DEVELOPMENT OF AN INTERLEAVED COMPOSITE WITH A TWO-STAGE SHAPE MEMORY CAPABILITY FOR DEPLOYABLE STRUCTURE APPLICATIONS

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Abstract
A carbon fibre epoxy composite laminate containing thermoplastic interleaves has been shown to provide an easy route for the manufacture of an expanded composite mesh. A two-stage shape memory composite using two different interleaf materials has been developed and this has been used to create a mesh that can deploy from the flat state into an expanded state. Creep of one of the interleaf materials, during flattening and deployment, limited the extent of the deployment but a better choice of interleaf materials should overcome this shortcoming.

1. Introduction

Carbon fibre/epoxy composite laminates with thermoplastic interleaves have been shown to exhibit controllable stiffness [1-3] and shape memory capabilities [4-6]. The mechanism responsible for these novel capabilities is illustrated in Figure 1 for a simple laminate consisting of two carbon/epoxy laminae separated by a thermoplastic interleaf. When heated to above the glass transition temperature, T_g, of the interleaf material, the stiffness of the interleaf is significantly reduced, so that the composite plies can slide relative to each other. As a result, the laminate has a low flexural stiffness and can be readily re-shaped in bending as shown here. This temporary shape is retained if held in this shape while cooling down to below T_g and the flexural stiffness of the laminate is restored. Upon re-heating to above the glass transition temperature of the interleaf material, the unconstrained laminate recovers towards its original shape due to the release of the stored elastic strain in the composite plies.

Trials have been conducted to demonstrate the potential of an interleaved composite for use in deployable structures [4]. Figure 2 shows the deployment process of a deployable box section made of the interleaved composite 'hinge' segments at corners adhesively bonded to straight segments of non-interleaved carbon fibre/epoxy laminate (i.e. possessing no shape memory capability). The interleaved segments were made of carbon fibre/epoxy composite laminates containing polystyrene interleaves. It can be seen that the box section deployed from the 'collapsed' state to the square shape within 150 seconds.

This paper describes the use of the interleaved composite to produce a composite expanded mesh (like the expanded metal mesh shown in Figure 3a) from a flat laminate and how a two-stage shape memory capability can be introduced to enable the composite mesh to deploy from the flattened state.

