



Integrated electrical connections in deployable composite tube flexures

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Received: 22 August 2025 / Revised: 13 November 2025 / Accepted: 7 January 2026
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Abstract

This study extends the functionality of ultra-thin carbon fibre composite tube flexures by interleaving a multi-layered conductive film along the laminate's midline to enable data and power transmission across the structural joint. Conductive tracks, created by silver nanoparticle deposition onto a polyimide substrate, are encapsulated by a thermoplastic film to prevent short-circuits with the carbon fibres. The paper first establishes the mechanical stability of the integrated structure through analysis and testing, then investigates the electrical signal integrity and the feasibility of thermal actuation for a shape-memory use-case. Repeated moment-rotation tests showed a progressive reduction in locking moment. The conductive track remained functional, without showing an appreciable degradation in signal quality or electrical resistance. Resistive heating tests reaching higher temperatures caused adhesive failure between the thermoplastic film and the tracks in the stowed state, leading to local delamination and catastrophic failure of the laminate. These findings demonstrate that novel inkjet-printed conductive interleaves are a viable solution for digital signal and low-power transfers in laboratory conditions, raising the challenge of extending testing to space-like environments and improving the bond strength of the silver tracks for enhanced thermal durability. This methodology represents a significant step forward in terms of structural power integration, enabling ultra-lightweight harnesses to be directly integrated within highly strained deployable members with applications on small and large satellites, as well as next generation space structures, such as space-based solar power stations.

Keywords Spacecraft mechanisms · Composite flexures · Embedded circuits · Multi-functional tape spring · Multi-functional composites · Silver ink-jet printing

1 Introduction

Spacecraft mechanisms enable the deployment of large apertures or booms, improving the photovoltaic energy generation, thermal management or radio-frequency capabilities of a subsystem while minimising its volume during launch. Despite the emphasis placed on reliability, mechanism failures were at the root of 8.7% of failures in spacecraft under 500 kg in the 2011–2021 period [1], and several high-profile geostationary assets such as ViaSat 3 [2]. Progress in materials, manufacturing technologies and computational modelling are enabling a transition from complex

electro-mechanical assemblies to compliant mechanisms which achieve motion by exploiting elastic deflections of flexible members. These advancements reduce mass and part count and avoid the risks of conventional mechanism: friction, cold-welding, backlash and wear [3, 4]. Tape springs, or the combination of a pair of tape springs into tube flexures, are one of several compliant mechanisms which have been thoroughly investigated, developed and flown. This study introduces and validates a novel methodology for co-curing arbitrarily shaped, low profile electrical conductors within composite tube flexures, transforming them from simple structural hinges into tightly integrated multifunctional elements. The incorporation of thin, embeddable tracks of any shape along a tube flexure's length unlocks a suite of new capabilities. By taking an experimental approach and merging advances in high-strain composites and structural health monitoring, we create a composite tube flexure that transmits power and data in both highly strained and deployed states, consolidating the wire harness into the

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structure itself. The embedded conductors are sufficiently low resistance to be used to supply low-power instruments, are able to successfully transfer digital data and show initial capabilities to serve as integral heaters, demonstrating some of the necessary building blocks for functionalities such as high speed data transfer, transfer of low power supplies and shape memory functionality enabled by localised thermal control.

1.1 Multifunctional tube flexures

Combining two tape springs into a tube flexure increases the bending stiffness and torsional stability in the deployed position [5]. Unlike tape-springs, the behaviour is symmetrical with the respect to the direction of the applied moment. In pure bending the tube elastically deforms linearly up to a critical moment M^{peak} , at which point the spring undergoing opposite-sense bending experiences a snap-through instability (see Fig. 1). The $M^{\text{peak}}/\theta^{\text{snap}}$ ratio represents the flexure's peak stiffness of the flexure. The stiffness then collapses and moment rapidly settles into a lower, approximately constant M^{const} [6].

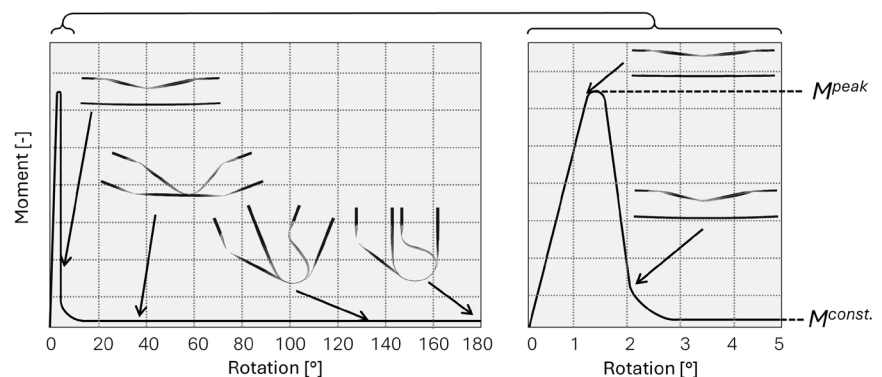
Analytical models fail to capture self-contact between the two tapes needed to form a tube as they do not account for the complex contact and sliding forces between the tapes [5, 8]. For macro-scale modelling, groups have converged on the use of quasi-static displacement-controlled explicit Finite Element Analysis (FEA) using reduced-integration quadrilateral shell elements and introducing small damping effects in the form of viscous pressure to limit numerical instabilities [5, 7, 9–11]. Quasi-static moment-rotation relationships have been compared between experiments and such analytical models, enabling the reconstruction of the deployment dynamics with good fidelity [12].

The development of a sufficiently accurate FE methodology to experiment with (and optimise) cutout geometries, material properties and cross-sectional thicknesses has spurred efforts to build on the established body of work to add functionality beyond the motorizing and latching behaviours. Some groups have adopted shape-memory materials to

respond to thermal inputs, improving the deployment reliability or dampening deployment shocks. Shape memory polymers were proposed as a substitute to thermoset matrices to obtain SMPs (shape-memory polymer composites). These flexures deploy when exposed to heat, removing the need for a burn-wire or latch system to maintain a stowed state [13]. Francis et al. successfully reduced deployment accelerations, but the deployment characteristics displayed a strong dependence on the number of thermo-mechanical cycles due to fibre micro-buckling caused by the hyper-elastic silicone matrix [14, 15]. To address the shortcomings deriving from soft matrices, Almuslmani and Santer applied the Controllable Stiffness Composite Material (CSCM) concept, first developed by [16], to a tape spring [17]. CSCM springs are fabricated by interleaving a thermoplastic sheet, typically Polystyrene (PS) within thermoset CFRP layers. The interleave is post-cured to the CFRP layers in the deployed configuration, “locking in” the desired deployed state. At temperatures exceeding the T_g of the interleave, the stiffness of the PS interleaves decreases by up to 98% [16], allowing the spring to deform to its stowed configuration, where it is cooled until the thermoplastic freezes, maintaining the spring in the stowed arrangement. Thus, at the moment of desired deployment heat is applied, once again exceeding the interleave's T_g , such that the elastic energy stored in the CFRP plies overcomes the reduced stiffness of the interleave, motorising the spring.

Both Francis et al. and Almuslmani and Santer attempted to augment the capability of shape-memory layups by heating them integrally beyond their interleave's T_g (without using an oven) but experienced difficulties integrating standard adhesive heater patches. These off-the-shelf devices are often thicker than the flexure itself and affect its properties in unpredictable ways. Moreover, they suffer from debonding due to the high strains on the external surfaces of the hinges, leading to non-uniform heating and asymmetrical deployment. NiCr heating elements 25 μm in diameter have been embedded within a 330 μm layup, but they were observed to buckle in the axis perpendicular to the axis of bending, generating stress concentrations leading to delamination [14].

Fig. 1 Schematic moment-rotation plot of a tube flexure, adapted from [7]



The majority of efforts in integral heating have focussed on the welding of thermo-plastic CFRPs [18] and anti-icing [19], but these are typically applied to thick-ply laminates in static applications as opposed to the highly-strained tube flexure. Thus, being able to generate heat internally to the laminate would enable the functionalities above without the need for bulky external heating, bringing their benefits closer to real applications. There have been further attempts to add electrical functionality, beyond thermal control, to high-strain composite structures. Polyimide-encased, surface-bonded piezoelectric actuators have been shown to produce highly repeatable piston, pitch, and roll tip motions for precision alignment of optical platforms post-deployment, but they were placed far from the highly strained regions to avoid the debonding issues described above without spanning the length of the hinge [20].

1.2 Interleaved circuits

As discussed, embedding insulated wires and surface-bonding films has not, to date, been capable of reliably adding electrical functionalities to tape springs. However, advances have been made in the structural health monitoring (SHM) field to embed conductive elements within a composite layup to monitor its integrity while minimally disrupting its original properties. These offer a potential path forward.

To reduce mesoscale defects that are generated by naively interleaving cylindrical cross-section wiring [21], some use the conductivity of the individual carbon fibres directly [22], though this requires continuous longitudinal fibres along the desired transmission direction and suffers from unreliable electrical connection between fibres and external terminals. Carbon-nanotube (CNTs) doped adhesive layers have been laminated within standard laminate to detect crack propagation [23]. Once non-linearities are accounted for during calibration, CNT yarns have been successfully used for strain-sensing applications within composites [24], with multi-walled yarns further improving linearity and stability for strain and damage sensing [25]. However, serial data/power transfer requires several insulated conductors in each laminate and crucially, must be insulated from the laminate itself in the case of tube flexures undergoing self-contact. Thus, multi-functional structures, like insulated conductive interleaves, are preferred over material modifications (e.g. CNT dispersion). Hornig et al. defined requirements for such insulated layers: low thickness, good interlaminar strength and adhesion, electrical insulation, sufficient track conductivity, and accessible terminals [26]. In [27], Hornig et al. formulated a series of film stackups using a combinations of polymeric substrates (polyimide, polyether-ether-ketone, polyamide, polyetherimide and polyolefine) embedded within panels composed of UD plies. Experimental

comparison of Mode I and II critical energy release (G_{Ic} and G_{IIc}) rates of the hybrid laminates, showed that the inclusion of PI-based films with a PO adhesive promoter film acting as an insulator was found to most significantly improve delamination resistance. Notably, the experiments do not control for the area of the tracks, and thus neglect any effects of the area being occupied by the track, as opposed to the direct PI-PO bond. Maples et al. [16, 28] evaluated Polystyrene (PS) interleaves, observing a 42% reduction in interlaminar shear strength (ILSS) in PS-interleaved 0° UD composites (14 ± 0.3 MPa) compared to controls (24 ± 0.2 MPa) in 4-point bending. The reduction was attributed to poor PS-epoxy adhesion, which was improved by utilising maleic anhydride (MAH) modified PS films to enhance surface energy and promote wettability, improving the bonding surface.

