

HIGH PERFORMANCE CARBON FIBRE REINFORCED POLYMER COMPOSITES WITH CONTROLLABLE STIFFNESS: CAN IT BE DONE?

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Abstract

Morphing wings have the potential to reduce drag, noise and vibration in aircraft. One of the main challenges associated with morphing wings is the development of a skin material that can be deformed with acceptable actuation forces and yet transfer aerodynamic loads. To achieve this, an interleaved carbon fibre reinforced polymer (CFRP) composite with controllable stiffness has been manufactured. The composite contain plies of polystyrene that when heated above their glass transition temperature result in a large reduction in flexural stiffness and so permits structural deformations with relatively low actuation forces. When heated to 120 °C this composite exhibited a 98% reduction in flexural stiffness from 65 GPa to 1 GPa. The process was found to be reversible as the composite could be returned to its original configuration and on cooling its flexural strength and stiffness returned to their full values with no damage observed.

1 Introduction

A morphing wing is in essence a continuous structure that can undergo a change of shape [1, 2]. There are numerous benefits associated with the use of such technology over and above those of conventional systems e.g. less drag, noise and vibration [3]. In many morphing wing designs a single skin covers a series of actuation mechanisms. An effective adaptive wing must combine a strong yet flexible skin with an actuation device that provides movement in multiple directions. The skin needs the ability to carry load but also deform quickly enough as not to hinder the performance of the aircraft [4]. Various materials such as elastomers have been suggested as potential morphing skins. Elastomers have high strain capability, elastic recovery and do not require heat to undergo large deformations. A significant problem is trying to develop an elastomer that can transfer aerodynamic loads [5-7]. One way to improve the mechanical performance of elastomers is to reinforce them. Flexible matrix composite (FMC) tubes can be embedded into an elastomer to provide actuation [8, 9]. When pressurized with a fluid they either expand or contract depending on their design, allowing the composite to deform. They therefore may be suitable for morphing skins.

A composite with controllable stiffness could prove to be a viable skin material as it would offer high stiffness and yet flexibility when required. Henry and McKnight developed a

variable stiffness composite with a polyurethane shape memory polymer (SMP) matrix [10, 11]. The SMP was heated until it softened, allowing the stiff, discontinuous elements to move, thus reducing the stiffness of the composite. It was found that the SMP had a weak recovery force and was therefore unsuitable for use as an actuator.

The concept of controllable stiffness in aluminium beams has also been studied [12-14]. Gandhi and Kang [12] developed specimens consisting of aluminium beams separated by layers of cast acrylic and polyvinyl chloride (PVC) type materials. Ultra-thin electric heating blankets were embedded into the polymer layers in order to heat them through their glass transition temperatures. The flexural moduli of the beams at room temperature were between two and four times greater than at elevated temperature.

2 The Concept

In this project we describe the production of an interleaved composite with controllable stiffness. The composite contains plies of polystyrene that can undergo large shear deformations when heated above their glass transition temperature (T_g). This allows the reinforced plies to slide relative to one another, dramatically reducing the flexural stiffness of the composite and permitting large structural deformations at low actuation forces.

3 Experimental Procedures

3.1 Polystyrene film production

5 g polystyrene pellets (ST316310, Goodfellow, UK) were arranged in a circular pattern (75 mm diameter) between four layers of polyimide release film ($250 \times 250 \text{ mm} \times 0.025 \text{ mm}$, UBE polyimide film, Upilex). A 19 cm diameter circle had been removed from the centre of the two inner films. The release films were then placed between two stainless steel plates ($250 \text{ mm} \times 240 \text{ mm} \times 3 \text{ mm}$) and put into a hot press (Model 4126 Manual, Hydraulic Press, Carver, USA) for 10 mins at $250 \text{ }^\circ\text{C}$ without pressure then at 3 ton for 40 minutes. The resulting polystyrene film was $130 \text{ }\mu\text{m}$ thick.

3.2 Composite lay-up and production

The interleaved composite consisted of 9 plies of unidirectional carbon fibre reinforced epoxy (HexPly, 914C-TS-5-34%, Hexcel, 1 ply thickness = $0.125 \text{ }\mu\text{m}$) and 8 layers of polystyrene ($130 \text{ }\mu\text{m}$ thick) arranged in an alternating sequence. A control sample consisting of 17 reinforced plies was also manufactured. The laminates were cured in a hot press (G969, George E Moore and Sons, UK) at $175 \text{ }^\circ\text{C}$ and 100 Psi for 1 h. The thickness of the interleaved composite was $2 \pm 0.04 \text{ mm}$. The thickness of the control sample was $2 \pm 0.03 \text{ mm}$. The composites were cut into $80 \text{ mm} \times 10 \text{ mm}$ coupons for flexural testing and $40 \text{ mm} \times 5 \text{ mm}$ test specimens for Dynamical Mechanical Thermal Analysis (DMTA) using a diamond bladed cutter (Diadisc 4200, Mutronic, Germany). In both cases the 0° direction was parallel to the longer dimension of the specimen.

