AN INVESTIGATION OF THE VISCOELASTIC BEHAVIOUR OF INTERLEAVED COMPOSITE WITH SHAPE MEMORY CAPABILITY

B. Zhang[1], P. Robinson[1], A. Bismarck[2,3], H.A. Maples[3] and C. Burgstaller[4]

[1] The Composites Centre, Department of Aeronautics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
Email: bohao.zhang12@imperial.ac.uk, p.robinson@imperial.ac.uk
[2] Polymer and Composite Engineering (PaCE) group, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
Email: a.bismarck@imperial.ac.uk
[3] Polymer and Composite Engineering (PaCE) group, Department of Material Chemistry, University of Vienna, Waehringer Strasse 42, A-1090 Wien, Austria
Email: alexander.bismarck@univie.ac.at, henry.maples@univie.ac.at
[4] Transfercenter für Kunststofftechnik (TCKT), Franz-Fritsch-Straße 11, A-4600, Wels, Austria

Keywords: Interleaved composites, Shape memory, Viscoelastic behaviour, Finite element analysis

ABSTRACT

A carbon fibre/epoxy composite with thermoplastic interleaves has been developed which exhibits shape memory capabilities upon heating. The shape memory capability was previously modelled using finite elements but the viscoelastic behaviour of the interleaf was not considered. This paper reports on an experimental and modelling investigation into the viscoelastic behaviour of the interleaved composite. This has a significant effect on the re-shaping of this interleaved composite and on the deployment time of structures made of this material.

1 INTRODUCTION

An interleaved composite, consisting of carbon fibre/epoxy laminae and polystyrene interleaf layers, has been developed which exhibits the shape memory capability on heating [1-4]. The shape memory mechanism of this composite is shown in Figure 1. By heating to 120°C which is significantly above the glass transition temperature of the interleaf, the polystyrene interleaf losses stiffness and thus the composite laminae can slide relative to each other. At this state, the composite can be readily re-shaped in bending. If kept in this temporary shape while cooling down, the composite regains its flexural stiffness and the new shape is retained. When re-heated to 120°C, the composite recovers its original shape due to the stored elastic stresses in the composite laminae.

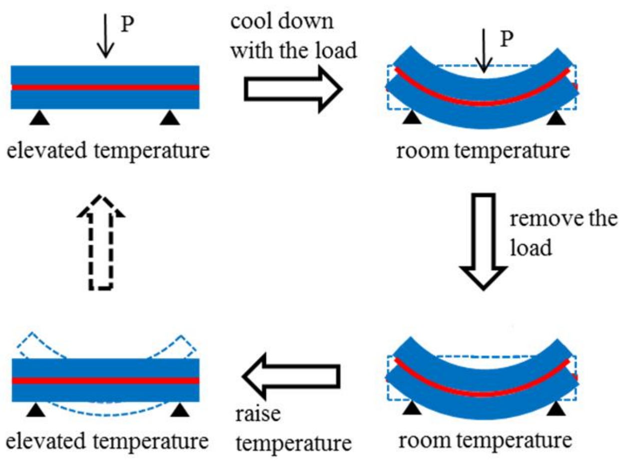

Figure 1: Concept of the interleaved composite with the shape memory capability.

Trials of this composite have been conducted to investigate the shape memory capability. The experimental results have shown that the composite exhibits excellent re-shaping and shape recovery capabilities [4]. However, it was found that some of the interior laminae were damaged and this may be due to the viscoelastic behaviour of the interleaf at elevated temperature. Finite element modelling has been conducted to predict the shape memory capability of these interleaved laminates [2], but did not consider the effect of viscoelasticity of the interleaf.

