Piezoelectric fibres integrated into structural composites.

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Abstract

This paper describes the manufacture of structural composites incorporating piezoelectric fibres which are finding interest in applications such as shape-changing applications, sensors to detect mechanical strain or vibration and energy harvesting. In this paper preliminary results are presented for a simple cantilever structure consisting of piezoelectric fibres with planar electrodes that are co-cured within a carbon fibre reinforced plastic (CFRP). Processing methods to embed functional fibres are described along with characterization of the piezoelectric and mechanical properties of the resulting material.

Keywords: Composite; Ferroelectric; Harvesting, Piezoelectric

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1. INTRODUCTION

The integration of piezoelectric materials into structural materials, such as reinforced composites, has attracted interest for applications such as sensing of vibration/impact, vibration control, shape-changing structures and energy harvesting [1-4]. These ‘adaptive’ or ‘smart’ structures are often initially fabricated using conventional composite processing routes and the piezoelectric device is subsequently bonded to the external surface of the structure [5-7]. The majority of past research has used commercially available piezoelectric modules, in particular the Macro Fibre Composite (MFC) developed by NASA Langley Research Center by Wilkie et al. [8]. The MFC consists of interdigitated electrodes (IDEs) to align the polarization direction along the length of the piezoelectric fibre so that the device operates in d_{33} mode and exhibits a high strain. Piezoceramic modules that are specifically designed for use with thermoplastic matrices are also being developed [1, 9]. It is advantageous to integrate the piezoelectric material into the body of the composite since it can protect the piezoelectric from the environment, provide more appropriate routes for the connection of the necessary electrical connections to the piezoelectric and enhance the design space for smart structures. This paper therefore presents initial results of methods employed to embed and co-cure polarized piezoelectric fibres in CFRP for potential applications such as sensing, actuation and harvesting.

2. EXPERIMENTAL

The piezoelectric and ferroelectric material used in this study was lead zirconate titanate (PZT) in the form of 250μm diameter fibres from Smart Material Corporation [10]. Fibres based on both PZT-5H and PZT-5A materials are commercially available and PZT-5A was chosen for this work. Although the 'softer' PZT-5H exhibits higher piezoelectric d_{ij} coefficients (strain per unit field) it has a lower Curie temperature (215°C) than PZT-5A (335°C) which makes it more susceptible to thermal depolarisation during the high temperature cure of the CFRP (~180°C). Previous research [12] has shown that the d_{ij} constants for PZT-5A increased when heated to 250°C, while PZT-5H no longer exhibited any measurable resonances above 170°C, thereby indicating that the PZT-5H had thermally de-polarised.

In order to construct a polarized piezoelectric device to embed into the CFRP the individual PZT-5A fibres were initially trimmed to the required length and aligned unidirectionally. The fibre ends were then bond together with a cyanoacrylate based adhesive to prevent movement during matrix impregnation to form a piezofibre-resin composite for embedding into the CFRP. To create the electrodes to polarise the fibres, apply electric fields for actuation and to extract charge for sensing/harvesting, aluminium foil was cut from the bulk sheet and placed on the upper and lower sides of the fibres to form planar electrodes. In this electrode configuration the polarization direction in through the thickness of the fibres so that the device in operating in d_{31} mode (see Figures 1 and 2). Such a configuration was chosen since it has the advantages of (i) a simple electrode structure, (ii) as the electrode spacing is the piezo-fibre diameter (250μm) a high electric field can be achieved at a relatively low voltage (MFC devices have a larger 1mm inter-digitated electrode spacing), (iii) this simple configuration is preferable in energy harvesting since it has a high source capacitance compared to an IDE configuration. The high capacitance (C) of the device leads to a low impedance ($Z=1/i\omega C$) [12] and also requires lower load resistances for impedance matching ($R_{load}=1/\omega C$) [13]; in addition a high capacitance can lead to lower, and easier to utilize, open circuit voltages (V) [14] as a result of the piezoelectric charge (Q), since $Q=CV$.

