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SHAPE-CHANGING (BISTABLE) COMPOSITES BASED ON VISCOELASTICALLY GENERATED PRESTRESS

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Summary: *Shape-adaptive or morphing structures offer opportunities for improved aerodynamic performance and functionality without the need for increased mass and complex construction. The simplest morphing structures are those which are bistable; i.e. they can 'snap through' between one of two states. Elastically generated prestress within polymeric composites can be used to create these structures, but potential processing difficulties and restrictions on product geometry have been recognised. Moreover, localised matrix creep at fibre-matrix interface regions within the composite may lead to progressive deterioration in prestress levels. In this paper, morphing bistable structures have been produced by exploiting 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. After 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 paper presents findings from viscoelastically prestressed thin plate structures which demonstrate bistability, including load and deflection characteristics. Since viscoelastic prestressing offers production flexibility and product longevity, it is envisaged that morphing structures based on these principles provide opportunities to overcome the potential limitations of elastic prestressing.*

1 INTRODUCTION

Shape-adaptive or morphing structures have received increasing interest in recent years, since they offer opportunities for improved aerodynamic performance and functionality (e.g. for possible use in aircraft aerofoils and wind turbine blades) 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]. To date, there has been significant interest in the use of elastically generated prestress within polymeric composites to create these 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 stresses occurring during moulding (e.g. from thermal expansion mismatch) in non-symmetrical multi-layer laminate composites [2-4]; however, there can be difficulties associated with the exploitation of thermal effects [1]. An alternative approach is to apply (elastic) tension to fibres during the moulding cycle in symmetrical laminates [1, 5] or beam structures [6] but there are potential drawbacks. First, fibre length, orientation and spatial distribution are restricted by the need to apply fibre tension whilst the matrix cures [7]; these restrictions can compromise fibre and mould geometries for more complex structural situations. Also, achieving suitable stretching rig and reliable fibre clamping designs can be technically challenging [5, 8]. Second, the matrix material is polymeric; thus localised matrix creep at the fibre-matrix interface regions within the composite may occur, in response to the elastically generated prestress. This can be expected to cause a progressive deterioration in prestress levels [7].

Viscoelastically prestressed polymeric matrix composites (VPPMCs) offer a feasible alternative. To produce a VPPMC, polymeric fibres are subjected to tensile creep so that they progressively extend through viscoelastic deformation; the creep load is then released before the fibres are moulded into a matrix. Following curing, the previously strained fibres continue to attempt viscoelastic recovery within the solidified matrix. This results in compressive stresses being generated within the matrix, and these are counterbalanced by residual tension in the fibres. Previous work has demonstrated notable improvements in mechanical properties from VPPMCs, especially in terms of impact toughness and flexural stiffness, using nylon 6,6 fibres [7, 9, 10] and UHMWPE fibres [11, 12]. There are significant opportunities offered by VPPMC processing, since the fibre stretching and moulding operations are decoupled. In addition to simplifying equipment requirements and procedures, there is total flexibility in terms of product geometry. A further benefit is longevity: any potential for deterioration through localised matrix creep would be offset by activity from longer term viscoelastic recovery mechanisms within the polymeric fibres [7]. Although viscoelastic activity is temperature sensitive, recent accelerated ageing (time-temperature superposition) experiments on nylon 6,6 fibre-based VPPMCs have demonstrated no deterioration in impact performance over a duration equivalent to ~25 years at 50°C [9].

The first details of a mechanically bistable composite structure were announced recently, based on VPPMC technology [13]. In this paper, we provide further information and an update on findings.

