FOLDING OF A BISTABLE TAPE-SPRING STRUCTURE BASED ON PLAIN-WOVEN COMPOSITE

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1 Introduction

Morphing structures using composite materials have received increasing interest in recent years, in the areas of aircraft aerofoils [1,2], automobile structures [3], and wind-turbine blades [4]. Multistable composite structures with more than one stable load-free shape can be produced by means of thermal residual stress [5], geometrical curvature effects [6], piezoelectric actuation [7], and prestress induced from either elasticity [8] or viscoelasticity [9]. A bistable structure of interest here is a thin-walled, laminated, open slit tube better known as a composite tape-spring (CTS), which is stable in both its unstressed cylindrical shape and coiled configuration. The mechanism of its bistability is well-understood, see for example [6]: other previous studies on CTS focus on their deployment behaviour as a single structure or integrated within deployable structures [10-13], as well as modelling their natural viscoelastic constitutive behaviour [14-16]. Here, we study the folding capability of a CTS proposed as a hinge safety connection within an aircraft landing gear system.

The bistable CTS is fabricated from a plain-weave, glass-fibre (GF) woven reinforced polypropylene (PP) composite. The mechanical lay-up properties are determined with embedded strain gauges (SGs), and a three-point bending set-up has been designed to investigate its folding behaviour under minimal constraints. Finite element (FE) analysis was also performed to characterise the CTS folding potential.

2 Characterisation

2.1 Production of composite samples

The lay-up consisted of three layers of 195 gsm GF woven PP sheet with a fibre volume fraction (V_f) of 30%, placed between two PTFE coated glass fabric papers. Flat monostable strips were produced to evaluate the mechanical properties and transversely curved bistable samples were made to study their folding potential as CTS.

In order to produce a flat strip, each lay-up was placed between of two flat steel plates (320 × 50 × 3 mm). Two orthogonal strain gauges (length 6 mm, resistance 120 Ω, Tokyo Sokki Kenkyujo Co. Ltd.) were embedded on the surface to capture longitudinal and transverse strains. The flat plate mould was then wrapped and tightened using heat-shrink tape. Tape-springs were produced the same way using a cylindrical former instead (diameter 25 mm, length 300 mm).

Each sample was cured by heating the mould in a pre-heated fan-assisted oven at 225 ˚C for 4 hours. Following removal of the shrink tape and PTFE paper, each composite sample was manually cut to the correct size before testing.

2.2 Mechanical testing

All mechanical tests were carried out using an Instron 5567 universal tensile machine with a 30 kN load cell at room temperature. Elastic properties in the ‘1’ and ‘2’ fibre directions were determined by testing flat samples, with warp fibres in the longitudinal and transverse directions following ASTM D3039 designated as $[0/90]_3$ and $[90/0]_3$, respectively. The shearing properties were derived from in-plane shear tests according to ASTM D3518, with warp fibres oriented at 45˚ and denoted as $[\pm45]_3$. Three samples for each test were made and tested to evaluate repeatability. Figure 1-a shows the experimental setup, where the ends were pulled apart at a constant speed of 2 mm/min in tests. A Canon EOS 700D camera recorded the deformation and any visual damage. The embedded SGs were soldered to a lead pad, and connected to a National Instrument PXIe-1071 transducer, measuring strains at a rate of 2 Hz. A sample dimension of 250 × 30 × 0.65 mm was employed with a gauge span of 190 mm.

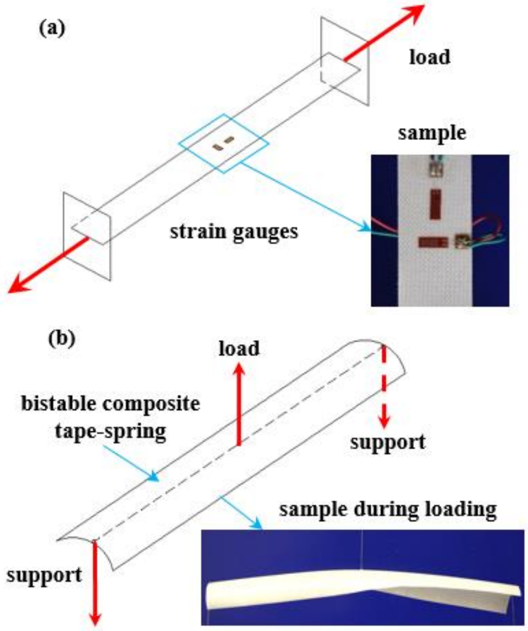

Figure 1 Experimental setup for (a) mechanical testing of composite samples with embedded strain gauges and (b) three-point bending of bistable composite tape-spring.

2.3 Folding behaviour

Each bistable CTS had a length of 200 mm and subtended 180 degrees on a transverse diameter of 25 mm. Experimental folding was first investigated by connecting the tape-spring using three steel wires to an Instron 5564 testing machine. These wires passed through holes located at each end and in the middle, where the outer pair were pulled downwards and middle wire pulled upwards, to simulate three-point bending, see Figure 1-b. Using wires permitted absolute torsional freedom along the length of the sample, which is known generally to exhibit a coupled bending-torsional buckling mode. The sample was bent in its softer “equal-sense” direction [17] as shown: if the CTS is installed the other way up, it bends in the opposite sense, which always leads to delamination. The wires were contracted at a rate of 60 mm/min and each test was conducted three times for repeatability’s sake.

