Thermoplastic composite tape spring hinge for space applications made by 4D Printing

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1. Abstract

This paper presents some behavior of tape spring hinge made of thermoplastic composites using the technique of 4D Printing of Composites (4DPC). The material is carbon fibres/LMPAEK thermoplastic composites. The tape spring has a radius of curvature of 10 cm and a length of 17 cm. Its intended use is to connect space panels together. The tape spring can help to store the space panels in a confined space during stowage and to deploy when it is necessary. A special fixture has been developed to investigate the relation between bending moment and bent angle of the tape spring. Relations between these are provided.

2. Introduction

Tape springs are thin slender shells that exhibit different bending performance along different directions. They have been used to make measuring tapes, snap bars, and hinges for the efficient stowing and deployment of space structures such as space solar cell arrays [1]. A typical configuration is shown in figure 1a. The deployment procedure of the solar cell arrays using tape spring hinge is shown in figure 1b. As manufactured, the tape spring has a curvature with radius R throughout the length of the tape L (figure 1a). The tape can be folded (bent) along its length, either in the equal sense or opposite sense. Due to the presence of the curvature with radius R, there is stiffness due to geometry which provides strong resistance against bending (as compared to a flat tape). Due to this deformation characteristic, the tape springs have been used to make hinges for space structures such as solar cells (figure 1b). When two solar cell panels are connected via tape springs, the two panels can be folded over each other (like closing two parts of a book) by bending and rolling the tape spring. Many solar cell panels can be stowed within a small box occupying a minimum amount of space. Once arriving in space, the solar cell panels can be deployed.

Tape springs have been made using metals, and composites such as carbon or glass fiber/epoxy composites. A lot of work has been done on understanding the behavior of tape springs made of metals (steel). Megha Thaker et al [1] gave a review on tape springs for deployable space structures. They provided the relation between bending moment and bending angle as shown in figure 2. The tape spring can be bent either in the equal sense direction, or in the opposite sense direction.

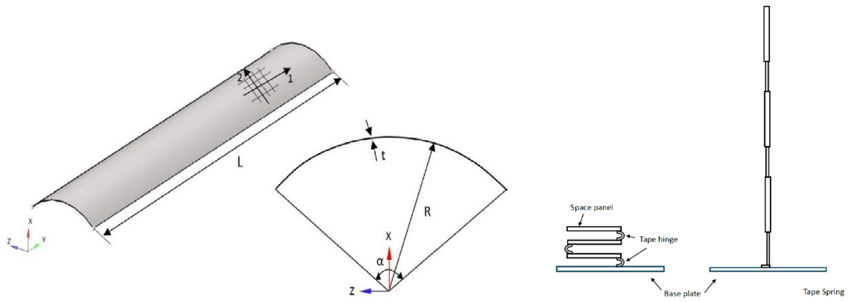

Figure 1: (a) Configuration of a tape spring. (b) Deployment of solar cell panels using tape spring hinge. (Left) Stowed. (Right) Deployed.

In figure 1, the tape has an initial radius of curvature *R*. Let the curvature corresponding to this be denoted as *Kz* (the curve runs along the z direction). Now in figure 2, when the tape is bent along its length (x direction), the curvature is denoted as *Kx*. For equal sense bending, *Kx Kz* > 0, and for opposite sense bending, *Kx Kz* < 0. It can be seen that the maximum bending moment in the opposite sense direction is larger than that in the equal sense direction. Also there is a drop in buckling load in the opposite sense bending.

