

Deployable, Shape Memory Carbon Fibre Composites Without Shape Memory Constituents

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Abstract

Trials have been conducted to investigate the shape memory capability of an interleaved composite consisting of carbon fibre reinforced epoxy laminae and polystyrene interleaf layers. It has been shown that the composite can be readily re-shaped by deforming it at an elevated temperature and then cooling the composite in the deformed state. On re-heating, the composite almost fully returns to its original shape. One potential application of the shape memory capability of the interleaved composite is in deployable structures and a simple structure has been manufactured to demonstrate this possibility.

1. Introduction

1.1. Carbon fibre laminates containing thermoplastic interleaf layers

Composites reinforced with polymer-coated fibres and interleaved composites were initially investigated for their improved impact performance and interlaminar toughness [1-4] but more recently several of the authors of the current paper have been developing and investigating these types of composites to exploit their potential to exhibit controllable stiffness [5-9]. Controllable stiffness materials possess stiffness that can be changed on demand. The mechanism for the stiffness control in the interleaved

configuration, which is the focus of the current paper, was described in our previous work [8,9]. Thermoplastic interleaved carbon fibre reinforced polymer (cfrp) composites are used and when the interleaf material is heated above its glass transition temperature (T_g), the loss in shear stiffness of the interleaf layers allows the unsoftened cfrp plies to slide relative to each other resulting in a reduced flexural stiffness.

This interleaved controllable stiffness concept was investigated by Ghandi et al in a beam consisting of aluminium layers separated by cast acrylic and polyvinyl chloride materials [10-12]. McKnight and Barvosa-Carter also patented various variable stiffness structure concepts which included the interleaved configuration [13]. Maples et al. [8,9] conducted experimental investigations of a polystyrene-interleaved carbon fibre reinforced epoxy composite which showed that the flexural stiffness was reduced by over 90% when the interleaved composite was heated to 120°C. (The T_g of the polystyrene is approximately 100°C.) In addition to controlling the flexural stiffness, Raither and colleagues 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 T_g of the elastomer [14].

1.2 Shape memory effect in thermoplastic-interleaved carbon-thermoset composites

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

Other composites that contain shape memory constituents, and which therefore exhibit shape memory capabilities, have been proposed [15-18]. However, in contrast to these composites, the shape memory capability of the interleaved composite investigated in this paper does not derive from the shape memory capability of its constituents.

1.3 Source of the shape memory effect in thermoplastic-interleaved carbon-thermoset composites

The source of the shape memory effect is illustrated in Table 1 by examining the longitudinal stresses in a three-ply thermoplastic interleaved cfrp composite beam-type specimen which is re-shaped into a bent configuration and then undergoes shape recovery. The specimen consists of two cfrp 0° laminae separated by a single thermoplastic interleaf ply. At the start of stage I the initially straight beam specimen is heated to a temperature T^* (higher than the T_g of the thermoplastic layer but less than that of the cfrp). At this temperature the interleaved composite will be in its low flexural stiffness state i.e. the carbon plies can slide relative to each other. When subjected to, for example, a three-point bend test at this elevated temperature, bending stresses will be induced in the carbon laminae with the form shown. In stage II the specimen is cooled to room temperature (RT), while maintaining the applied displacement achieved in stage I. The laminate is now in its high flexural stiffness state since all three laminae act together as an integral laminate. When the laminate is unloaded the decrease in the mid-point displacement will be small compared to that applied in stage I and the specimen remains in a deformed shape. The stress change due to removal of the bending load and the resulting total stresses will have the forms shown and the total stresses will be self-equilibrating. Stages I and II represent the process of re-shaping the interleaved composite.

In Stage III, the specimen, now free to deform, is heated to T^* and the stresses that were introduced in stage II in the thermoplastic interleaf reduce to zero as this has lost its stiffness. The specimen is again in its low stiffness state, the cfrp plies can slide relative to each other and so, in the absence of any externally applied loading, the stresses in each of these laminae reduce to zero as the plies return to their straight form. In Stage IV the laminate is cooled to room temperature, it remains straight and regains its full stiffness i.e. it recovers the shape and stiffness it had at the start of stage I. Stages III and IV represent the shape recovery process of the interleaved laminate.

A shape memory capability is exhibited by the interleaved composite because a bending deformation imposed at high temperature can be 'locked in' to the material on cooling and the associated stresses stored elastically in the cfrp laminae are available to return the laminate to its original shape on re-heating. (Note that superimposed on the stresses shown in Table 1 there will also be thermal stresses, induced due to the temperature changes and differing thermal expansion coefficients of the interleaf and cfrp, but these do not contribute to the shape memory capability.)

1.4 Aim

The current paper describes an investigation into the shape memory effect of carbon fibre laminates containing thermoplastic interleaf layers. The investigation examined the ability to re-shape these composites at elevated temperature, the recovery of the original shape when heated in an unconstrained state and the behavior of a simple deployable structure manufactured using the interleaved composite.

