EXPLORING THE POTENTIAL OF CONTROLLABLE STIFFNESS HYBRID COMPOSITES

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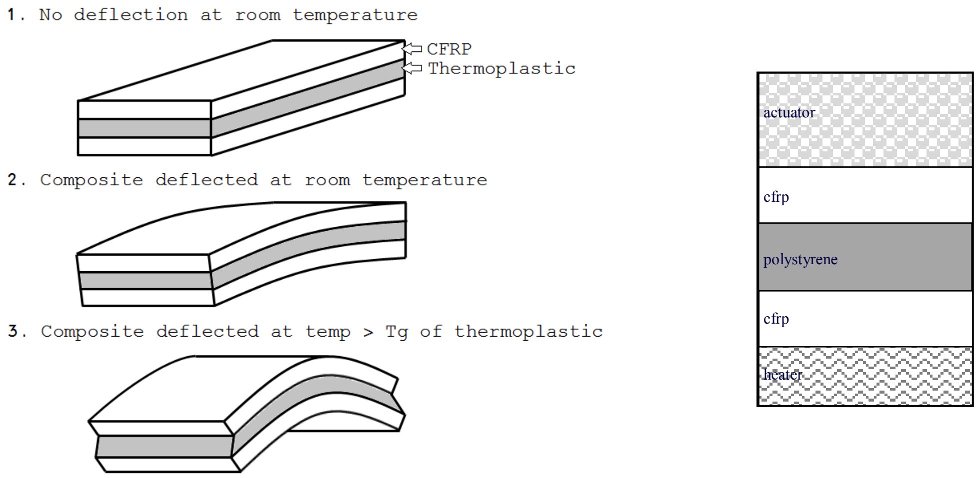
Abstract
A hybrid composite, which consists of carbon fibre reinforced epoxy laminae and polystyrene interleaf layers, has been shown to exhibit a significant loss in flexural stiffness on heating. Trials have been performed to demonstrate that the cured hybrid composite can be readily re-shaped and that the re-shaped specimens can recover their original shape on heating. One potential application of this shape memory capability is in deployable structures and a simple structure has been manufactured to illustrate this possibility.

1. Introduction

1.1. Brief overview of controllable stiffness materials

Controllable stiffness materials possess stiffness that can be changed on demand. These materials may find applications in deployable and adaptive shape structures [1-6] for which the ability to lower the stiffness can significantly reduce the actuation requirements. One class of controllable stiffness material consists of constant stiffness elements joined together by a variable stiffness material [2]. This paper is concerned with a particular form of this class of controllable stiffness materials which consists of an interleaved laminate of continuous layers of the constant stiffness material separated, and joined, by the variable stiffness material. The mechanism for the stiffness control in this interleaved configuration is illustrated in Figure 1a for a laminate consisting of carbon fibre reinforced polymer (cfrp) layers (the constant stiffness material) and thermoplastic interleaves (the variable stiffness material). The thermoplastic interleaf material is chosen to have glass transition temperature ($T_{g\text{-}t}$) less than that of the fibre reinforced composite plies ($T_{g\text{-}c}$). At temperatures lower than $T_{g\text{-}t}$ the laminate is in a high flexural stiffness state but when the temperature is increased to above $T_{g\text{-}t}$ (but less than $T_{g\text{-}c}$) the loss of shear stiffness of the interleaf layers allows the constant stiffness plies to slide relative to each other and this results in a reduced flexural stiffness [7, 8].

Maples et al. [7, 8] have conducted preliminary experimental investigations of a polystyrene-interleaved carbon fibre reinforced epoxy hybrid composite which have shown that large reductions of over 90% in flexural stiffness are possible when the interleaved composite was heated to 120°C (the T_g of the polystyrene was 100 °C).



(a) (b)

Figure 1. a) Concept of interleaved composite with controllable stiffness. b) Cross-section of actuated cantilever specimen containing controllable stiffness composite.

In addition to simply controlling the flexural stiffness, Raither and colleagues [9] were able to demonstrate that the bend-twist coupling could be reduced by a factor 10 in a cfrp multidirectional laminate containing elastomer interleaf layers when heated above the glass transition temperature of the elastomer.

