Gamma}_{sc}$ is the specific energy of the structural capacitor, C the capacitance, V the voltage at dielectric breakdown and m_{sc} the mass of the structural capacitor. It should be pointed out that the specific energy of a single dielectric layer capacitor, like the ones assessed here, will be lower than that of a conventional multilayer capacitor. This is due to the more effective use of electrodes in a multilayer capacitor. A single layer capacitor has two electrodes and one dielectric layer. Generally, an n-layer capacitor will have n+1 electrodes and n dielectric layers. Here the specific energy will be used to evaluate the multifunctional efficiency of the structural capacitor configurations.

3 Results and discussion

3.1 Electrical properties

Dielectric	Capacitance* [nF/m^2]	tanδ*	Dielectric strength [kV]	Specific energy [J/g]
PET-film 50µm	447±3.8	0.002±0.0007	14.6±2.3	0.06±0.02
PET-film 50µm PT	442±2.6	0.002±0.0007	15.4±1.7	0.06±0.01
PET-film 75µm	300±2.6	0.002±0.0005	22.4±3.6	0.08±0.03
PET-film 75µm PT	300±4.5	0.002±0.0005	20.8±1.8	0.07±0.01
PET-film 125µm	193±4.6	0.003±0.002	29.4±4.1	0.09±0.02
PET-film 125µm PT	195±1.6	0.001±0.0001	29.8±4.8	0.09±0.03

* @ 1V and 0.1Hz

Table 2. Summary of electrical properties for various structural capacitors

The results from the capacitance and dielectric strength experiments are presented in Table 2. The results are measured average capacitance, tanδ, dielectric strength and calculated specific energies with standard deviations, for respective dielectric. The difference in capacitance and tanδ for measurements at 1 and 10V was negligible. Therefore only values for 1V are presented. Also, in an automotive application the frequency of charging/discharging will most likely be low. Hence the results achieved at 0.1Hz are presented.

3.1.1 Capacitance and tanδ

As expected the capacitance is highest for the thinnest dielectric, 50µm, and decreases with an increase in separator thickness. All results for capacitance are consistent, only small scatter in data indicating a stable electric response from the manufactured materials. Also, the measured tanδ for the materials is small showing that there are only minor electrical losses in the capacitors. This is a good result showing that the carbon fibre weaves works acceptable as electrodes. The losses are most likely a result of the resistivity of the carbon fibres.

An important result is that there is no significant difference in capacitance nor tanδ for as received and plasma treated films. This supports the assumption made in previous studies [4-6] that plasma treatment does not affect the dielectric properties of the film.

The theoretical areal capacitance for a flat plate capacitor can be calculated according to

$$C = \frac{\varepsilon_r \varepsilon_0}{d}, \qquad (2)$$

where ε_0 is the electric constant approximately equal to $8.86 * 10^{-12}$ Fm^{-1} [13], ε_r the separator dielectric constant and d the separator thickness.

Using a dielectric constant, ε_r, of 3.3 for the PET-films [14] one will find that the theoretical capacitance, calculated using eq. 2, is 584, 390 and 234 nF/m^2 for 50, 75 and 125μm film thicknesses respectively. Comparing these results to the values measured for the structural capacitor materials one will find that the measured vales are approximately 80% of the theoretical for respective film thickness.

In previous studies [4-6], capacitance values higher than the theoretical was presented. 1860 nF/m^2 was measured compared to the theoretical 1460 nF/m^2 for a 20 μm PET-film. One reason for the lower experimental than theoretical capacitance values found in this study may be that the thicker films do not follow the wavy shape of the carbon fibre weaves making less use of the electrode area available and therefore results in lower capacitance. There is also a difference in the test method chosen, in this study all measurements was done dynamically compared to the static approach employed in previous studies [4-6].

3.1.2 Dielectric strength and specific energy

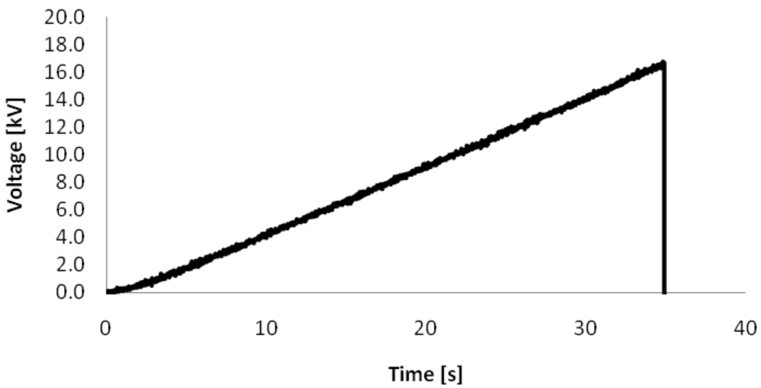


Figure 3. Voltage history of a typical dielectric strength test.