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

2.1 Materials

Two epoxy matrix cfrp materials (T300-914C and T800-924C, both produced by Hexcel, UK) were used in this investigation (their mechanical properties are given in the

supplementary information). The interleaf material was polystyrene (ST316310, purchased in pellet form from Goodfellow, UK) and manufactured into a film using a heated press (Model 4126 Manual, Hydraulic Press, Carver, USA) as described in our previous work [8]. For the purpose of the analysis described below, the Young's modulus at RT of the polystyrene was taken as 2.5 GPa. The T_g of the 914 epoxy was 180 °C, of the 924 epoxy was 190 °C and that of the polystyrene was approximately 100 °C.

2.2 Preliminary design of test specimens

A 90° bend specimen, see Figure 1a, was chosen for this investigation. In this specimen the bend was formed of a circular arc with an inner radius of 12 mm. To test the re-shaping capabilities, it was decided to re-shape this specimen to form two configurations: a 180° bend shape (Figure 1b) with an inner radius of 10 mm and a flat shape (Figure 1c). Two specimen layups were investigated; a cross ply laminate [0°/PS/90°/PS/90°/PS/0°] and a quasi-isotropic laminate [0°/PS/90°/PS/+45°/PS/-45°/PS/-45°/PS/+45°/PS/90°/PS/0°] in which PS represents the polystyrene interleaf (see Figure 2).

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.

Consider the cross-ply laminate of Figure 2a is heated to 120°C. At this temperature the polystyrene layers have low stiffness and it is assumed that the cfrp plies can freely slide relative to each other (i.e. the polystyrene stiffness is assumed to be zero). If the heated laminate is subjected to a change in curvature about the n -direction (see Figures 1 and 2c for s and n directions), the maximum magnitude of s -direction strain induced in the cfrp laminae of thickness t_c is $t_c/2R$ where $1/R$ is the change in curvature of the mid-

plane of that lamina. For the cfrp materials used in this study $t_c = 0.125$ mm. On re-shaping the 90° bend specimen (Fig. 2a) to the 180° bend configuration (Figure 1b) the maximum change in curvature is $1/10 \text{ mm}^{-1}$ (ignoring the small offset due to the lamina thickness) which occurs in the innermost plies in the parts between $s_{1'}$ and s_1 and between $s_{2'}$ and s_2 (see Figure 1b), i.e. the originally straight portions of the specimen. The maximum magnitude of the applied strain in the s -direction is therefore 6.25×10^{-3} . On re-shaping the 90° bend specimen to the flat configuration (Figure 1c) the maximum change in curvature is $1/12 \text{ mm}^{-1}$ which occurs in the innermost plies in parts between s_1 and s_2 (see Figure 1c), i.e. the originally curved portion of the specimen. The re-shaping process to form the 180° bend configuration is therefore the more critical. As noted earlier, two cfrp materials were used in this investigation. For both materials the failure strains (taken as the failure stress divided by the corresponding modulus – see the supplementary information) significantly exceed the anticipated applied strain and so no failure of the cfrp laminae are expected during the re-shaping process of the cross ply specimen.

Using the same approach for the quasi-isotropic laminate of Figure 2b, it follows that no failures will occur in the 0° and 90° plies during the re-shaping process. For the $\pm 45^\circ$ laminae their allowable applied strain in the 0° direction of the laminate can be estimated using the maximum strain criterion and assuming that the strain in the transverse n -direction and the in-plane, s - n shear strain of the lamina are negligible. With these assumptions the magnitude of applied strain in the s -direction of the laminate to cause failure of the $\pm 45^\circ$ plies is the lesser of

- the ultimate shear strain of the ply in the principal material axes;
- twice the magnitude of the failure strain (tensile or compressive) in the transverse direction of the ply;

- twice the magnitude of the fibre-direction failure strain (tensile or compressive) of the ply.

Comparing this failure strain to the strains that were to be applied during re-shaping showed that for both materials no failure of the cfrp plies is anticipated during the re-shaping process of the quasi-isotropic laminate.

When a specimen is released at room temperature after re-shaping it will undergo a small amount of deflection towards the original cured shape, i.e. there will be a certain amount of spring-back. The magnitude of the spring-back angle $\emptyset$ (see Figures 1b and c) can be estimated from the moments required to produce the re-shaped form. For a given cfrp lamina i (of thickness t_c and width w) the moment, M_i , required to produce a change of curvature $1/R_i$ at the mid-surface of the lamina is given by:

$$M_i = \frac{E_i w t_c^3}{12 R_i} \quad (1)$$

where E_i is the longitudinal (i.e. in the s -direction of the laminate) Young's modulus of the lamina (135 GPa for T300/914C and 168 GPa for T800/924C - see supplementary info). E_i for the $\pm 45^\circ$ laminae was approximated as 10% of the 0° lamina value [19].