This paper investigates the viscoelastic behaviour of the interleaved composites in both experiments and modelling. It describes the design and manufacture of the interleaved composite specimens, the development of the finite element model to investigate the viscoelastic behaviour and examines the importance of this behaviour in three-point flexure tests.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

A carbon fibre/epoxy composite (TS300/914, thickness of 0.125 mm, purchased from Hexcel) was used in the current work. Polystyrene, supplied as films from TCKT, was selected as the interleaf material (0.1 mm thickness). Basic mechanical properties of these materials are shown in Table 1. The glass transition temperature (T_g) of the polystyrene is 87°C measured in DSC and this is lower than the T_g of the cured epoxy matrix at 180°C.

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	3.7
Styrolution polystyrene (25°C) (isotropic)	E, GPa	2.5
	ν_{12}	0.35
	G_{12}, GPa	0.9
Styrolution polystyrene (120°C)	E, MPa	1.0
	ν_{12}	0.35
	G_{12}, MPa	0.05

Table 1: The properties of the materials.

2.2 Specimen design and manufacture

Laminates consisting of 8 plies of carbon fibre/epoxy composite laminae and 7 polystyrene (PS) interleaves were manufactured in a unidirectional layup [0°/PS/0°/PS/0°/PS/0°/PS/0°/PS/0°/PS/0°/PS/0°]. These laminates were cured in an autoclave according to manufacturer’s recommendation. After this, the cured laminates were c-scanned to check for defects. Sections of the laminates were mounted in polyester resin, polished by an automatic grinding-polishing machine (SAPHIR 550, Germany) using diamond (9μm), alumina (0.3μm) and silica (0.06μm) abrasives and examined under optical microscope (ZEISS, Germany). Flexure specimens (80 mm long and 10 mm wide) were prepared from the laminates (see Figure 2).

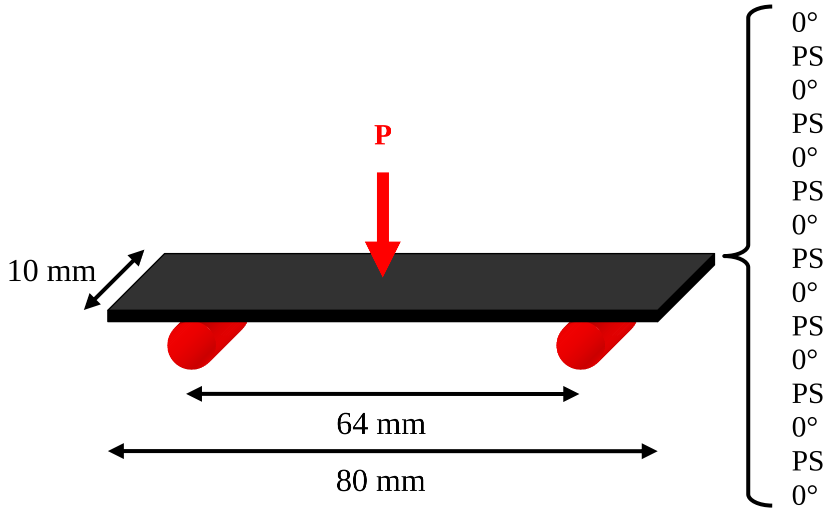

Figure 2: A sketch of the flexure specimen with the layup configuration.

2.3 Flexure testing

Flexure testing was conducted to investigate the stiffness variation and the viscoelastic behaviour of the interleaved composite. Specimens were subjected to three-point bend tests according to ASTM D7264 standard. They were placed on a three-point bending fixture at a support span of 64 mm. Rollers of 6 mm in diameter were used. The test was performed on an Instron universal test machine (Instron 5985 fitted with a 1 kN load cell) within an environmental chamber.

For the investigation of the stiffness variation, specimens of the material were initially loaded to a 1.5 mm displacement at 1 mm/min and then unloaded at the same rate at room temperature. The specimens were then heated to 120°C in the chamber and kept at this temperature for 15 minutes. The heated specimens were loaded to a 5.0 mm displacement at 1 mm/min and then unloaded at the same displacement rate. Load and displacement were measured for all tests.

