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A bistable morphing composite using viscoelastically generated prestress

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Abstract

Elastically generated prestress within polymeric composites can be used to create bistable morphing structures; i.e. they can 'snap through' between one of two states. In this paper, a morphing bistable structure has been produced, utilising viscoelastically generated prestress. Here, polymeric fibres are subjected to a tensile (viscoelastic) creep load which is released before the fibres are moulded into a matrix. Following curing, the previously strained fibres continue to attempt viscoelastic recovery, creating compressive stresses within the matrix that are counterbalanced by residual tension in the fibres. The bistable structure consists of prestressing strips bonded to the sides of a thin, flexible resin-impregnated fibre-glass sheet. Bistability is achieved through pairs of strips orientated to give opposing cylindrical configurations within the sheet. It is envisaged that viscoelastically prestressed morphing structures may overcome the potential limitations of elastic prestressing; i.e. production flexibility and product longevity.

Highlights

- The first morphing composite created through viscoelastically generated prestress.
- The composite structure can snap between one of two cylindrical states.
- Offers potential for flexibility in manufacture and longevity in service.

Keywords: Polymeric composites; Functional; Viscoelasticity.

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1. Introduction

Shape-adaptive or morphing structures offer opportunities for improved aerodynamic performance and functionality without the need for increased mass and complex construction. Thus for example, morphing aerofoils can enable camber and twist changes without conventional actuation mechanisms [1]. There has been significant interest in the use of elastically generated prestress within polymeric composites to create morphing structures, the simplest being those which are bistable; i.e. they can ‘snap through’ between one of two states. The elastic prestress can be created by residual (thermally-derived) stresses occurring during moulding in non-symmetrical multi-layer laminates [2,3]; however, exploitation of thermal effects can be problematic [1]. An alternative approach is to apply (elastic) tension to fibres during the moulding cycle in symmetrical laminates [1,4] or beam structures [5] but there are potential drawbacks. First, the need to apply fibre tension during matrix curing can compromise mould geometry [6]; also, suitable stretching rig and fibre clamping designs can be technically challenging [4,7]. Second, as the matrix material is polymeric, prestress-induced matrix creep at fibre-matrix interface regions is expected to cause a progressive deterioration in prestress levels [6].

Viscoelastically prestressed polymeric matrix composites (VPPMCs) offer a viable alternative. Here, polymeric fibres are subjected to tensile (viscoelastic) creep and the creep load is released before the fibres are moulded into a matrix. Following curing, the previously strained fibres continue to attempt viscoelastic recovery, producing compressive stresses within the matrix that are counterbalanced by residual tension in the fibres. Previous work has demonstrated notable improvements in mechanical properties from VPPMCs, especially impact toughness and flexural stiffness, using nylon 6,6 fibres [6,8,9] and UHMWPE fibres [10]. A key benefit here is production flexibility: the fibre stretching and moulding operations are decoupled, which can simplify equipment requirements and procedures. A further benefit is longevity: potential deterioration through localised matrix creep would be offset by activity from longer term viscoelastic recovery mechanisms within the polymeric fibres [6]. Although viscoelastic activity is temperature sensitive, recent accelerated ageing experiments on nylon 6,6 fibre-based VPPMCs demonstrate no deterioration in performance over a duration equivalent to ~25 years at 50°C [8]. In this paper, the first details of a bistable VPPMC are presented.

2. Principle

The bistable structure is based on four identical VPPMC strips bonded to a thin, flexible resin-impregnated fibre-glass sheet, as shown schematically in Fig. 1. The cross-sectional spatial density of prestressing fibres in VPPMC strips can be non-uniform due to open casting [6,8,9]; thus a thin strip could undergo bending, to give a mid-span deflection, δ, in Fig. 1. For a VPPMC strip in isolation, the prestressed beam relationship may be considered [11]:

$$\delta = \frac{P\,eL^2}{8EI} \qquad (1)$$

Here, P = prestress force, L = beam length, E = matrix modulus and I = second moment of area, which is ($bh^3/12$) for a rectangular beam of width b and thickness h. The distance between beam and fibre centroids, e, can be estimated from the cross-sectional spatial density of fibres in a composite strip sample. Since the upper and lower strips in Fig. 1 are oriented to deflect in opposite directions, the whole assembly should be capable of demonstrating bistability.