2 PRINCIPLE

To create a simple bistable structure, four identical VPPMC strips can be bonded to a thin, flexible resin-impregnated fibreglass sheet, as shown schematically in Figure 1. The cross-sectional spatial density of fibres, such as nylon 6,6, used for producing the prestress in a VPPMC strip is normally non-uniform, due to the use of open casting. This arises from fibres settling towards the bottom of the mould prior to curing taking place [7, 9, 10]. Therefore, the resulting non-uniform stress distribution created through the thickness of a thin flat strip can be expected to cause bending, to give a mid-span deflection, δ, in Figure 1. If a VPPMC strip is considered in isolation, δ can be associated with the prestressed beam relationship [14]:

$$\delta = \frac{PeL^2}{8EI} \tag{1}$$

Here, P = force generated from the prestress, L = beam length, E = elastic modulus of the matrix material 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. As shown in Figure 1, the upper and lower strips are oriented to deflect in opposite directions, giving opposing cylindrical configurations within the structure; hence the whole assembly should be capable of demonstrating bistability.

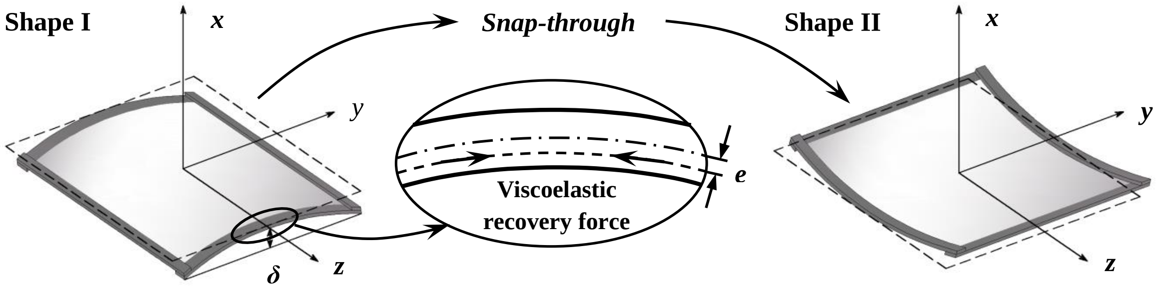

Figure 1: Schematic representation of bistable VPPMC principles, showing the VPPMC assembled structure in both states (Shapes I and II) and also the prestress-generated deflection in accordance with Eq. (1).

For a situation where a simple concrete beam is prestressed by steel rods which occupy a relatively small proportion of the total beam volume, Eq. (1) can be expected to give realistic predictions [15]. For the current work however, the assumption that E in Eq. (1) can be represented by the matrix modulus alone may be unrealistic. This arises from (i) the nylon fibres occupying a significant proportion of the total beam volume and (ii) the addition of the resin-impregnated fibreglass sheet. Thus a more appropriate value for E in Eq. (1) may be obtained by measuring the deflection from a representative composite beam. From the conventional three-point beam-bending relationship [16], the flexural modulus $E(t)$ can be determined from deflection $\delta(t)$ at the centre of the beam at time t using:

$$E(t) = \frac{F L^3}{48\,\delta(t)\,I} \tag{2}$$

Where F is the load applied at the centre of the beam. By measuring $\delta(t)$, when $t = 5$ s, the result for $E(t)$ from a beam, where $h << L$, is close to the true elastic modulus [10, 11]. Therefore, Eq. (2) may be used to obtain a more realistic E value for Eq. (1).

3 EXPERIMENTAL PROCEDURES

3.1 Bistable composite sample production

Production of the VPPMC strips followed previously described procedures [7, 9, 10] and the main points are outlined here. A continuous multifilament yarn of nylon 6,6 fibres, similar to material that had been previously studied (140 filaments, 26 μm filament diameter, 94 tex), was used. This was supplied by Ogden Fibres Ltd, UK. The yarn was annealed at 150°C in a fan-assisted oven for 0.5 h; this step was essential for providing long-term viscoelastic recovery following the applied creep load. The yarn was then subjected to a 330 MPa tensile creep stress for 24 h under ambient conditions (20-21°C, 30-40% RH). The creep load was subsequently released and 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 (at 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 following the fibre stretching procedure. Each mould had a polished channel that was 10 mm wide and 1 mm deep, for casting a 460 mm strip of material. The average (macroscopic) fibre volume fraction was ~18%. The two composite strips were removed from the moulds after ~2 h and each strip was 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 × 200 mm square of fibreglass tissue, with an areal density of 30 gm^{-2}. This was impregnated (by hand lay-up) with the same resin used for the VPPMC strip 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 at 20-21°C for subsequent evaluation.