For the investigation of the viscoelastic behaviour, specimens were initially heated to 120°C in the chamber and kept at this temperature for 15 minutes. They were repeatedly loaded to a 5.0 mm displacement for crosshead speeds of 1, 10, 100 and 200 mm/min. After loading, specimens were kept at this displacement for 10 minutes to measure any change in applied load, and then were rapidly unloaded at 400 mm/min. Upon unloading, the specimens recovered towards the original straight configuration. Throughout these tests the vertical displacement of the specimens was monitored by an iMetrum optical video gauge system.

3 MODELLING

3.1 Details of the finite element model

The stiffness variation and viscoelastic behaviour of the interleaved composite was investigated using finite element modelling in Abaqus (Abaqus 6.14). A 2-dimensional model of the interleaved laminate flexure test was developed, as shown in Figure 3. The laminate consisted of 8 carbon fibre/epoxy composite plies and 7 polystyrene interleaves (see Figure 2). The composite plies were assigned the orthotropic properties shown in Table 1 for both room and elevated temperature states. For the polystyrene, at room temperature the isotropic properties shown in Table 1 were used. Whereas at elevated temperature, the polystyrene was assigned the orthotropic properties shown in 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 to reduce the tendency for the polystyrene to be compressed excessively in the through-thickness direction.

Viscoelastic properties of the polystyrene at elevated temperature were also included in the finite element model. These were measured in DMTA tests. Rectangular polystyrene specimens (12 mm long, 16 mm wide and 1 mm thick) were subjected to a frequency sweep test in shear model in a DMTA machine (RSA-G2, TA Instruments). The maximum applied shear strain was 12% and the frequency in the range from 0.09 rad/s to 11.9 rad/s. (These values are consistent with the shear strain rate measured from the three-point bending tests.) The resulting storage and loss modulus were measured and input into the Abaqus using Prony series provided in the software (Abaqus 6.14).

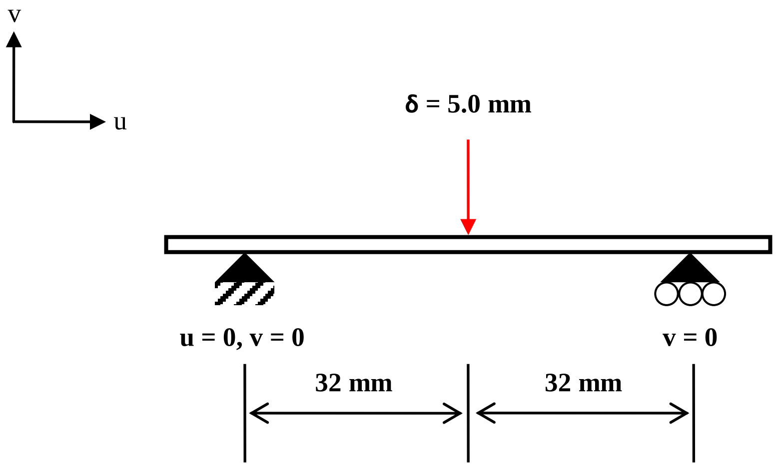

Figure 3: A sketch of the model of three-point bending an interleaved laminate in Abaqus.

The laminate (80 mm long and 1.7 mm thick) was meshed with two-dimensional, 4-node, plane stress elements with reduced integration. Typically, a square mesh with a side length of 0.1 mm (i.e. one element through the thickness of the polystyrene interleaf) was used for the polystyrene interleaf, so that the hourglass effect can be avoided.

Surface-to-surface tie constraints were applied at interfaces of the polystyrene interleaf with adjacent composite plies to prevent ply separation during modelling. Node constraints were introduced to achieve the supporting conditions on the lower surface of the laminate. A vertical displacement of 5.0 mm was applied to the laminate at the position shown in Figure 3.

