The Influence of Graphene Oxide on the electrical conduction in unidirectional CFRP laminates for wind turbine blade applications

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Abstract

The incorporation of composite CFRP in wind turbine blades to allow for longer and lighter blades challenges the efficiency of their lightning protection system. The electrical anisotropy of CFRP materials is a key factor and affects their performance. The present study investigates the influence of adding Graphene Oxide (GO) nanoinclusions to CFRP as a means to improve their electrical conductivity in the transverse and through-thickness directions. Epoxy resin containing GO in filler contents of 5wt% and 6wt% was prepared and infused in unidirectional (UD) laminates. The GO nanofiller was dispersed in the epoxy resin prior to the infusion by means of speed mixing. The sample morphology was examined by optical microscopy. DC electrical resistance measurements were conducted in the transverse and through-thickness directions to quantify the influence of the nanofiller. For both filler volume contents an increase was observed for both the transverse and through-thickness directions compared to the neat CFRP.

1 Introduction

Carbon Fibre Reinforced Polymer (CFRP) composites have become one of the most valuable type of materials in the aircraft/aerospace and automotive industry as well as for many load carrying applications. Their excellent mechanical properties including strength, stiffness and fatigue resistance relative to their weight has made them favourable compared to traditional metallic engineering materials such as steel and aluminium. Despite their attractive properties CFRPs are not yet widely used in wind turbines, mainly due to their relatively high costs. Only recently wind turbine blade manufacturers have started incorporating CFRP materials into the main load carrying spars or sparcaps [1, 2]. The addition of CFRPs in wind turbine blades allows for longer and lighter blades compared to Glass Fibre Reinforced Polymer (GFRP), thus reducing the blade mass as well as the cost due to reduced gravity and inertia loads [3]. As the blades become longer the overall height of the wind turbine can reach up to 230m (current designs) or more. The exposure to lightning strike of such structures increases non-linear to their height, and with the addition of a semiconducting materials such as CFRP the lightning protection systems face new challenges. The higher electrical and thermal conductivity exhibited by these materials compared to insulating GFRP introduces new issues for their lightning protection system. During the lightning incident internal flashovers between the down conductor and the CFRP structure may occur, at high peak currents and current gradients, causing instant structural damages or extended delamination during continued operation [4]. To avoid these phenomena several equipotential bonding points have to be realized along the length of the blade. The electrical anisotropy that characterizes CFRPs can play a key role in the damage that occurs in these bonding points since the electrical conductivity varies up to 5 orders of magnitude in the three main directions for unidirectional laminates. The lower electrical conductivity in the transverse and through-thickness directions are responsible for local heat release and associated delaminations in the equipotential bonding areas that can degrade the integrity of the blade spar and potentially lead to major structural damage over time. Effective ways to evenly distribute current at the CFRP bonding points is a major research area and several approaches have been developed over the years, using conducting paints, copper foils etc. [5-7] Unlike aerospace application where repairs can be made, in wind turbines blades the service intervals are significantly longer and repairs in the internal structure of the blade are virtually impossible. A viable solution for such applications is to alter the material properties by increasing the conductivity, as a permanent part of the lightning protection design. This can be achieved by increasing the electrical conductivity in the transverse and through-thickness directions (normal to the fibres). The mitigation of the electrical anisotropy in CFRP materials has been the subject of scientific interest for several since they are increasingly in demand as structural materials in aerospace and automotive applications [8-10]. One of the most promising strategies is the incorporation of conductive nanoinclusions. Several studies have been conducted in which both carbon based inclusions (CNTs, Graphene, GNPs etc.) and metallic nanoparticles or nanostructures (Silver nanoparticles and nanowires) have been added to the polymer matrix [11, 12]. It has been observed that fillers with high aspect ratios are more suitable since they allow the formation of direct paths between the fibres allowing easier current flow [8]. Graphene Oxide

(GO) is a promising candidate for this type of application because of its high aspect ratio, high electrical conductivity as well as ease of processing and compatibility with several polymers. The focus of this study is to investigate the influence of the incorporation of conductive GO nanoparticles on the electrical conductivity in the transverse and through-thickness directions of CFRP used in wind turbine applications.