A 'control' sample of the composite assembly was also required, this being structurally identical to the VPPMC-based test samples, but 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. Therefore, the control sample provided a reference to determine whether other production-based stresses might be significant.

3.2 Bistable composite sample evaluation

The test samples were evaluated for static deflection at the centre of each VPPMC strip, this being associated with δ in Eq. (1). Nevertheless, since δ was measured for the assembled structure, i.e. the sum of the VPPMC strip thickness and fibreglass-resin sheet, some caution was required (as discussed in Section 2) when considering the applicability of Eq. (1). This led to the production and evaluation of separate composite strips, as described in Section 3.3.

The dynamic (snap-through) characteristics were evaluated for the bistable samples. A Lloyd Instruments EZ-50 testing machine was used with a 2.5 N load cell and a test speed of 60 mm/min. Each test sample was supported on a three-point bending jig and a jig span of 190 mm enabled the supports to be centred on the VPPMC strips at the sample edges. Bending was achieved using an indenter with a 6 mm nose radius. The three samples were each tested three times to give a total of nine readings in each snap-through direction. Figure 2 shows the arrangement.

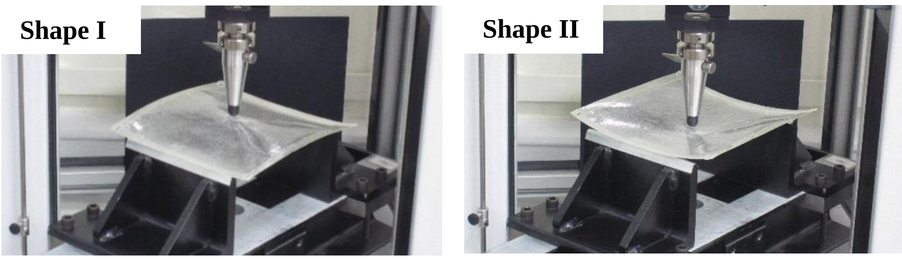

Figure 2: Set-up used to evaluate the snap-through characteristics from the VPPMC-based test samples.

Both static and dynamic evaluations of the bistable samples were performed on two occasions. The first evaluations were made after the samples had been stored for 350-650 h and these have been recently reported [13]. The same samples were then returned to storage (at 20-21°C) for a longer period and re-evaluated at 3800-4100 h, to determine any time-dependent changes within these structures.

3.3 Composite strip samples: production and evaluation

To determine a more representative value for E in Eq. (1), a simple three-point bend test was required, from which Eq. (2) could be used to evaluate $E(t)$. This was achieved by open casting four nylon fibre-resin control strips (i.e. no prestress), each 200 mm in length, by using the aluminium moulds as described in Section 3.1. A 10 mm wide strip of resin-impregnated fibreglass tissue (the same sheet material used for producing the bistable samples) was then bonded to the open-cast strips to produce beam-shaped samples representing the cross-sectional structure of the bistable samples. Following storage for ~350 h, bend tests were performed on each beam sample, using the arrangement shown in Figure 3.

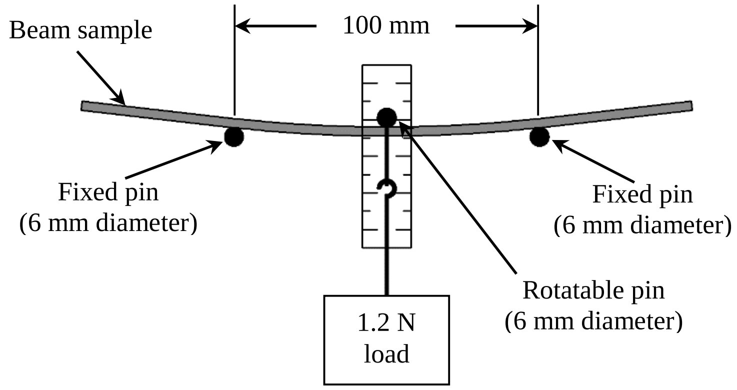

Figure 3: Schematic representation of the three-point bend testing set-up to determine E for Eq. (2).