3.2 Procedures

The modelling investigated the stiffness variation and viscoelastic behaviour of the interleaved composite. It was performed as follows.

Stiffness variation The specimen was firstly assigned the room temperature properties and was loaded with a mid-span vertical displacement of 1.5 mm to bend the specimen. The displacement was applied at a speed of 1 mm/min. In a second load case, the specimen was then assigned the elevated temperature properties and was loaded at the same rate to a mid-span displacement of 5.0 mm. A dynamic, explicit solution including non-linear geometry was used for both cases.

Viscoelastic behaviour The specimen was assigned the elevated temperature properties and was loaded in displacement control at speeds of 1, 10, 100 and 200 mm/min. The displacement was applied to 5.0 mm and then held constant for 10 s. It was then removed at 400 mm/min and the specimen allowed to recover towards the original straight shape. A dynamic, explicit solution including non-linear geometry was again used. Figure 4 summaries the modelling steps.

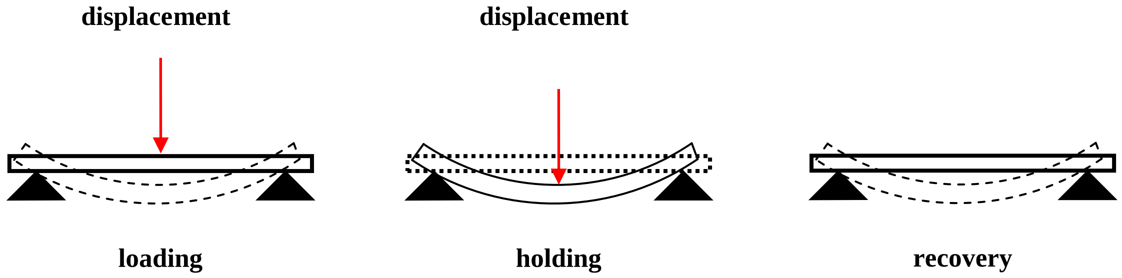

Figure 4: The modelling steps of the viscoelastic flexure test in Abaqus.

4 RESULTS AND DISCUSSION

4.1 Stiffness variation

Figure 5 shows the experimentally observed load-displacement responses of the interleaved specimen subjected to three-point bend tests at room temperature and 120°C. It can be seen that on heating the flexural stiffness of the specimen reduces significantly by over 98%.

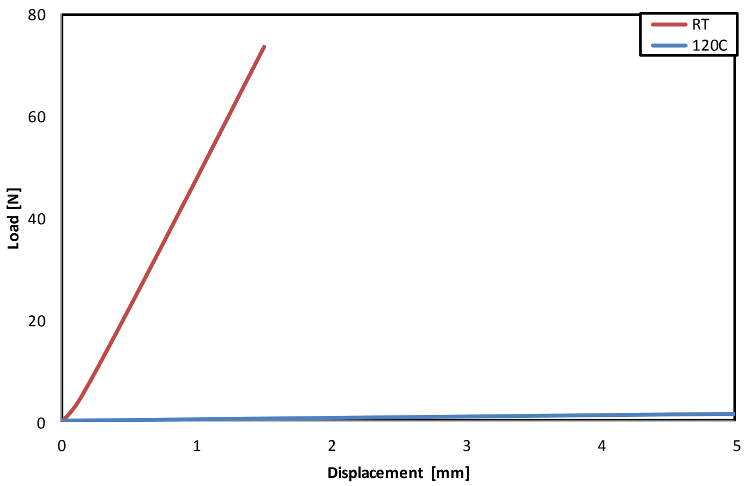

Figure 5: The load-displacement curves of the interleaved flexure specimen loaded at room temperature and 120°C.

