Modelling the shape memory capability of an interleaved composite

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Abstract

A composite, consisting of carbon fibre reinforced epoxy laminae and polystyrene interleaf layers, has been developed which exhibits controllable stiffness and a shape memory capability upon heating. This paper investigates finite element modelling of the shape memory capability of this composite. Such modelling could be useful in the design of deployable structures made of this shape memory composite.

1. Introduction

Interleaving has been explored as a method for producing materials which possesses stiffness which can be adjusted on demand. Recently, an interleaved composite, consisting of carbon fibre reinforced epoxy laminae and polystyrene interleaf layers, has been developed which exhibits controllable stiffness and a shape memory capability [1, 2]. Figure 1a shows the stiffness control mechanism of this interleaved composite. When heated to 120°C (above the glass transition temperature of the polystyrene interleaf) the composite losses flexural stiffness because the composite laminae are free to slide relative to each other. The loss in stiffness can be seen in the flexural test plots shown in Figure 1b. At this elevated temperature the composite can be readily deformed in bending. When held in this deformed shape on cooling, the new shape is retained and if subsequently heated, the unconstrained specimen exhibits a shape memory capability as it returns to its original shape, driven by the elastic stress in the composite layers.

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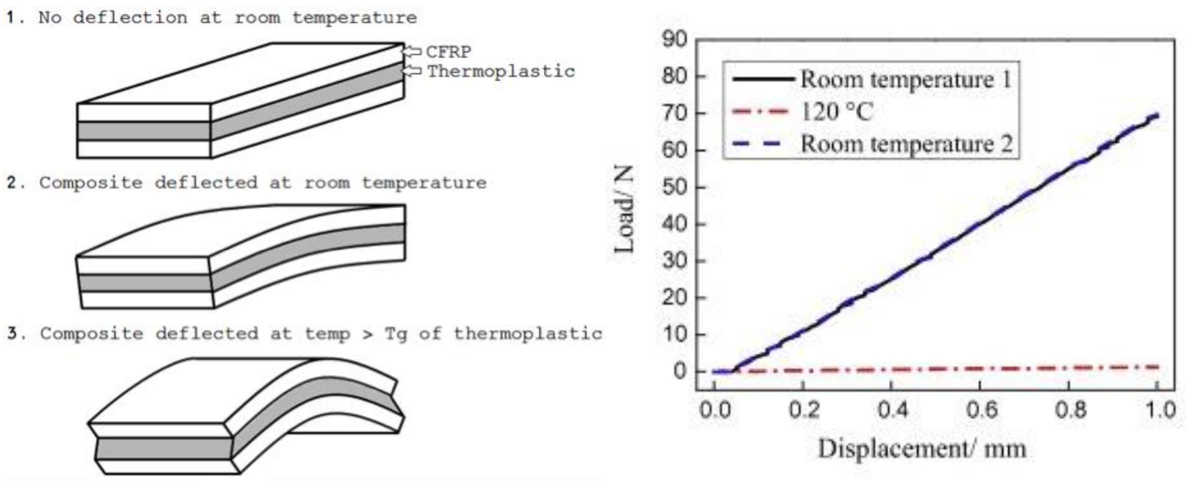

a) b)

Figure 1. a) Concept of interleaved composite with controllable stiffness and b) the load-displacement relationship of a polystyrene-interleaved carbon epoxy composite specimen in 3-point bending at different temperatures [2].

Trials of this composite have been previously performed to experimentally investigate the shape memory capability [1]. A 90° bend specimen, see Figure 2a, in which the bend is formed of a circular arc with an inner radius of 12 mm was used in the investigation. The layup of the specimen was [0°/PS/90°/PS/90°/PS/0°] where PS is a polystyrene interleaf and the other plies are unidirectional carbon epoxy. To test the re-shaping capabilities, this specimen was heated to 120°C and re-shaped manually under a vacuum bag to form a flat specimen (Figure 2b). The specimen was then cooled to room temperature, while maintaining the vacuum, and removed from the mould (Figure 2c). To assess the shape memory of the re-shaped specimen, it was re-heated to 120°C and the extent to which it returned to the original shape was observed (Figure 2d).