The voltage history for a typical dielectric strength test series is depicted in Figure 3. Note the absence of clearing, reported previously in tests on structural capacitors employing structural dielectric separators [11]. This result is consistent with observations in previous studies [5, 6]. Results from the dielectric breakdown voltage measurements are presented in Table 2.

As expected, structural capacitors with the thickest separator exhibit the highest breakdown voltage. However, considering the breakdown voltage divided by the separator thickness the thickest film presents the lowest breakdown strength per mm. This is also expected as a larger volume of material has a higher probability of flaws.

No adverse effects from the plasma treatment could be concluded from the tests. The small variations are most likely normal variations within a set of specimens.

The average capacitance, average breakdown voltage and average weight were used to calculate the specific energy according to Equation (1). The calculated specific energies are presented in Table 2.

The highest value of specific energy is 0.09J/g for the 125mm thick PET-film. Hence, the lower capacitance of the thicker film capacitors is compensated for by a higher breakdown voltage. The value is however lower than the 0.28J/g reported for structural dielectric separator capacitors developed by O'Brien et al. [11].

3.2 Mechanical properties

Dielectric	E [GPa]	σ_{ult} [MPa]	ILSS [MPa]
PET-film 50µm	42.7±3.0	354±66	29.5±1.3
PET-film 50µm PT	42.5±2.1	320±47	32.0±1.1
PET-film 75µm	44.6±0.8	377±15	30.6±1.7
PET-film 75µm PT	41.7±5.2	344±35	30.7±2.0
PET-film 125µm	36.5±1.9	317±36	32.5±1.4
PET-film 125µm PT	37.8±4.3	339±35	31.8±1.1
CFRP Ref.	56.1±1.7	631±73	54.4±1.5

Table 3. Summary of mechanical properties for various structural capacitors and the CFRP reference

The results from the tensile and ILSS tests are presented in Table 3. The results are measured Young's modulus (E), ultimate tensile strength (σ_{ult}) and interlaminar shear strength with standard deviations, for respective dielectric and the CFRP reference.

3.3 Tensile properties

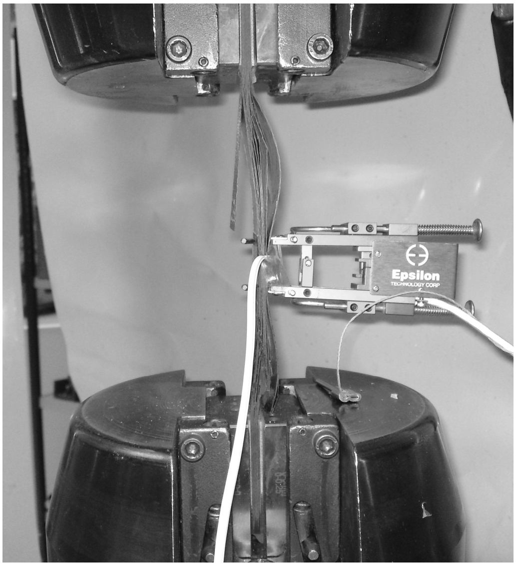


Figure 4. Typical failure of a tensile specimen

Typical features of a failed tensile specimen are depicted in Figure 4. As seen in the picture a significant amount of delamination has occurred at the polymer film/epoxy interfaces. This failure characteristic was evident in all structural capacitor materials, including the plasma treated ones.

Young's modulus was calculated between 0.05-0.15% strain, and not between 0.1-0.3% strain as recommended in the ASTM standard [8]. This was due to the failure onset beyond 0.2% strain.

Considering the values of stiffness, there is a knockdown of approximately 15GPa regardless of film thickness. A small knockdown is expected from the interleaving of the CFRP with a less stiff material (PET). All structural capacitor materials show stiffness around 40GPa.