The total moment M^T required to re-shape the laminate is given by summing M_i for all the cfrp plies:

$$M^T = \sum_{\text{for all cfrp laminae}} M_i \quad (2)$$

This moment, M^T , will vary depending on which part of the specimen is being considered. Consider, for example, the re-shaping of the 90° bend specimen (Figure 1a) to form the 180° bend configuration (Figure 1b). The part between s_1 and s_2 (where s_1 and s_2 correspond to the locations on the midline at $\theta = -45^\circ$ and $\theta = 45^\circ$, respectively, in Figure 1a), in which the inner surface curvature has changed from $1/12 \text{ mm}^{-1}$ to $1/10 \text{ mm}^{-1}$, will have a certain value of M^T . However the parts between s_1' and s_1 and between

s_2' and s_2 (where s_1' and s_2' correspond to the positions $\gamma = -90^\circ$ and $\gamma = 90^\circ$, respectively, in Figure 1b) will have a different value of M^T (larger as the inner surface curvature has changed from zero to $1/10 \text{ mm}^{-1}$). Neglecting the small reduction in the moment required to hold the laminate in its re-shaped configuration as the laminate is cooled to room temperature, the ‘spring back’ angle $\emptyset$ (see Figure 1) as the specimen is released after re-shaping can be calculated by considering the deformation of the re-shaped specimen due to the moments M^T applied in the opposite direction. The calculation can be expressed as:

$$\emptyset = \frac{1}{(EI)_{RT}} \int_{\text{over entire midline of specimen}} M^T ds \quad (3)$$

in which s is the distance along the midline of the specimen wall thickness and $(EI)_{RT}$ is the flexural stiffness of the laminate at room temperature which can be determined from either laminate theory or from beam theory for a beam section of multiple materials [20]. (There are additional sources of spring-back, such as the difference between the through-thickness and in-plane thermal expansion coefficients [21], but these will give rise to relatively small spring back angles.)

An approximate value of the spring-back angle $\emptyset$ can be derived if the variation of R_i across the laminate thickness is small (i.e. the thickness of the laminate is small compared to the values of R_i .) In this situation the term $1/R_i$ can be approximated to the change in curvature of the midplane of the laminate, $1/R_0$. Equation 2 can then be rewritten as:

$$M^T = \frac{1}{R_0} \sum_{\text{for all cfrp laminae}} \frac{E_i w t_c^3}{12} \quad (4)$$

Substituting this into equation 3 gives:

$$\emptyset = \frac{\sum_{\text{for all cfrp laminae}} \frac{E_i w t_c^3}{12}}{(EI)_{RT}} \int_{\text{over entire midline of specimen}} \frac{1}{R_0} ds \quad (5)$$

In equation 5 the integral expression is the angle change imposed on the straight arms of the original 90° bend specimen during the re-shaping process. The magnitude of this angle change is 90° for the reshaping into both the 180° bend configuration and the flat configuration. The term preceding the integral in equation 5 is simply the ratio of the flexural stiffness at elevated temperature to that at room temperature. The spring back angle $\emptyset$ for both re-shaped configurations can therefore be expressed as:

$$\emptyset = \frac{\text{flexural stiffness at elevated temperature}}{\text{flexural stiffness at room temperature}} \times 90^\circ \quad (6)$$

Table 2 gives the values of M^T and $\emptyset$ that were calculated for both re-shaped configurations according to equations 2 and 3 and the approximate value of $\emptyset$ according to equation 6. It can be seen that for both re-shaped configurations and for both cfrp materials the predicted spring-back is less than 1°. The approximate spring back values determined from equation 6 show good agreement with those calculated using equations 2 and 3, and for each combination of material and laminate layup the approximate value is very close to the mean of the accurate values of $\emptyset$ calculated for the 180° and flat configurations.

2.3 Experimental investigation

As mentioned earlier, the polystyrene interleaf films were manufactured from polystyrene pellets using a heated press [8]. For the re-shaping and shape recovery trials, the 90° bend specimens (Figure 1a) were manufactured using the T800-924C cfrp (see supplementary info). The laminates were laid up on a wooden mould using rectangular layers (140 mm x 120 mm, the longer dimension in the s-direction of the laminate) of cfrp plies and polystyrene interleafs and enclosed with a matching upper

mould of aluminium alloy using release films on the upper and lower surfaces of the specimen and two silicone layers each 1.6 mm thick immediately beneath the aluminium mould (see Figure 3a). The whole assembly was placed in a heated press (2.5 ton hydraulic press, Moore, UK) and cured at 175°C for one hour at a compression force of 7.1 kN. Each cured 90° bend laminate was cut into specimens of width 20 mm and the straight portions were trimmed to a length of 31 mm (Figure 1a). The angle enclosed between the straight arms of each specimen was then measured.

To re-shape the 90° bend specimens into the 180° bend configuration, the specimens were placed on a wooden mould (see Figure 3b) covered with a breather cloth and overlaid with a vacuum bag which was then sealed to the baseplate on which the mould was mounted. The vacuum bagged assembly (without the vacuum applied) was placed in an oven and was heated to 120° C and held at this temperature for 15 min. The specimens were manually deformed towards the mould surface and the vacuum pump was then switched on to ensure the specimens were firmly held against the mould tool. The specimens were 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 performed for re-shaping of the 90° bend specimens into the flat configuration. A 90° bend specimen was placed on a thick aluminium plate (Figure 4a) and covered by a peel ply and a breather layer. The whole assembly was sealed in a vacuum bag (taking care to ensure that the specimen was resting symmetrically on the plate) and heated to 120°C in an oven. After 15 min at this temperature, the straight parts of the specimen were manually flattened towards to the plate surface and the vacuum pump was switched on to maintain the new shape (Figure 4b). The specimen was cooled to room temperature under vacuum. Finally, the re-shaped specimen was

removed from the mould (Figure 4c) and the angle was measured between the outer portions which were the straight arms of the 90° bend specimens.