Concurrently to Hornig et al.'s screen-printed conductors, researchers have developed silver nanoparticle inkjet-printed circuits on Kapton substrates. This process generates lightweight conductive tracks with more uniform and controllable thicknesses and similarly to Hornig et al., also makes use of PO thermoplastic films to post- or co-cure the conductors to laminates [21, 29–31]. Multiple passes of a triethylene glycol monomethyl suspension with 30–35% silver nanoparticle concentration are dispensed at a 30 μ m drop spacing, followed by sintering at 150 $^\circ$ C [29]. Having hot-bonded the Kapton-Silver layer to flat, 16-ply UD coupons using a PO layer, mechanical fatigue testing at a stress ratio of 0.1 showed a 2% deterioration of the circuit's original resistance over 10^9 cycles, while electrical fatigue testing (150 kHz Hanning tone-burst at 6 V) showed a degradation of less than 1% over the same number of cycles. Attempts to determine the effects of the silver ink on the interlaminar strength via comparison of room temperature, single-lap shear tests did not produce statistically significant results [21]. While inkjet printed circuits have been primarily used as interconnects between embedded piezo-electric sensors and remote data-acquisition systems, studies have also been performed in which the change in resistance of such tracks was used to identify bondline defects and fracture with the aim of comparing the performance of composite repair patches [21, 29]. SHM applications typically seek to monitor thick laminates under low, operational strains or detect catastrophic failure from impacts. If technology developed in this field is to be transferred to composite flexures, it must be shown to be able to operate at high strains, though literature on this topic is sparse. Kim et al. [32] demonstrated inkjet-printed copper traces, showing reliable signal connections up to 1% strain and power connections up to 0.45%. The study also reported that the most reliable method for connecting the printed tracks to external wires was the manual deposition of silver paste, as opposed to soldering which in some cases damaged the substrate.

2 Manufacture and process validation

2.1 Flexure geometry

This study builds on the body of work reported in [11, 33]. The flexure considered in this paper was designed with two concentric, diametrically opposed tape springs, as opposed to creating a cut-out slot in a tube via laser or machining methods. In order to utilise existing tooling, the tape springs are fabricated with a nominal total length of 146 mm and internal radius of 15 mm, with a subtended angle of 65°.

2.1.1 Composite layup

The composite system used is a UD pre-preg Mitsubishi Pyrofil TR50S fibres and a K51 Skyflex resin with fibre areal weight of 20 g/m². The material properties for this pre-preg are shown in Table 1. Properties followed by values in parenthesis (which represent standard deviation) come from material tests performed in [11]. Additional properties are either given by the material data-sheet [34] (single asterisk) or estimated in [11] due to lack of available data (double asterisk).

The plies have a nominal thickness of 20 µm and are provided scrim-free, thus being suitable for the creation of thin laminates requiring low defect rates. Previous numerical studies focussing on subtractive tube flexures had made use of a $[\pm 45]_2$ balanced 4-ply layup, identifying the expected twisting issues due to the asymmetry [11]. Herein the chosen layup is $[\pm 45]_s$, which being both balanced and symmetric reduces internal bending or twisting moments following the cure or while operating in the thermal environment of space. The flexible circuit layer is embedded along the mid-plane of the layup.

Table 1 Pyrofil-Skyflex UD—cured mechanical properties

Properties [unit]	Values
Tensile modulus, E_1 [GPa]	76.5 (10.9)
Transverse modulus, E_2 [GPa]	6.2 (0.5)
Poisson's ratio (in-plane), ν_{12}	0.28*
In-plane shear modulus, G_{12} [GPa]	2.5 (0.1)
Shear modulus in plane 1–3, G_{13} [GPa]	2.5 (0.1)
Shear modulus in plane 2–3, G_{23} [GPa]	2.1**
Density, ρ (kg/m ³)	1597*
Longitudinal tensile strength, F_{1t} [MPa]	2500*
Longitudinal compressive strength, F_{1c} [MPa]	1200*
Longitudinal shear strength, S_{12} [MPa]	175*
Transverse tensile strength, F_{2t} [MPa]	120**
Transverse compressive strength, F_{2c} [MPa]	120**
Transverse shear strength, S_{21} [MPa]	120**

2.1.2 Flexible circuit

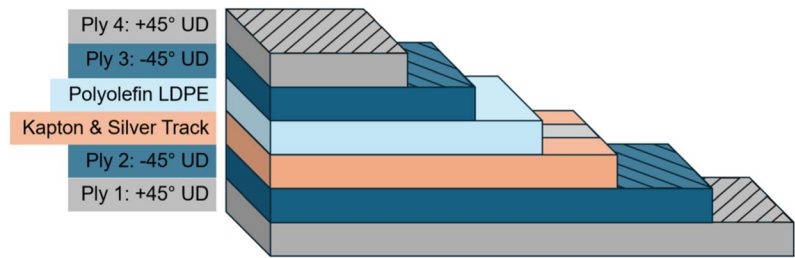
The conductive tracks were printed using a Fujifilm Dimatix DMP 2820 printer to deposit the Sigma-Aldrich 736465 35% concentration Silver Suspension or “ink” [35] onto a 25 µm thick Kapton substrate. The substrate is heated to 60 °C during the deposition to evaporate the solvent. The piezo-electric nozzles were actuated at 25 V with a 5 kHz square wave and 30 µm drop spacing. Four sequential passes provide an acceptable compromise between fabrication time and the final resistance of the tracks. A final sintering step at 150 °C evaporates the remaining solvent and promotes bridging between silver nano-particles yielding a uniform conductive track [36]. The geometry of the conductors is a rectilinear continuous track extending for the length of the tape spring with a width of 3 mm. Using these settings, the measurement track thickness by means of a profilometer scan at equally spaced sections shows a track thickness of 3 µm [37]. The conductive elements were limited to a single track per tape spring (thus a pair per flexure), though additional tracks could be incorporated for additional functionality using the same process. Based on the comparison of interlaminar bond strength tests conducted by Hornig et al. and summarised in Sect. 1.2, a thermoplastic PO layer with nominal thickness of 35 µm (22.100, Pontacol) was used as the insulating and adhesive layer protecting the silver tracks from short-circuiting with the conductive carbon fibres. The final stackup including both composite and conductive layers is arranged in the order [+45/ − 45/Kapton+Silver Ink/PO/−45/ + 45] and is illustrated in Fig. 2.

The Kapton film's material properties are accessible via datasheet [38]. The specific PO film used, however, is a proprietary formulation of LDPE and the datasheet was not made available, so properties were assumed [39]. The properties are reported in Table 2.

An investigation examining how alternative thermoplastic films affected the consolidation of the conductive tracks was outside the scope of this research. However, since the layup's cure takes place after the tracks are sintered, the flow properties of the thermoplastic do not significantly affect the consolidation of the silver. As has been observed in research focussed on interleaved composites [27], a higher strength polymer, providing it comes with sufficiently good interlaminar adhesion, may increase the toughness of the whole laminate, as opposed to directly improving the stability of the conductive track.

2.1.3 Tape spring manufacturing process

The composite plies and flexible circuit are brought together at the layup stage. In preparation for the layup, the composite plies are extracted from storage at −18 °C 30 min before being cut to minimise the penetration of moisture in

Fig. 2 Illustration of the complete layup**Table 2** Film elements-mechanical properties (23 °C)

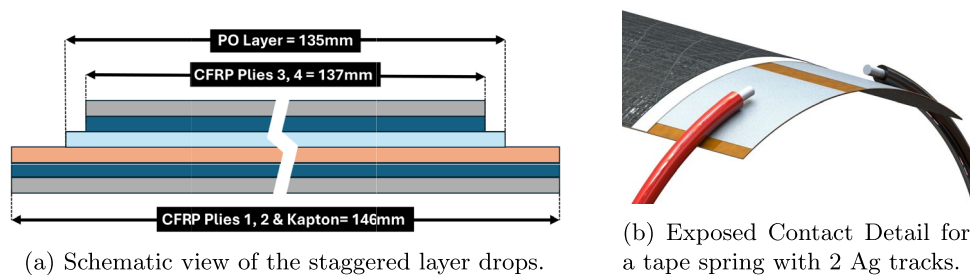
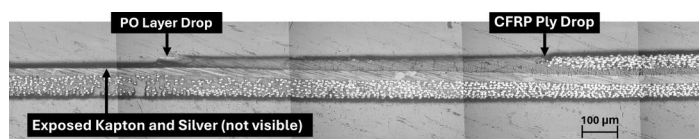
Properties [unit]	Kapton	LDPE
Tensile modulus, E_1 [GPa]	2.8	0.2
Poisson's ratio (in-plane), ν_{12}	0.34	0.45
Longitudinal tensile strength, F_{1t} [MPa]	231	15
Recommended bondline temperature, T_b [°C]	140	–

the laminate. Concurrently, two female aluminium mould-halves are hand-polished, de-greased and coated with 5 coats of Chemlease 41–90 EZ mould-release agent. Similarly, a 30 mm PTFE mandrel is inspected for surface defects, de-greased and coated with mould-release. The mandrel is then covered in a layer of release film, which is kept taut by means of adhesive tape. Having brought the pre-preg to room temperature, it and the Kapton/PO films are trimmed: since the total thickness of the laminate is minimal, the arc-length difference in width between the bottom and top ply is negligible and all layers are trimmed 17 mm leading to a subtended angle α of 65°. The first two 146 mm long strips of [+45/–45] pre-preg are deposited atop the mandrel covered in release film, followed by a 146 mm long strip of Kapton substrate with the conductive track facing upwards. In order to expose the ends of the conductive traces at the ends of each spring, the top 3 layers are trimmed shorter. The conductive tracks are followed by a 137 mm long PO

strip, and the final [–45/+45] 135 mm long CFRP plies. In the prototyping stage, it was found the staggered length of the PO and top CFRP strips is critical in preventing short circuits between the final CFRP plies and the conductive tracks. This stepped geometry is shown conceptually in Fig. 3a and b, and is clearly visible upon inspection with a microscope, as shown in Fig. 4.