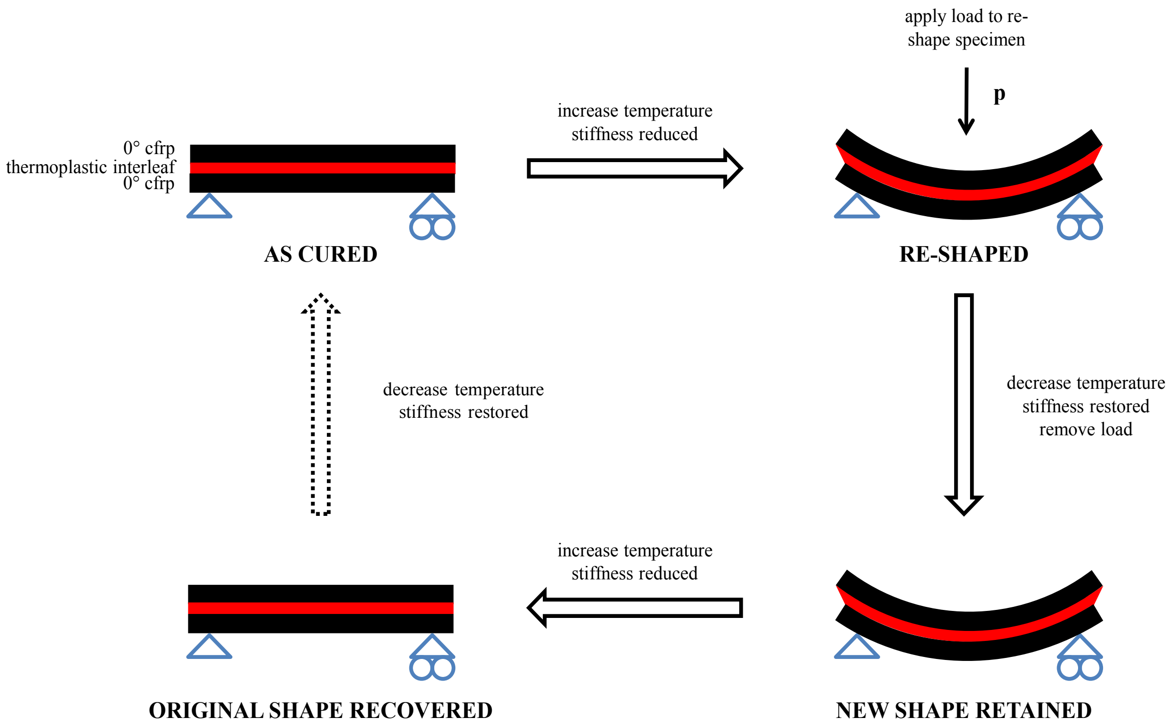

Figure 1. Mechanism of stiffness control and the shape memory capability of the interleaved composite.

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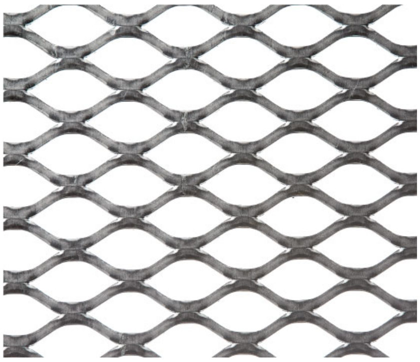
Figure 2. A sequence of frames from the deployment video of a deployable box section structure using interleaved composite 'hinges' [4].

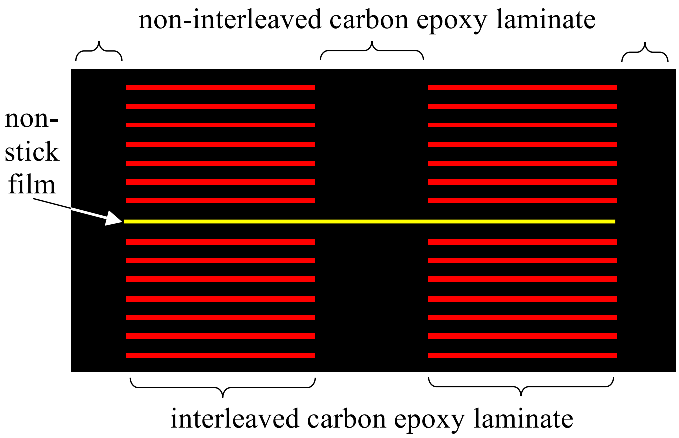
2. Design and manufacture of a composite expanded mesh

2.1 Design concept

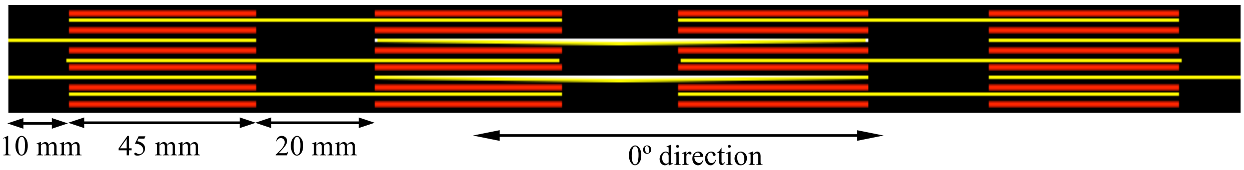
The concept was to manufacture a flat composite laminate containing specific sections interleaved with a thermoplastic as shown in Figure 3b. The laminate layup would also include non-stick films at locations which would become open in the expanded state. After curing the flat laminate (see Figure 3c) would be heated to above the T_g of the interleaf and then, with the interleaved laminate sections in their low stiffness state, the laminate is pulled open to expand the mesh and then cooled to 'lock in' the expanded shape (see Figure 3d).