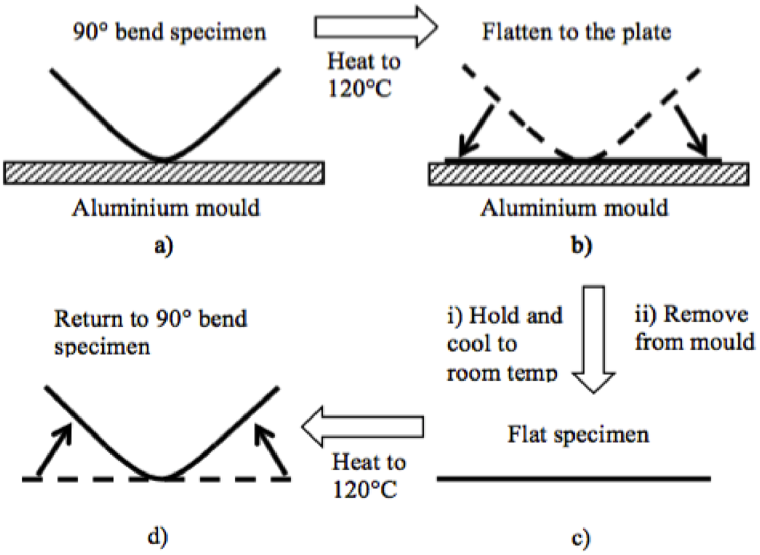

Figure 2. Experimental procedure to assess shape memory capability (a) Initial state of 90° bend specimen (b)-(c) Re-shaping for production of flat configuration and (d) Shape recovery.

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This paper investigates finite element (FE) modelling of the shape memory capability of interleaved composites.

2. Trial shape memory problem

As an initial target FE modelling of the re-shaping and shape recovery of a simple curved interleaved laminate shown in Figure 3 was investigated. The laminate consists of two 0° carbon fibre reinforced polymer (CFRP) plies of thickness 0.125mm separated by a polystyrene interleaf of thickness 0.1mm. For the purposes of the modelling the CFRP is assumed to have the properties of TS300/914 carbon epoxy composite produced by Hexcel and the interleaf to be of polystyrene (general purpose polystyrene 124N/L produced by Styrolution) as used in the previous experimental investigation. The properties that were used in the FE modelling for these materials are shown in Table 1.

Table 1. The properties of the selected carbon epoxy composite and interleaf material in this investigation.

Materials	Property	Value
Hexcel TS300/914 carbon epoxy composite	E_1, GPa	118
	E_2, GPa	8.5
	ν_{12}	0.32
	G_{12}, GPa	3.7
Styrolution polystyrene (25°C)	E, GPa	2.5
	ν_{12}	0.35
	G_{12}, GPa	0.9
Styrolution polystyrene (120°C)	E, GPa	0.03
	ν_{12}	0.35
	G_{12}, GPa	5×10^{-6}