The resin matrix for the piezofibre-epoxy device must be able to withstand the peak temperatures of up to 180°C that would be experienced in the autoclave during curing of the CFRP pre-preg. The matrix selected based on heat treating resins was a ‘Resintech RT-323’ high temperature epoxy resin system which is formulated to operate at temperatures up to 200°C (Resintech Limited, Gloucestershire, UK). The separate components of the device (aligned and bonded fibres, resin and electrodes) were then arranged so that the fibres were contained between two electrodes and the whole device was hot pressed at 100°C for 30mins for the resin to cure. Hot pressing was employed to ensure a good contact between the fibres and electrodes since the presence of a small amount of low dielectric constant epoxy between the electrode and fibre reduces the piezoelectric and dielectric properties [15]. Copper wire was then attached to the aluminium electrodes and the PZT-fibre actuator was finally covered in Kapton film (a polyimide stable to 400°C) to electrically insulate it from the conductive CFRP host. The final dimensions of the device based on 250μm diameter fibres was a 75mm x 10mm and poling of the fibres was achieved using a voltage 400V at 120°C.

The carbon fibre reinforced composite material was a Hexcel M21/T800 pre-preg and a simple cantilever structure of 60 by 300mm was fabricated as a test structure. The cantilever structure was made by hand lay-up in a $[0/90]_T$ configuration and the piezoelectric device was embedded near the root of the CFRP cantilever during the lay-up procedure. This particular layup is bistable as it is able to 'snap' from one state to the other due to internal thermal stresses [5]; but data for a single state are reported in this paper. The whole structure was then cured in an autoclave at 180°C at a pressure of 85 psi (586 kPa).

3. RESULTS

Figure 3 shows the frequency dependent capacitance and phase angle of the piezoelectric fibre actuator embedded into the CFRP after the autoclave treatment. The capacitance gradually decreases with an increase in frequency, which is typical for PZT type materials [16]. The phase angle between voltage and current remains close the 90° indicating that the device is behaving as a capacitor and no electrical short-circuit or leakage is present although the device in embedded into a conductive CFRP. At 1kHz the device capacitance (C) is 5.5nF (Figure 3) and based on the area (A) of 75mm by 10mm and an electrode thickness (t) of 250μm (the piezofibre diameter) the medium between the electrodes has an effective relative permittivity ($\varepsilon_r = C.t/A.\varepsilon_0$) of approximately 200, where ε_0 is the permittivity of free space. The relative permittivity at constant strain (ε^s_{33}) of monolithic (dense) PZT-5A is 830, and the difference is associated with the presence of the resin matrix of lower permittivity (ε_r ~5) between the fibres (Figure 2) and small discontinuities or resin at the electrode-fibre interface [15]. To examine if the piezoelectric fibres retained their polarisation after being subjected to a high temperature autoclave cycle the cantilever was subjected to vibration using an electrodynamic shaker (LDS V455) with a signal generator via a power amplifier (Europower EP1500). On removal of the vibration, the gradual decay of the cantilever oscillation could be observed as a decrease in the voltage generated by direct piezoelectric effect of the embedded device (Figure 4). Potential applications of embedded piezoelectric devices could be sensing of vibration or impact, as examined by Sodano et al. [6] who used patches externally attached to host structures; vibration damping and energy harvesting [17] has also been considered. To examine the potential for energy harvesting applications the cantilever was subject to a small vibration level of 0.6g at a range of frequencies and the current generated dissipated across of load resistance of 70.1kΩ. Figure 5a shows the power generated as a function of frequency for the cantilever with a peak power of approximately 1μW at a frequency of 17Hz. Maximum power corresponds to the resonant frequency of the structure, as highlighted by the maximum vibration amplitude of the structure at that frequency (Figure 5b). The application of an electric field across the electrodes to induce strain by the converse piezoelectric effect resulted in actuation of the cantilever structure as shown in Figure 6. There is hysteresis in the deflection behaviour during voltage controlled operation, as observed in piezoelectric modules by Hufenbach et al. [1], which is associated with the extrinsic contribution of domains to the displacement. A tensile test of the CFRP material and CFRP with the embedded device is shown in Figure 7 where the tensile strength decreases from 1070MPa to 910MPa due to the presence of the piezoelectric. Failure was observed to initiate at the position of the piezo-fibre device and is likely to be due to the lower failure strain of the piezeoelctric fibres (~0.05%) compared to the carbon fibres (0.5%)