Having confirmed best possible symmetry at each end of the spring, each of the two exposed 5 mm segments of conductive contacts are covered by two strips of release film, also kept under tension by tape. This is to ensure that the exposed conductors are not contaminated during the phases of the cure cycle in which the thermoset resin and the thermoplastic PO are flowing, making the connection to external measurement equipment impossible. The strips covering the exposed section of the conductive layer also serve the important purpose of compensating for the missing thickness of the top two CFRP plies, equalising the pressure exerted by the mould during the curing cycle along the part and preventing stress concentrations that may lead to the severing of the conductors. The entire layup is covered with a final layer of release film tensioned with tape, and the stack is completed by sandwiching the mandrel amongst the two female moulds, with the spring being positioned far from the mould seams.

The stack is cured within a heated vacuum table under 600 kPa of pressure at 150 °C for 1 h, followed by 2 h at

Fig. 3 Tape spring design and contact configuration**Fig. 4** Micrograph of the staggered ply-drop region: longitudinal cross-section—20 times magnification

130 °C. At the conclusion of the cure, the heater is switched off but the sample is kept under vacuum until it cools down below 80 °C. The sample is finally extracted and laid to rest until it reaches room temperature. A sample was inspected via optical microscopy (see Fig. 5b) to determine the assured material thickness, which differs from the nominal thickness due to supplier tolerances and consolidation under vacuum. The thicknesses were sampled transversally and longitudinally. The results, reported in Table 5a, demonstrate good agreement for all layer in both directions with the associated standard deviations. Notably, the UD plies, whose bottom and upper pair's thickness is measured together due to lack of a distinguishable interface, deviate from the nominal value of 40 μm most likely due to resin bleed throughout the curing cycle.

The consistency of fibre-to-matrix distribution was analysed by processing micrographs taken at several locations, yielding an average of 50.0% (std. dev. = 1.8%, $n = 10$, see Fig. 6) which suggests uniform consolidation of the UD across the sample. Note that, given the $\pm 45^\circ$ orientation of the UD plies, this is not strictly a measure of the fibre volume fraction, but rather a proxy for the consistency of consolidation across the part. Given the low areal weights of all the layers involved, performing the layup manually is intricate, requiring utmost precision and is vulnerable to defects especially, outside of a clean room setting. Given the thickness of the layup of 127 μm a human hair (ca. 100 μm) or flecks of dust are sufficient to visibly affect the laminate surface finish and cause bridging between the CFRP and conductive track. The encapsulating layers of release film, as well as the thorough cleaning of the work-station and use of masks and gloves helps reduce the risk of these foreign contaminants affecting the quality of the laminate. Despite best efforts, minor voids and inclusions could be observed in the final specimen cross-sections.

The flexible conductive layer must be sintered immediately after being deposited to prevent introducing handling damage during its integration with the composite layup. The layer is exposed to the temperature of 150 °C twice: for its initial sinter (30 min) and as part of the integrated layup (1 h at 150 °C, 2 h at 130 °C). Greer et al. investigated the

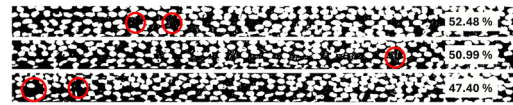


Fig. 6 Post-processed cross-sectional images. Voids marked with red circles

time- and temperature-dependence of the conductivity silver nanoparticle thin films and found that, when sintering at 150 °C, resistivity stops improving for cycle times greater than 30 min (Fig. 3, [40]). Thus, in the context of the methodology proposed herein, additional time spent by the conductive layer during the curing of the layup does not bring improvements in the conductivity of the track. The measurements of the resistance of the tracks were taken before and after with no noticeable difference. The successful electrical functionality after the cure cycle (Table 9) suggests that any effect is non-detrimental to the circuit's low-power performance.

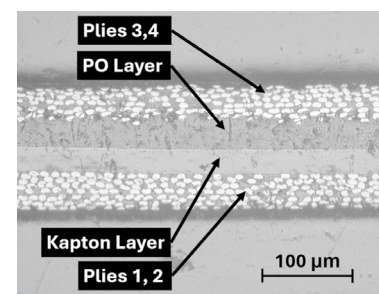
2.1.4 Tube flexure assembly

Having repeated the procedure above to produce two tape springs, they are paired to produce the tube-flexure geometry. The tape springs are bonded on each end to 3D printed coupler components (shown in blue in Fig. 7) using cyanoacrylate adhesive and clamped over an 8 mm length by a tightly fastened 3D printed ring (in green in the same figure). This procedure is conducted by hand, and thus introduces misalignment and asymmetry in the assembly. Having fixed the springs in place, conductive silver paint (RS-Pro, [35]) is used to create a secure electrical connection between the spring's exposed conductive contacts and a printed circuit board (PCB) housed in each coupler, which enables simple (dis)connection of the wiring harness leading to instrumentation. After waiting for the solvent in the silver paint to fully evaporate overnight, more cyano-acrylate adhesive is used to secure the jumper wires and coat the silver electrical connections to the tape springs. Having finalised the assembly

Fig. 5 Material thickness characterisation

Layer	Thickness [μm]	Std. [μm]	Dev.
CFRP 1,2	36.27	2.45	
Kapton	25.65	0.84	
PO	29.35	2.99	
CFRP 3,4	35.41	1.60	
Total	126.68	5.28	

(a) Thickness Measurements ($n=17$).



(b) Cross-section - 20 times mag.

Fig. 7 Render of a fully assembled tube flexure with four conductive tracks (2 per spring)

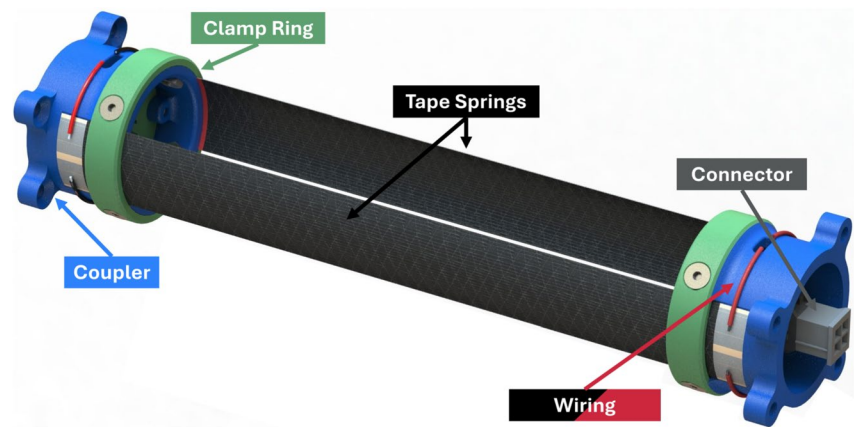
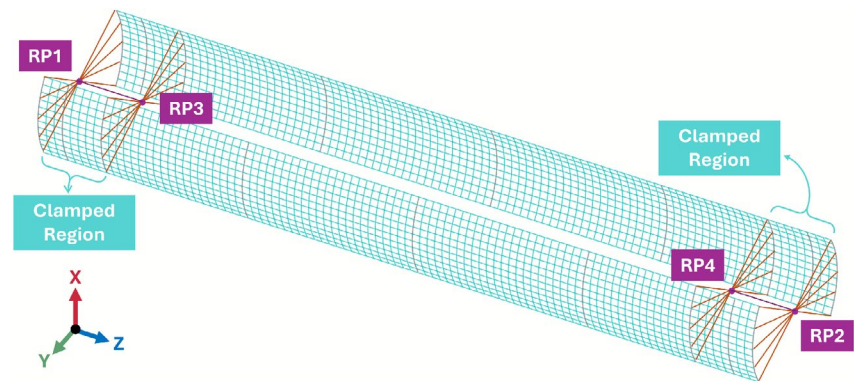


Fig. 8 FE Model with visible 1.5 mm mesh and MPC constraints



and layup, a total of eight tape springs were manufactured and assembled into four tube flexures used for final testing.

2.2 Experimental and numerical methods

The integration of electrical and thermal functionality must not compromise the fundamental mechanical performance. Therefore, this work first establishes an analytical and experimental mechanical performance baseline for the integrated flexure. This baseline serves to validate the structural integrity of the conductive laminate and to ensure that the material alterations introduced by the conductive interleave do not catastrophically degrade the tube's primary structural function as a sprung hinge. The Abaqus/Explicit commercial solver [41] was used for preliminary exploration of the design space and for final correlation of the physical prototypes. The modelling methodology follows the one proposed by Mallikarachchi and Pellegrino [7, 42] and recently extended by Kunakorn-ong and Santer [11].

