CONTROLLABLE STIFFNESS COMPOSITES: AN OVERVIEW

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Abstract
Composites with controllable stiffness have a number of potential applications including their use as skin materials in morphing aerostructures. Much work has focused on the development of such materials, which are required to withstand aerodynamic loads but also deform on demand at relatively low actuation forces. We provide an overview of the work carried out at Imperial College London on the development of high performance controllable stiffness composites. Two composite designs were explored, 1) composites containing thermoplastic interphases and 2) composites containing thermoplastic interleaf layers. Large reductions in stiffness of up to 99% were achieved when the composites were heated above the glass transition temperatures of the polymer interphase or interleaf layer. At these temperatures the composites could be deformed significantly and would retain their shape when cooled to room temperature. The process was completely reversible as the composites would return to their original configuration when reheated without an applied load. Self-deploying structures have also been manufactured from the controllable stiffness materials using the shape memory effect of the composites.

1. Introduction

There has been considerable interest in the development of composites with controllable stiffness [1-3]. These composites could prove to be viable skin materials for use in morphing applications as they would offer high stiffness with increased compliance when required [4, 5]. Controllable stiffness materials may also find applications in deployable structures [1,6]. In this paper we describe an overview of our work on developing controllable stiffness composites. We developed have two composite designs and these are described in sections 2 and 3.

2. Composites containing thermoplastic interphases

In the first design (Fig. 1), each fibre within a polymer matrix composite is coated with a thin thermoplastic or thermoset layer with a glass transition temperature (T_g) lower than that of the composite matrix. Heating the fibre coatings until they soften allows the fibres to slide within the matrix. The coatings can be softened by passing a current through the carbon fibres, which act as electrical resistance heaters. This can greatly reduce the flexural stiffness of the composite by up to 88 % [5]. This process is reversible, with the stiffness returning to its original value once the coating has cooled down. The choice of fibre coating depends primarily on the thermal properties of the polymer. It is required to have a T_g or melting point (T_m) below that of the matrix but above the maximum service temperature of the structure in which it is used. The matrix can be either a thermoset or a thermoplastic provided that its T_g is much higher than the T_g of the fibre coating. One such polymer

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selected for coating onto carbon fibres was polyacrylamide (PAAm). Tridech et al. [5] coated PAAm onto carbon fibres using a continuous electrocoating technique. PAAm is a suitable coating as it has a T_g at approximately 84 °C when partially hydrated (20 % moisture content). By altering the moisture content in the PAAm coating, the reduction in composite stiffness can be tailored to occur at different temperatures. However, water soluble fibre coatings like PAAm are unlikely to be suitable for use in high performance applications such as morphing wings. For this reason we also coated non-water soluble polymers such as poly(methyl methacrylate) (PMMA) onto carbon fibres and produced and tested the resulting composites [7].

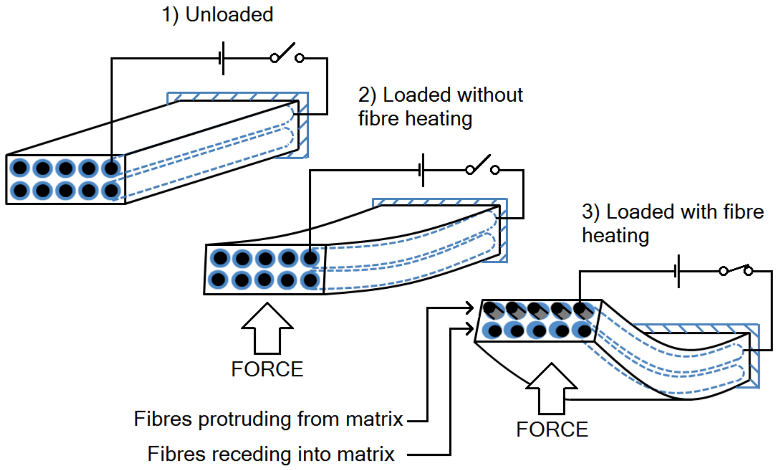

Figure 1. Concept of the controllable stiffness composite [5].

The benefit of using coated carbon fibre reinforced epoxy composites with controllable stiffness in morphing applications is that only a thin thermoplastic coating is required (<1 μm), which can be heated quickly by passing a current through the carbon fibres. This allows the stiffness to be controlled on demand. Another advantage is that the matrix remains stiff when the carbon fibre coating has softened. The composite can therefore withstand loading at elevated temperature without the risk of fibre misalignment. Below the softening temperature of the fibre coating the composites also have very similar flexural stiffness values (up to 87 GPa) compared to those of unsized carbon fibre reinforced epoxy composites and are therefore suitable for high performance applications [7]. The disadvantage of using these composites is that the maximum deflection at elevated temperatures is limited to the maximum strain of the matrix material.

3. Composites containing thermoplastic interleaf layers

The second design is an interleaved carbon fibre reinforced epoxy composite. Heating the composite above the T_g of the interleaf material softens the interleaf layers and allows the reinforced plies to slide relative to each other (Fig. 2). At this temperature the flexural stiffness of the composites can be reduced significantly (up to 98 %) and large bending deflections (midspan deflections up to 17.8 mm at a span of 64 mm) are achievable [4, 8]. For this design, the interleaf material must have again a glass transition temperature above the maximum service temperature of the structure in which it is used but well below the T_g of the matrix. Polystyrene (PS) was chosen as the interleaf material as its T_g is around 100°C. The matrix used in the reinforced plies can be a thermoset or a thermoplastic as long as its glass transition temperature is well above the T_g of the interleaf material.