The FE analysis used the commercial software package ABAQUS [18]. The woven composite lay-up was simulated following the Naik’s model [19]. Thus, the effects of fibre weaves and crimps were optimised, and a unidirectional (UD) laminate was utilised in the model. The properties of the UD laminate in the warp and weft directions were informed by tests as well as the composite cylinder assemblage (CCA) based micromechanical model [20].

3 Results and discussion

3.1 Mechanical properties

Figure 2 shows a typical tensile stress-strain curve for a $[0/90]_3$ composite sample. It is linear elastic until failure, where the strain gauges begin to detach from the sample surface at a strain around 0.0025, as highlighted in Figure 2. The modulus can therefore be determined using the strain values from both the strain gauges as well as Instron data from the crosshead motion of the load cell; furthermore, since the transverse-sensitivity effects on strain values can be corrected using SGs [21], the former gives more accurate data than the crosshead method. The elastic moduli are found to be E_1^{PW}=12.99 ± 0.48 GPa and E_2^{PW}=16.06 ± 1.39 GPa. Though the GF woven has the same fibre counts in both directions, the differences in modulus values contribute to different bundle geometry. Since the bundle geometry is not considered in the CCA model, for GF/PP woven composite with 30% V_f, it gives $E_1^{PW} = E_2^{PW}$=13.70 GPa, which agrees well with the mean measured modulus value of 14.53 GPa. The strain at failure is determined from the crosshead motion. The tensile strength in warp (σ_1^{PW}) and weft (σ_2^{PW}) directions are 215 ± 9 MPa and 198 ± 3 MPa, respectively, corresponding to failure strains of ε_{1f}^{PW}=3.46 ± 0.01% and ε_{2f}^{PW}=2.34 ± 0.10%.

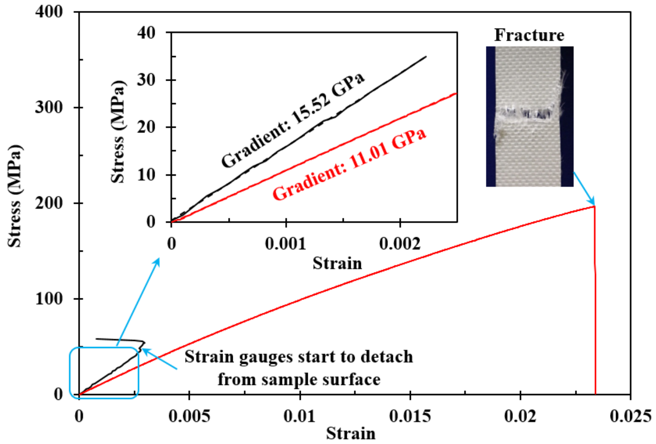

Figure 2 Tensile stress-strain curve of a $[0/90]_3$ composite sample, showing the stress-strain curves derived from both strain gauges (black) and crosshead motion (red).

Similarly, the shear strength and shear strain at failure are found to be 42.3 ± 0.6 MPa and 26.9 ± 0.7%, respectively. The shear modulus calculated via the strain gauge data is 824 ± 59 MPa, compared to 978 MPa from the CCA model.

3.2 Bistable folding

Figure 3 shows the reaction force-displacement curves during bending of the CTS sample from experiments, where the maximum crosshead displacement is 70 mm, corresponding to a fold angle of 80˚. FE simulation results are also shown. There is clear agreement between the trends but a major difference is the sharp peak in the simulation at the onset of initial bending. It is due to a very pronounced bifurcation when torsional buckling occurs, as highlighted in the inset figures. There is also torsional buckling in the experiments but these are more gradual owing to the presence of initial imperfections. Conversely, if the perfectly symmetrical boundary conditions are relaxed in the FE analysis, this peak is reduced in height and becomes rounder, as per experiments.

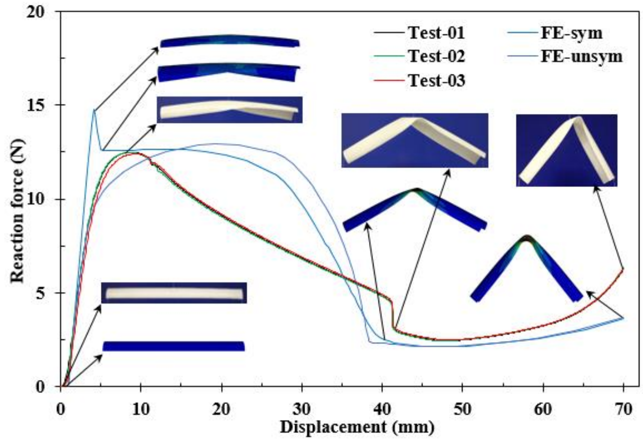

Figure 3 Reaction force-displacement curves of the bistable tape-spring structure. Inset figures show the folding shapes at different stages from experiments and FE simulations (with/without symmetric boundaries).

4 Conclusions

A plane-weave GF/PP composite is used to produce a bistable composite tape-spring structure. Its mechanical properties are evaluated through embedded strain gauges, which provide reliable strain data after corrections of the transverse-sensitivity compared to the crosshead method. An FE model is established to simulate the folding behaviour. It correlates well with the experimental results, and provides further insights into the highly nonlinear folding capability of these tape-springs.

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