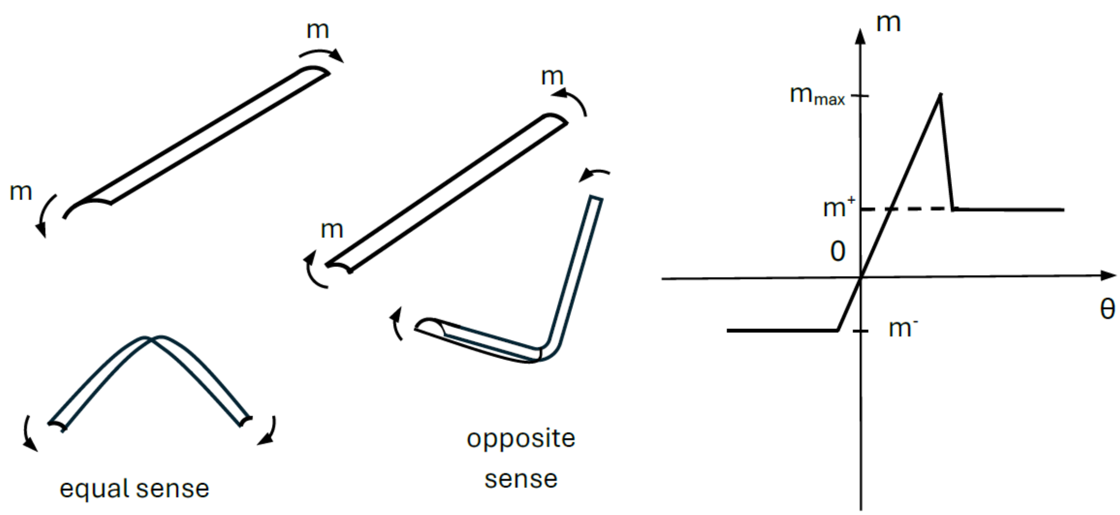

Figure 2: Relation between bending moment and bending angle for metallic tape springs [2].

There has also been a significant amount of work in using composite materials to make tape spring hinges. Omer Soykasap [2] provided an analysis for a boom made of plain weave T300 carbon/polyetherimide. The folding hinge consists of three tape springs obtained by removing material from a cylindrical boom after manufacturing. Huina Mao et al [3] studied the behavior of three tape springs made of thermoset matrix composites. The tape springs were made using pre-impregnated Hexply M77/38%/107 P/G fabric. It is an epoxy E glass plain weave prepreg where M77W is the resin type (38 w/o corresponding to 44 v/o) cured for 2 hours at 125 ºC. Nominal areal weight is 107 g/m^2, with 53 g/m^2 in the 0º direction and 51 g/m^2 in the 90º direction. Three tape springs with three lay-up sequences were produced: [-45/0/90/45], [-45/0/45], and [-45/45] where the 0º direction was oriented along the length of the tape spring. Every angle in these lay-up sequences corresponded to the orientation of one plain weave layer. The +/- 45º layers provided the bi-stability and added shear and local bending stiffness to the laminate, but these layers are sensitive to viscoelastic strain energy relaxation. Thus, the 0º/90º were added to provide deployment force and axial stiffness to ensure long term stowing-deployment capability. Manufacturing was hand-lay-up on a half-circle mandrel. The tested average natural coiling radii for the four-, three- and two-layer tape springs were 12.5 mm, 11.0 mm, and 10.7 mm, respectively. Relaxation test at room temperature (figure 11 in reference [3]) shows that the radius of curvature of the three laminates change by about 8%, 9% and 10% for the four-, three-, and two-layer laminates respectively. Kawai Kwok et al. [4] also studied the viscoelastic behavior of tape springs made of composites but these results are at temperature higher than room temperature. Kwok and Pellegrino [5] provided micromechanics models for viscoelastic plain-weave composite tape springs. Galletly and Guest [6] provided a shell model for bistable composite slit tubes. Guest and Pellegrino [7] proposed analytical models for bistable cylindrical shells. They indicated that for shells with no coupling between bending and twisting (i.e. $D_{16} = D_{26} = 0$), the condition for a cylindrical shell to show bi-stability is:

$$4\overline{D_{66}} + 2\overline{D_{12}} - 2\,\frac{\overline{D_{22}}}{\overline{D_{12}}} > 0 \qquad (1).$$

where $\overline{D_{66}}, \overline{D_{12}}, and\ \overline{D_{22}}$ are the reduced bending stiffness coefficients of the laminates. They also concluded that isotropic shells are not bistable, simple antisymmetric lay-ups of composites are bistable, and symmetric lay-ups of composites tend to coil into helix rather than a compact coiled state.