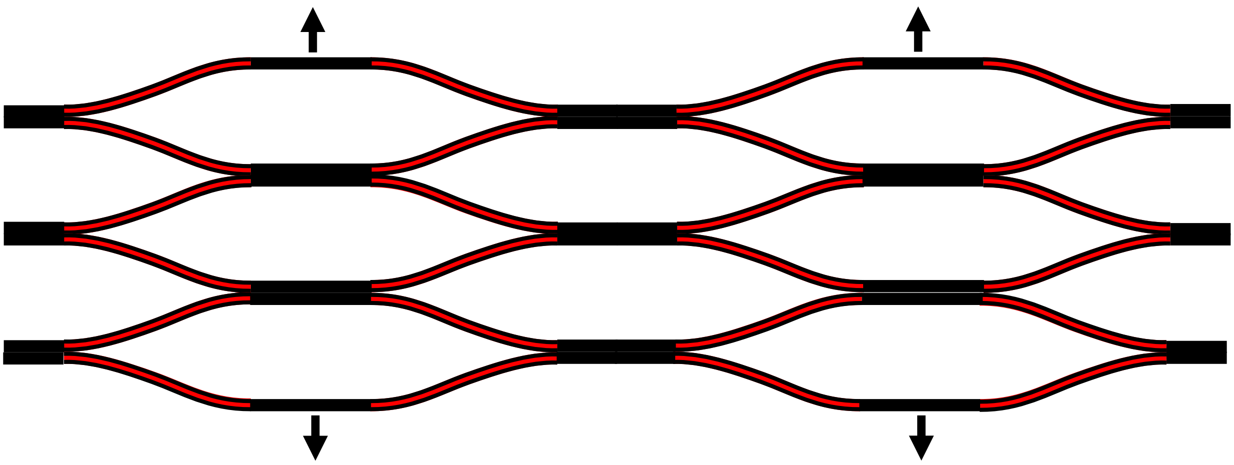
a) Example of expanded metal mesh



b) Layup of single cell for composite mesh



c) Laminate for making a composite mesh (2 cells wide, 3 cells high)



d) Expanded composite mesh

Figure 3. Concept for making an expanded composite mesh

2.2 Materials and Manufacture

The materials used were unidirectional carbon fibre/epoxy composite prepreg (T300/914 produced by Hexcel) with a cured ply thickness of 0.125 mm, and, as the interleaf, a 0.1 mm thick polystyrene film (supplied by TCKT). The glass transition temperature (T_g) of the polystyrene was measured to be 85°C using a DSC. (This is considerably lower than the T_g of the cured epoxy matrix at 180°C.) Basic mechanical properties of these materials are shown in Table 1. The non-stick film was a fluoro polymer film with a thickness of 0.012 mm.

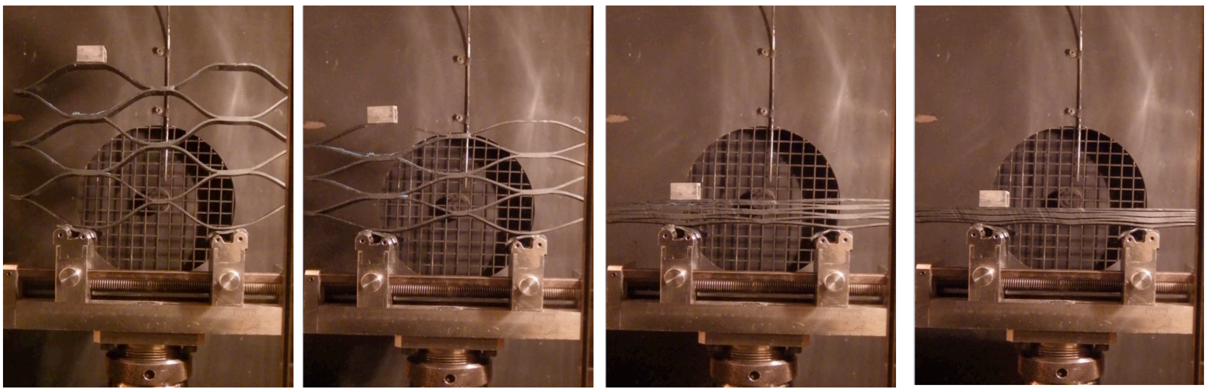
Table 1. The properties of the materials.

Materials	Property	Value
Hexcel TS300/914 carbon epoxy composite	E_1, GPa	135
	E_2, GPa	8.5
	ν_{12}	0.32
	G_{12}, GPa	3.42
Styrolution polystyrene (120°C)	E, GPa	0.08
	G, GPa	0.03

For the single cell shown in Figure 3b, the non-interleaved sections consisted of thirty 0° carbon-epoxy plies and the interleaved sections of consisted of sixteen 0° carbon-epoxy plies and fourteen polystyrene interleaf films arranged as indicated in the figure. The width of the non-interleaved and interleaved sections are shown in Figure 3c.