Finite element model setup The model incorporates both springs of the flexure to capture essential contact interactions, managed using a frictionless General Contact condition. A padded contact constraint of 5 mm was placed between the ends of the springs in the fully stowed

configuration to account for the thickness of the collars clamping them to the test rig. Beam-type multi-point constraints (MPCs) were used to tie nodes at the ends of the springs (between points 1 and 3, and 2 and 4 respectively, Fig. 8), replicating clamped conditions and defining an effective spring length of 122 mm. Stowage was simulated by prescribing rotations of 90° and -90° about the x -axis for Points 1 and 2, respectively (coordinate system in Fig. 8). Point 1 was constrained to enforce pure bending by fixing all rotational and translational degrees of freedom except the prescribed rotation. Point 2 had similar constraints but was permitted to translate in the z -direction. An additional study was conducted to assess the model's sensitivity to assembly imperfections: the folding sequence is kept the same, but it is preceded by a 0.2 s sequence, where point 1 and 2 undergo $\pm 0.25^\circ$ rotations in the y -direction, respectively for a combined out of plane bend of 0.5° . Reduced integration, 4-node plane-stress shell elements were used for the mesh, with a discretisation study assessing the convergence Peak Moment M^{peak} , initial Buckling Angle θ^{snap} , and Constant Moment M^{const} showing convergence at a nominal element size of 1.5 mm.

Quasi-static settings The stowing simulation was performed such that quasi-static conditions were maintained,

Table 3 Simulation results: key metrics

Metric	0.0° Bend	0.5° Bend
Peak moment [Nmm]	414	336
Constant moment [Nmm]	12.5	13.1
Snap angle [°]	0.55	0.55

Table 4 Maximum Hashin–Rotem failure indices

Failure index	Straight	0.5° bend
Fibre tension	0.0215	0.0228
Fibre compression	0.1064	0.1149
Matrix tension	0.1131	0.1237
Matrix compression	0.3056	0.3202

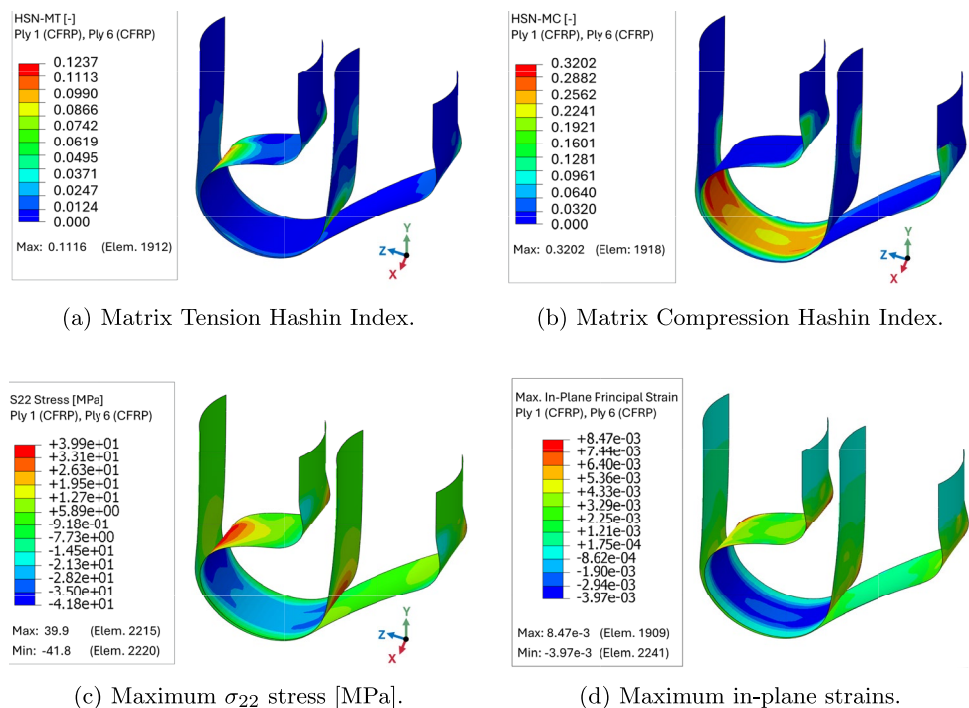
taking place over 0.5 s. Displacement was programmed to follow a 5th-order polynomial function of time (*SMOOTH setting in Abaqus/Explicit) to mitigate inertial effects. The above-mentioned studies show that a viscous pressure load can be applied to all surfaces to further eliminate spurious dynamic effects, reducing simulation time and improving accuracy. Since the value of viscous pressure is formulated in relation to the material wave speed, and this study uses the same composite material as Kunakorn-ong's, their suggested value of 7.07×10^{-8} Pa was adopted. These measures stabilise the simulation as demonstrated by the Kinetic Energy briefly exceeding 1% of External Work, the threshold suggested by

Mallikarachchi for loading to be considered quasi-static, and well below the 5% limit proposed in adjacent studies on the stowage of lenticular-section composite beams [43].

Material properties The properties outlined in Tables 1 and 2 were assigned to the UD and polymer films respectively using the “Composite Layup” functionality within Abaqus. The UD layers were defined as non-isotropic laminae, while the polymer layers were defined as isotropic interleaves. The silver track thickness is negligible compared to the thickness of the neighbouring plies, and is thus not modelled. Material failure in the composite plies was studied via Hashin Failure Criteria, proposed by Hashin and Rotem in [44] to study the in-plane failure of unidirectional fibres, and implemented in Abaqus/Explicit as per [45]. The four failure indices HSN-FT, HSN-FC, HSN-MT and HSN-MC represent fibre tension, fibre compression, matrix tension, and matrix compression respectively. These indices are computed using the current value of the field variables for in-plane longitudinal (σ_{11}), transverse (σ_{22}) and shear stresses (τ_{12}) and the strength variables defined in Table 1. If any index exceeds unity, the material is likely to have undergone permanent damage in line with the index's respective failure mode.

2.3 Simulation results

The moment-rotation plots show that, for the geometrically perfect case, a peak moment of 414 Nmm is expected to be reached at an angle of 0.55°, followed by a constant

Fig. 9 Simulation contour plots at final folded state

moment averaging 12.5 Nmm (dotted lines, Fig. 12) over the 20° to 180° range. The model accounting for mounting imperfections leading to an out-of-plane bend of 0.5° yielded an 18% reduction in peak moment to 336 Nmm, occurring at the same snap angle and followed by a constant moment of 13.1 Nmm (summary in Table 3). In both cases the peaks, which can be challenging to capture due to their instantaneous nature appear well characterised.

Inspection of the damage criteria suggests failure is not expected: their maximum values are reported in Table 4 and the distribution of matrix-related indices for the 0.5° misaligned geometry are shown in Fig. 9a and b. The maximum transverse stresses (σ_{22}) and in-plane principal strains are obtained in the fully stowed arrangement and are shown, for the misaligned geometry, in Fig. 9c and d.

2.3.1 Mechanical testing

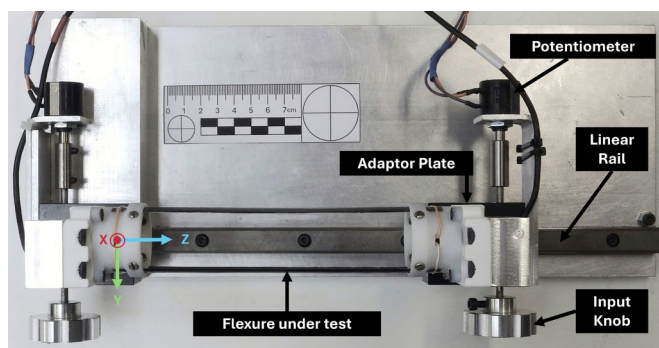
A labelled photograph of the test setup, is shown in Fig. 10. Each end of the tube flexure is rigidly connected via 3D printed adapter plates to a thin-walled shaft instrumented with a full-bridge rosette of strain gauges arranged $\pm 45^\circ$ to the shaft axis. One shaft is fixed, while the other is allowed to translate along a linear rail, ensuring that the sample under test remains in pure bending. As the test progresses and each end rotation increases from 0°, the translating end approaches the fixed one, until they come into contact as both sides achieve 90° rotation. Each shaft is mounted to a worm wheel, driven by worm gear coupled to a user-actuated knob and an analogue potentiometer, whose output voltage was related to the output shaft rotation. As the knob is rotated, a corresponding rotation is imparted on the shafts, thus on the ends of the tube flexure via the adapter plates and the couplers. The non-backdriveable nature of worm drive maintains the end-rotation, resisting against the moment imparted by the flexure in bending. Since the base of the shaft is restricted from rotating, the thin walled shafts are in a state of pure torsion, which is measured by the strain gauges. Each shaft's strain is correlated to the imparted moment in a calibration process.

Fig. 10 Labelled top-down photograph of the experimental setup with a flexure installed

2.4 Data acquisition and experimental procedure

Data acquisition was performed via a suite of National Instruments and Keysight tools. The 350 Ω strain-gauge bridges are read with a NI-9237 card, while the analogue output of the potentiometers is measured using a NI-9239 card with 24-bit ADCs ($\pm 5.4\mu^\circ$ theoretical resolution over 0°–90° range). Both cards were mounted to a NI-9185 CompactDAQ chassis. The excitation voltages used were ± 5 V and 0–10 V for the strain gauges and potentiometers, respectively. The resistance of the conductive tracks was measured using a Keysight 34410A digital multi-meter with 22-bit ADC ($\pm 1\mu\Omega$ theoretical resolution over 0–100 Ω range). Track resistance was logged simultaneously to moments and rotation, throughout the folding tests to detect the angle at which failure occurred, if at all. The resistance of the spring undergoing opposite-sense bending was tracked. A custom LabView program enabled the real-time capture, and display of the data, with potentiometer and strain gauge channels polled at 1 kHz and averaged at a 10 Hz, obtaining a low-pass filtered average. The LabView VI was provisioned with taring functionality on potentiometers, which may be used at the beginning of a test to compensate for assembly imperfections leading to the right hand-side adapter coupler not being parallel to the XY-plane as defined in Fig. 10. Misalignments about the ZY-plane or the Z axis cannot be corrected by the current setup, thus may pre-strain the flexure before the end-rotations are applied.