2 Experimental methodology

2.1 Materials

A two-component epoxy system supplied by BASF was used as matrix material. The system was consisting of the Baxxores® ER 5300 epoxy resin and the Baxxodur® EC 5310 curing agent. The components were mixed by weight at a ratio of 100/20 according to the specifications of the manufacturer. The Graphene Oxide (GO) (edge-oxidized) was provided by Garmor Inc, USA, consisting of approximately 10 graphene layers and a nominal particle size diameter of 500nm. Finally a unidirectional non-crimp carbon fabric supplied by SAERTEX GmbH & Co, Germany, with Zoltek Panex 35 50K carbon fibres and an areal weight of 882g/m^2 was used as reinforcement.

2.2 Preparation of GO/modified CFRP

The dispersion of GO into the epoxy was achieved by means of high speed mixing, Speedmixer™ DAC 150.1 FV. This approach introduces high shear forces in the mixture, reducing the formation of agglomerates and achieving homogenous mixtures. GO/epoxy nanocomposite mixtures were prepared in filler contents of 5wt% and 6wt%. GO nanoparticles were added in the epoxy in the respective quantities followed by high speed mixing for 10 min at ambient temperature. After the mixing the curing agent was added and the mixture was hand stirred for 5 min followed by degassing at ambient temperature for 10 min. The preparation of the GO/modified CFRP was achieved by means of Vacuum Assisted Liquid Resin Infusion (VALRI) since this is one of the predominant manufacturing routes for wind turbine spars. Five layers of dry carbon fabric were stacked in a steel plate. Because of the areal weight of the fabric, flow media was placed in both sides of the fabric stack, mold and upper side, to facilitate the resin flow. After the infusion process the laminates were cured for 6h at 70ºC. No significant influence in the viscosity was observed after the mixing and during the infusion.

2.3 Sample morphology

Optical microscopy, using an Olympus BX51 microscope, was utilised to verify the fibre volume content of the manufactured laminates. Samples were cut from the CFRP plates and polished with Silicon Carbide abrasive papers (400, 800, 1200 and 4000) to obtain micrographs. The fibre volume fraction was found to be approx. 57%. Significant differences were observed between the neat and the GO/modified samples during the observations in the transverse direction. From Figure 1 it is seen that GO particles are grafted on the surface of the fibres compared to the neat CFRP, Figure 2. This behaviour is sign of high filler loading and it is expected to have an influence at the electrical conduction properties.