that it is embedded in [18]. In summary, this paper has demonstrated the feasibility of embedding PZT fibres within structural composites. By using high temperature resin matrix and PZT materials with a sufficiently high Curie temperature (in this case PZT-5A) it is possible to fabricate and polarise a high capacitance piezoelectric composite device with simple planar electrodes that can be embedded and co-cured into CFRP pre-preg for potential sensing (Figure 4), harvesting applications (Figure 5) and actuation (Figure 6).

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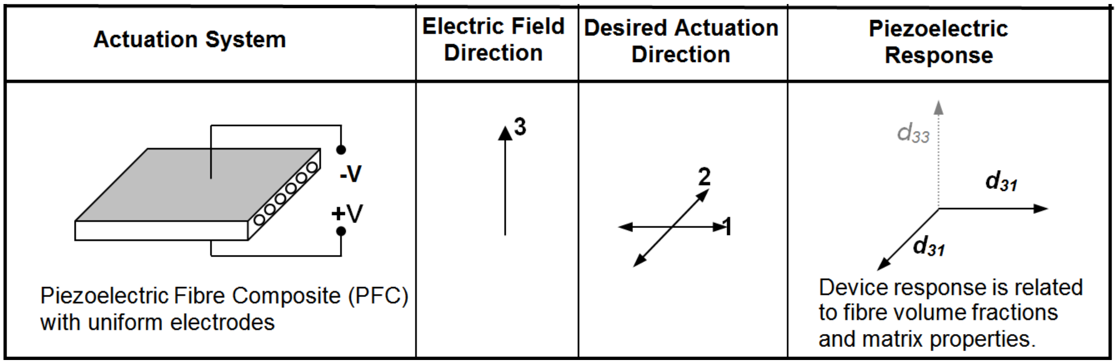


Figure 1. Electrode configuration for piezoelectric actuator.

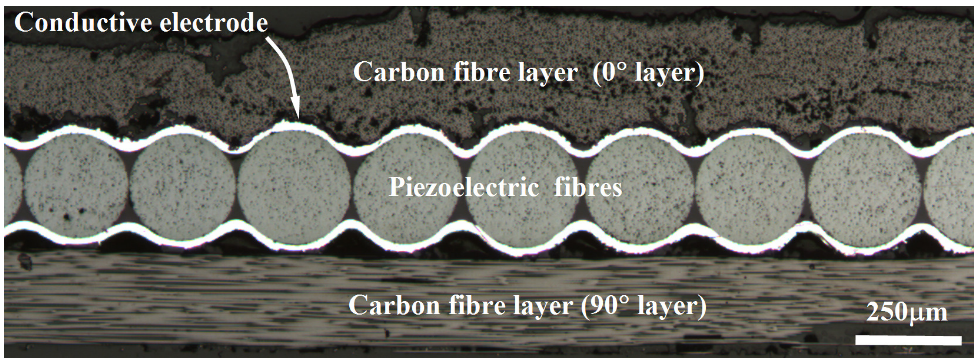


Figure 2. Optical micrographs of PZT fibres embedded into CFRP composite.