The springs' ability to transmit signals was checked at the end of each fold, as the RS-232 adapter interfered with the resistance reading and thus the instruments could not be used simultaneously. A 100-byte sized test payload was transmitted at a speed of 115,200 baud. If transmission failures occur, the transfer speed is reduced until communication is re-established, otherwise the connection is declared too damaged to transmit. The wiring harness is not pictured in Fig. 10 for clarity, but is connected to the connectors mounted to the 3D printed couplers, with wires then directly connected to the digital multi-meter or serial test device by means of screw terminals.



Preliminary tests and previous experimental studies show that the preferred folded arrangement of a tube flexure is not necessarily geometrically symmetric [7]. To ensure the sample is loaded as closely as possible to a theoretical pure bending state, moment-rotation readings are logged when the end-moments match to within a tolerance of 5 Nmm of each other. Because of the mechanical snap through, the behaviour of tube flexures is path-dependent, consequently rotations were monotonically increased. The setup was mounted on foam blocks, and before logging each reading, the aluminium base-plate was gently struck with a light-weight screwdriver to release the translating mount by overcoming static friction along the rail. Once each end is fully rotated, the RS-232 communications were tested along each tape spring's conductive path and finally the flexure is slowly unfolded, ensuring the moments match on each side to confirm the sample remains within the pure bending envelope.

2.5 Thermo-electrical testing

To validate the ability of the flexure to transfer the current required by a low-power instruments, a circuit as shown in Fig. 11 was assembled. The load resistance R_L was



Fig. 11 Electrical schematic for power transmission test

composed by a set of parallel resistors such that under a 31 V input voltage it would dissipate 2.5 W, affording a 200–250% margin on the consumption of COTS devices such as AAC Clyde Mag-3 and NewSpace DS [46, 47]. The magnitude of R_L depends on the resistance of the manufactured tracks R_A and R_B , and is determined ahead of the test using basic circuit analysis. The temperature is monitored using a Fluke Ti400 infrared camera. To validate the ability of the flexure to perform integrated heating that for initiating shape memory based deployment, the resistive load is disconnected and the two springs forming a flexure are connected in series such that the power is entirely dissipated by the flexure. Having achieved a temperature of $\approx 50^\circ\text{C}$ by gradually increasing the current supply, the spring is folded using the moment-rotation rig to determine whether thermal effects cause structural failure throughout the stowage process. The temperature of 50°C is chosen to provide a generous margin on the T_g of the Polyolefin interleave, which would need to be exceeded to show the system can function as an integrally actuated shape memory device.

The flexure analysed in this work is not fabricated as a shape memory device. That would require a different manufacturing process where the CFRP elements are cured in the deployed state, then bent to the stowed state at a temperature above the interleaf's, and left to cool (as described in [17]), resulting in a flexure which at room (or operational) temperature is stowed, and is deployed by passing current and generating heat necessary for actuation. The aim of the thermal testing herein is, therefore, not to replicate shape memory functionality itself, but rather explore whether the proposed architecture is capable of providing the heat

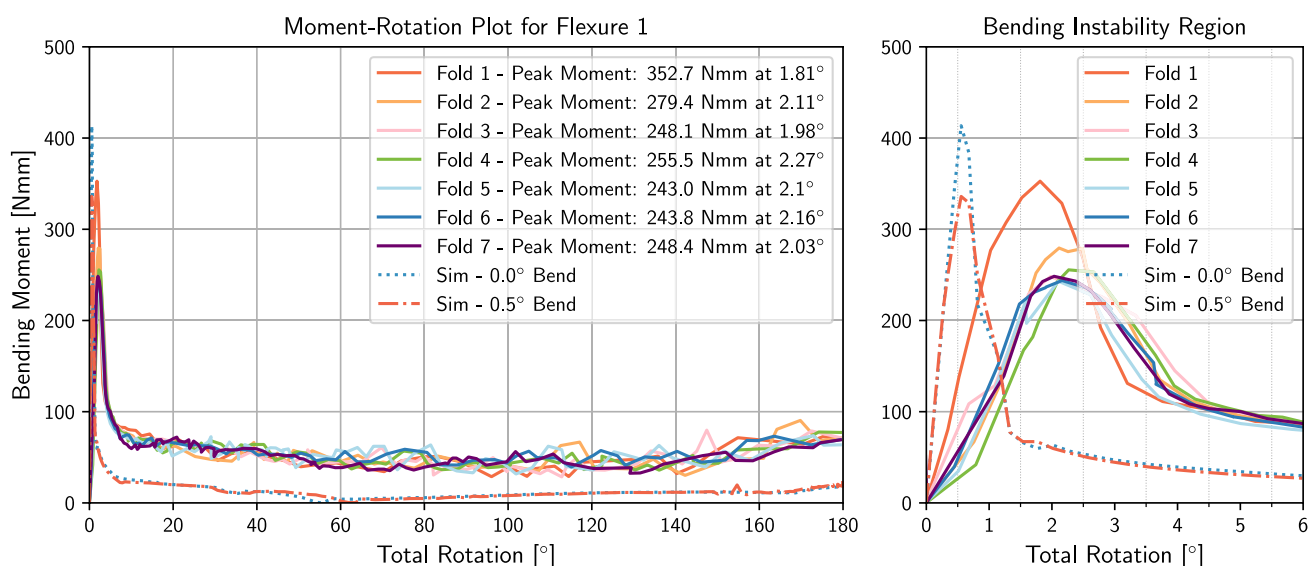


Fig. 12 Moment-rotation dataset for Flexure 1

input necessary to initiate the melt of the interleave and consequent actuation of the flexure.

3 Results

3.1 Moment-rotation

Four samples were folded 7 times, yielding a total of 28 moment-rotation relationships describing the behaviour of the proposed tube flexure design. Figure 12 shows these graphically for Spring 1, with key metrics of Peak Moment (M^{peak}), Constant Moment (M^{const}) and Snap Angle (θ^{snap}) for each fold, averaged over the four springs. In the following analysis M^{const} is defined as the average of all moment readings past 20° .

Figure 12 highlights two key aspects:

1. There is a clear decrease in peak moment between folds,
2. Both Peak Moments and Snap Angles differ consistently from the simulations.

The variation between folds and between individual springs is analysed and discussed first, followed by a comparison of the experimental results to the simulations.

3.1.1 Variation between folds

The statistical significance of the variation in the key metrics across the number of folds is analysed and discussed, considering all 4 flexures as a population. A Repeated Measures Analysis of Variation (RM-ANOVA) determines whether the variation of each metric under test with respect to the number of folds performed is statistically significant (defined by obtaining a p -value below 0.05). For those metrics which pass the RM-ANOVA test, Tukey Honest Difference (HSD) Pairwise T -tests are performed to identify exactly between which folds the difference is significant, using the same threshold. This procedure ensures that where effects are detected, they are significant across all flexures, though it must be noted that a population of 4 samples is small meaning that in-group normality cannot be guaranteed. Results are plotted in Fig. 13 and summarised in Table 5. In Table 5, the values are averaged over the population of four springs (with the value in brackets showing the standard deviation). In the final row, the average represents the average between folds, but this is only given if the statistical tests discussed in the section above show that any fold-wise variance is not statistically significant.

Peak moment The set of Peak Moment measurements, shown in Fig. 13a, was the only one to exhibit statistically significant effects. After passing the RM-ANOVA test

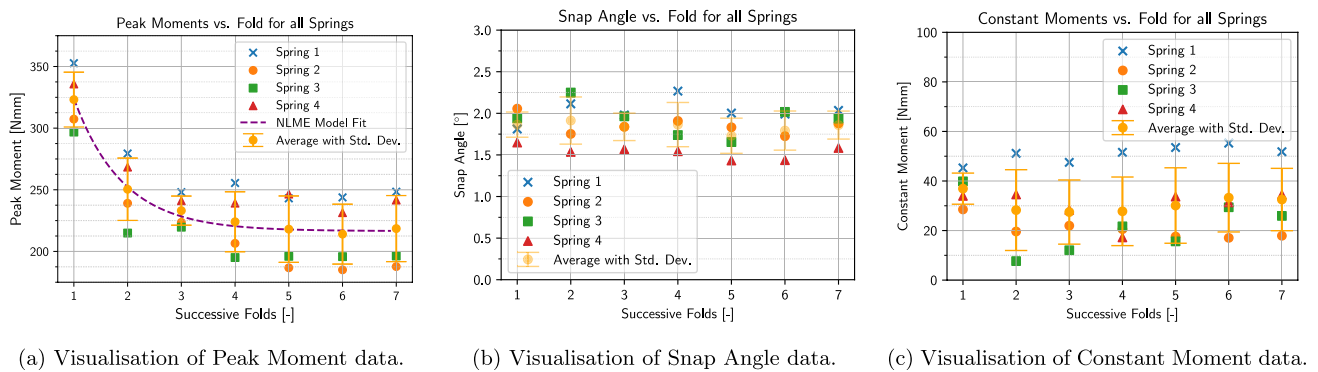


Fig. 13 Plots showing the results of mechanical testing

Table 5 Average M^{peak} , θ^{snap} and M^{const} vs. fold. Std. Dev. in brackets

Fold	Peak moment [Nmm]	Snap angle [$^\circ$]	Const. moment [Nmm]
Fold 1	323.2 (22.2)	1.87 (0.16)	36.9 (6.3)
Fold 2	250.4 (25.2)	1.91 (0.28)	28.3 (16.3)
Fold 3	233.1 (11.8)	1.81 (0.21)	27.5 (12.9)
Fold 4	224.1 (24.3)	1.86 (0.26)	27.8 (13.8)
Fold 5	218.1 (26.9)	1.73 (0.21)	30.1 (14.3)
Fold 6	214.0 (24.3)	1.80 (0.24)	32.8 (13.8)
Fold 7	218.5 (26.8)	1.84 (0.21)	31.5 (12.6)
Fold-wise average	n/a	1.83 (–)	30.7 (–)

$[F_{6,18} = 81.88, p < 0.001]$, the Pairwise T -test identified a significant decrease between the first and successive folds $[p < 0.0016]$, followed by non-significant variations thereafter. The behaviour described by the statistics is that of rapid decline of 32.4%, on average, followed by stabilisation, consistent with a “breaking in” behaviour.