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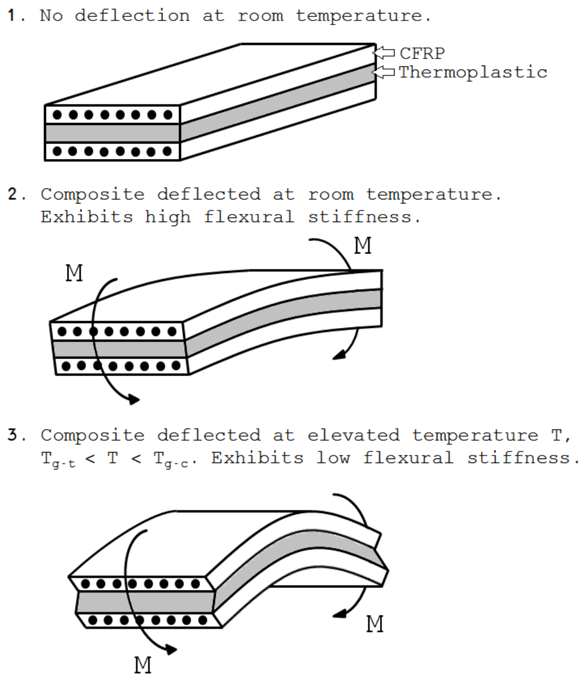

Figure 2. Concept diagram of an interleaved composite with controllable stiffness.

The advantage of using interleaved composites in morphing applications is that very large deformations can be achieved once the interleaf material has fully softened. The interleaved composites can undergo much larger deformations than the composites reinforced with coated fibres (first design), as each reinforced layer is effectively disconnected at elevated temperature. As with the coated fibre reinforced epoxy composites, the carbon fibres within the Carbon Fibre Reinforced Polymer (CFRP) plies can be used as heating elements although they are not in direct contact with the interleaf material. One way to overcome this is to place the carbon fibres into the interleaf layers. A disadvantage of interleaved composites is that delamination can occur under certain loading conditions and when interleaf materials with weak adhesion to the reinforced composite layers are used. We encountered this problem with PS interleaved composites as that the interface between the PS and CFRP layers is very weak, which led to premature failure during flexural tests [8]. We therefore looked at improving the ply/interleaf interface in PS interleaved composites [9]. We exchanged the PS layers with a more suitable Styrene Maleic Anhydride (SMA) resin which dramatically improved the flexural strength of the composites whilst still allowing for significant, reversible reductions in stiffness at elevated temperature.

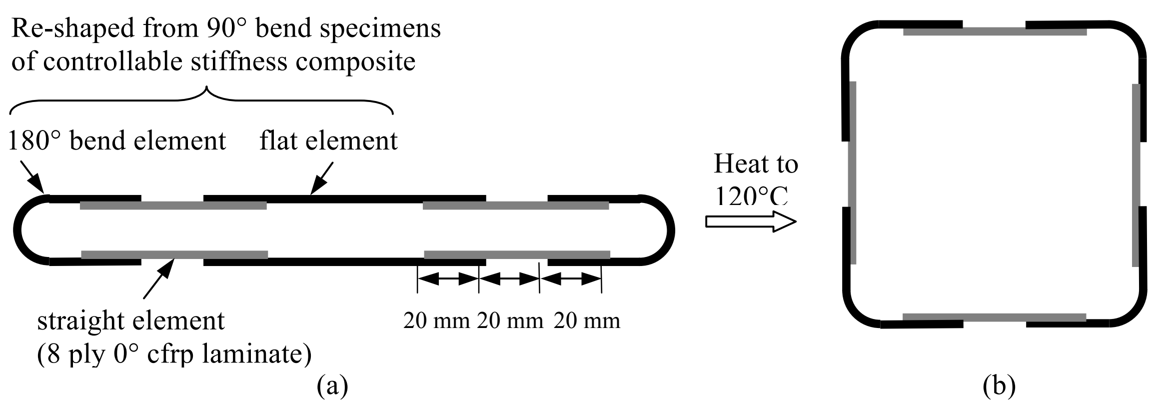

Figure 3. Simple deployable structure diagrams a) As-manufactured (folded) form, b) Deployed form [6]

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A potential application for interleaved composites is to use their shape memory capability in deployable structures and a simple structure has been manufactured to illustrate this possibility (Fig. 3) [6]. PS interleaved composites were cured at a 90° angle and then reshaped to either a flat or 180° bend configuration. The reshaped interleaved were then combined with pure CFRP composites to create a structure (Fig. 3a) that deployed when heated to 120°C (Fig. 3b).

3. Conclusions

A significant challenge in the design of adaptive structures, such as morphing wings, is the development of a stiff skin material that can be deformed on demand with acceptable actuation forces. To overcome this, the concept of carbon fibre reinforced epoxy composites with controllable stiffness was investigated. Two designs of controllable stiffness composite have been developed. The composites contain either thermo-responsive interphases or interleaf layers, which are simply polymer coatings or layers with a T_g higher than the service temperature of the composites but much lower than the T_g of the composite matrix. These composites have acceptable flexural stiffness prior to activation and therefore with appropriate developments may have potential for use in aerospace applications. When heated above the T_g of the polymer interphase or interleaf, the flexural stiffness of the composites was reduced by up to 98 %. At this temperature the composites could undergo reversible deflections without delaminating. The composites were able to return to their original configuration and their flexural modulus restored to their full values.

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