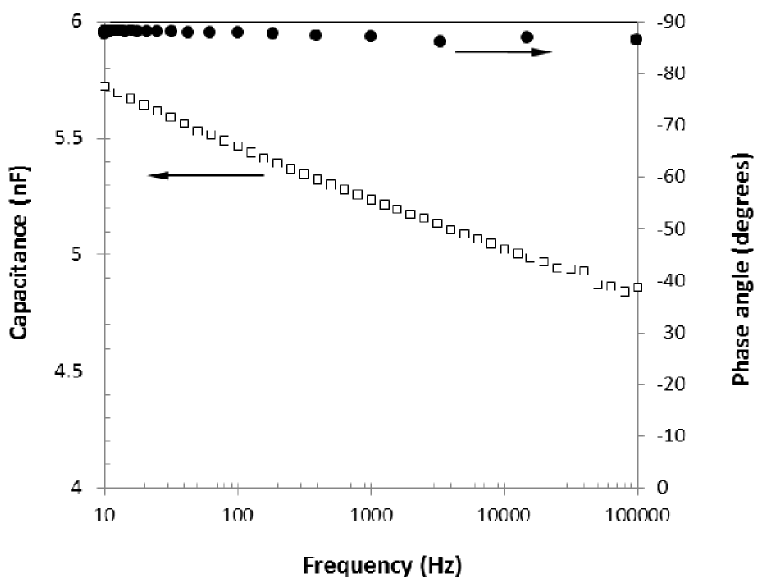


Figure 3. Capacitance and phase angle of piezoelectric device with frequency

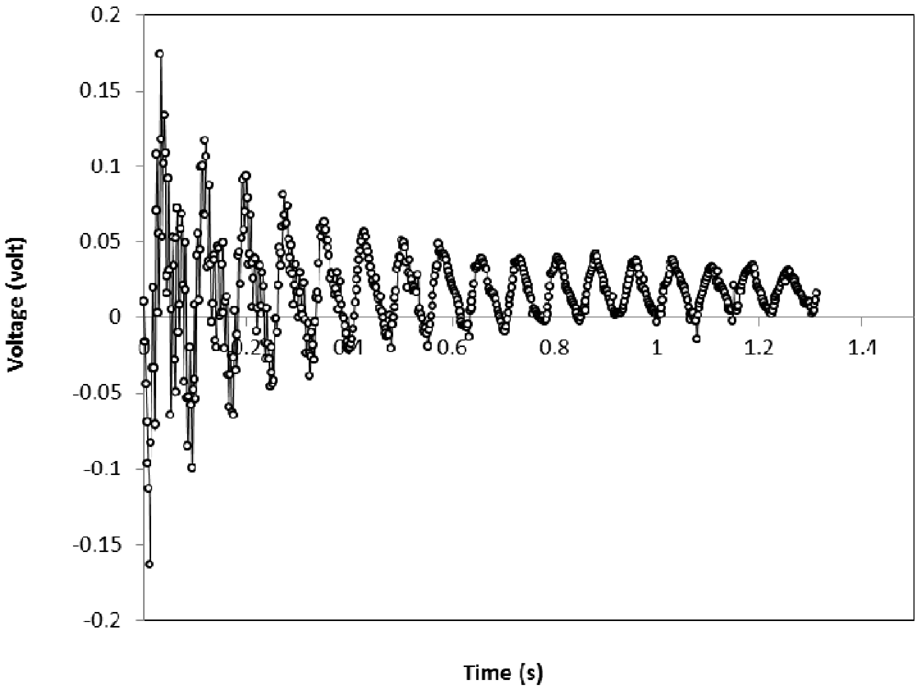
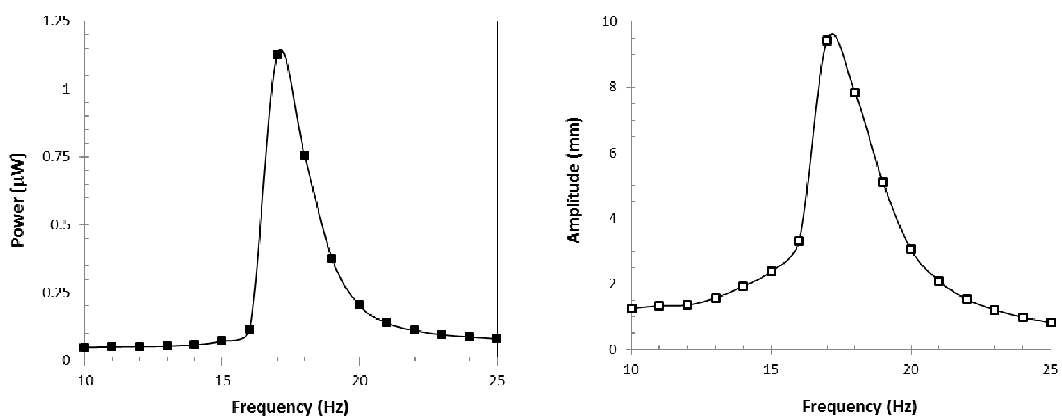


Figure 4. Sensing due to piezoelectric effect after vibration



(a) **(b)**

Figure 5. (a) Power and (b) amplitude during vibration. Load resistance is 70.1kΩ.