3.3 Evaluation of viscoelastic properties of composites

DMTA was performed in three point bending mode on a Tritec 2000 (Triton Technology Ltd., Keyworth, UK). The gauge length was 15 mm. A heating rate of $5 \text{ }^\circ\text{C min}^{-1}$ was used from room temperature to $120 \text{ }^\circ\text{C}$ at a frequency of 1 Hz.

3.4 Flexural tests

The flexural properties of the composites were determined at room temperature and 120 °C using three point bending tests. The tests were carried out on an Instron 4505 (Bucks, UK) with a 1 kN load cell. ASTM D7264 was followed [15]. The span-to-thickness ratio was 32:1. The diameter of the loading nose and supports was 6 mm and a crosshead speed of 1 mm min⁻¹ was used. Measurements were taken at room temperature and then at 120 °C using an environmental chamber (SFL, Eurotherm, West Sussex, UK). The flexural modulus was calculated by deflecting the composites by 1 mm. In one technique to heat the specimens a direct current was passed through the carbon fibres. Both the upper and lower surfaces at each end of the samples were sanded down with sand paper and painted with silver conductive paint (186-3600, RS Components Ltd.). Copper tape was then wrapped around the silver paint and the loose ends of the tape connected to a power supply (HY3003-3, Digimess, UK). To heat a specimen to 120 °C approximately 1.8 A and 3 V were needed for the interleaved composite and 1.3 A and 4 V for the pure CFRP composite.

The flexural modulus of the specimens was calculated using equation 1, where E_f is flexural modulus (MPa), L is support span (mm), b is beam width (mm), h is beam thickness (mm) and m is the gradient (N mm⁻¹) of the load - displacement curve.

$$E_f = \frac{L^3 m}{4bh^3} \quad (1)$$

The flexural strength was calculated using equation 2, where σ is the maximum stress at the outer surface at the mid-span of the specimen (MPa) and P is applied force at failure (N).

$$\sigma = \frac{3PL}{2bh^2} \quad (2)$$

3.5 Preparation of microsection specimens

Microsection specimens were prepared in order to analyze the cross sections of the composites. The composite samples were embedded into an epoxy resin (Epoxicure, Buehler, UK) and cured for 8 h at room temperature. The samples were polished using a grinder-polisher (MetaServ/ MetaPol, Buehler, UK). A sequence of four sand papers with varying grit sizes were used initially (Si P120, P320, P800 and P2500) followed by three diamond based dispersions (6 μ , 3 μ and 1 μ). The samples were then analyzed using an optical microscope.

4 Results and Discussion

4.1 Viscoelastic properties of interleaved composite

The viscoelastic properties of the interleaved composite measured using DMTA are shown in Figure 1. The maximum testing temperature was limited to 120 °C as this is above the T_g of polystyrene, at which point the composite is expected to experience a loss in flexural stiffness, and below the T_g of the epoxy resin. At room temperature the storage modulus was recorded at 58 GPa. The T_g of the polystyrene was calculated at 90 °C from the peak in the loss modulus.

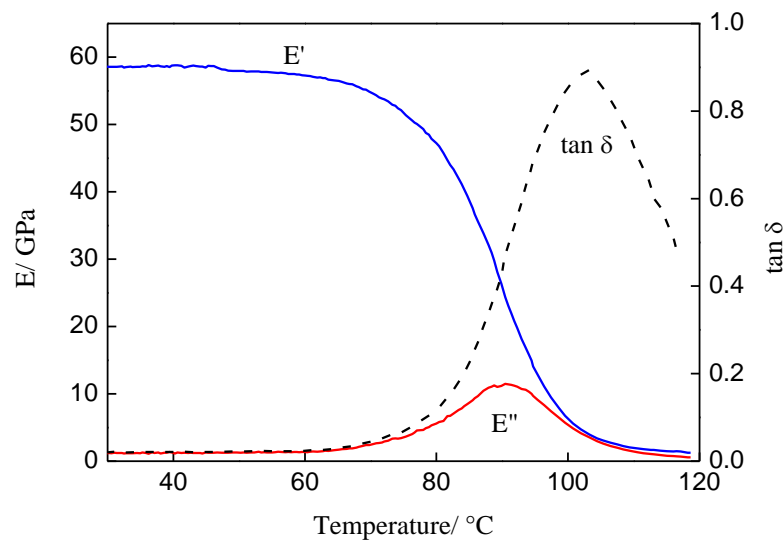


Figure 1: DMTA curves showing the storage modulus (E'), loss modulus (E'') and $\tan \delta$ of the interleaved composite as a function of temperature.