Snap angle, constant moment The Snap Angle and Constant Moments datasets (plotted in Fig. 13b and c, respectively) underwent the same RM-ANOVA test, but showed no significant effects ($[F_{6,18} = 1.08, p = 0.41]$ and $[F_{6,18} = 0.43, p = 0.85]$, respectively), suggesting these metrics are not significantly affected by the number of folds. The lack of statistically significant variation in snap angle shows that the Peak Stiffness of the samples, defined as the ratio of Peak Moment to Snap Angle is governed by the settling-in of the former, decreasing by 37% between folds 1 and 7 from 172.9 Nmm/° to 118.8 Nmm/°.

The standard deviations reported in the Snap Angle and Constant Moment columns of Table 5 highlight some shortcomings in the experimental procedure. Readings for the constant moment have large standard deviations (up to 50.6% of the average values) which indicate a significant difference between each flexure. The clear outlier is Flexure 1, indicating a potential systematic error across all of that flexure’s tests, such an un-noticed wiring harness becoming taught and affecting the strain readings, or imperfections in its mounting to the adapter plates. A greater number of samples would shed light whether Flexure 1 is indeed an outlier. Standard deviations of the snap angles do not exceed 14% of the average values, showing much closer agreement amongst flexures.

3.1.2 Discussion and comparison with the simulation

The general behaviour (high stiffness followed by a buckling instability and a region of constant moment) was replicated by the simulation but some key discrepancies are quantified and discussed.

Peak Moment Table 6 compares the average Peak Moments for all springs for the first fold, and for all springs over all successive folds to both simulations. Notwithstanding progressive damage and only considering the first fold, the experimentally results depart significantly from the Peak

Moment predicted by the numerical study. Introducing the 0.5° misalignment in the ZY plane as discussed in Sect. 2.3 reduces the simulated peak moment bringing it within 4% of the average of the measurements for the first fold. The percentage over-shoot of the simulations with respect to measured peak moment shows closer agreement between the experiments and the simulation featuring the misalignment.

While best efforts were used to align the samples, there are random effects in bond-line thickness, accuracy and stiffness of 3D-printed supports and sample manufacturing that could have contributed to creating assembly misalignments and structural defects within the samples. Making use of metallic mounting hardware, performing the layup within a clean room environment, as well as utilising subtractive laser machining to repeatably trim excess material off of the individual springs would reduce these effects. While the bending instability is near-instantaneous and the manual nature of the logging process makes capturing the Peak Moment highly unlikely, the high angular resolution of the data captured suggests that the actual peak values would depart significantly from the reported ones.

The ratio of the peak moment and the snap angle determines the peak locking stiffness of the tube flexure, and the discrepancy between simulations and experimental data is immediately visible in Fig. 12, with the gradient preceding the snap angle being lower in the experiments than in the simulations even at Fold 1, preceding any damage from folding. To determine the nature of this discrepancy, both numerator and denominator of the stiffness term need to be considered. Since the average peak moment at Fold 1 matches the peak moment predicted by the simulations accounting for a 0.5° mounting misalignment within 4%, the obvious difference in stiffness can be neither fully nor exclusively attributed to a mischaracterisation of the peak moment, and must be accounted for in the snap angle, as discussed below.

Snap angle Snap angle is found to be highly consistent amongst all springs and all folds. However, upon comparison with the simulations given in Table 7 experiments appear to under-predict the onset of the bending instability by an average of 70%. This significant difference is attributed to backlash in the testing apparatus, specifically in the worm gear set to which the rotating shaft with the flexure adapter is coupled. The worm gear is not spring-loaded, meaning any

Table 6 Comparison in peak moment statistics—experimental vs. simulations

Fold	All spring average (Std. Dev.)	Sim 0.0° bend	Δ %	Sim 0.5° bend	Δ %
Fold 1	323.2 (22.2)	414	+ 28%	336	+ 4%
Folds 2–7	226.4 (23.2)	414	+ 84%	336	+ 32%

Table 7 Comparison in snap angle statistics—experimental vs. simulations

Fold	All spring avg (Std. Dev.)	Sim 0.0° bend	Δ %	Sim 0.5° bend	Δ %
Folds 1–7	1.83 (0.22)	0.55	−70%	0.55	−70%

wear or manufacturing tolerances cannot be compensated and leading to the worm wheel loosely constrained. This backlash is easily perceivable by hand, and was measured using a protractor as approximately 0.4° on both rotating shafts for a total uncertainty on the combined rotation of $\pm 0.8^\circ$. The effect of the backlash is challenging to eliminate post-hoc because its onset is governed by when the flexures reaction moment overcomes the static friction of the gearset bearing and seals, meaning it cannot be treated as a constant offset throughout the entire range or rotations.

Attempting to correct for the maximum possible backlash measurement of approximately 0.8° leads to a reduced, yet still considerable error between measurement and simulation of 46%, meaning that backlash alone does not fully explain the discrepancy and that further work must be done on the simulation to improve the reliability, specifically tackling the snap angle by performing material-level testing of the PO layer, whose properties were only estimated based on those of LDPE in this study. The viscoelastic effect of the polymeric PI-PO interleave was not considered in the simulation, so further work could increase the fidelity of the simulation by incorporating more reliable figures for the material properties of the PO layer (specifically its elastic and viscoelastic performance), as performed for PS in [17]. As per the peak moment, higher stiffness mounting hardware and tighter control of the materials and manufacturing processes would likely contribute to further reducing the discrepancy.

Damage Snap Angle remains highly consistent between folds, but peak stiffness decreases 37% fold-by-fold. Thus, while the discrepancy in peak stiffness for the first fold is attributed to poor stiffness measuring equipment, approximate material properties of the interleave, and lack of consideration for through-thickness effects, the decrease in stiffness on a fold-by-fold basis must be attributed to the decrease in peak moment (32.4% between the first and

seventh fold on average), and thus related to the lack of material damage modelling in this analysis methodology. The Hashin Indices for both simulations (Table 4) peak below their threshold values. However, analysis of the experimental results shows evidence of a “settling-in” behaviour between folds. The indices reported in Table 4 suggest compressive matrix cracking is the most likely failure mode, though no signs of matrix degradation were visible by direct inspection. In [11], a similar decrease in stiffness was identified in an interleave-less tape spring by studying the fold-to fold increase in recovery time of a tube flexure from stowed to deployed. Their numerical studies (on which the modelling used herein is based) did not predict any failures either, but an 85% reduction in effective stiffness, attributed to compressive matrix damage, was reported between first and fifth folds. The presence of this phenomenon on a fully composite flexure suggests this settling-in behaviour is least partially driven by damage in the CFRP plies, though direct comparing the magnitude in stiffness reduction would not consider the different methodology and cutout geometry of the two studies. For this study, flexures without interleaves were not fabricated and tested, so a comparison to a version of the model without the interleaf is not possible and it cannot be conclusively said whether the FE model presented performs differently with the addition of an interleave. Bhagatji et al. addressed matrix failure by proposing a Continuum Damage Mechanics (CDM) subroutine within Abaqus for studying single-ply, lenticular CFRP flexures, successfully correlating the model’s prediction of matrix failure to measurements of reduced peak moments [43]. A further limitation of this modelling approach is that the use of plane-stress elements limits its ability to predict interlaminar damage. As seen in [16, 28], composites interleaved with thermoplastics fail at lower interlaminar shear stresses due to poor adhesion issues and the inherently lower shear strength of the interleave.

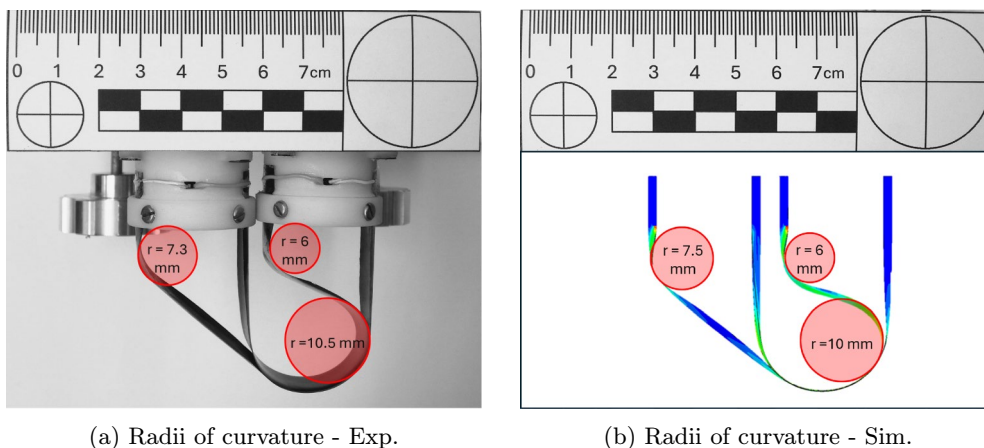


Fig. 14 Experimental and simulated radii of curvature comparison

Table 8 Comparison in average constant moment statistics—experimental vs. simulations

Fold	All spring avg (Std. Dev.)	Sim 0.0° bend	Δ %	Sim 0.5° bend	Δ %
Folds 1–7	29.9 (13.0)	12.5 (4.8)	−58%	13.1 (5.3)	−56%

No evidence of shear failure in the PO layers were visible in the samples observed under the optical microscope, but it is possible that areas other than the ones observed may present such failures. Expanding the FE model with cohesive elements or layered shell elements, which have been used to model tape springs and curved panels highly sensitive to interlaminar effects may identify areas at higher risk of such failures [17, 48]. Despite the model's inability to fully capture damage, Fig. 14a, b show the radii of curvature in the experiments were comparable to those of the simulations, suggesting deflections are well captured.