Murphey et al. [8] developed deployable booms and multi-element antennas using bistable tape springs made of composite materials. These structures occupy approximately one quarter of a Cubesat volume (50 x 50 x 100mm) when packaged and self-deployed to lengths of several meters. They indicated that the ratio of the as-rolled curvature to the fabricated curvature is simply the laminate Poisson ratio with respect to the boom axes:

$$\nu_{xy} = \frac{k_{rolled}}{k_{fabricated}} \qquad (2)$$

Also, they indicated that the necessary condition for bi-stability for the laminate is:

$$\frac{E_1}{G_{12}} > 2(3 + \nu_{12}) \qquad (3)$$

Where E_1, and G_{12} are longitudinal Young' modulus and shear modulus, and ν_{12} is Poisson ratio. ν_{12} is generally small for plain weave composites, so E_1 must be about 6.4 times larger than G_{12} for bi-stability to occur. Isotropic materials are not bistable without pre-stress since this ratio is about 2.7 (assuming ν = 0.33).

3. Tape springs made of thermoplastic composites and 4D Printing of Composites (4DPC):

The literature survey shows that a significant amount of work has been done on the use of composites to make tape springs. These are mostly thermoset matrix composites. The samples have been made using a mold such as half pipes. Recently there is a push toward the use of thermoplastic composites due to many advantages such as better resilience at low temperature, higher fracture toughness, no shelf life, and better chance to be recycled. Besides, there has been recent development in the technique of 4D printing of composites where composite structures can be made without the use of a mold of complex shape. Only a flat mold is used [9]. The ability to manufacture without the need of a complex mold can save a lot of time and cost.

This paper examines the feasibility of using high performance thermoplastic composites such as carbon/Low Melting point Poly Aryl Ether Ketone (LM/ PAEK) composites as tape springs. The technique of 4D Printing of composites (4DPC), based on residual stress management, is used for their manufacture. An automated fiber placement machine (AFP) was used. Figure 3 shows the samples made. The radii of curvatures for the samples are 8.0 cm for [0/90] laminate, 10.2 cm for[0_2/90] laminate, 9.1 cm for [0_3/90] laminate, and 16.0 cm for [0_2/90_2] laminate.

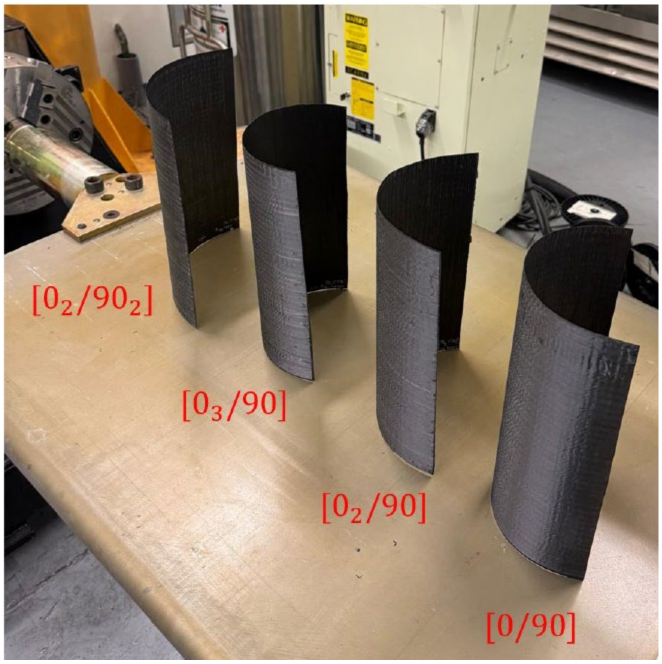

Figure 3: Samples of thermoplastic composites (carbon fibres/LM PAEK) made using AFP and 4DPC.

4. Bending of tape springs made of thermoplastic composites and 4DPC:

Bending fixture:

A bending fixture was developed for bending the tape spring, as shown in figures 4a and 4b. The fixture consists of a fixed part (cross hatched part on the right of figure 4b), and a rotating part (white part of the left of figure 4b). The sample is attached to tight grooves on the left and right. A wrench is used to rotate the left part relative to the right part. A torque sensor is used to measure the torque and an angle sensor is used to measure the corresponding bent angle. The sample can be bent in either the same-sense direction or in the opposite-sense direction. Figure 5 (left) shows the dimensions of the sample and the bending results.