To investigate the ability of the specimens to recover their original shape, the 180° bend and flat specimens were returned to the oven and heated to 120°C. Each specimen was supported by a narrow clamp at the center of the specimen (see later Figures 5 & 6). When the specimens showed no further change in shape they were cooled to room temperature and the angle between the straight portions was again recorded.

Samples were cut from selected 180° bend and flat configuration specimens which were mounted in an epoxy resin (Epoxicure, Buehler, UK) and cured for 8 h at room temperature. The mounted samples were polished in a grinder-polisher machine (MetaServ/MetaPol, Buehler, UK). Five sandpapers in decreasing grit sizes (SiC P320, 600, 1000, 2500 & 4000) were used followed by 3 diamond-based dispersions (6 µm, 3 µm and 1 µm). The samples were then examined using an optical microscope (BX51 M/DP70, Olympus, Japan) to establish if the re-shaping and shape recovery processes had any effect on the integrity of the interleaved laminate.

2.4 Results of re-shaping and shape-recovery trials

Table 3 shows the enclosed angle measured between the straight arms after curing, after re-shaping and after shape recovery for the cross-ply and quasi-isotropic laminates.

For the cross ply laminates, 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. (More recent testing has shown that a prolonged period in the oven will usually produce a shape much closer to the as-cured shape.)

For the quasi-isotropic specimens, Table 3 shows that the as-cured shape, the re-shaped geometry and the recovered shape are generally all within 1° of the intended shapes except for one of the flat configurations which was within 2° of the intended shape.

Figures 5 and 6 show frames extracted from videos of quasi-isotropic laminate specimens recovering from the 180° bend and flat configurations. Full recovery of the 180° bend specimen took around 9 min after placing the specimen in the oven and recovery of the flat specimen took a similar duration. (During the early part of this period the oven was recovering its temperature after mounting the specimen and so precise determination of shape recovery times using the current experimental procedure is difficult.) The thinner cross-ply specimens recovered their original shapes in around 2 to 3 min.

Figure 7 shows micrographs from the optical microscope inspection of polished cross sections of specimens taken after the shape recovery process. In all cases there is evidence of voids in the polystyrene layers. These voids form because of outgassing of polystyrene and constricted film shrinkage during the curing of the cfrp plies. This is more significant in the quasi-isotropic specimens. The photographs also show there are breaks (most likely due to transverse tensile failure) in the off-axis plies in some of the laminates.

3. Manufacture and evaluation of a simple deployable structure

3.1 Configuration and manufacture

The adhesively bonded configuration shown in Figure 8a was manufactured. This configuration consisted of flat and 180° bend elements which were formed by re-shaping 90° bend interleaved specimens and these were joined together with straight

carbon epoxy elements. The aim was to investigate the deployment of this configuration to the square shape form shown in Figure 8b.

The re-shaped elements of the assembly were made of the interleaved cross ply laminate shown in Figure 2 but in this case the T300/914C carbon epoxy system (see supplementary info) was used. These elements were the same size as described in section 2.2, and the same manufacturing and re-shaping techniques were used. The ‘straight’ elements of the configuration were formed of an eight-ply unidirectional laminate of T300/914C (non-interleaved). An adhesive (P-2, TML, Japan) was used to bond the re-shaped and straight elements together at room temperature to form the assembly shown in Figure 9. (This adhesive has a maximum operating temperature of 180°C and so can tolerate the temperature required for the deployment process.) The assembly was then placed in an oven and heated to 120°C and the deployment process was videoed. 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 measured.

3.2 Deployment behavior

Figure 10 shows a sequence of frames from a video recording of the deployment process. It can be seen that the deployment occurred as planned and took just under 2½ min to reach the fully deployed shape. Figure 11 shows a photograph of the final shape for the specimen and includes the enclosed angle at each of the corners. The corners labelled 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 intended shape has not been fully achieved as the corners 3 and 4 have an enclosed angle significantly less than the intended value of 90°. Further inspection of the geometry of the specimen showed that this was due to a small manufacturing error at the lower edge where the

spacing between the elements at corners 3 and 4 was 23 mm instead of the intended dimension of 20 mm.

4. Discussion and Conclusions

It has been shown that a polystyrene interleaved carbon-epoxy laminate can be easily deformed when heated to a suitable temperature. This shape is accurately retained when cooled to room temperature with only a small amount of spring-back as indicated by a simple analysis. However examination of the specimens after shape recovery showed that there was damage to the off-axis plies (which was not predicted by the simple analysis) and also voids in the polystyrene interleaf layers. The analytical equations for the maximum ply strains due to the re-shaping process were derived assuming that at elevated temperature the cfrp plies were free to slide relative to each other. In reality the polystyrene will behave viscoelastically which was not considered in the analysis. The rate at which the specimens were re-shaped will be an important consideration and it is therefore likely that there would have been less damage if the specimens had been re-shaped at a slower speed.

Despite the internal damage, the interleaved laminates retained sufficient integrity for the re-shaped specimens to return towards their original cured shape when re-heated. This is because the energy required for the shape recovery stage is largely stored in the 0° laminae, which were undamaged during the re-shaping process. The time required for shape recovery will depend on the viscoelastic properties of the polystyrene at temperatures above its T_g . The recovery times were significantly longer for the quasi-isotropic laminates (8-9 min) than for the cross-ply laminates (2-3 min) but this as expected since each of these laminate layups has two 0° laminae but the quasi-isotropic laminate contains more polystyrene interleaves to be sheared during the shape recovery

process. A simple deployable structure consisting of an assembly of re-shaped elements of the interleaved composite was shown to deploy as intended.