To demonstrate the potential of a controllable stiffness material in a morphing or deployable structure Robinson et al [8] manufactured a simple controllable stiffness cantilever beam (Figure 1b) consisting of two plies of unidirectional cfrp separated by one layer of polystyrene with a free length of 85 mm and a width of 20 mm. The beam had a thin Kapton film encapsulated heater bonded to the lower surface which was used to increase its temperature up to 120°C to achieve flexural stiffness reduction. A macro fibre composite (MFC) actuator (by Smart Material Corp under licence from NASA) bonded to the upper surface was used to deflect the beam. For the same actuator voltage, the experiments showed that the tip deflection of the cantilever increased by over 100% when the flexural stiffness of the interleaved composite was reduced by heating. Much greater increases in deflection will be achieved with laminates consisting of more cfrp plies interleaved by polystyrene.

1.2 Shape memory effect in thermoplastic interleaved carbon-epoxy composites

In the flexural stiffness tests on polystyrene interleaved carbon epoxy composite laminates conducted by Maples et al [7, 8], it was observed that when testing at 120°C (i.e. higher than the T_g of the polystyrene) a deflection imposed in a 3-point bend test would be retained by the specimen if it was cooled down in the deflected state i.e. this material can be re-shaped. When this specimen, now unloaded, was reheated to 120°C it recovered its original straight form. This controllable stiffness material therefore exhibits a shape memory effect and this is because the carbon epoxy layers remain elastic during the high temperature deformation.

1.3 Aim

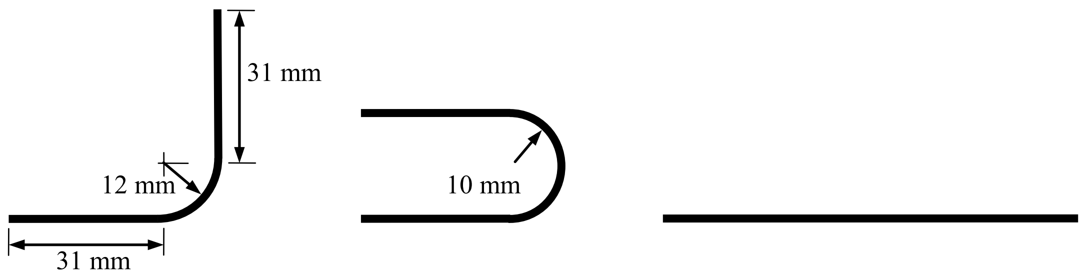
The current paper describes an investigation into the shape memory effect of these controllable stiffness, interleaved hybrid composites for use in deployable structures. The investigation examines the ability to re-shape these composites at elevated temperature, the recovery of the original shape when heated in an unconstrained state and the behaviour of an assembly of these composites as a simple deployable structure.

2. Investigation of the re-shaping and shape-recovery capabilities

2.1. Preliminary design of test specimens

The 90° bend specimen, see Figure 3a, in which the bend is formed of a circular arc with an inner radius of 12 mm was chosen for this investigation. To test the re-shaping capabilities, it was decided to re-shape this specimen to form a 180° bend specimen (Figure 3b) with an inner radius of 10mm and a flat specimen (Figure 3c). The layup of the specimens was [0°/PS/90°/PS/90°/PS/0°], see Figure 4.

Simple calculations were performed to ensure the carbon epoxy plies would not fail during the re-shaping process and to assess the likely size of any spring back when released at room temperature after re-shaping.



(a) (b) (c)

Figure 3. Specimen for investigating re-shaping and shape-recovery capability: a) as-cured shape, b) re-shaped 180° bend configuration, c) re-shaped flat configuration

When the laminate configuration of Figure 4, at 120°C (i.e when the polystyrene layers have low stiffness and allow the cfrp plies to slide relative to each other) is subjected to a change in curvature, the maximum magnitude of strain induced in the cfrp laminae of thickness t_c is $t_c/2R$ where R is the radius of curvature of the mid-plane of that lamina. For the cfrp used in this study t_c = 0.125 mm. On re-shaping from the 90° bend specimen to the 180° bend specimen the maximum change in curvature is 1/10 mm^{-1} (ignoring the small offset due to the lamina thickness) which occurs in the innermost plies in the originally straight portions of the specimen. The maximum magnitude of the applied strain is therefore 6.25x10^{-3}. On re-shaping from the 90° bend specimen to the flat specimen the maximum change in curvature is 1/12 mm^{-1} which occurs in the innermost plies in the originally curved portion of the specimen and so it is the re-shaping to the 180° bend specimen which is the more critical. Two cfrp materials (TS-914C and HTS-924C, both produced by Hexcel) were used in this investigation and the properties are given in Table 1. For both materials it can be seen that the failure strains (taken as the failure stress divided by the corresponding modulus) significantly exceed the anticipated applied strain and so no failure of the cfrp laminae is expected during the re-shaping process.