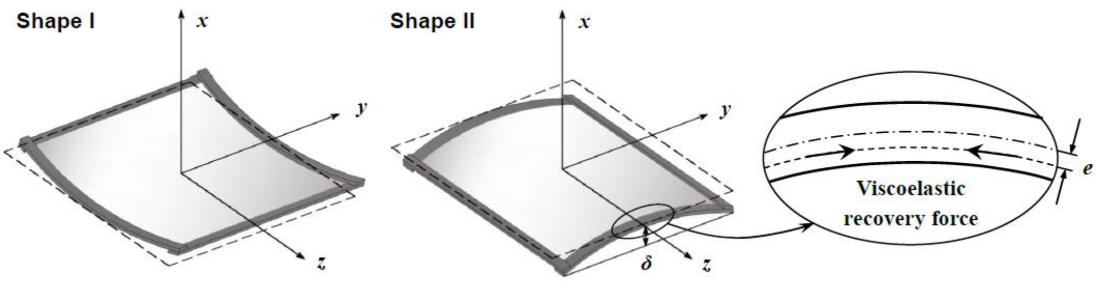

Fig. 1. Schematic representation of bistable VPPMC principles, showing the VPPMC assembly in both states (Shapes I and II) and prestress-generated deflection in accordance with Eq. (1).

3. Experimental procedure

Production of the VPPMC strips followed previously described procedures [6,8,9], the main points being outlined here. A continuous multifilament yarn of nylon 6,6 fibres, similar to material previously studied (140 filaments, 26 µm filament diameter, 94 tex), was used. This was supplied by Ogden Fibres Ltd, UK. The yarn was annealed in a fan-assisted oven (150°C, 0.5 h), this being essential for long-term viscoelastic recovery. The yarn was then subjected to 330 MPa tensile creep stress for 24 h under ambient conditions (20-21°C, 30-40% RH). On releasing the creep load, the yarn was folded, cut into 500 mm lengths and brushed into flat ribbons ready for moulding.

The matrix material was a clear-casting polyester resin, Reichhold Polylite 32032, mixed with 2% MEKP catalyst, supplied by MB Fibreglass, UK. Gel-time (room temperature) was ~0.3 h. Unidirectional continuous fibre composites were open-cast in two aluminium moulds, the process being completed within 0.5 h of the fibre stretching procedure. Each mould had a 10 mm wide, 1 mm deep channel for casting a 460 mm strip of material and the average (macroscopic) fibre volume fraction was ~18%. Following demoulding (after ~2 h), the two composite strips were each cut into two 200 mm lengths to provide the four VPPMC strips.

The sheet, to which the VPPMC strips would be bonded, was a 200 x 200 mm square of fibre glass tissue, 30 gm^{-2}. This was impregnated (hand lay-up) with the same resin used for VPPMC production. After ~24 h, the VPPMC strips were also bonded to the sheet with this resin. The assembled composite sample was then held under a weighted solid plate for a further 48 h. Three of these VPPMC-based 'test' samples were produced and stored for periods of 350-650 h at 20-21°C prior to evaluation.

A 'control' sample (no prestress) of the composite assembly was also required, as a reference to determine whether other production-based stresses might be significant. This was identical to the VPPMC-based samples, with the 24 h fibre stretching stage omitted. Instead, the annealed yarn at this stage was stored under the same ambient conditions for 24 h, prior to composite production.

The VPPMC-based samples were evaluated for (i) deflection, associated with δ in Eq. (1), and (ii) snap-through characteristics. For (i), deflection was measured for the assembled structure which, based on the sum of the VPPMC strip thickness and fibre glass-resin sheet, makes Eq. (1) oversimplified. Thus two separate (isolated) VPPMC strips were also produced, enabling direct comparison with Eq. (1). For (ii), a Lloyd Instruments EZ-50 testing machine was used, with three-point bending jig and indenter (6 mm nose radius). A jig span of 190 mm enabled the supports to be centred on the VPPMC strips at the sample edges. A 2.5 N load cell was used with a test speed of 60 mm/min and each of the three samples was tested three times to give nine readings in each snap-through direction.

4. Results and Discussion

In Fig. 2, the mid-span deflections can be clearly seen in a typical test sample undergoing snap-through testing. These test sample deflections can be attributed to viscoelastically generated prestress effects, since they were not observed in the control sample. Prior to the snap-through tests, static measurements of deflection, based on six readings (i.e. three test samples in both bistable states) at the edge of each test sample, gave a mean (± standard error) of 11.6 ± 0.4 mm.

The results of loading force and displacement from the snap-through tests are also shown in Fig. 2. Good repeatability, both within and between samples is indicated by the close scatter of data points in Fig. 2. The resulting mean (± standard error) peak force and displacement were 1.32 ± 0.04 N and 16.0 ± 0.5 mm respectively. Here, displacement was the maximum result recorded during snap-through from the centre of each sample; thus additional flexibility within the glass fibre sheet may have contributed to this displacement being higher than the steady state value for δ.