Further research is being conducted to investigate the viscoelastic properties of the interleaf material and its significance in the re-shaping and shape recovery processes.

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References

- [1] J.H. Williams Jr, N. Kousiounelos, Thermoplastic fibre coatings enhance composite strength and toughness, *Fibre Sci Technol.* 11 (1978) 83-88.
- [2] X-Z. Hu, Y-W. Mai, Mode I delamination and fibre bridging in carbon-fibre/epoxy composites with and without PVAL coating, *Comp. Sci. Tech.* 46 (1993) 147-56.
- [3] J.E. Masters, Improved impact and delamination resistance through interleaving, *Key Eng. Mat.* 37 (1989) 317-48.
- [4] O. Ishai, H. Rosenthal, N. Sela, E. Drukker, Effect of selective adhesive interleaving on interlaminar fracture toughness of graphite/ epoxy composite laminates, *Composites*, 19 (1988) 49-54.
- [5] H.A. Maples, P. Robinson, A. Bismarck, Carbon fibre reinforced polymer composites with controllable stiffness: Can it be done? *ECCM15*, Venice, Italy; June 2012.
- [6] P. Robinson, H.A. Maples, O. Gaite, S. Smith, A. Bismarck, High performance carbon fibre reinforced epoxy composites with variable stiffness for use in morphing aerostructures, *ICCM19*, Montreal, Canada; July 2013.
- [7] C. Tridech, H.A. Maples, P. Robinson, A. Bismarck, High performance composites with active stiffness control, *ACS Appl. Mater. Interfaces* 5 (2013) 9111-19.

- [8] H.A. Maples, S. Wakefield, P. Robinson, A. Bismarck, High performance carbon fibre reinforced epoxy composites with controllable stiffness, *Comp. Sci. Tech.* 105 (2014) 134-43.
- [9] H.A. Maples, O. Smith, C. Burgstaller, P. Robinson, A. Bismarck, Improving the ply/interleaf interface in carbon fibre reinforced composites with variable stiffness, *Comp. Sci. Tech.* 128 (2016) 185-92.
- [10] F. Gandhi, S.G. Kang, Beams with controllable flexural stiffness, *Smart Mater. Struct.* 16 (2007) 1179-84.
- [11] G. Murray, F. Gandhi, Multi-layered controllable stiffness beams for morphing: energy, actuation force, and material strain considerations, *Smart Mater. Struct.* 19 (2010) 045002.
- [12] F. Gandhi, G. Murray, S.G. Kang, Flexural stiffness control of multilayered beams, *AIAA J.* 47 (2009) 757-66.
- [13] G.P. McKnight, W. Barvosa-Carter, Variable stiffness structures, Patent US 7892630 B1; 2011.
- [14] W. Raither, A. Bergamini, F. Gandhi, P. Ermanni, Adaptive bending-twist coupling in laminated composite plates by controllable shear stress transfer, *Comp. Part A-Appl. S.* 43 (2012) 1709-16.
- [15] C.P. Henry, G.P. McKnight, A. Enke, R. Bortolin, S. Joshi, 3D FEA simulation of segmented reinforcement variable stiffness composites, SPIE 6929, San Diego, USA; March 2008.
- [16] X. Lan, X.H. Wang, Y.J. Liu, J.S. Leng, Fiber reinforced shape memory polymer composite, its application in a deployable hinge, *Smart Mater. Struct.* 18 (2009) 024002.
- [17] J-P. Kong, N.X. Li, Y-M. Kim, M-S. Kim, S-H. Ahn, M. Cho, Numerical simulation and verification of a curved morphing composite structure with embedded shape memory alloy wire actuators, *J. Intel. Mat. Syst. Str.* 24 (2013) 89-98.

- [18] H. Tobushi, S. Hayashi, K. Hoshio, Y. Makino, N. Miwa, Bending actuation characteristics of shape memory composite with SMA and SMP, *J. Intel. Mat. Syst. Str.* 17 (2006) 1075-81.
- [19] L.J. Hart-Smith, The ten-percent rule for preliminary sizing of fibrous composite structures, *Weight Eng.* 52 (1992) 29-45.
- [20] P.C. Powell, *Engineering with Fibre Polymer Laminates*, Chapman and Hall, 1994.
- [21] D.W. Radford, R.J. Diefendorf, Shape instabilities in composites resulting from laminate anisotropy, *J. Reinf. Plast. Comp.* 12 (1993) 58–75.
- [22] F. Pierron, A. Vautrin, Measurement of the in-plane shear strengths of unidirectional composites with the Iosepescu test, *Comp. Sci. Tech.* 57 (1997) 1653-60.
- [23] B.G. Falzon, K.A. Stevens, G.O. Davies, Postbuckling behaviour of a blade-stiffened composite panel loaded in uniaxial compression, *Comp. Part A-Appl. S.* 31 (2000) 459-68.