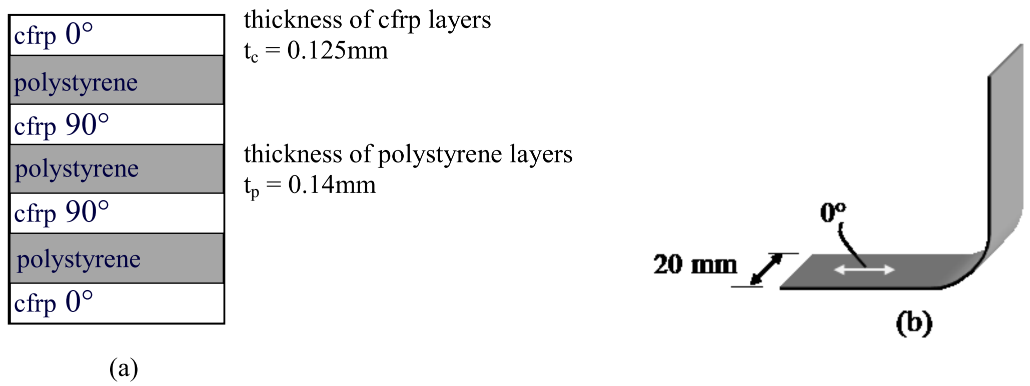


Figure 4. a) Specimen layup, b) 0° fibre direction in 90° bend specimen

When the specimen is released at room temperature after re-shaping it may undergo a small amount of deflection towards the original cured shape i.e. there may be a certain amount of spring-back. The magnitude of the spring-back can be estimated from the moments required to produce the re-shaped form. Calculations based on beam theory indicate that for both re-shaped configurations the spring-back will be less than 1°.

2.2. Experimental investigation

For the re-shaping and shape recovery trials, the 90° bend specimens were manufactured using the HTS-924C cfrp (Table 1). The [0°/PS/90°/PS/90°/PS/0°] laminate was laid up on a wooden mould using rectangular layers and enclosed with a matching upper mould of aluminium alloy using release films on the surfaces of the moulds (see Figure ?). The whole assembly placed in a heated press and cured at 175°C for one hour at a pressure of 100 psi. The cured 90° bend plate was cut into six specimens of width 20 mm and with straight portions of 31 mm (Figure 3a). The angle enclosed between the straight arms was measured after curing.

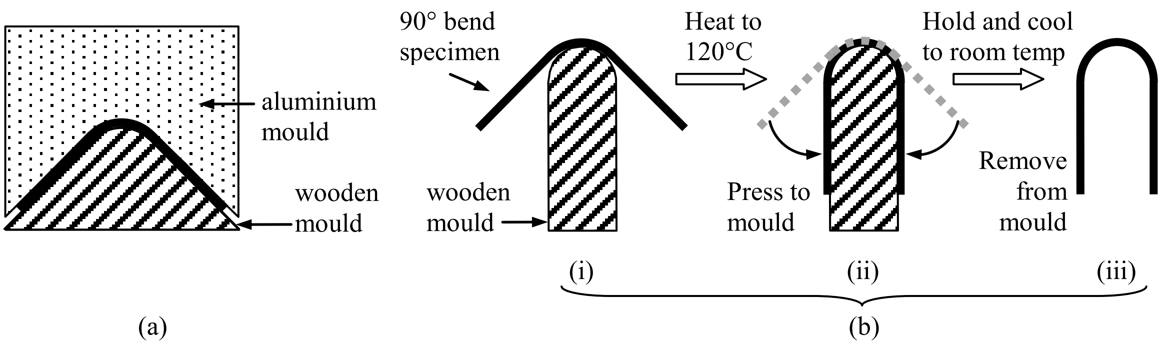


Figure 5. a) Mould arrangement for manufacture of 90° bend specimen b) Re-shaping process steps for production of 180° bend configuration

The specimens were re-shaped on a wooden mould (see Figure 5b) which was enclosed in a vacuum bag. The vacuum bagged assembly (without the vacuum applied) was placed in an oven and the specimens were heated up to 120° C and held at this temperature for 15 minutes. The specimens were then manually deformed towards the mould surface and the vacuum pump then switched on to ensure the specimens were firmly held against the mould tool. The specimens were then cooled, while maintaining the vacuum. The re-shaped specimens were removed from the mould and the angle between the straight portions was measured. A similar process was repeated for re-shaping of the 90° bend specimens into the flat configuration.