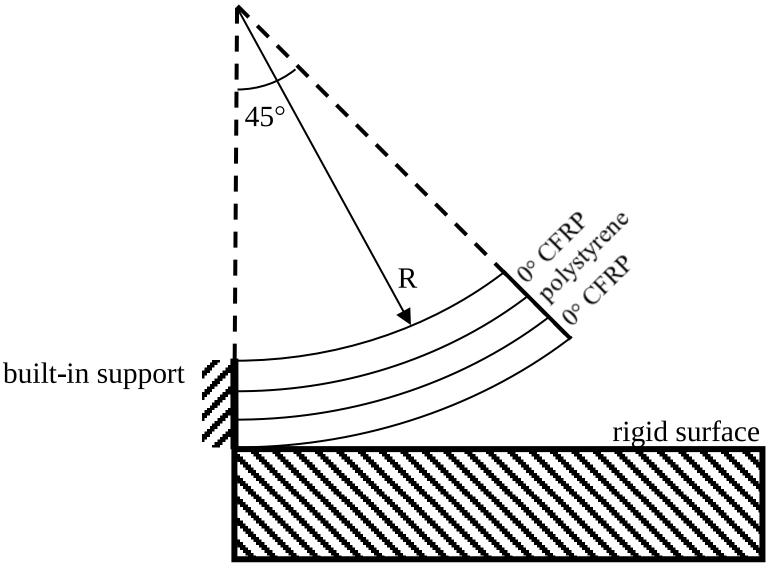

Figure 3. A sketch of the interleaved laminate to be modelled.

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In its initial state the specimen has an upper surface radius of 10 mm, has a subtended angle of 45° and rests on a horizontal rigid surface which is tangential to the lower surface at the left hand end. The specimen is supported by a built-in support at the left hand end as shown.

The steps to be modelled (see Figure 4) are as follows.

step i. *Reshaping* With the polystyrene in its low stiffness state (i.e. as at high temperature), flatten the specimen onto the horizontal rigid surface using a uniformly distributed pressure loading.

step ii. *Springback* When flattened, reset the stiffness of the polystyrene to its room temperature value. Remove the pressure loading and observe any spring back.

step iii. *Shape Recovery* Change the stiffness of the polystyrene to its low value (i.e. as at high temperature) and observe the extent to which the specimen returns to its original shape.

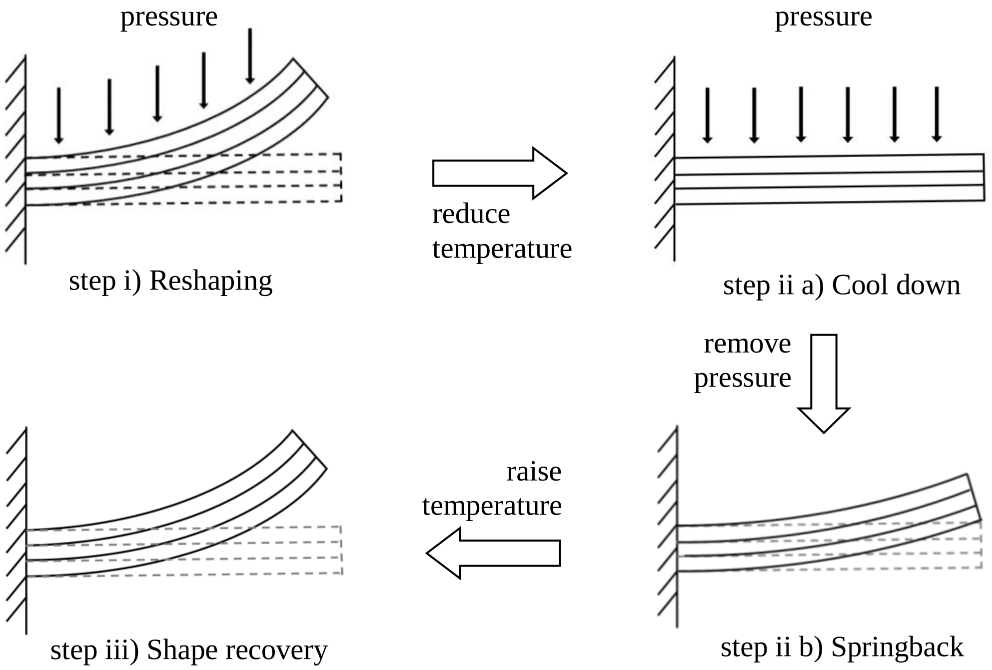

Figure 4. A sketch of the reshaping and shape recovery cycle of a curved interleaved composite

3. FE model and results

3.1. Details of the finite element model

The modelling was performed with the ABAQUS finite element software. Two-dimensional, 4-node, plane stress elements with reduced integration were used to model the specimen. A fine mesh was used with the smallest elements being square with a side length of 0.02mm. The elements of the composite were assigned the orthotropic properties shown in Table 1 for both high and low temperature states. For the polystyrene, at room temperature the isotropic properties shown in Table 1 were used. For elevated temperature, the polystyrene was assigned the orthotropic properties shown in

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Table 1. These elevated-temperature properties consisted of a very low shear modulus (to allow the CFRP plies to slide relative to each other) and a relatively high Young's modulus (but still much lower than the room temperature value) to reduce the tendency for the polystyrene to be extended or compressed excessively in the through-thickness direction.