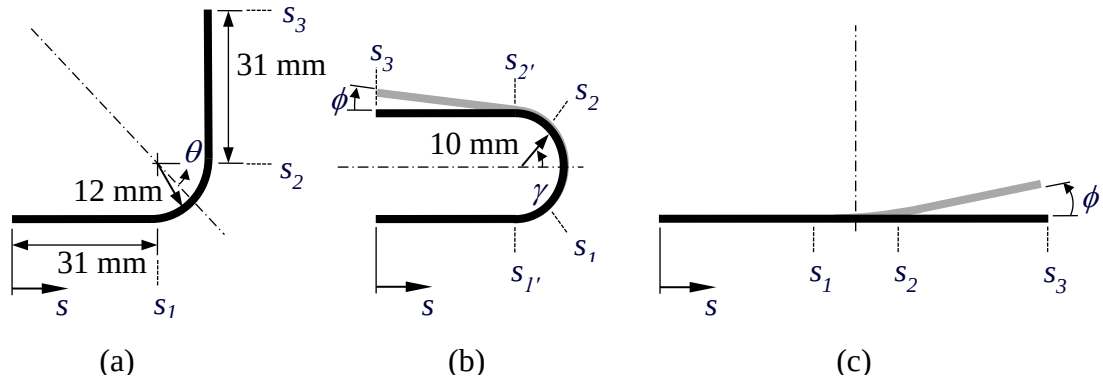


Figure 1: Specimen detail: (a) as-cured shape, (b) re-shaped 180° bend configuration, (c) re-shaped flat configuration. In (b) and (c) the intended re-shaped configurations are shown in black; imperfectly achieved shapes are shown in grey. The parameter s represents locations along the midline of the laminate.

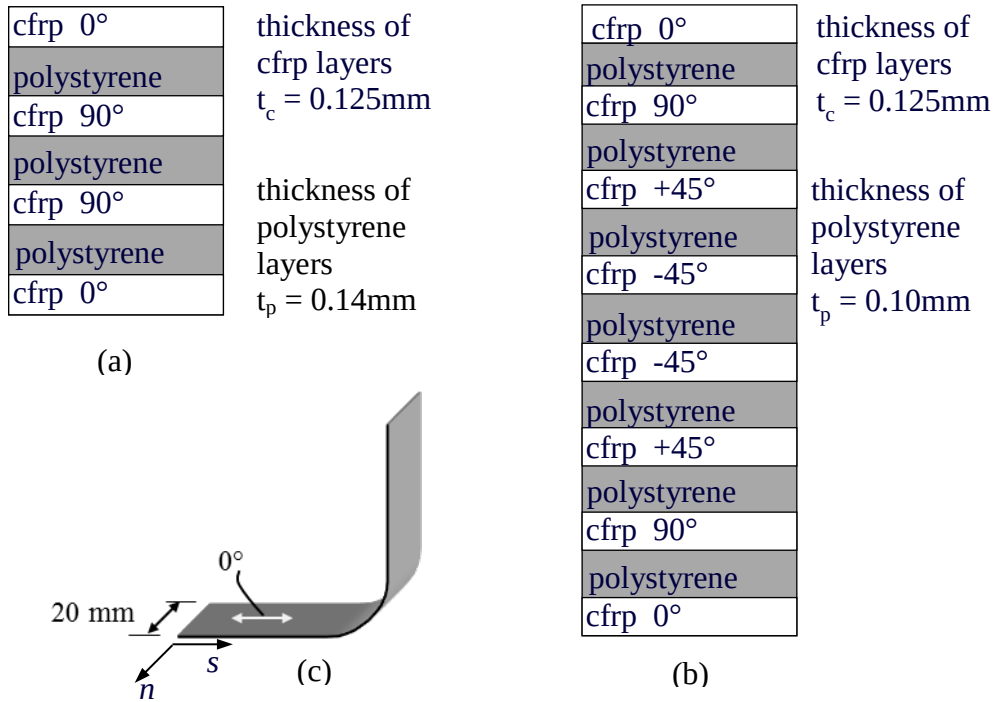


Figure 2: a) Cross ply layup, b) Quasi-isotropic layup, c) 0° fibre, s and n directions in 90° bend specimen.

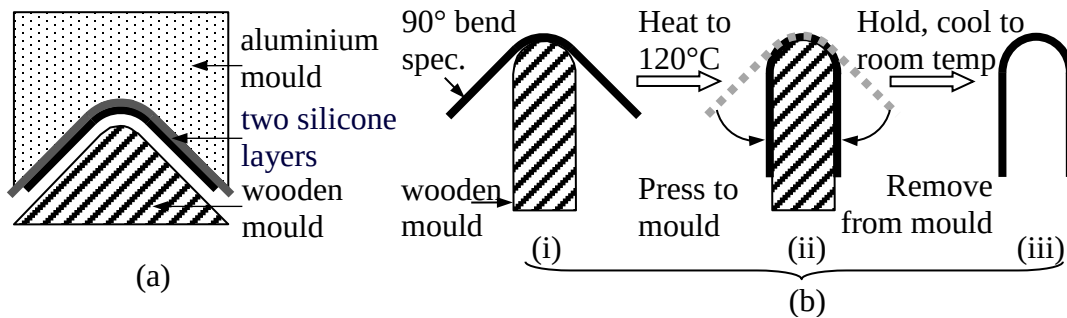


Figure 3: a) Mould arrangement for manufacture of 90° bend specimen b) Re-shaping process steps for production of 180° bend configuration.