The laminate was cured according to the manufacturer's recommended schedule. A 20 mm wide strip cut from the cured laminate was heated to 120°C and the laminate was pulled open into the expanded mesh with each cell opened up to 54 mm. On cooling, the mesh retained the expanded form and confirmed that the controllable stiffness of the interleaved laminate could be exploited to enable the manufacture of a mesh structure that would be difficult to produce by other means.

As noted earlier the interleaved composite has a shape memory and in this case the composite mesh 'remembers' its original flat form. On heating to 120°C in an unconstrained state, the mesh returned to its original, flat configuration within 8 minutes as shown in Figure 4.



t = 0 s (a) t = 80 s (b) t = 170 s (c) t = 470 s (d)

Figure 4. Still images extracted from a video of the shape recovery of the expanded composite mesh

3. Design and manufacture of a composite mesh that deploys from the flat state

For practical applications, it would be more useful if the mesh can deploy from the flat state to the expanded state. There are several methods by which a deployable mesh could be achieved and this section describes one technique which involves the use of two different interleaf films to create a composite with a two stage shape memory.

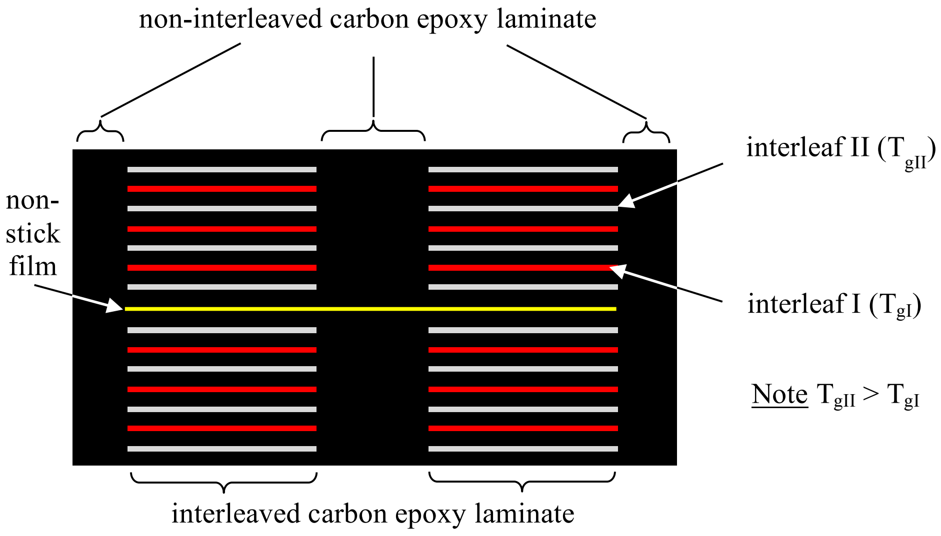
3.1 Design concept

The concept for achieving a two stage shape memory is illustrated for a single cell of the mesh in Figure 5. The interleaved laminate sections now contain two interleaf materials as shown in Figure 5a. These are labelled as interleaf materials I and II and have glass transition temperatures of T_{gI} and T_{gII} respectively where $T_{gII} > T_{gI}$. After curing, the laminate can be trained as shown in Figure 5b. Initially, the laminate is heated to a high temperature, T_H, where $T_H > T_{gII}$. At this temperature both interleaf materials are in a softened state and so the carbon-epoxy plies in the interleaved sections can slide relative to each other. In this state the laminate can be easily deformed into the expanded mesh geometry. The mesh is now cooled to an intermediate temperature, T_M, where $T_{gII} > T_M > T_{gI}$. At this temperature only interleaf material I is in a softened state and so the sublaminates formed by pairs of carbon epoxy plies immediately adjacent to a layer of interleaf material II will have their full flexural stiffness. When the laminate is pressed back to flat at this temperature, bending stresses will be developed in these sublaminates and if cooled down to room temperature while held in the flattened state these stresses will be 'locked in' and the flattened state will be almost fully retained when released. When subsequently heated back to T_M in an unconstrained state, the laminate will deploy to the expanded state driven by the stresses stored in the sublaminates containing interleaf II material layers.