At 120 °C the storage modulus dropped by 98 % to 1.2 GPa. The storage modulus at room temperature and the stiffness loss at high temperature did not change when the test was repeated three times on the same sample. Therefore, under these test conditions the process is reversible.

4.2 Flexural properties of interleaved composites

The flexural modulus of each sample was determined using three point bending tests at room temperature (RT 1), 120 °C and again at room temperature (RT 2). The composites were heated to 120 °C in either an environmental chamber or by applying a direct current to the carbon fibres. The results are shown in Table 1. The values of flexural modulus obtained using the two heating methods are the same which indicates both techniques are viable heating methods. With direct current heating, temperatures around the contacts exceeded 120 °C and some polystyrene was observed to seep from the composite at these positions. This problem did not occur when using the environmental chamber.

At both room temperature and 120 °C the flexural modulus of the pure carbon fibre reinforced composite remained at approximately 116 GPa. The flexural modulus of the interleaved composite at room temperature was 65 GPa and at 120 °C, above the T_g of polystyrene, the modulus fell by 98 % to 1 GPa. At room temperature the flexural strength of the pure carbon fibre reinforced composite and the interleaved composite were 1550 MPa and 979 MPa, respectively. The values of flexural strength and modulus for both composites were in agreement with theoretical prediction. The interleaved and the pure carbon fibre reinforced composites were re-tested after heating to 120 °C and cooling to room temperature and no loss in flexural modulus was observed.

Composite	Flexural Modulus [GPa]						Flexural Strength* [MPa]
	Environmental Chamber			Applied Current			
	RT 1	120 °C	RT 2	RT 1	120 °C	RT 2	
Carbon fibre-reinforced epoxy	118 ± 3	112 ± 2	116 ± 3	113 ± 11	110 ± 8	114 ± 7	1550
Interleaved	65 ± 3	1 ± 0.2	65 ± 4	68 ± 3	1 ± 0.2	66 ± 3	979

* Tests performed at room temperature

Table 1: Flexural properties and interlaminar shear strengths of the interleaved and pure carbon fibre reinforced epoxy composites

Representative load displacement curves for the pure carbon fibre reinforced composites tested in three point bending are shown in Figure 2. The gradient of the slopes remain approximately the same despite the changes in temperature and heating technique.

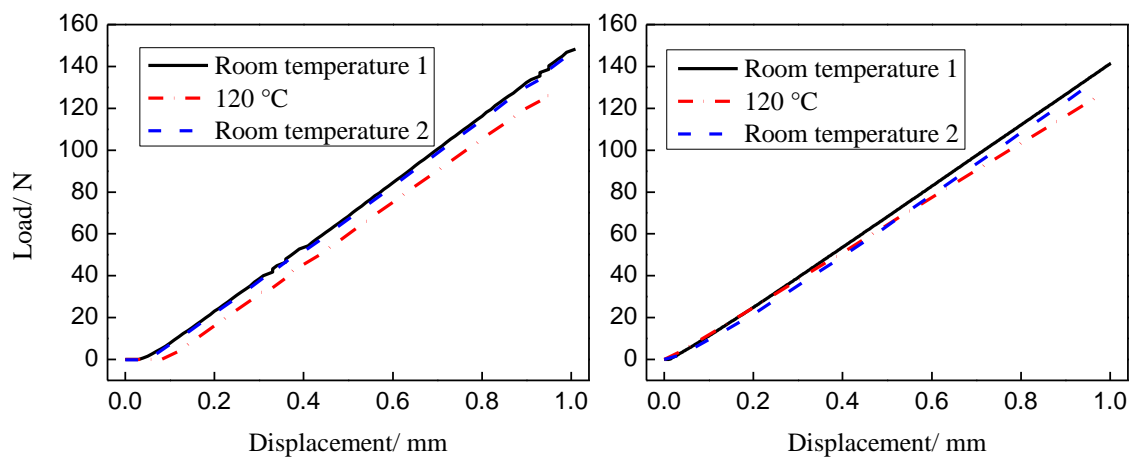


Figure 2: Representative load displacement curves of carbon fibre reinforced epoxy composites at room temperature and 120 °C [composites heated using an environmental chamber (left) and an applied current (right)]

Load displacement curves for the interleaved composite tested in flexure can be seen in Figure 3. The gradient is significantly lower at 120 °C than at room temperature and fully returns to its original value when cooled back to room temperature. Although a displacement of only 1 mm is shown, a maximum deflection of 17.8 mm was applied for one sample at 120 °C without initiation of failure. When this deformed sample was cooled to RT while under load and then unloaded the specimen retained nearly all the applied deformation with only a small amount of recovery due to the high flexural stiffness at room temperature. The composite then returned to its original shape (<0.5 mm residual deflection) when left at 120 °C without load.