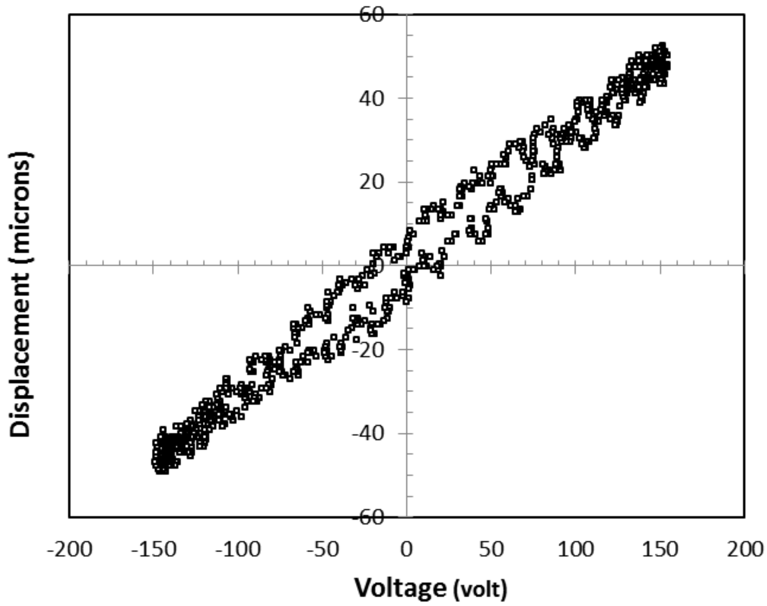


Figure 6. Displacement of CFRP due to actuation of piezoelectric fibres.

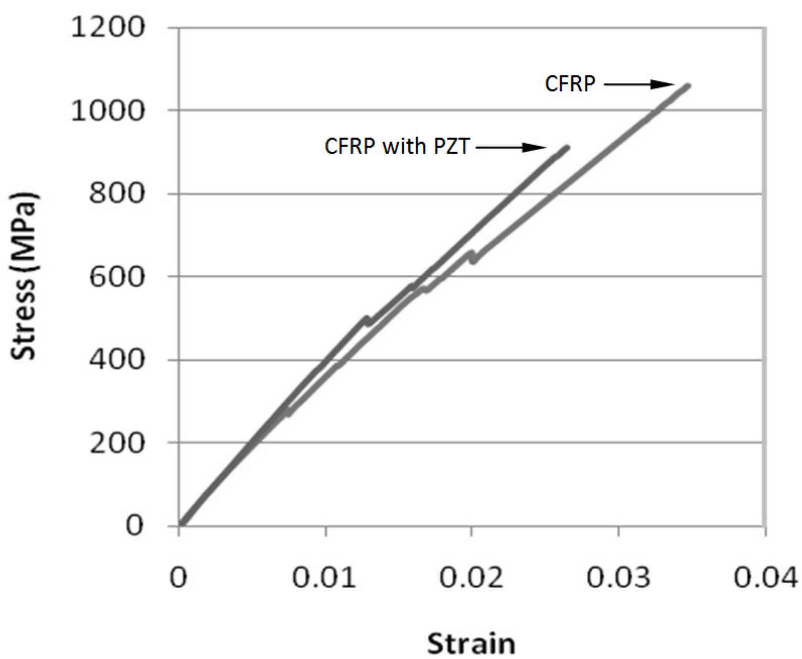


Figure 7. Mechanical properties of CFRP and CFRP with embedded PZT fibres. Strain includes machine characterstic.