Considering the ultimate tensile strength, there is a significant knockdown in the strength of the material compared to the CFRP reference. This is most likely a result of the delamination behaviour triggered in the structure capacitor materials.

The delamination behaviour is not found in the CFRP reference. The reference specimens break at an approximate 90^{o} angle to the loading direction, featuring a flat fracture surface. Furthermore, a subsequent secondary fracture surface, most likely a compressive failure, is found in all CFRP reference specimens.

3.4 ILSS

As seen in table 3 all capacitor material specimens show significantly lower ILSS values then the reference. Note the effect of plasma treatment which is more evident for the thinnest film where an increase of 1.5MPa is achieved whereas for the thickest film a decrease of 0.7MPa is found. The difference in performance between the as received PET-film and the plasma treated PET-film is small and considering the extra step in manufacturing the reward is low or non-existing.

The capacitor material specimens are not easily separated at the interface after failure. Additional examination of the specimens is needed to clarify if the failure is at the interface between epoxy and PET-film or if it is a shear failure in the PET-film. The small differences in failure stress across all structural capacitor materials could be an indication of this.

3.5 Multifunctional performance

Multifunctional performance is evaluated by assessment of measured specific energy vs. specific stiffness, specific strength and specific interlaminar shear strength.

Employing specific energy as the parameter to assess multifunctional performance allows us to compare the different structural capacitor designs for their applicability in a structural system, where energy needs to be stored, with respect to their potential to reduce system weight. Consequently, this approach allows us to evaluate the structural capacitors influence on system weight, as described by O'Brien et al. [11]. This is important as even though the multifunctional element exhibits specific energy and strength and/or stiffness that usually are lower than those of the best monofunctional materials, at a system level the multifunctional material may still enable an overall mass saving. In the paper by O'Brien et al. [11] a procedure to evaluate multifunctional capacitor designs, following an approach suggested by Wetzel [15] is presented. O'Brien and co-workers [11] define a total system mass M equal to the sum of the mass of the capacitors m_c and the mass of the structure m_s. The design metric for capacitor performance is specific energy $\overline{\Gamma}$ (in J/kg) with overall system energy storage defined as $\Gamma = \overline{\Gamma} m_c$. Similarly, the mechanical performance, e.g.

specific modulus or ILSS (J/kg), can be defined as $\overline{E}$ and $\overline{\tau}$. From these, the energy density and specific mechanical properties of the structural capacitors can be found as $\sigma^e\overline{\Gamma}$, $\sigma^s\overline{E}$ and $\sigma^s\overline{\tau}$. σ^e and σ^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

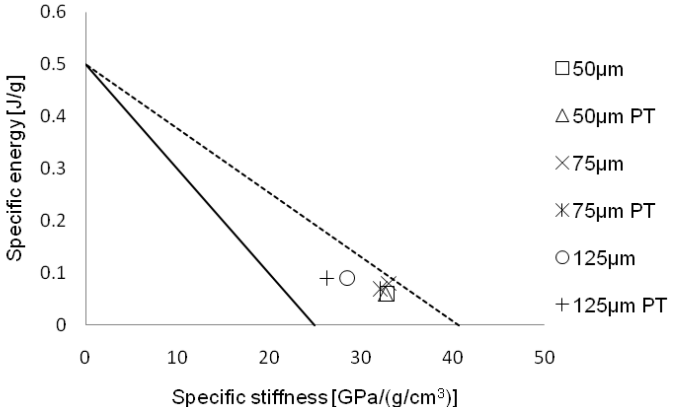
$$\sigma^{mf} \equiv \sigma^e + \sigma^s > 1. \quad (3)$$

Multifunctional performance is depicted in Figures 5a, b and c. In the Figures, two lines are plotted, representing Equation (3) with a multifunctional efficiency, σ^{mf}, equal to one for two scenarios. The dashed line represents a target scenario where specific energy for a state of the art capacitor material set to 0.5J/g as reported in the literature as a maximum value for a electric field energy storage devise (aluminium electrolytic capacitor) [16] (1J/g, was used by O'Brien and co-workers [11]) and specific mechanical properties are set to those of the tested CFRP reference material. The solid line in figure 5a and 5b represents a second scenario where the specific energy is the same but the mechanical properties are the maximum values found for steel, which is a likely candidate material to be replaced by the multifunctional material. Values chosen are specific stiffness 25GPa/(g/cm^3) [17], and specific strength 150MPa/(g/cm^3) [16]. ILSS is not applicable for steel and hence there is no solid line in Figure 5 c.