Constraints were introduced to achieve the built-in end condition for the left side of the specimen. A rigid body was modelled to provide the horizontal surface below the specimen. A surface-to-surface penalty contact was used between the lower surface of the specimen (slave surface) and the horizontal rigid surface (master surface).

A dynamic, explicit solution including non-linear geometry was used. Mass-proportional damping was applied to the specimen to control excessive oscillations during the solution.

3.2 Modelling strategy for processing steps

The modelling of the individual processing steps was performed as follows.

step i. *Reshaping* The specimen was assigned with the high temperature stiffness properties and was loaded with a uniform downward pressure loading to drive the specimen down on to the horizontal rigid surface. The pressure loading was linearly increased from zero to 0.81 MN/m^2 in 2 seconds and then held constant. The mass damping coefficient was set at 0.1 s^{-1}.

step ii. *Springback* From the equilibrium state achieved at the end of step i a restart analysis was performed. The deformed geometry of the interleaved laminate was imported together with the stresses in the upper and lower carbon epoxy plies. The polystyrene stresses were set to zero and its stiffness was reset to its room temperature value i.e. its high stiffness. The pressure loading was held constant at 0.81 MN/m^2 (the peak value applied in step i for 4 seconds and then linearly reduced to zero in 2 seconds. The mass damping coefficient was kept at 0.1 s^{-1}.

step iii. *Shape Recovery* From the equilibrium state achieved at the end of step ii a second restart analysis was performed. Again, the deformed geometry of the laminate was imported from the previous analysis together with the stresses in the upper and lower composite plies. The polystyrene stresses were set to zero and its stiffness was now returned to its high temperature value i.e. its low stiffness. The mass damping coefficient was set at 0.5 s^{-1} for this final stage.

3.3. Results and discussion

step i. *Reshaping* The deflected form of the specimen at the end of the re-shaping process is shown in Figure 5. The specimen is not completely flattened to the rigid surface; a small portion at the right hand end does not reach the horizontal but this is as expected. The stresses in the CFRP laminae are close to pure bending stresses and the magnitudes are very similar to those predicted by simple beam theory. The shear stress in the polystyrene varies almost linearly from zero at the left hand end to 2600 N/m^2 at the right hand end.

step ii. *Springback* The FE analysis predicted only a small upward displacement of 0.39 mm at the right hand end at the end of step ii and this was accompanied by a small change in the stress state of the CFRP laminae. The magnitude of the shear stress in the polystyrene significantly increased to 1.3×10^6 N/m^2.

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step iii. *Shape Recovery* The predicted final equilibrium state achieved at the end of step iii is shown in Figure 6 and is compared to the initial shape of the specimen. It can be seen that the specimen has almost fully returned to its initial geometry. The stresses in the CFRP are now small (maximum value of approx. 2.0×10^7 N/m^2) and the stresses in the polystyrene are also very low.

