Deployment Testing of Flexible Composite Hinges in Bi-Material Beams

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Composites have excellent properties for strength, thermal stability, and weight. However, they are traditionally highly rigid, and when used in deployable structures require hinges bonded to the composite material, which increases complexity and opportunities for failure. Recent research in composites has found by adding an elastomeric soft matrix, often silicone instead of an epoxy, the composite becomes flexible. This work explores the deployment repeatability of silicone matrix composite hinges which join rigid composite beams. The hinges were found to have sub-millimeter linear deployment repeatability, and sub-degree angular deployment repeatability. Also, an interesting relaxation effect was discovered, as a hinges deployment error would decrease with time.

I. Introduction/Background

COMPOSITES have excellent strength characteristics, are lightweight, and thermally stable. Unfortunately, they are usually highly inflexible and require hinged joints when used in deployable structures. This is a challenge for CubeSats/SmallSats as the hinges and actuation mechanisms get very small and require multiple custom precision parts. On larger satellites, hinges are not desirable as they increases piece part count, introduces a potential weakness as hinges must be bonded, and often the metals used in hinges are not thermally stable. A new field of research, high strain composites, which is a subset of deployable space structures[1], provides solutions for compliance which may eliminate the need for hinges in deployables. Specifically of interest in this paper are elastomeric soft matrix composites. Thus far, there have been advances in elastomeric soft matrix flat sheets and flexible rods[1]. However, as of yet, composite beams which have rigid section with flexible hinges in between have not been developed.

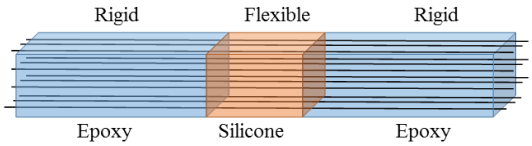

Figure 1: Concept for a Flexible Composite Hinge in a Bi-Material Beam

While there are a large number of temporarily flexible composites, like those used in rigidizing inflatable structures[2], our interest is in composites which remain flexible, enabling constant hinge-like characteristics, which limits the materials under consideration to elastomeric soft matrix flexible composites. Prior research has identified three types of elastomeric flexible composites, UV cured silicone matrix in composites sheet[3], FLASH (Ultra-Flexible Lightweight Adjustable Stiffness Hinge) material by L'Garde which is a silicone infused carbon fiber rods[1], and triaxially woven carbon fiber reinforced silicone (TWF CFRS) developed in Europe[4]. While flexible sheets would be convenient for the development of sunshades, solar panels, and reflective surfaces, the interest of this work was beams. Therefore, the L'Garde FLASH material was the best candidate for research.

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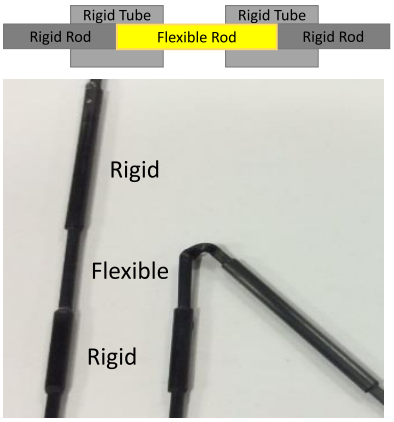

Figure 2: Bonded Bi-Material Flexible Composite Beams

II. Research Objective

The objective of this research was to build and test a proof-of-concept flexible composite hinge. The hinge consists of a two rigid beams joined by a flexible section. The hinge decreases the number of parts required for joints, which consequently lessens the likelihood of failure. Cost and weight are also reduced by using a one-piece hinge, as the use of precisely machined metal parts is avoided. Composite flexible hinges store strain energy which means they are self-actuating. Hinges with these properties may be especially useful in enabling origami based deployables. Developing a proof of concept flexible composite hinge would establish a foundation for future proposals in Flexible Material Systems with applications towards innovative antennas, booms and solar arrays.