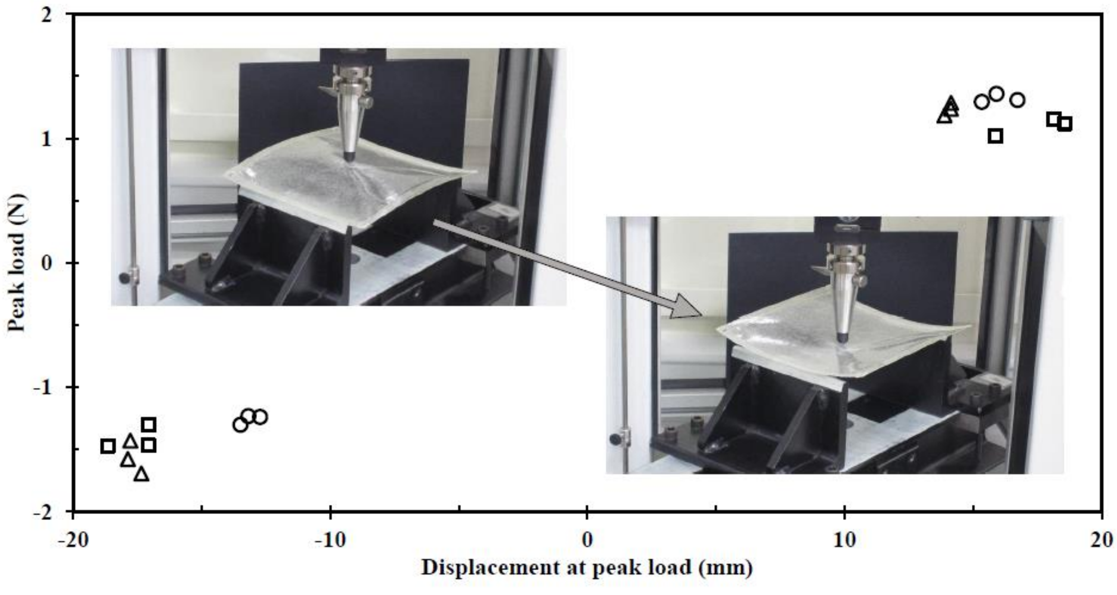

Fig. 2 Plot of loading force versus displacement from snap-through tests for all three VPPMC-based samples; inset pictures show a typical sample under test.

A typical cross-sectional view of a VPPMC strip attached to the glass fibre-resin sheet is shown in Fig. 3. From this, an estimation of e for Eq. (1) can be made and δ can be predicted from Eq. (1) for an isolated VPPMC strip, since E for the polyester resin at 3.3 GPa [9] is equal to nylon 6,6 fibres [12]. Conversely, the modulus of the glass fibre-resin layer may be substantially greater. From Fig. 3, h for the VPPMC strip is ~1.3 mm and we estimate e to be ~0.2 mm. Based on a viscoelastic recovery stress of ~10 MPa across the nylon fibres [13], P is calculated to be 18 N, which predicts δ from Eq. (1) to be ~3 mm. Mid-span deflections from the two isolated VPPMC strip samples ($h \approx 1.3$ mm) were 2.5-3.5 mm at ~350 h, verifying the predicted result. Since this is significantly less than the measured (static) deflection of 11.6 mm from the bistable samples, it is clear that the glass fibre layer has a major influence on δ, through its effects on I, hence the position of the beam centroid. A more detailed analysis of this aspect will be part of a future investigation.

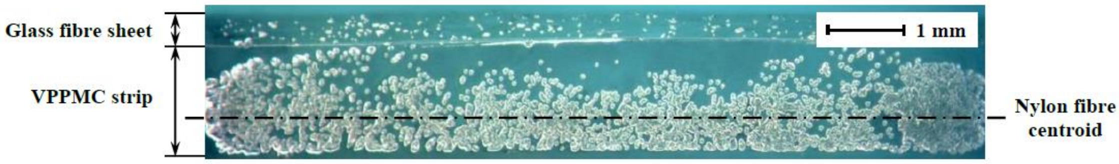

Fig. 3. Representative composite strip cross-section from a VPPMC strip attached to glass fibre-resin sheet, with estimated location for the nylon fibre centroid.

5. Conclusions

This work demonstrates that a morphing bistable structure can be produced, based on the principles of viscoelastically generated prestress. Specifically, we have created a composite plate structure that can snap into one of two cylindrical states. Since morphing structures should benefit from the potential for manufacturing flexibility and longevity in service, these findings open new opportunities for VPPMC research.

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