The set-up and procedures were similar to those performed with composite samples based on nylon fibre [10] and UHMWPE fibre [11], i.e. a deflection reading was taken at 5 s after applying the freely suspended load. In the current study, each sample was mounted horizontally, with the fibreglass layer facing downwards, as this represented the bending orientation created through prestress in the main VPPMC-based test (bistable) samples. To achieve deflections comparable to those observed in the bistable samples, a load of 1.2 N was adopted. Deflections were measured at 20-21°C on each sample just once and a video recording of the deflection in progress was made, to improve measurement accuracy.

As a further consideration for beam deflection analysis, prestressed strips were also produced as described above; these consisted of (i) four VPPMC strips, each with a 10 mm wide fibreglass layer, and (ii) four VPPMC strips, with no fibreglass layer. These were stored for ~350 h and δ was measured to enable direct comparison with predictions from Eq. (1).

4 RESULTS AND DISCUSSION

4.1 Static evaluation of the bistable structure

Figure 4 shows one of the VPPMC-based test (bistable) samples in comparison with the control sample. Clearly, the control sample is flat, signifying that there were no other production-based residual stresses of any significance.

Measured static deflection was based on six readings, i.e. three test samples in both bistable states. At a sample age of ~500 h, the mean deflection (± standard error) was 11.6 ± 0.4 mm; after further storage to an age of ~4000 h, these measurements were repeated, and the deflection had increased to 15.2 ± 0.5 mm. This progressive increase following sample production is consistent with viscoelastic recovery force-time studies monitored to 2700 h [17] and subsequent monitoring to 26300 h [18]. The force produced by viscoelastically recovering nylon 6,6 yarn at a fixed strain can be estimated from force output-time data in Ref. [17] at 500 h and the subsequent work [18] at 4000 h. This output increases by 29% at 4000 h

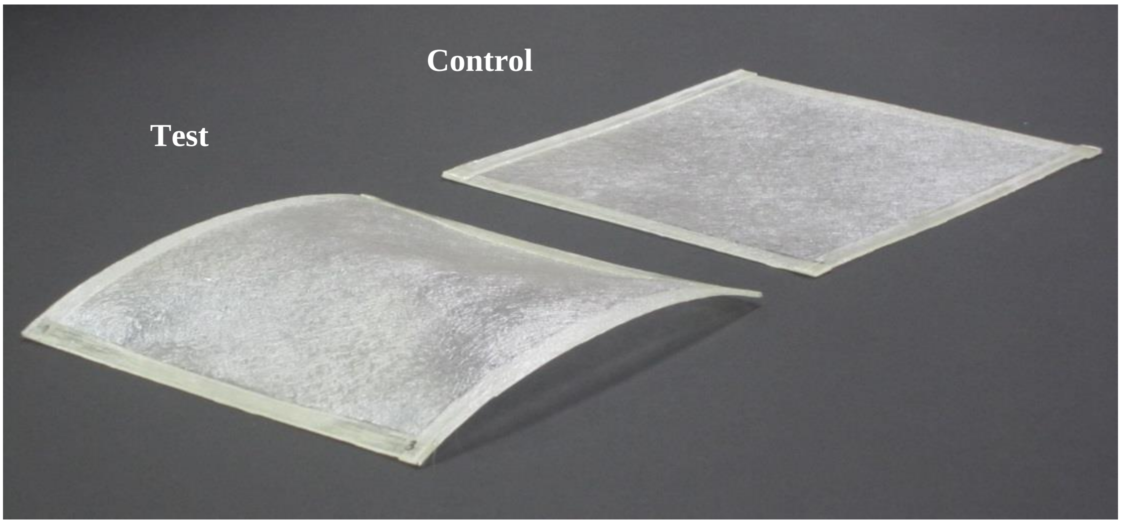

Figure 4: An assembled VPPMC-based test sample, compared with the equivalent control (with no prestress) sample.

relative to 500 h and, as δ is directly proportional to P in Eq. (1), it may be expected to correspond with the measured deflection increase. Since the latter is ~31%, it is evident that Eq. (1) may have some applicability when the assembled bistable structure is considered.