Constant Moment Similarly to Snap Angle, the average constant moment was found to not vary significantly with number of folds, and showed a considerable and consistent discrepancies with the simulations, which under-predict it by over 50% (see Table 8). This deviation is attributed to friction in the linear bearing: when the reaction moment generated by the flexure is small, as expected in the case of the constant moment region, it is insufficient to overcome the rolling resistance. Any hindrance to the translation of the bearing applies tension to the spring, thus causing it to depart from the boundary conditions specified in the simulation. As outlined in Sect. 2.4, attempts were made to

overcome this friction but these appear to have been unsuccessful in completely eliminating its effects.

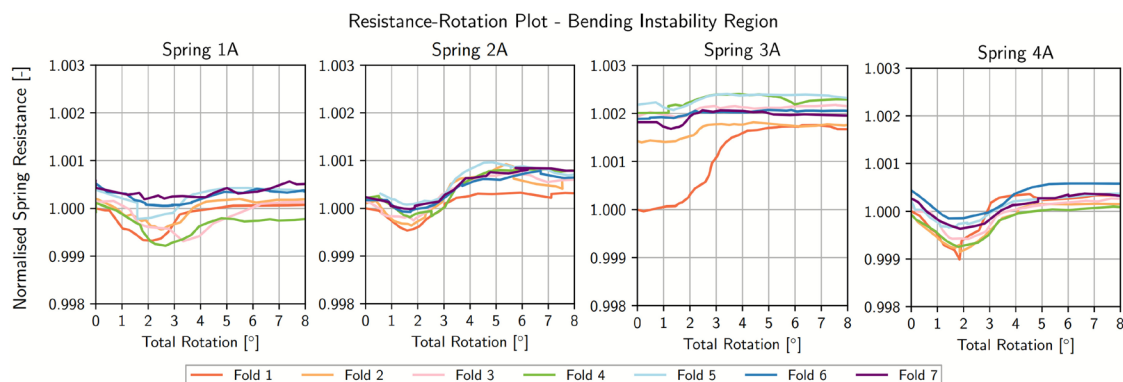
3.2 Electrical performance

The initial electrical resistance of each spring is given in Table 9, net of the contributions from connectors and instrumentation wiring. The springs are identified by the flexure they were assembled into (1 to 4) and the sense of their bending (those terminating in A undergo opposite-sense bending, those terminating in B undergo equal-sense bending). Continuity checks between the conductive layers and the external surfaces confirmed that none of the tracks had shorted to the CFRP layers throughout manufacturing.

Initial Resistance The average initial resistance is 37.41Ω with a standard deviation of 5.28Ω . The spread in resistance is attributed to misalignments in the Inkjet Printer gantry, leading to variable thickness of the traces across the substrate. Inconsistencies in the handling of the samples during the layup process may have resulted in defects such as kinks in the substrate or light scratches across the track. Track resistance is high compared to a wire harness of equivalent length, however with the given geometry there is scope for tripling track width, increasing the effective cross-section and reducing resistance, as demonstrated for copper-based inkjet prints [32]. In addition, the low power draw of the instruments likely to be powered by these tracks and the relatively high 28–34 V voltage used on board of satellites, mean the current draw and associated resistive losses may be acceptable. This topic is further discussed in Sect. 3.2.2

Table 9 Initial resistance of the tape springs

Spring 1A	Spring 1B	Spring 2A	Spring 2B	Spring 3A	Spring 3B	Spring 4A	Spring 4B
41.33 Ω	47.16 Ω	29.46 Ω	32.21 Ω	34.84 Ω	32.20 Ω	40.24 Ω	38.93 Ω

**Fig. 15** Normalised resistance vs rotation about the onset of snapthrough

Track Failure No track failures were detected. Figure 15 shows resistance-rotation plots of the tracks embedded in springs in opposite-sense bending over the 0° – 8° range. To compare each sample's fold-wise changes, the data was normalised by each spring's initial resistance (the first resistance reading of the first fold, reported in Table 9).

Over the 0° – 8° interval, Springs 1A, 2A and 4A behave similarly: the value of resistance dips about the angle at which the bending instability takes place, then stabilises close to the fold's initial resistance. The direction of the dip in resistance can be explained by the fact that the region containing the silver ink experiences heightened compressive strains which create additional bridging amongst the metallic nanoparticles and reduces resistance. Spring 3A shows a different behaviour, with a greater difference in the initial resistance of each fold, a more sigmoid-shaped increase in resistance and no discernible dip.

Average resistance Average resistance over the 0° – 180° range, normalised by each spring's initial resistance, was found to vary with statistical significance [$F_{6,18} = 3.46, p = 0.021$] by 0.1%, but Pairwise t-tests failed to isolate fold-by-fold effects. The relatively high p-value and the lack of significant variations in other relevant metrics such as Initial Resistance [$F_{6,18} = 2.42, p = 0.076$] and Maximum Resistance [$F_{6,18} = 1.87, p = 0.14$], suggest that a weak trend may exist, but due to the modest number of samples, small size of the effect, and large spread of the data, it is not considered practically significant.

As discussed in Sect. 1.2, inkjet printed circuits have been successfully used to identify bondline defects and fracture. As discussed in [21, 29, 37], the increased resistance of the embedded track has been interpreted as a degradation of the thermoplastic bond lines. However, the lack of a convincing statistical correlation between number of folds and the metrics relating to the health of the track described above suggest that the thermoplastic bondline between the Kapton and LDPE layer which encase the silver track does not degrade significantly over the 7 folds performed at room temperature (24°C).

3.2.1 Signal integrity

The ability to transfer signals was tested by means of an RS-232 test loop running along both springs of each tape, and the start and end of each fold. Each of the 4 flexures successfully transferred the 100-byte test packets at a speed of 115,200 baud (the maximum commonly used RS-232 communication data rate, equivalent to 115.2 kbps using UART modulation) in both stowed and deployed configurations. An additional test with the 4 flexures in series was performed, achieving the same rate of 115,200 baud. This shows that it would be possible to daisy-chain at least four

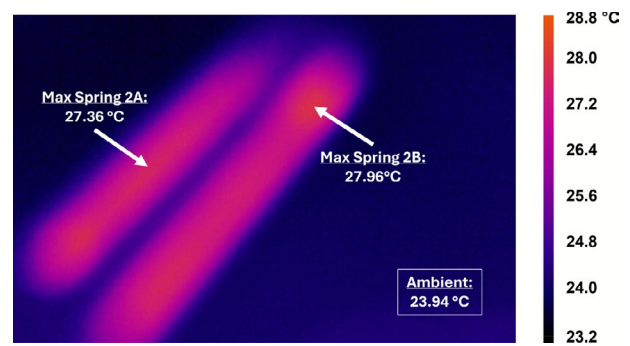


Fig. 16 Infrared thermal imagery of flexure 2 transferring 101 mA at steady state

flexures with a combined resistance of 286.87Ω together to obtain a multi-articulated boom while retaining the ability to transfer signals.

3.2.2 Resistive losses

The ability to power a low-power instrument when the flexure is fully deployed was demonstrated by passing a 100 mA current over both springs of the Flexure 2, as discussed in Sect. 2.5 and pictured in Fig. 11. Given the springs' resistances (see Table 9), basic Ohm's law relations were used to determine the load needed to generate the desired power draw. A load resistance of 256Ω , in combination with the individual spring resistances, a current flow of 101 mA at an input voltage of 31.5 V is induced. The voltage drop over Spring 2A was measured to be 2.95 V, yielding a power dissipation of 295 mW. Over Spring 2B, the voltage drop was measured to be 3.18 V, yielding a higher power dissipation of 318 mW. The test was allowed to run for 30 min, with no measured difference in the voltage drop across the springs. Infrared imagery (Fig. 16) confirmed that Spring 2B, with higher resistance and dissipating more power, experienced a higher temperature increase with respect to the ambient temperature (4.0°C compared to 3.42°C for Spring 2A).

The test was conducted at atmospheric conditions, in which convective cooling plays a role in achieving a steady-state temperature. Further studies may wish to characterise thermal behaviour through thermal vacuum cycling to determine the impact of convection and environmental temperature on the steady state temperature. While these results may be acceptable for a single-jointed boom, adding several flexures in series would generate significant transmission losses. As discussed above, increasing track width, track thickness and additional tailoring and development of the Inkjet process would reduce losses, though it is estimated that these measures would not exceed the an order of magnitude improvement and as such, this technology may only offer system-level benefits on booms with few joints.

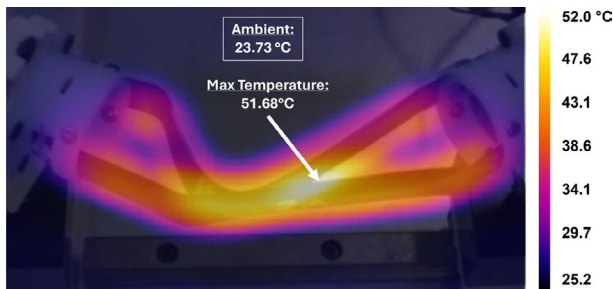
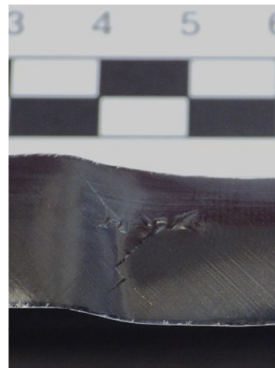


Fig. 17 Superposed infrared and optical imagery immediately preceding the failure



Fig. 18 Flexure 2 following the thermal failure

Fig. 19 Detail, showing the failure



3.2.3 Integrated heating

A voltage of 28 V was applied to Flexure 2, and the current limit was increased until the flexure reached a temperature of $\approx 50^\circ\text{C}$ (220 mA), and the ends rotated as per the mechanical testing. At a total rotation of 42° , coinciding with the first

instant of contact between the two springs, the power supply stopped supplying current, indicating the failure of one of the tracks. Due to the sudden interruption in thermal energy supply the structure cooled rapidly, with the thermoplastic layer “freezing” in a deformed state. Upon the release from the rotation rig, the structure retained the deformed geometry at the location of damage. This cycle broadly replicates the cure-heat-deform-freeze cycle exploited by Almuslmani and Santer to create shape memory, controllable stiffness composite tape springs [17]. Figure 17 shows an overlay of thermal and optical imagery taken at a rotation of 40° , before the springs had made contact.