III. Construction of a Flexible Composite Hinge

Research by L'Garde Inc. and Caltech has investigated using a silicone matrix with carbon fiber to make a composite flexible[1,3]. This work extends the prior work by developing a rigid composite beam with a flexible section in the middle acting as a hinge. To start, we collaborated with L'Garde and Caltech to determine the best approach for building a flexible composite hinge. Originally, there were two concepts for creating a rigid composite beam with a flexible section in the middle acting as a hinge. The first was to layup the fibers lengthwise, and then apply a rigid epoxy to either end and apply silicone in the middle (as seen in Figure 1). This was the most desirable method, as the long fiber strands running through both the rigid and flexible hinge portions of the beam would add strength. A second option was to build the hinge by first laying up a small piece of flexible silicone composite as a hinge, and then bonding rigid carbon fiber beams to either side of the hinge (Figure 2). L'Garde provided JPL with ten 1.5 mm diameter rods of the Ultra-FLASH material and one 3 mm diameter rod of the FLASH material. In collaborating with L'Garde and performing material tests it was learned while there were continuous fibers impregnated with epoxy and silicone in different sections in the 1.5 mm Ultra-FLASH material, the epoxy does not impregnate the fibers well and fatigue occurs at the epoxy-silicone joint. Therefore, the best approach was to build a flexible composite hinge by bonding rigid carbon fiber rods to a flexible epoxy rod with a rigid tube overlapping the two (Figure 2). As the 3 mm FLASH material had a greater cross-sectional area, it was decided to use these rods in constructing the flexible composite hinges. Three prototypes of flexible composite hinges were built by butting the 3mm FLASH material to 3mm composites rods and then overlapping the rods with a 3.2mm ID composite tube (4.75mm OD). Loctite 401 was used to bond the rods and tube.

Figure 3: Flexible Locking Mechanism, Concept and Prototype

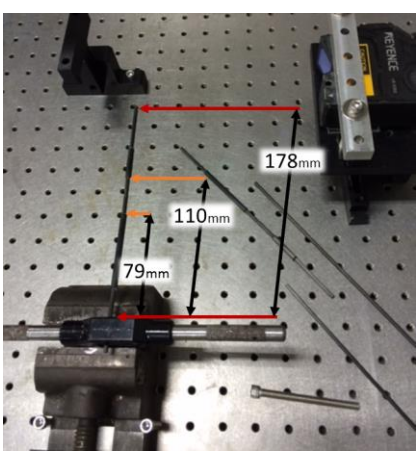

Figure 4: Deployment Test 1 Set-Up

One of the challenges with a flexible composite hinge, is that in order to deform up to 180 degrees, a significant length of the hinge (up to a half inch) is required to be flexible. This results in the hinge being "soft" in all directions except for when in tension, which means the beam can not support a bending load. To provide resistance to bending, a locking mechanism for the flexible composites was developed, where rigid section of tubing would slide over the composite. The rigid tube was spring loaded, automatically locking the beam in place when the flexible composite deployed the beam and the two rigid sections became aligned. The locking mechanisms provided two interesting degrees of freedom. The first was rotational about the beams center axis, as the locking mechanism did not resist torsional loads, and the flexible composite allowed movement up to 120 degrees. The design also provide a small amount of freedom for compression, as the flexible composite would buckle inside the tube. The

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compression degree of freedom only occurred because the diameter of the flexible composite was about half the diameter of the locking tube, as the locking tube had to surround the rigid tubes.

IV. Deployment Testing of the Flexible Composite Hinge

One of the key properties of interest for the flexible composite hinge was deployment repeatability. Deployment repeatability is a critical property for deployable structures, especially when they support RF or optical instruments. Two key research questions exist when investigating deployment repeatability. How closely does the hinge return to its previous position? How do multiple deployments influence deployment repeatability?

To test deployment repeatability, the prototype beams with flexible composite hinges were secured in a vice. A Keyence LK-G152 head with a LK-G3001 readout was used to measure the position of the deployed position of the beam. A total of four different deployment repeatability tests occurred, each measuring different aspects.