To examine the shape recovery of the specimens unconstrained 180° bend and flat specimens were returned to the oven and heated to 120°C. When the specimens showed no further change in shape they were allowed to cool and the angle between the straight portions was again recorded.

Mechanical Property	**TS/914C**		**HTS/924C**	
	0°	*90°*	*0°*	*90°*
Tensile modulus (GPa)	135	8.5	168	9.5
Tensile strength (MPa)	1650	79	2700	93
Tensile failure strain (x 10^{-3})	12.2	9.3	16.1	9.8
Compressive modulus (GPa)	131	10	161	11.5
Compressive strength (MPa)	1350	230	1520	214
Compressive failure strain (x 10^{-3})	10.3	23.0	9.4	18.6

Table 1. Mechanical properties of TS/914C and HTS/924C carbon epoxy composites.

2.3. Results

Table 2 shows the enclosed angle measured between the straight arms after curing, after re-shaping and after shape recovery. It can be seen that the as-cured angle is very close to the intended value of 90°. On re-shaping to form the 180° bend specimen the enclosed angle is within 1° of the intended value and after shape recovery the specimens return almost perfectly to their as-cured shapes. On re-shaping the specimen to the flat configuration the enclosed angle is up to 5° less than the intended value of 180° and although the specimens show significant shape recovery during subsequent heating they do not fully return to the as-cured shape with the enclosed angle being about 8° too large.

Mechanical Property	**Specimen no.**	**Intended enclosed angle(°)**	**Measured enclosed angle (°)**
As cured	1, 2,3,4	90	All 89.6
After re-shaping to 180° bend	1,2	0	0.8, 0.7
After shape recovery from 180° bend	1,2	90	89.6, 89.7
After re-shaping to flat	3,4	180	175.2, 177.6
After shape recovery from flat	3,4	90	97.8, 97.7

Table 2. Enclosed angle measurements for as-cured, after re-shaping and after shape recovery

3. Manufacture and evaluation of a simple deployable structure

3.1. Configuration and manufacture

The adhesively bonded configuration shown in Figure 6a consisted of flat and 180° bend elements formed by re-shaping 90° bend specimens which were joined together with straight carbon epoxy elements. When re-heated this configuration should deploy to form a square shape with rounded corners as shown in Figure 6b.

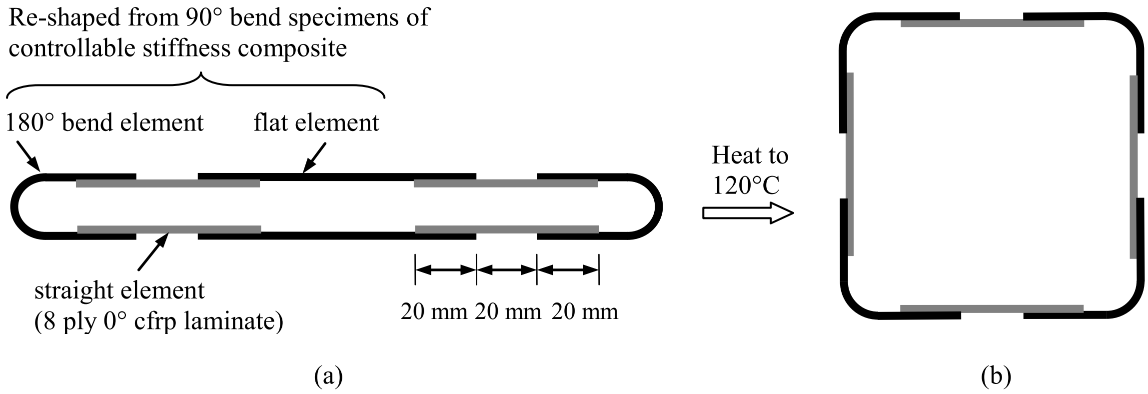
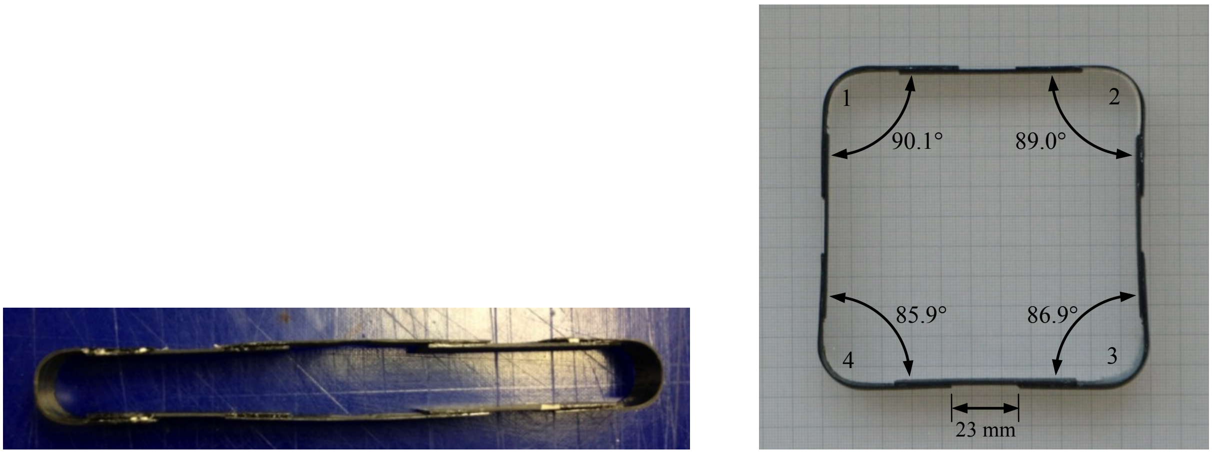