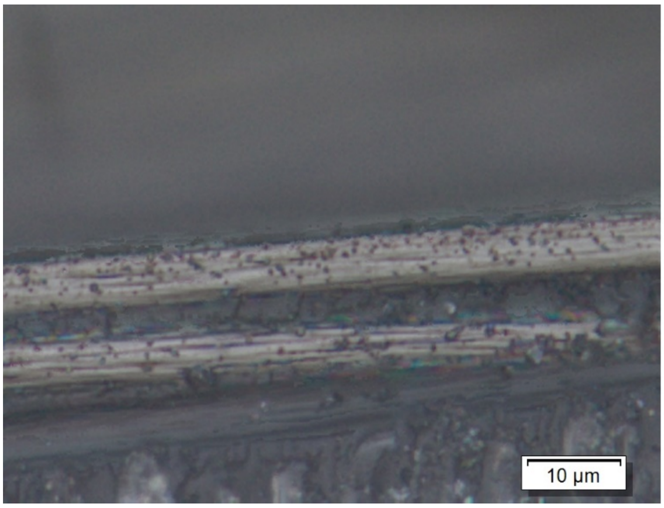

Figure 1: GO modified CFRP morphology

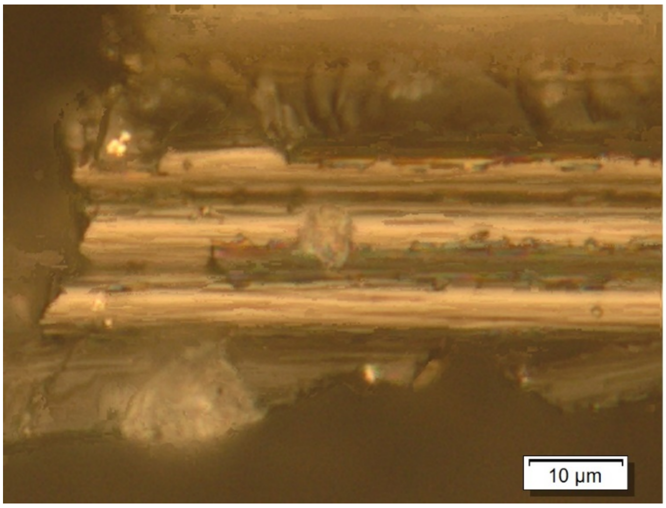

Figure 2: Neat CFRP morphology

2.4 DC resistance measurements

Measurements of the DC resistance in the transverse direction were conducted with the use of a two-probe method in rectangular strips that were cut from the manufactured CFRP plates. A test cell featuring a screw actuator was utilised to provide consistency over the measurements by applying a constant pressure at the electrical contact. Measurements in the through-thickness direction were realised in disk shaped specimens with a diameter of 50 mm which were placed between disk shaped electrodes. The upper electrode was utilising a guard ring to prevent surface resistance interferences. All of the measurements were carried out with the TTi BS-407 Ohmmeter. To obtain accurate resistance values the sample surfaces were sanded to remove excess insulating polymer layers. Both for the transverse and through-thickness directions the same protocol was used for preparing the electrical contact points. A similar process as used for polishing the samples for optical microscopy was used, i.e. Silicon Carbide abrasive papers (800 and 1200 grit) were employed. A silver containing epoxy based adhesive was then applied at the intended electrical contact areas to mitigate any issues related with surface roughness and to provide ohmic contact across the contact area. All of the experiments were carried out at ambient temperature and 55% RH.

Figure 3: Experimental setup for transverse direction measurements.

3 Results

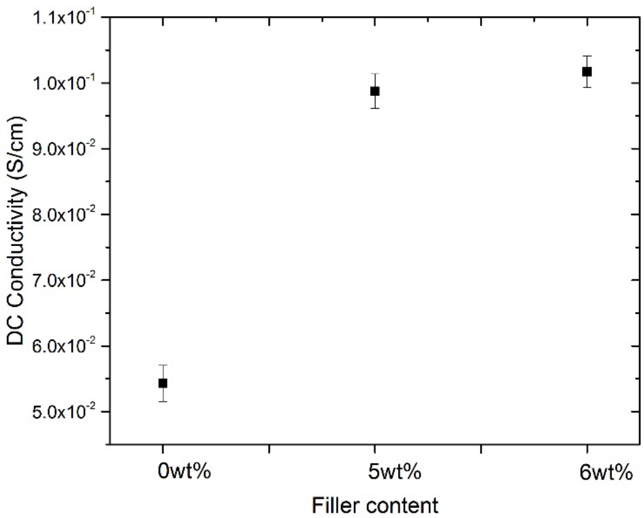

Figure 4: Through-thickness electrical conductivity versus filler content.

Figure 4 depicts the calculated through-thickness DC electrical conductivity for the neat CFRP as well as the GO/modified CFRPs with 5wt% and 6wt% filler content respectively. From the plot it is seen that a sharp increase in the conductivity occurs for both the GO modified samples compared to the neat CFRP. By comparing the values for the two GO/modified samples it can be observed that the increase of the 6wt% sample is negligible compared to the 5wt% sample, Table 1.

Sample	**Neat**	**5wt%**	**6wt%**
Conductivity (S/cm)	$5.43*10^{-2}$	$9.87*10^{-2}$	$1.01*10^{-1}$

Table 1: Through-thickness direction conductivity

For the 6wt% sample the conductivity increases up to the point a change in the order of magnitude occurs.
The influence of GO in the transverse direction conductivity is depicted in Figure 5. The measured values obtained for the nanomodified samples appear to be slightly increased compared to the neat CFRP. The increase for the 5wt% sample is higher compared to 6wt% as it is reported in Table 2.