4.2 Viscoelastic behaviour

Figure 6 shows the load-displacement curves from three-point bend tests of the interleaved specimen loaded at different crosshead speeds. These curves confirm that there is a rate dependence due to the viscoelastic behaviour of the polystyrene interleaf (the initial slope increases with increasing displacement rate). Such rate dependence indicates that the force required to re-shape such an interleaved composite and the stress developed with the composite will depend on the speed of the re-shaping process. Figure 6 also includes the FE-predicted behaviour for the 200 mm/min loading rate. The rate dependence of the interleaved composite in flexure is reasonably predicted by the finite element modelling.

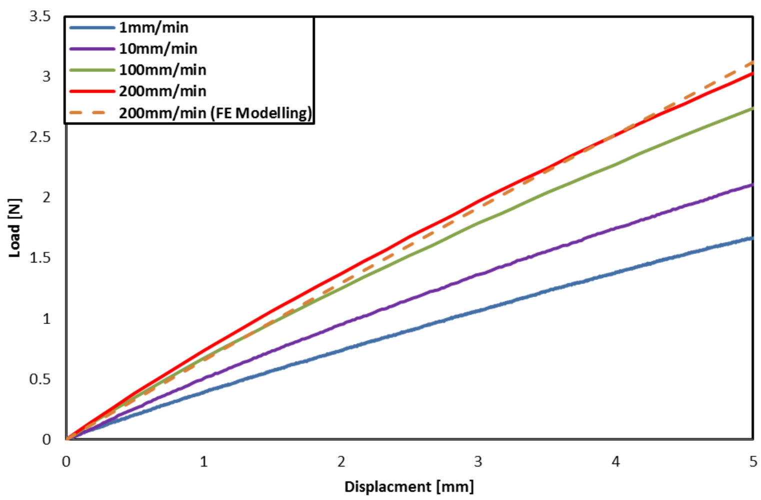

Figure 6: The load-displacement curves of the interleaved specimen subjected to three-point bending tests at various crosshead speeds.

Figure 7 plots the force versus time response of an interleaved specimen loaded at the lowest (1 mm/min) and the highest (200 mm/min) crosshead speeds. The higher crosshead speed leads to a higher force during the loading phase. The force relaxes due to the creep of the polystyrene interleaf during the fixed displacement state. It can also be seen that the force measured from the test performed in 200 mm/min tends towards that in the lowest crosshead speed case. Figure 7 also shows the FE-predicted behaviour is under predicting the relaxation and this is being investigated further.

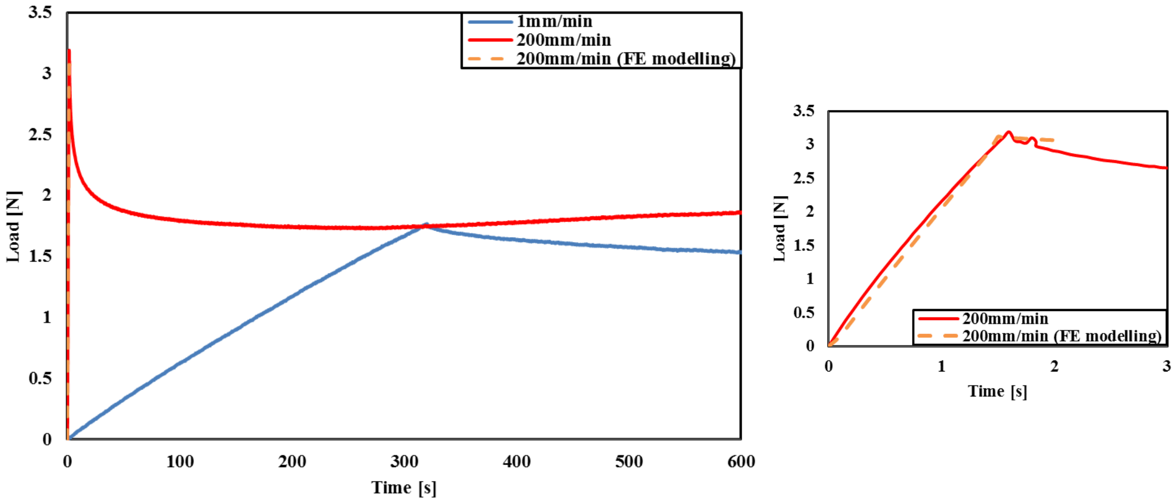

Figure 7: The measured force versus time curves from three-point bend tests of the specimen loaded at 1 and 200 mm/min. The insert plot shows the initial experimental and modelling load relaxation curves of the 200 mm/min loading case.