Figure 5. Simple deployable structure diagrams a) As-manufactured (folded) form, b) Deployed form

The re-shaped elements of the assembly were of the same layup and size as described in section 2.2, and the same manufacturing and re-shaping techniques were used except in this case the TS/914C carbon epoxy system (see Table 1) was used. The ‘straight’ elements of the configuration were formed of an eight-ply unidirectional laminate of TS/914C (non-interleaved). TML P-2 adhesive was used to bond the re-shaped and straight elements together at room temperature to form the assembly shown in Figure 6a. (This adhesive has a maximum operating temperature of 180° C and so can withstand the temperature required for shape recovery.) The assembly was then placed in an oven and heated to 120°C and the shape recovery process was observed. When the specimen showed no further change in shape, it was cooled to room temperature and the enclosed angles at the four corners of the deployed shape were recorded.

3.2. Results

Figure 7 shows a sequence of frames from a video recording of the shape recovery process and confirms that the structure deploys as intended. Figure 6b shows a photograph of the final shape and includes the enclosed angle at each of the corners. In this photograph corners 1 and 3 correspond to the flat elements in the as manufactured form and corners 2 and 4 correspond to the 180° bend elements. It can be seen that the recovered shape has not returned fully to the intended shape with an enclosed angle of 90° at each corner but this is likely to be due to an error during manufacture as the spacing between the corner elements on the lower edge is 23 mm instead of the intended dimension of 20 mm.



(a) (b)

Figure 7. Photographs of simple deployable structure a) As-manufactured (folded) form, b) Deployed form

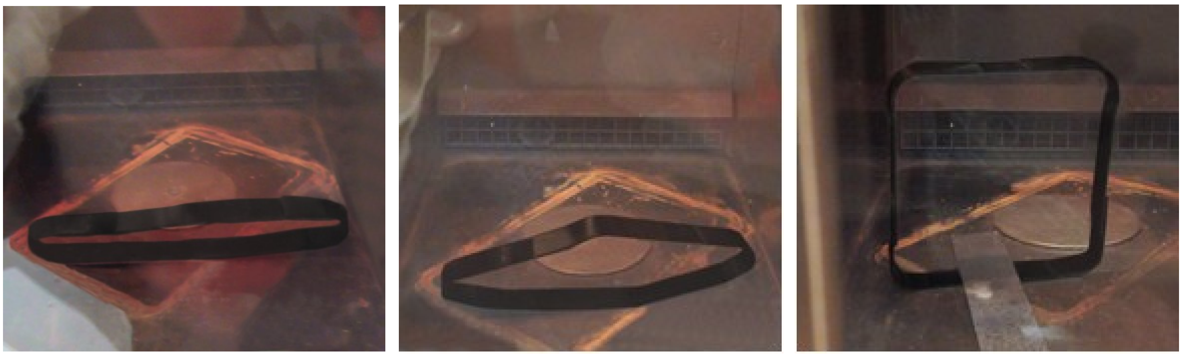


Figure 8. Frames from a video recording of the shape recovery process

4. Conclusions

The shape memory capability of a hybrid composite consisting of carbon fibre reinforced epoxy laminae and polystyrene interleaf layers has been demonstrated by investigating the re-shaping and shape recovery of specimens cured in a 90° bend shape. A simple deployable structure has been manufactured and was shown to deploy as intended. Further work is underway to explore more fully the shape memory behaviour of this interleaved composite

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