4.2 Dynamic (snap-through) tests

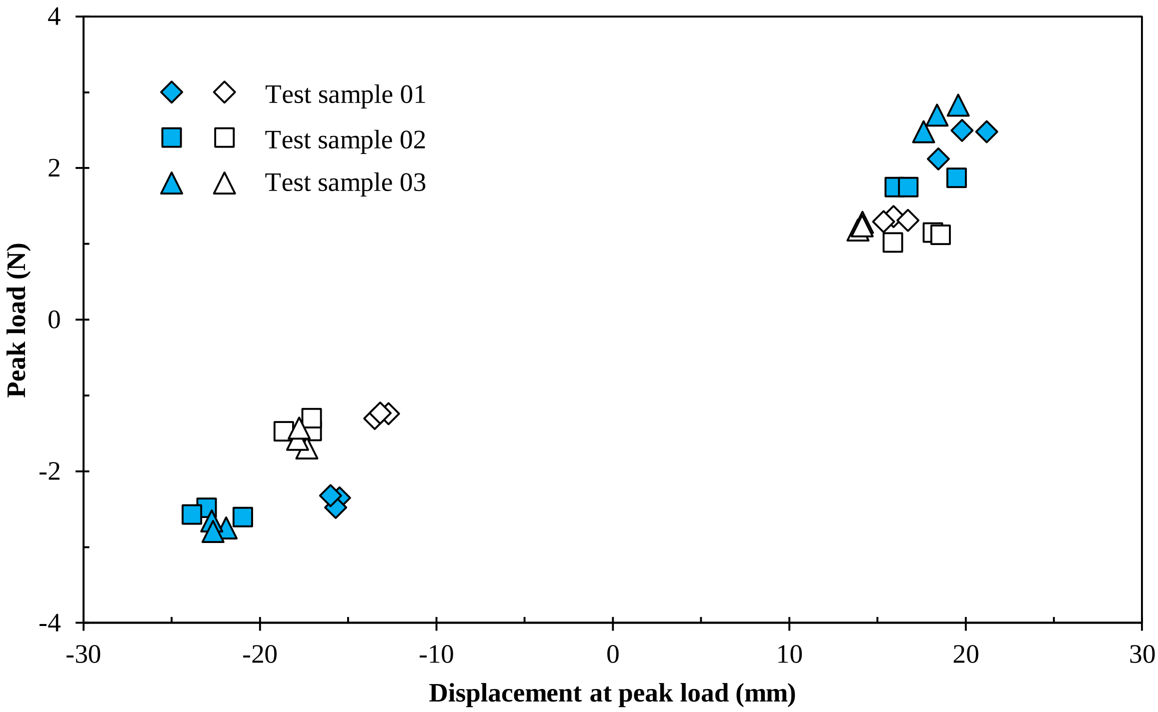

Figure 5: Snap-through tests for the three VPPMC-based bistable assemblies. Hollow symbols represent testing at ~500 h; filled symbols at ~4000 h.

Figure 5 is a plot of peak loading force versus displacement from the snap-through tests. Each sample was tested three times in both snap-through directions. The close scatter of data points shows good repeatability within the samples. Results give a peak force and displacement of 1.32 ± 0.04 N and 16.0 ± 0.5 mm respectively, at ~500 h, and after further storage to ~4000 h, the peak load increases to 2.42 ± 0.08 N with 19.4 ± 0.7 mm displacement. Clearly, the displacement values are larger than the static values reported in Section 4.1. Since displacement recorded during snap-through was the maximum value from the centre of each sample, the differences may be explained by flexibility effects within the fibreglass sheet.