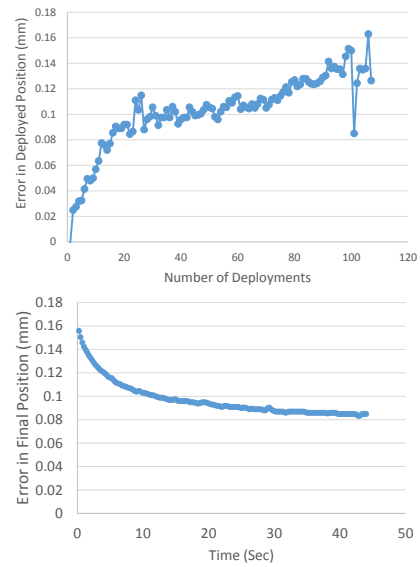

Figure 5: Test 1: Deployment Error and Relaxation

A. Test 1: Rapid Deployments

For Test 1, laser measurements were taken 178mm away from the where the beam was clamped in the vice, with the flexible composite hinge beginning at 79mm to and ending at 110mm from the vice (Figure 4). A total of 107 deployments were conducted sequentially, where the hinge was bent to approximately 160 degrees and then allowed to freely deploy. After each deployment, the hinge was allowed 2-3 seconds to damp out vibrations, at which point the Keyence system produced a consistent reading. Deployment repeatability tests found that initially the error in deployed position increased rapidly (up to 0.02mm per deployment), but after 25 deployments the error in deployed position grew much more slowly

Another fascinating result, occurred on the 100th deployment, where instead of 2-3 seconds of time between deployments, a total of 45 seconds was allowed to pass. During this time, it was observed that the composites error in deployed position relaxed by almost fifty percent (Figure 5, bottom), and there appears to be some type of memory in the material of its original unstrained state. This observation caused the researchers to perform further investigations.

B. Test 2: Alternating Deployments

Test 2 was a rough repeat of the first test. Once again 100 deployments of the hinge occurred. However, this time the hinge was allowed to relax for 15 seconds between each test, and each deployment alternated between positive 90 degrees and negative 90 degrees from center.

From the data collected in this test (Figure 6), it can be observed there is no increasing creep with the number of deployments. The deployment repeatability error generally alternates between positive and negative with each deployment, which follows the alternating deployment angle. This test seems to demonstrate that the relaxation effect follows the most recent strain position. The material has a "memory" of its last position. However, because of the alternating deployment angles, this test did not demonstrate how an extended relaxation period played a part in reducing deployment repeatability errors. To investigate this, a third test was designed.

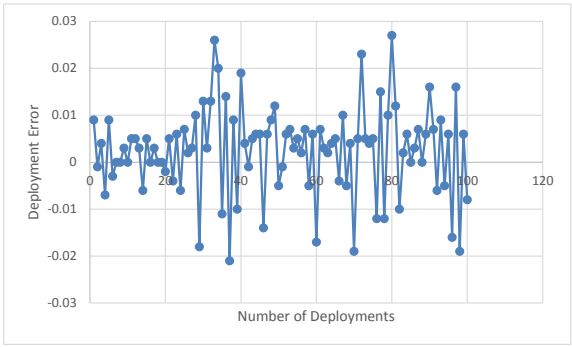

Figure 6: Test 2 Results, Alternating deployment Angles

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C. Test 3: Alternating Deployments

Test 3 consisted of three different trials. The test was set up with two Keyence heads, measuring two different locations on the rigid rod after the flexible hinge. The first measurement occurred at 64mm after the start of the composite section, and the second 102mm (Figure 7). This setup allowed the deployed angle of the rod to be measured. The change in deployed angle was used for the rest of the tests to measure deployment accuracy (for comparison to the previous tests, a difference of 0.01mm was approximately equal to 0.015 degrees of deployment angle).

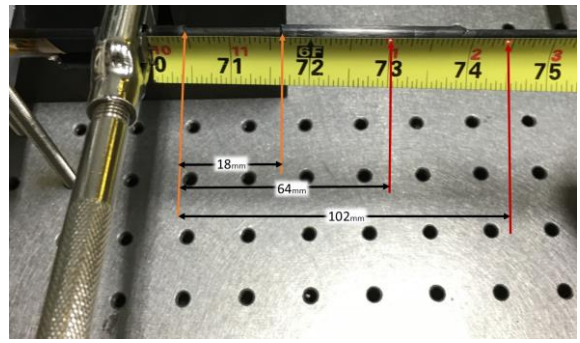

Figure 7: Test 3 Setup

The first trial explored 90 degree stow (without alternating deployment angles) with approximately 20 seconds between each deployment. The second explored a 180 degree stow, with approximately 15 seconds between deployments. The third explored 180 degree deployments where the element was held in the strained state for 20 seconds (instead of being released immediately). A measurement was taken 20 seconds after release, but the element was allowed to stay in the unstrained state for another 10 seconds after release.