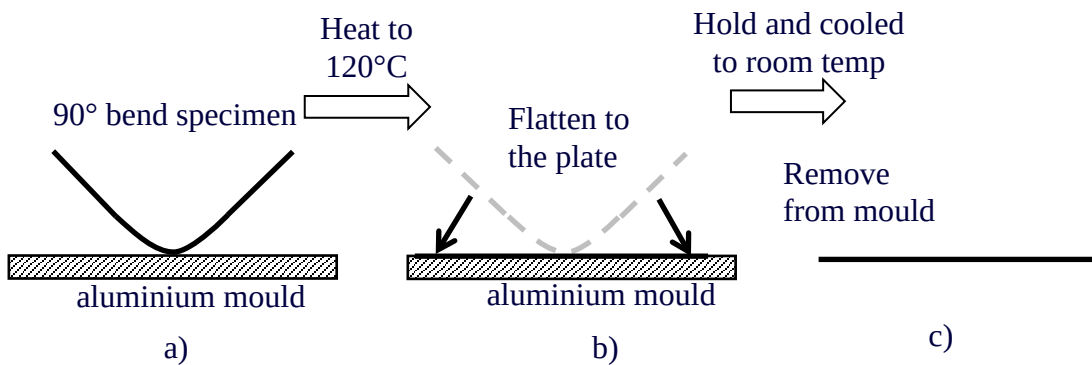
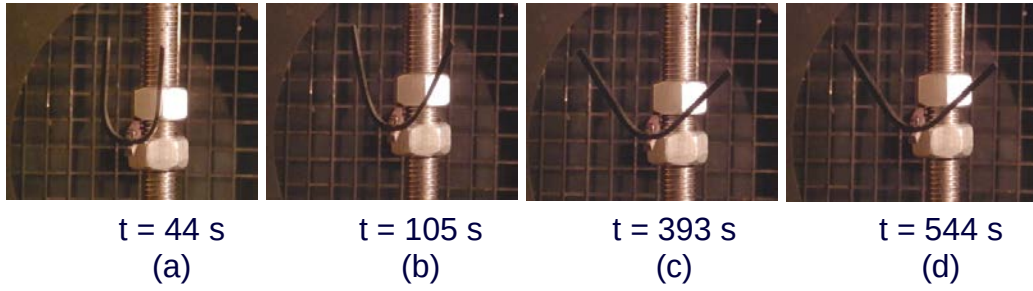
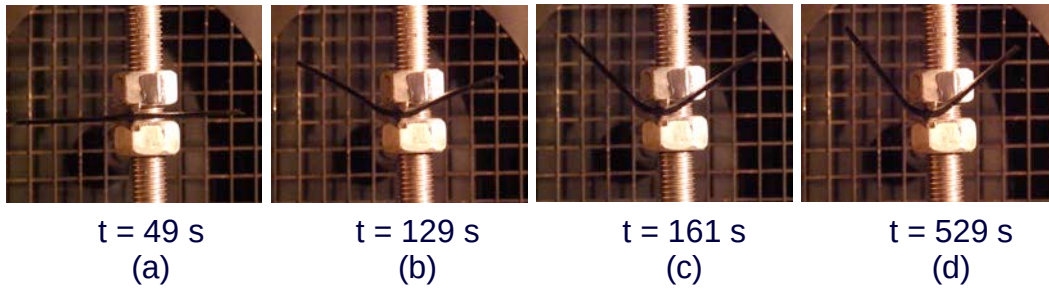


Figure 4: Re-shaping steps for production of flat configuration.