Due to the instantaneous and irreversible nature of the failure, it was not possible to capture a thermal image immediately after. However, having occurred at the instant and location of contact between the two springs, the failure is hypothesised to have been caused by locally increased temperatures due to a reduced surface area available for convective heat rejection. Figures 18 and 19 show the permanently deformed flexure with a detail view of the blister-like failure on the spring undergoing opposite-sense bending (only visible on its external plies, loaded in bi-axial compression throughout the stowage process). The flexure was brushed with 99% Dibromoethane solution and inspected under X-ray, which confirmed the delamination was contained within the area directly above the conductive track without propagating, and that the spring undergoing equal-sense bending was undamaged (Fig. 20).

The morphology of the failure is consistent with Local Delamination Buckling, wherein a composite loaded in pure bending or pure compression while presenting interlaminar defects (delamination or cracks, typically arising from impact) shows reduced buckling resistance of the external plies [49, 50]. Compression loading triggers a bending instability of the de-bonded, thus transversally unconstrained, sub-laminate. This failure mode is typically induced in a laboratory setting by interleaving thin PTFE or Teflon films to simulate poor interlaminar adhesion [51].

In this study, given the location of the blister and lack of delamination at room temperature, the defect appears to have been induced by the resistive heating of the track. The failure was replicated on another sample and examined under a scanning electron microscope, with key images shown in Fig. 21. The sub-figure on the bottom right (taken deep into the delamination and far from the cut) highlights

Fig. 20 Top-down X-ray of the delamination of the Opposite-Sense spring on its conductive track



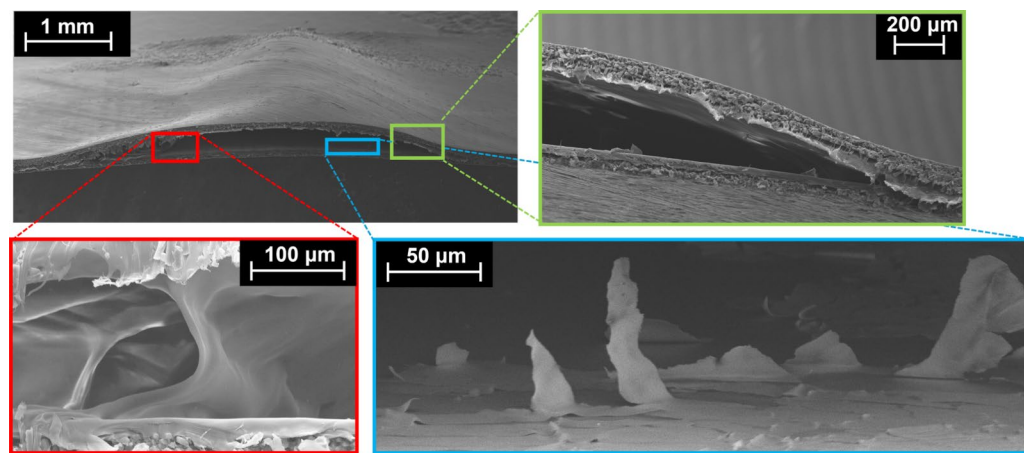


Fig. 21 SEM images with varying magnifications. The sample was cut transversally at the failure

how the silver track is cracked, damaged and peeled away from the Kapton substrate in the delamination process, ultimately leading to loss of electrical continuity. The lack of PO residue on the silver track suggests poor adhesion amongst them, likely further compromised by the increased temperature. The sub-figure on the top right supports this hypothesis by showing a clean adhered surface above the track. In contrast, the bottom right sub-figure illustrates how the failure differs in regions neighbouring the track: polyolefin is visible on both upper and lower surfaces, suggesting a higher quality bond between the Kapton and PO. The structures bridging the delamination are characteristic of cohesive failure expected from a heated, flowing thermoplastic. These bridging structures dissipate energy, delaying de-bonding and the propagation of the delamination [52].

This failure mode suggests the solution presented may not be suitable for integral heating applications, though there are some further opportunities to strengthen the adhesive bond between the track and the PO layer such as improved surface preparation of the polyolefin film by plasma treatment (as suggested in [53]) and micro-texturing of the silver track by laser ablation (as suggested in [54]). Humidity or otherwise trapped moisture may represent an additional detrimental, but easily addressable effect.

The thermal environment, and thus the required heat flux to be generated, would vary significantly, both between the atmospheric laboratory environment and space, as well as from mission to mission based on mission design, operational planning, packaging on board of the spacecraft, availability of thermal control coatings and desired stiffness. As mentioned in Sect. 1.2, other groups experimenting with shape memory have used Polystyrene, which has a T_g of 100 °C. Provided that interlaminar adhesion between a given thermoplastic film and the Kapton/CFRP interfaces is sufficient, the interleave may be selected from a range of materials to best suit a missions power requirements or

operating environment—for example a CubeSat operating in lunar orbit will operate at cool temperatures and have a reduced power output capabilities, so PO may be better suited as it reaches a flow state at lower temperatures. A large science mission operating at Venus may select a higher T_g material to ensure that deployed stiffness is maintained in the higher temperature environment, and may be able to provide a higher power to the hinge to provide the temperatures necessary to reach the high T_g .

3.2.4 Summary of results

The key findings can be summarised as follows.

1. It is possible to embed a Kapton-PO interleave featuring silver ink within an thin composite tape spring to add electrical functionality including:
 - Serial communications up to 115,200 Baud with up to four flexures in series,
 - Power transfer of up to 2.5 W,
2. There is no strong evidence of electrical performance degradation (measured in terms of track resistance and maximum bit-rate) over 7 fold-unfold cycles.
3. Integral heating functionality was demonstrated in the fully deployed state, but was found to cause structural failure in the stowage process. The failure is hypothesised to be delamination-buckling driven by thermal degradation of bondline between the silver track and the Polyolefin film. While the ability to resistively heat the flexure are demonstrated, this structural failure suggests that further work on the track geometry, interlaminar adhesion, insulating surface coatings as well as testing in representative thermal environment are needed before this methodology is ready to be integrated into a shape memory experiment.

4. On average, the samples exhibit a settling-in behaviour manifesting as a 37% reduction in Peak Stiffness between the first and seventh fold, which has been observed to a similar degree in adjacent studies involving non-interleaved composite flexures.

4 Conclusion

This study has successfully demonstrated a novel methodology for embedding inkjet-printed silver nanoparticle circuits within thin CFRP tube flexures, creating a multifunctional compliant mechanism capable of electrical power and signal transmission. The key achievement is the validation of these integrated flexures for reliable digital signal and low-power transfer in a laboratory environment. Prototypes successfully transmitted data at rates up to 115.2 kbps and transferred 2.5 W of power, with no appreciable degradation in electrical performance or signal integrity observed over seven fold-unfold cycles at ambient temperature in a population of four flexures. These findings represent a significant step toward developing ultra-lightweight, integrated harnesses for deployable members on future space structures.

However, the study also identified critical points of development that must be addressed in future research. The application of this technology for integral heating was found to be unviable, with the current methods leading to structural failure in the stowed state. This failure is hypothesised to be a delamination-buckling instability, driven by the thermal degradation of the adhesive bond between the silver track and the polyolefin insulating film at approximately 50 °C. Furthermore, a “settling-in” behaviour, manifesting as a progressive 37% reduction in peak stiffness, was consistently observed in mechanical tests but was not predicted by the FEA model using standard Hashin failure criteria, indicating a gap in the model’s ability to capture matrix damage or interlaminar effects under cyclic high-strain loading.

To build upon these findings and address the identified shortcomings, future work should proceed along several key fronts.

- **Improved bonding strength:** Improved surface preparation techniques, such as plasma treatment of the polymer films or micro-texturing of the silver track to increase bondline integrity should be explored with the aim of circumventing delaminations and enabling shape-memory functionality.
- **Modelling Fidelity:** The predictive capability of the numerical models must be improved to capture the observed stiffness degradation, simulations should incorporate more sophisticated material models, such

as a Continuum Damage Mechanics (CDM) framework. Alternatively, a greater number of samples should be prepared and tested to obtain a more reliable estimation of the expected long-term stiffness.

- **Experimental Validation:** Third, a true quantitative validation of these improved models requires a higher-fidelity test apparatus. Future experimental campaigns should utilise larger, stiffer tube flexures and rigs with anti-backlash gearing and lower-friction bearings to reduce the relative effect of measurement uncertainties, especially in terms of the snap angle.

In conclusion, despite current challenges with thermal performance and modelling, this work validates inkjet-printed conductive interleaves as a viable solution for integrating digital communication and low-power wiring into deployable composite structures. By systematically addressing the areas for improvement outlined above, this technology holds significant promise for enabling the next generation of highly integrated, lower-mass, and more reliable spacecraft. This has demonstrated that a deployable hinge can serve simultaneously as a structural and electrical pathway enables new spacecraft designs where deployable systems are not just structural, but inherently functional, enabling lighter, simpler, and smarter missions.

Acknowledgements The authors thank Messrs. Senior, Cole, Thornton and Giammaria for their assistance with the flexure manufacture and instrumentation setup. Additional thanks to the Imperial College Structural Health Monitoring Group for providing access to track samples and, and to Dr. de Sá Rodrigues in particular for providing practical assistance with the setup of the inkjet process.

Author contributions A.P.: conceptualization, methodology, fabrication, investigation, and first draft. M.S.: conceptualization, supervision, and draft editing.

Data availability Datasets generated during testing are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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