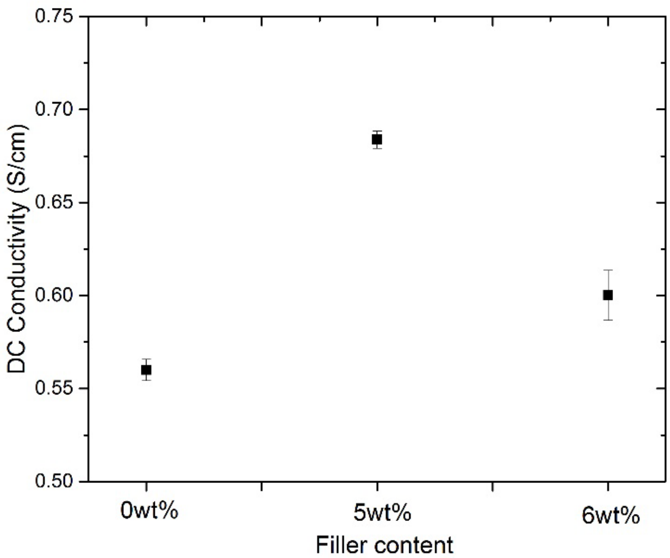

Figure 5: Transverse electrical conductivity versus filler content.

Sample	**Neat**	**5wt%**	**6wt%**
Conductivity (S/cm)	$5.6*10^{-1}$	$6.83*10^{-1}$	$6.01*10^{-1}$

Table 2: Transverse direction conductivity.

4 Discussion

Compared to the majority of the studies incorporating a type of conductive filler, a different manufacturing process was followed [8, 10]. A vacuum infusion process was utilised to produce samples with higher fibre volume fraction compared to hand layup methods. No significant alteration of the viscosity was observed during the infusion process and the method appears to be effective for the manufacturing of high quality nano-reinforced CFRPs. The addition of conductive GO particles in the epoxy used for infusion CFRP appear to increase the conductivity both in the through-thickness and transverse directions. The influence of nanoparticles seem to be more noticeable in through-thickness direction, Figure 5. The existence of resin rich layers in between the carbon fibre reinforced layers/laminae is a key reason why the conductivity

in this direction is lower compared to the transverse direction. The use of conductive fillers with high aspect ratios such as GO allows the formation of physical conducting paths, when the filler volume content is high, in the interlaminar region allowing current flow through the insulating polymer matrix, Figure 6a.
During the characterization of the morphology of the samples it was observed that GO particles were grafted on the surface of the fibres enabling the formation of a path between the fibres and the particles dispersed in the resin. This conducting mechanism (described above) is assessed to be responsible for the sharp increase in the through-thickness conductivity.

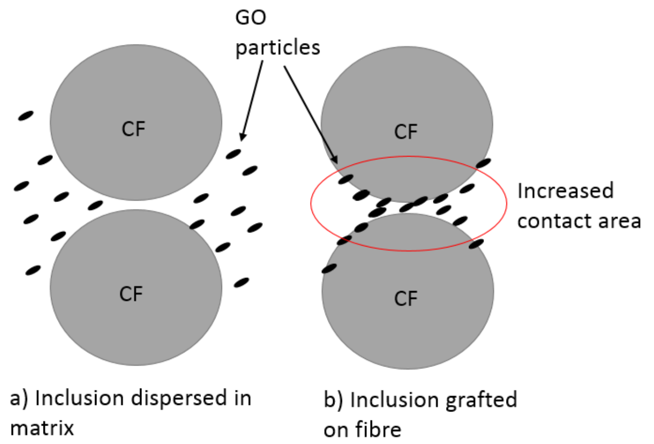

Figure 6: Nano-inclusion incorporation concepts.

Although a slight increase was observed in the transverse conductivity, Figure 5, it was not as pronounced as observed in the through-thickness conductivity, since fibre to fibre contact points is the predominant conduction mechanism in this direction. It is hypothetised that an increase of conductivity in this direction may occur if the conductive inclusion was to be grafted directly on the surface of the fibres, thus providing increased contact area between fibres, Figure 6b. This will enable the current flow between fibres in more areas compared to the existing fibre to fibre contact points.

5 Conclusions

A novel method for incorporating conductive GO nanoparticles in CFRP is presented. The manufacturing procedure was not affected by the addition of nanoparticles allowing for this method to be utilised in large scale production. The mitigation of the electrical anisotropy on CFRP with the controlled implementation of conductive nanoinclusions have the potential for wind turbine and aerospace lightning protection applications. An increase of conductivity at relatively low filler loadings was observed both in the transverse and through-thickness directions. Further research should be conducted in higher filler contents to determine the effects both in the manufacturing procedure as well as the conductivity in both directions.

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