Figures 5: Video frames of quasi-isotropic specimen recovering from 180° bend



Figures 6: Video frames of a quasi-isotropic specimen recovering from flat

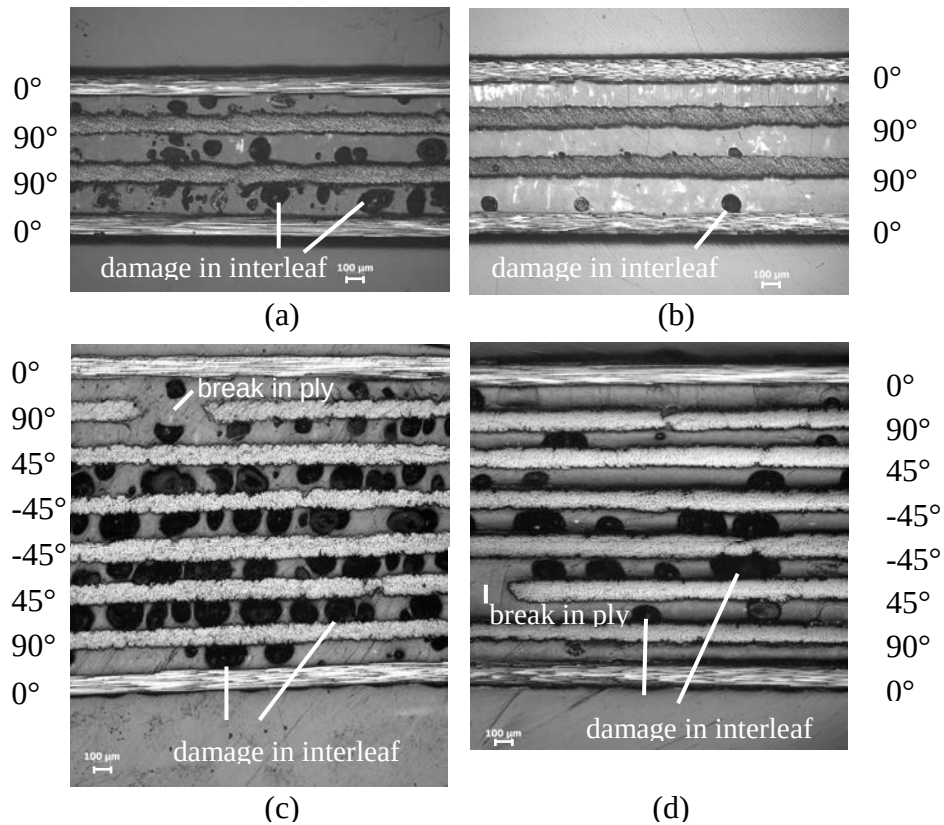
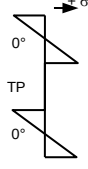
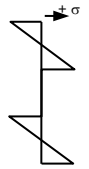
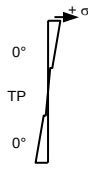
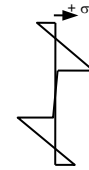
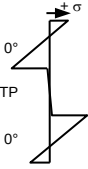
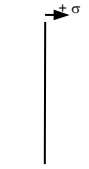
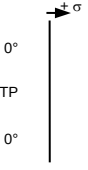


Figure 7: Micrographs from optical microscope inspection of polished cross sections taken after the shape recovery process a) 180° bend cross ply, b) flat cross ply, c) 180° bend quasi-isotropic and d) flat quasi-isotropic.

Table 1: Source of shape memory capability for thermoplastic interleaved laminates.

Stage	Temperature change/ Load	Change in flexural stiffness	Change in stress	Total stress [†]	Spec. shape [‡]
I	Heat to T*, perform 3-pt bending	High $\rightarrow$ Low			
II	Cool to RT at displacement applied in stage I, remove load	Low $\rightarrow$ High			
III	Heat to T*	High $\rightarrow$ Low			
IV	Cool from T* to RT	Low $\rightarrow$ High			

[†]Total stresses are relative to cured state and neglect thermally induced stresses

[‡]Deflected shape prior to stage is shown in grey; shape at end of stage is shown in black

Table 2: Calculated spring back angles.

Calc. method	New shape	Portion of midline	TS/914C				HTS/924C			
			Cross ply		Quasi- isotropic		Cross ply		Quasi- isotropic	
			M^T (N- mm)	ϕ ($^{\circ}$)	M^T (N- mm)	ϕ ($^{\circ}$)	M^T (N- mm)	ϕ ($^{\circ}$)	M^T (N- mm)	ϕ ($^{\circ}$)
Eqns. 2 and 3	180 $^{\circ}$ bend	0 to $s_{1'}$, $s_{2'}$ to s_3	0	0	0	0	0	0	0	0
		$s_{1'}$ to s_1 , s_2 to $s_{2'}$	89	0.77	103	0.22	110	0.77	125	0.22
		s_1 to s_2	14	0.12	16	0.04	18	0.12	20	0.04
		<i>Total</i>	-	0.89	-	0.26	-	0.89	-	0.26
	Flat	0 to s_1 , s_2 to s_3	0	0	0	0	0	0	0	0
		s_1 to s_2	75	0.65	87	0.19	93	0.64	107	0.19
<i>Total</i>		-	0.65	-	0.19	-	0.64	-	0.19	
Eqn. 6	180 $^{\circ}$ bend & Flat	<i>Total</i>	-	0.77	-	0.22	-	0.77	-	0.22

The room temperature flexural stiffness, $(EI)_{RT}$, required for eq 3 and 6 was determined from beam theory for a beam section of multiple materials [20]

Table 3: Enclosed angle measurements for as-cured, after re-shaping and after shape recovery of cross ply and quasi-isotropic laminate specimens.

Specimen	State	Spec. no.	Intended enclosed angle(°)	Measured enclosed angle (°)
Cross ply laminate	As cured	1, 2,3,4	90	89.6*
	Re-shaped to 180° bend	1,2	0	0.8, 0.7
	Recovered from 180° bend	1,2	90	89.6, 89.7
	Re-shaped to flat	3,4	180	175.2, 177.6
	Recovered from flat	3,4	90	97.8, 97.7
Quasi-isotropic laminate	As cured	1, 2,3,4	90	89.2, 89.3, 89.1 89.6
	Re-shaped to 180° bend	1,2	0	0.8, 0.3
	Recovered from 180° bend	1,2	90	89.3, 90.9
	Re-shaped to flat	3,4	180	179.2, 179.2
	Recovered from flat	3,4	90	91.7, 89.8

*For this set only specimen 1 was accurately measured in the as-cured state but visual comparison of these specimens indicated that they all had a very similar enclosed angle close to 90°