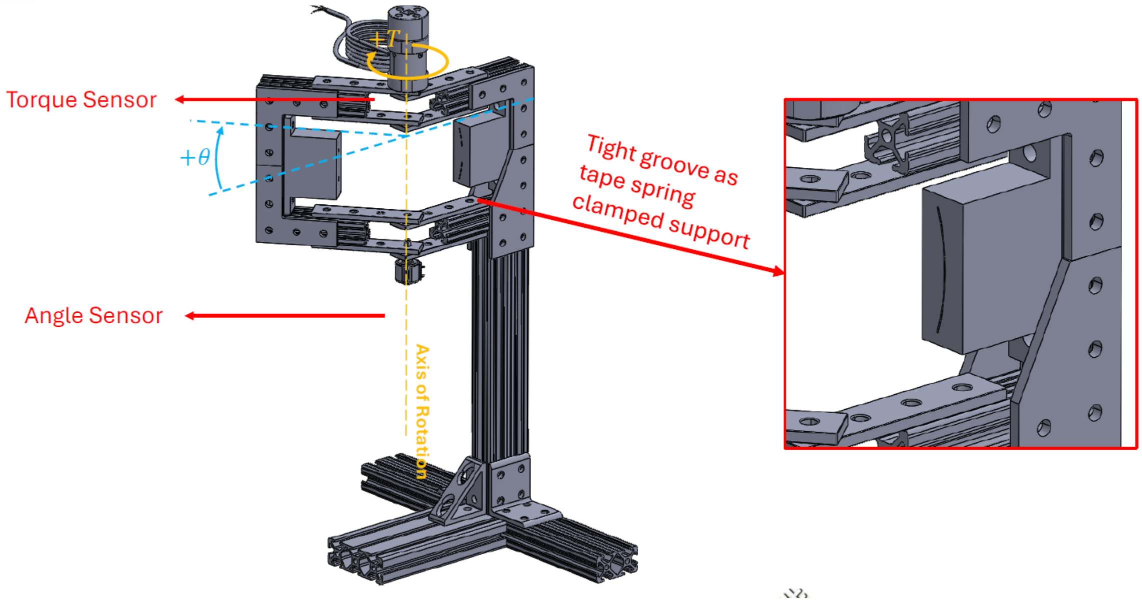

Figure 4a: Fixture for bending the tape spring.

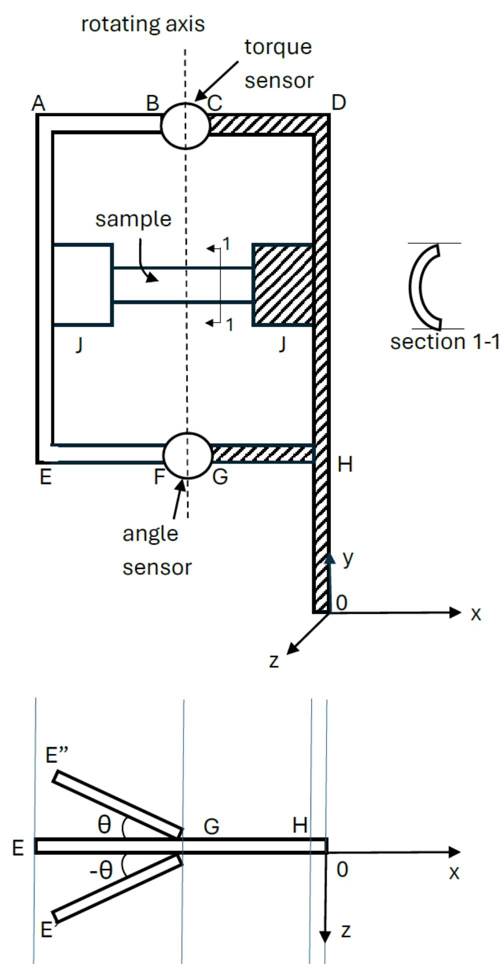

Figure 4b: Schematic of the bending fixture.

Bending test results:

The results from the bending test are shown in figure 5 (right). The behavior of the composite tape spring looks different from the behavior of the bending curves for metallic tape spring. In figure 2 for the metallic tape spring, after the buckling load drop, the bending moment stays constant as the bending angle increases. In figure 5, the bending moment keeps on increasing with the bending angle. Also in figure 5, even though the slope of moment versus bent angle is larger for the case of opposite sense bending, the buckling load drop for opposite sense bending is much bigger than that for equal sense bending. This results in the maximum load for equal sense bending to be larger than that of opposite sense bending.