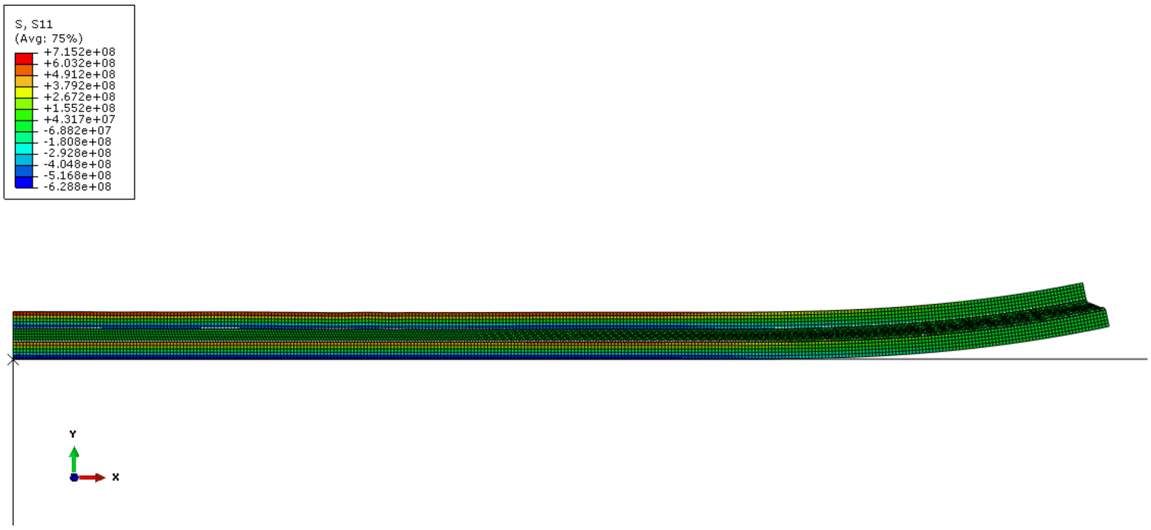

Figure 5. The deflected geometry of the interleaved laminate at the end of the reshaping process.

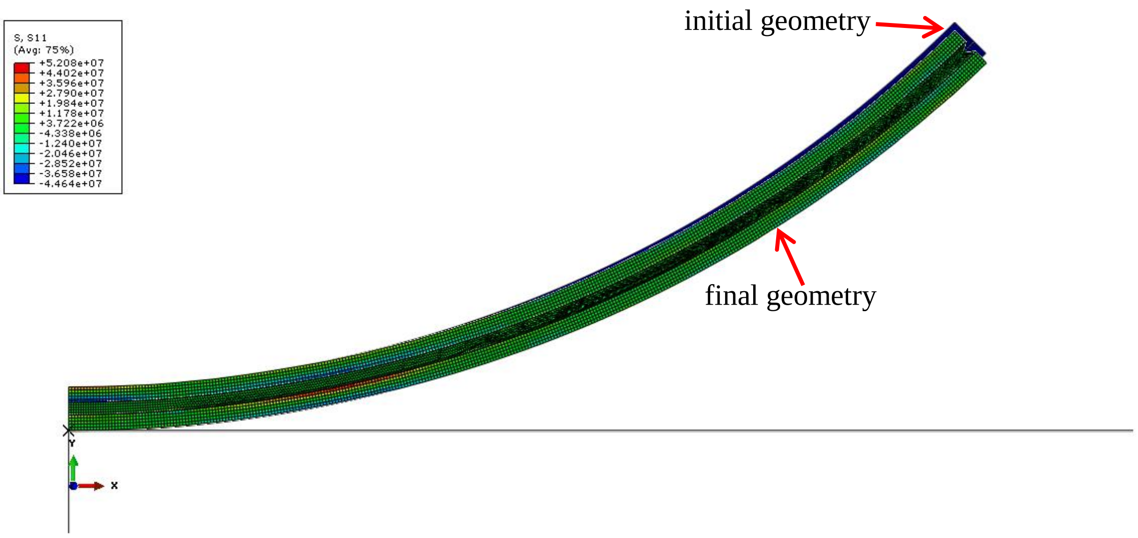

Figure 6. The final geometry of the interleaved laminate at the end of the shape recovery process.

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4. Conclusion

Finite element modelling has successfully been performed of the reshaping, springback and shape recovery of a specimen made of an interleaved composite. The modelling is now being applied to other specimen shapes for which experimental observations are available for validation.

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