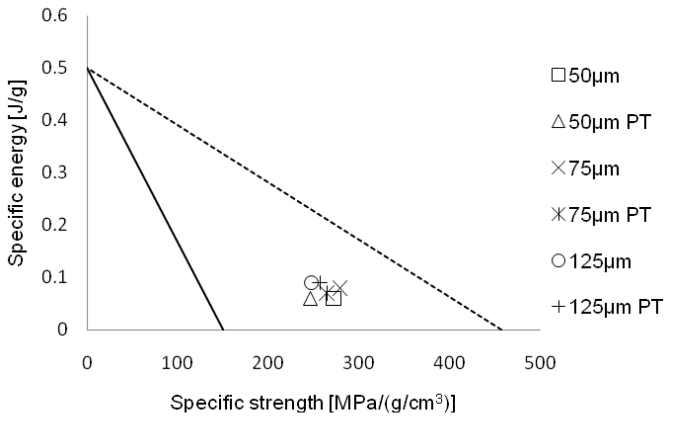
In Figure 5a specific energy is plotted as function of specific stiffness. As seen in the figure, none of the manufactured materials are to the right of the dashed line. Hence, none of the manufactured materials will meet or exceed the target. However, all materials are to the right of the solid line meaning that compared to steel the multifunctional material would provide a weight saving. Comparing these results to those reported in previous studies [5, 6] it is obvious that the overall performance of the new materials are worse than those found the previous studies. However, it must be noted that the stiffness and density in previous studies [5, 6] were calculated while measured in the current study.

In figure 5b specific energy is plotted as a function of specific strength. As for stiffness the manufactured multifunctional materials will not meet the target values but will provide a weight saving when compared to steel.

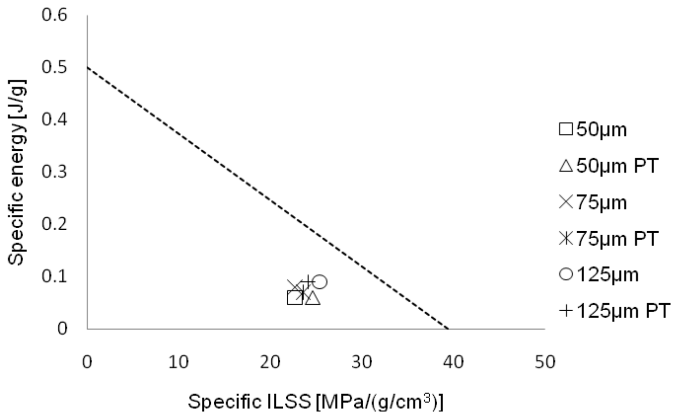
In figure 5c specific energy is plotted as a function of specific ILSS. And as for the other mechanical properties the multifunctional materials are below the targeted line. Since ILSS is not applicable on steel there is no solid line. Comparing these results with those found in previous studies [5, 6] it is apparent that the performance of the current and old materials is of the same magnitude. The main reason that the new materials falls under the dotted line is the much improved performance of the reference material in this study compared to that found in previous studies [5, 6]. One reason for this could be an improved manufacturing procedure and more experienced personnel in this study.



a)



b)



c)

Figure 5. a) Specific energy versus specific stiffness for the structural capacitors b) Specific energy versus specific strength for the structural capacitors c) Specific energy versus specific ILSS for the structural capacitors

4 Conclusions

A number of multifunctional materials have been successfully manufactured. However, none of them provides a solution that meets the target. The main reason for this is the loss in mechanical performance which needs to be addressed in order to make an efficient multifunctional material. Further work with a fractographic examination of the failed tensile and ILSS specimen will hopefully give a greater understanding of what needs to be altered in order to improve the mechanical performance.

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 5a and 5b

On electrical performance there might be some improvements to be done in the selection of separator film. Finding films with higher dielectric constant and high dielectric strength will give better electrical performance.

Another route to achieve higher capacitance could be to manufacture polymer films with fillers that raise the dielectric constant.

The fastest way to improve the capacitance would be to use thinner films, with the drawback of lower breakdown voltage. However, many applications will not need an upper limit as high as 15-30kV, and there is the possibility to adjust the film thickness to suit the maximum voltage required in the application and get higher capacitance.

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