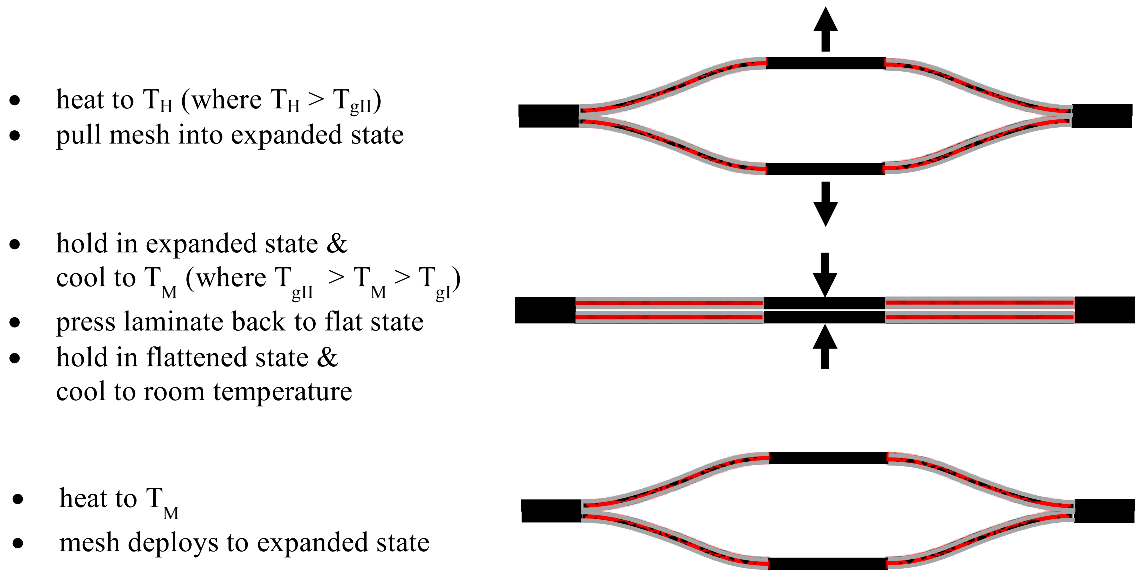
3.2. Materials, Manufacture and Deployment Trial

The two stage shape memory laminate for a single cell was manufactured using the same materials described in section 2.2 together with polycarbonate (with a Tg of 153°C) which was used as interleaf material II.

The new laminate was re-shaped at 160°C (i.e. T_H) into the expanded configuration with the mesh opened by 20 mm and this was then cooled to room temperature. As expected the expanded shape was retained on cooling. (This shape is the 'trained' shape.) The expanded mesh was then re-heated to 120°C (i.e. T_M) and pressed down to the flat configuration. While held in the flattened configuration, the laminate was cooled to room temperature and it was observed that the laminate retained the flattened state when released. On re-heating to 120 °C in an unconstrained state the mesh started to deploy towards the expanded geometry configuration but the final opening displacement was only 6 mm (i.e. significantly less than the geometry of the trained state).



a) Layup of single cell for two-stage composite mesh



b) Training sequence and deployment of two-stage shape memory composite mesh laminate

Figure 5. Concept for making an expanded composite mesh

4. Discussion and Conclusions

It has been shown that an expanded composite mesh can be readily manufactured using carbon-epoxy laminates containing thermoplastic interleaves. Due to the controllable stiffness exhibited by these laminates, it was possible to cure a flat laminate and then pull the laminate open at a suitably elevated temperature to create the expanded mesh. It was shown that this mesh could recover its original flat form when heated because of the shape memory of the interleaved composite.

An investigation was conducted to develop an interleaved composite laminate with a two-stage shape memory and to use this laminate to make a mesh that can deploy from the flat to the expanded state when heated. The two-stage laminate used two interleaf materials; polystyrene and polycarbonate. The mesh did deploy from the flat state but did not fully achieve the intended geometry. Subsequent tests have shown that the polycarbonate interleaf layers exhibit significant creep at a temperature of 120ºC (the temperature used when flattening the laminate and for the deployment process). Due to this creep, stresses were lost during the flattening and deployment stages, and this is what caused the mesh expansion during deployment to be less than intended. If a suitable low-creep replacement for polycarbonate can be identified there is good reason to expect the two-stage shape memory laminate will be a successful means of creating an expanded composite mesh that can deploy from the flattened state.

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