Finally, Figure 8 shows the displacement versus time plots of the specimen loaded at the lowest (1 mm/min) and the highest (200 mm/min) crosshead speeds for all phases of the viscoelastic flexure test procedure (i.e. loading, fixed displacement and final shape recovery). It is shown that in the final phase, the specimen recovers towards the original shape. Both the lowest and the highest loading cases show that the 90% of the recovery is achieved within 100 s after the load is removed. Finite element modelling is currently being conducted to predict the shape recovery phase.

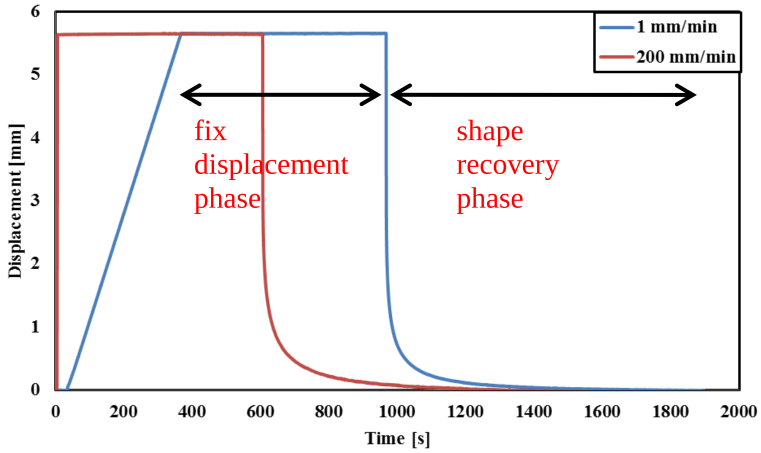

Figure 8: The displacement versus time plots of the specimen loaded at 1 mm/min and 200 mm/min crosshead speeds.

5 CONCLUSIONS

The viscoelastic behaviour of an interleaved composite has been investigated by experiment and finite element modelling. The key conclusions are the following:

- The flexural stiffness of the interleaved composite reduced by over 98% on heating.
- Upon loading at different speeds, the laminate exhibited the viscoelastic behaviour at elevated temperature.
- In the fixed displacement phase at elevated temperature, the force relaxed and tended towards to a constant value.
- When removing the displacement, the laminate recovered to the original shape.
- Finite element modelling predicts the key features of the viscoelastic behaviour of the interleaved composites.

REFERENCES

[1] P. Robinson, A. Bismarck, B. Zhang, and H. Maples, Exploring the potential of controllable stiffness hybrid composites, *Proceedings of the 16th European Conference on Composite Materials ECCM-16, Seville, Spain, June 22-26,* 2014.

[2] B. Zhang, P. Robinson, A. Bismarck and H.A. Maples, Modelling the shape memory capability of an interleaved composite, *Proceedings of the 17th European Conference on Composite Materials ECCM-17, Munich, Germany, June 26-30,* 2017.

[3] H. Maples, A. Wakefield, P. Robinson, and A. Bismarck, High performance carbon fibre reinforced epoxy composites with controllable stiffness. *Composites Science and Technology*, **105**, 2014, pp. 134-143.

[4] P. Robinson, A. Bismarck, B. Zhang, and H. Maples, Deployable, shape memory carbon fibre composites without shape memory constituents. *Composites Science and Technology*, **145**, 2017, pp. 96-104.