4.3 Beam deflection analysis

Since the four VPPMC strips produced without a fibreglass layer represented an isolated prestressed beam case, the measured deflection may be expected to correspond with the value for δ predicted by Eq. (1). A typical cross-sectional view of a VPPMC strip bonded to the fibreglass layer is shown in Figure 6. This enables an estimation of e for Eq. (1) to be made

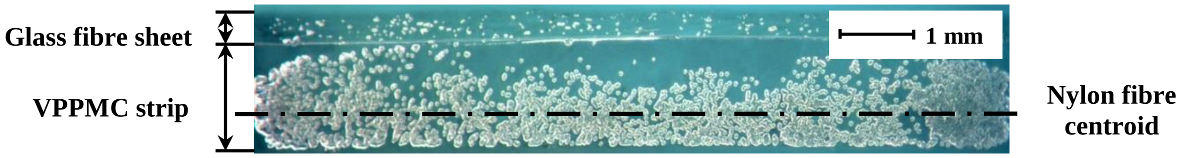

Figure 6: Representative composite strip cross-section view of a VPPMC strip attached to fibreglass-resin sheet, with estimated location for the nylon fibre centroid.

and, for an isolated VPPMC strip, E for the polyester resin at 3.3 GPa [10], is equal to E for the nylon 6,6 fibres [19]. From the four VPPMC strips (no fibreglass layer), the beam thickness, h, is ~1.3 mm. This corresponds with the VPPMC strip thickness in Figure 6 and we estimate e to be ~0.2 mm. From recovery force data [17], the viscoelastically generated stress across the nylon fibres at ~350 h is ~10 MPa, from which P is calculated to be 18 N, predicting δ from Eq. (1) to be ~3 mm [13]. A recent evaluation however, of viscoelastic recovery force from the batch of nylon 6,6 fibre used in this study, suggests that P would be ~22.5 N. Using these values in Eq. (1) predicts δ to be ~3.7 mm. The mean (± standard error) mid-span deflection from the four isolated VPPMC strips at ~350 h was found to be 3.6 ± 0.1 mm, which compares well with the predicted result for δ under these conditions.

Referring to the composite strips with a fibreglass layer, Figure 7 shows a typical VPPMC-based strip with equivalent control sample. At ~350 h, the measured deflection from the four strips (mean ± standard error) was 19.7 ± 0.8 mm. To predict deflection from Eq. (1) for this case, required the value for E determined from the four control sample strips; this was found to be 1.85 ± 0.07 GPa (mean ± standard error) at 350 h. From Figure 6, for the full strip thickness, h is ~1.7 mm and we estimate e to be ~0.4 mm. If P is assumed to be ~22.5 N (from above), then δ from Eq. (1) is 6.0 mm. Therefore, the measured deflection is more than three times that of the predicted value.

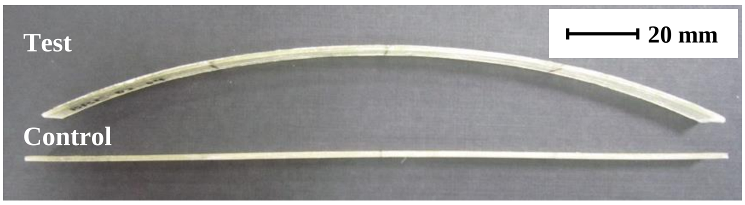

Figure 7: VPPMC strip bonded to fibreglass sheet impregrananted with resin compared with an equivalent control (no prestress) sample, ~350 h after manufacture.

It is evident that although Eq (1) may have some applicability (Section 4.1), there are significant limitations regarding its use for more detailed analysis involving the full beam structure. These limitations arise from the following: (i) the predicted value for δ is based on an idealised equation that (for example) assumes deflection depends only on elastic behaviour; (ii) uncertainties in estimated parameter values for Eq. (1), e.g. influence of the non-uniform nylon fibre spatial distribution on e; (iii) effects of porosity (due to air entrapment within fibres) and interfaces (i.e. fibreglass sheet and fibre-matrix interface regions) on I and E. Thus (iii) may be a factor contributing to the observed discrepancy between the E value (3.3 GPa) for neat polyester resin [10], and the value (1.85 GPa) determined from the VPPMC/fibreglass strip samples.