Relaxation test was also performed. This was done by keeping the angle of rotation fixed, while measuring the required torque at increments of time from the start of the test session. Measurements were made each day for 10 days. There was no significant change in the torque required to keep the bending angle at 45°. This shows that relaxation is negligible for bending angle of 45°.

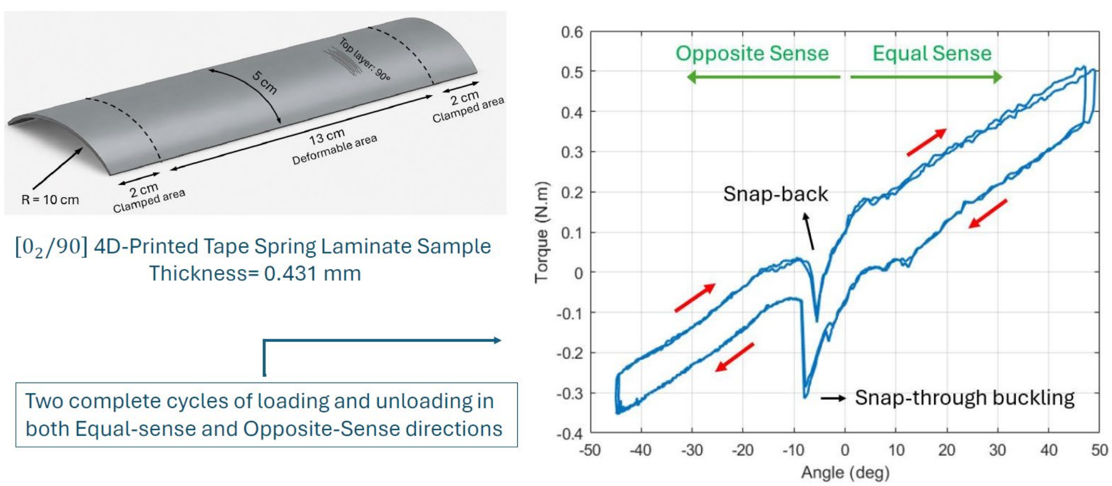

Figure 5: Sample dimensions (left) and bending results (right).

5. Conclusion:

Tape springs are important for the effective stowing and deployment of space structures such as solar arrays, booms etc. Composite tape springs have been made using mostly thermoset matrix composites. This paper presents an initial effort in making tape springs out of thermoplastic composites using AFP machine and the technique of 4D Printing of Composites. The initial results show significant potential. Further work needs to be done in order to take into account the bi-stability and robustness of the structures.

6. References:

[1] Megha Thaker, Shashikant J. Joshi, Hemani Argra, and Dhaval B. Shah, "Tape springs for deployable space structures: A review ", Advances in space research, 73, 2024, 5188-5219.

[2] Omer Soykasab, "Deployment analysis of a self-deployable composite boom" Composite Structures, 89, 2009, 374-381.

[3] Huina Mao, Anton Shipsha, Gunnar Tibert, "Design and analysis of laminates for self-deployment of viscoelastic bi-stable tape springs after long-term stowage", Journal of Applied Mechanics, Trans. ASME, 84, 2017 .

[4] Kawai Kwok and Sergio Pellegrino, "Folding, stowage and deployment of viscoelastic tape springs", AIAA journal, 51, 1908-1018, 2023.

[5] Kawai Kwok and Sergio Pellegrino, "Micromechanics models for viscoelastic plain weave composite tape springs", AIAA Journal, Vol. 55, No. 1, January 2017.

[6] Diana A. Galletly and Simon D. Guest, "Bistable composite slit tubes: A shell model", International Journal of Solids and Structures, 41, 2004, 4503-4516.

[7] S.D. Guest and S. Pellegrino, "Analytical models for bistable cylindrical shells", Proc. Royal Society A, 2006, 462, 839-854.

[8] Thomas W. Murphey, Sungeun Jeon, Adam Biskner, and Gregory Sanford, " Deployable booms and antennas using bi-stable tape springs", 24th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, Utah, USA.

[9] Hoa Suong Van, "4D printing of composites", De Gruyter 2015,