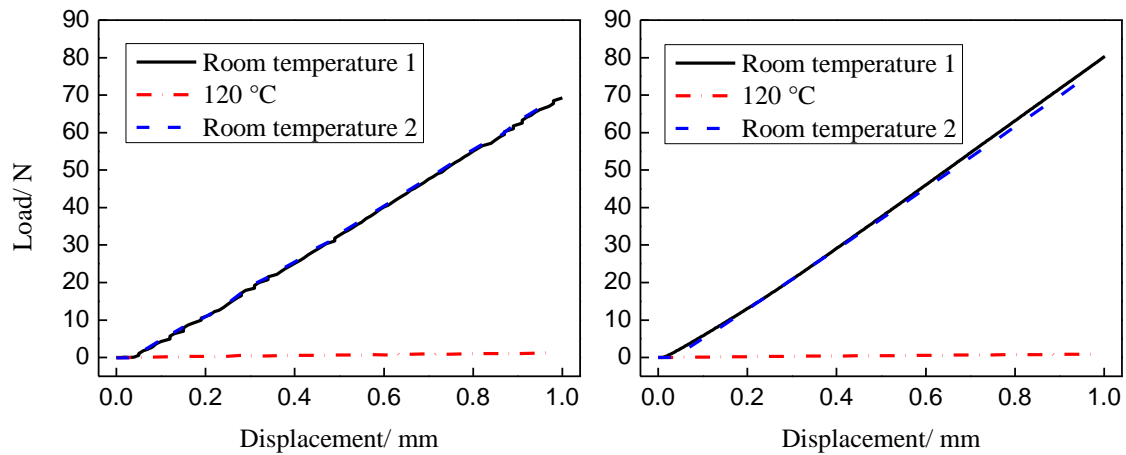


Figure 3: Representative load displacement curves of the interleaved composite at room temperature and 120 °C [environmental chamber (left), applied current (right)]

A microscopy image of the interleaved composite having been cooled in the deformed state during flexure testing is shown in Figure 4. The initially plane end face of the specimen clearly shows that at elevated temperature the softened state of the polystyrene lamina allowed the carbon – epoxy to slide relative to each other. No delamination could be seen after the composite was tested indicating that the adhesion between the epoxy and polystyrene remains good.

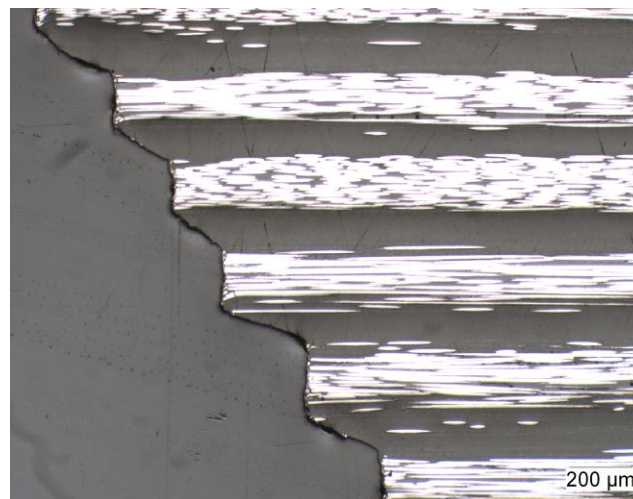


Figure 4: Cross section of interleaved composite in its deformed state at 20 × magnification

5 Conclusions

An interleaved composite containing plies of polystyrene was manufactured and tested for its ability to undergo reversible stiffness loss. DMTA results showed a 98 % loss in storage modulus occurred when the composite was heated to 120 °C. Similarly, flexure tests showed a 98 % reduction in flexural modulus when the composite was heated from 25 °C to 120 °C. When unloaded at 120 °C the composite returned to its original shape prior to bending and after re-testing at room temperature no loss in flexural stiffness was observed. From

microsection images of the tested samples no delamination was observed indicating good adhesion between the polystyrene and epoxy.

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