5 CONCLUSIONS

A shape-changing bistable structure has been successfully developed through the use of viscoelastically generated prestress. Bistability is achieved through pairs of deflecting VPPMC strips, which are orientated to give opposing cylindrical configurations within a thin, flexible resin-impregnated fibreglass sheet. This arrangement enables the structure to 'snap through' between one of two states. Deflection from the VPPMC strips occurs through bending forces due to non-uniform fibre spatial distributions. An equation widely used to predict deflection within prestressed concrete beams has demonstrated some agreement with measured deflection from isolated VPPMC strips, but only limited applicability for the complete bistable structure.

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REFERENCES

[1] S. Daynes, P.M. Weaver, Stiffness tailoring using prestress in adaptive composite structures. *Composite Structures*, **106**, 282-287, 2013.
[2] W. Hufenbach, M. Gude, Analysis and optimisation of multistable composites under residual stresses. *Composite Structures*, **55**, 319-327, 2002.
[3] M. Gude, W. Hufenbach, C. Kirvel, Piezoelectrically driven morphing structures based on bistable unsymmetric laminates. *Composite Structures*, **93**, 377-382, 2011.
[4] C.R. Bowen, D.N. Betts, P.F. Giddings, A.I.T. Salo, H.A. Kim, A Study of Bistable Laminates of Generic Lay-Up for Adaptive Structures. *Strain*, **48**, 235-240, 2012.
[5] S. Daynes, C.G. Diaconu, K.D. Potter, P.M. Weaver, Bistable Prestressed Symmetric Laminates. *Journal of Composite Materials*, **44**, 1119-1137, 2010.
[6] X. Lachenal, S. Daynes, P.M. Weaver, A non-linear stiffness composite twisting I-beam. *Journal of Intelligent Material Systems and Structures*, **25**, 744-754, 2013.
[7] K.S. Fancey, Fiber-reinforced polymeric composites with viscoelastically induced prestress. *Journal of Advanced Materials*, **37**, 21-29, 2005.
[8] S. Krishnamurthy, *Pre-stressed advanced fibre reinforced composites fabrication and mechanical performance*. PhD thesis, Cranfield University, UK, 2006.
[9] K.S. Fancey, A. Fazal, Prestressed polymeric matrix composites: Longevity aspects, *Polymer Composites*, DOI: 10.1002/pc.23387, in press, 2015.
[10] J.W.C. Pang, K.S. Fancey, The flexural stiffness characteristics of viscoelastically

prestressed polymeric matrix composites. *Composites Part A: Applied Science and Manufacturing*, **40**, 784-790, 2009.

[11] A. Fazal, K.S. Fancey, Viscoelastically generated prestress from ultra-high molecular weight polyethylene fibres. *Journal of Materials Science*, **48**, 5559-5570, 2013.

[12] A. Fazal, K.S. Fancey, UHMWPE fibre-based composites: Prestress-induced enhancement of impact properties. *Composites Part B: Engineering*, **66**, 1-6, 2014.

[13] B. Wang, K.S. Fancey, A bistable morphing composite using viscoelastically generated prestress. *Materials Letters*, in press, 2015.

[14] PCI industry handbook committee, *PCI design handbook: Precast and prestressed concrete* (7th Edition). Chicago, 2010.

[15] A.S. Kasat, V. Varghese, Finite element analysis of prestressed concrete beams. *International Journal of Advanced Technology in Civil Engineering*, **1**, 27-31, 2012.

[16] S. Timoshenko, *Strength of materials part I. Elementary theory and problems* (3rd Edition). Krieger, New York, 1976.

[17] J.W.C. Pang, B.M. Lamin, K.S. Fancey, Force measurement from viscoelastically recovering Nylon 6,6 fibres. *Materials Letters*, **62**, 1693-1696, 2008.

[18] K.S. Fancey, School of Engineering, University of Hull, unpublished data.

[19] Goodfellow Cambridge Ltd., UK. Online catalogue (material properties). http://www.goodfellow.com (accessed October 2014).