The results from the first and second trials show very similar results, implying that stowed angle is not a driving factor. Instead, it appears that the amount of time the element is given to relax between deployments is a fundamental factor in deployment repeatability, given the results from test 1 where only 3 seconds were allowed for relaxation. Because of the lack of relaxation time, the results from test 1 make it appear that deployment accuracy decreases with the number of deployments. Additionally, trial 3 demonstrates that not only is relaxation time important, but the amount of time the hinge is held in the strained state is a driving factor. This raised the question and motivation for the fourth test, "What happens when the composite is held in a strained position for a long period of time?" This scenario aligns with those encountered in spaceflight, as often a satellite is stored stowed for long periods of time before launch.

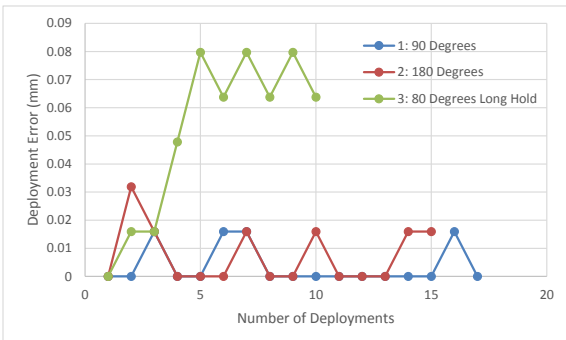

Figure 8: Test 3 Results

D. Test 4: Long Term Stowing and Deployments

Test 4 had an identical set-up to test 3. However, instead of performing multiple different deployments, this test focused on a single long term deployment. The hinge was bent at 180 degrees, and held in position for 155 hours (almost 1 week) before it was released. Then the release was tracked over a 24 hour period. The initial release happened rather quickly, with the hinge deploying to within 15 degrees of its original angle in seconds. During the first 90 minutes, the deployed angle dropped sharply from 14 degrees of error, to less than two. Going from just two degrees of error to one degree took nearly 10 hours. After 24 hours of deployment, the rate had slowed even further, only improving be 0.2 degrees from the measurement taken at 10 hours post deployment. From the deployment angle vs. time curve, it appears some small amount of permanent deformation occurs in the structure.

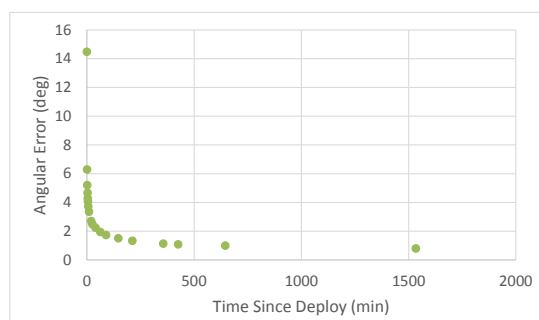

Figure 9: Test 4 Results

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V. Conclusion

This paper has discussed the development of bi-material beams, how they are constructed, and deployment repeatability testing results. These beams have applications as support structure for reflectarrays, solar arrays, booms, and other deployables. From the results of deployment tests, we can ascertain the following conclusions:

- Time the elastomeric composite hinge is stowed and given for relaxation directly influences deployment repeatability. Less stowed time and more recovery time is desirable.
- The elastomeric composites require relaxation time to erase their memory of a strained state.
- Long term stowed states seem to create some small amount of permanent deformation.

Finally, the observations on the long-term deployment have demonstrated that this material is "almost" good enough for precision deployables, as it deploys with an accuracy of less than 1 degree. Some of the most stringent requirements for reflectarrays require 0.5 to 0.2 degrees of deployment repeatability.

There are also a number of unanswered questions. How does temperature fluctuations while the antenna is stowed influence relaxation time? Would stowing the beam for longer than 1 week, perhaps months, produce different results? How do different beams designs vary with deployment repeatability? How would thickness and flexible portion length influence deployment repeatability? These are all questions for future work.

High strain composites are a new exciting field, especially in the area of spacecraft structures. It stands enable novel deployable structures which consist would consist of fewer parts. Thus far, flexible composites provide a lot of promise, but many further tests need to occur to understand their true value.

Acknowledgments

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