Senior Design Project: Test Fixture for a Lenticular Offset Composite Hinge

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Abstract

My team and I developed a test method to verify the torque specification of a Lenticular Offset Composite (LOC) hinge. This engineering senior design project was sponsored by Opterus R&D, a company that specializes in deployable spacecraft structures. These hinges are typically mounted in deployable solar array configurations, so research was done to orient to the market demand. A material understanding of the hinge was developed by exploring how high strain composite materials store energy as they deform. After developing this understanding, the previous and current test methods were evaluated to guide my team's prototype iterations. The final design is a test fixture that improves the user interface when compared to the current method, accommodates a variety of hinge geometries, and mimics the behavior of simulated LOC hinge data. My two main roles throughout the project were to ensure that my team was on track for all deliverables, and machine half of the custom aluminum components for the final product. I gained valuable experience in project management, used many skills that I've developed throughout my degree program, and now embody the confidence to start my career as an engineer.

Keywords: engineering senior design project, deployable spacecraft structures, high strain composite materials, test methods

Senior Design Project: Test Fixture for a Lenticular Offset Composite Hinge

In January of 2024, I was selected to join a team of four to design a test fixture for Opterus Research and Development (R&D), a small-scale aerospace manufacturing company specializing in deployable spacecraft structures. My team and I completed a year-long project to design a test fixture for a Lenticular Offset Composite (LOC) hinge that verifies a torque specification. Validating this specification ensures that there are no defects in the component impacting its functionality, which guarantees reliability in its applications. One main application for these hinges is to create deployable solar array configurations, enabling satellites to launch in a more compact form and expand once they reach orbit. After orienting to the market demand of these hinges, exploring the hinge material behavior, and evaluating the current test methods, my team developed an innovative test fixture that measures a LOC hinge bending moment throughout its range of motion to verify the torque specification of various hinge geometries.

Deployable Spacecraft Structures

A key design feature of modern spacecraft is deployable structures. These can be defined as structures where the goal is “to attain different configurations depending on the service requirements” (Kiper & Soylemez, 2009, p. 131). A few examples of these structures are “solar panels, antennas, radars and masts” which are folded up to “keep the device compact during launch” (Kiper & Soylemez, 2009, p. 131). Any issues with deployment of these structures would be catastrophic, especially since “primary electrical power is obtained from solar arrays” (Ding et al., 2012, p. 276). If a spacecraft’s solar array configuration does not deploy properly, it would lose access to power, causing system failures. When considering modes of failure, “space systems experienced their highest failure rate during deployment, but have typically performed well once deployed properly” (Kiper & Soylemez, 2009, p. 131). Therefore, minimizing the complexity at the interfaces of critical deployable structures increases the reliability of the overall system. This is where Opterus R&D meets the market demand.

One way to increase the reliability of these deployable structures is to lower complexity by implementing “strained composite joints rather than mechanical interfaces” (Reynolds et al., 2013, p. 2). By replacing mechanical systems with a single component that deploys based on a measurable and predictable material property, the likelihood for successful structure deployment is increased. This is why the hinges are typically used in deployable solar array applications. In addition to increasing reliability, eliminating mechanical systems that would normally deploy a new configuration also alleviates the power requirements of the overall system. This would mean that other functions of a spacecraft “could be greatly enhanced by increasing the available on-board power, while maintaining the compactness and volume limitations” (Santoni et al., 2014, p. 211). Deployable spacecraft structures enable spacecraft to achieve far more complex configurations and functionalities once they reach orbit. Opterus R&D is innovating with products that increase the reliability of these deployable systems, so this test stand will need to uphold that same standard of reliability to verify the hinge torque specification.

The LOC Hinge

The Lenticular Offset Composite (LOC) hinge is a thin, concave laminate with pairs of mounting holes on opposite ends of the material. These hinges typically range about two to four inches in length, about one inch in width, and can sometimes have an angled mounting interface of positive or negative ten degrees. To make one fixture that can test all types of LOC hinges, the test fixture will need to be versatile to account for various hinge interfaces and magnitudes for ranges of motion. All LOC hinges have a 180-degree range of motion, but the angled mounting interface can increase or decrease this by ten degrees. The most unique property for these hinges is that the geometry creates a floating focal point as it bends. The focal point is the main axis the hinge bends around. This point changes location as the hinge moves through its full range of motion. To account for this behavior, the test stand will need to apply a force that bends the hinge without compressing the material to both accurately measure the moment and avoid damaging the hinge itself.

High Strain Composite Material

The LOC hinge is made of a high strain composite (HSC) material, which means the hinge can be thin and lightweight while experiencing large amounts of deformation without failing. These materials "are constructed with only a few plies of ultra-thin unidirectional tape and biased weaves to achieve high strains in bending and high axial stiffness when unfolded" (Reynolds et al., 2013, p. 2). For Opterus's proprietary material, "It is assumed that the primary mechanism that enables the large deformations associated with tight folding is micro-buckling of the fibers in the softened matrix" (Murphey et al., 2012, p. 5). This enables the hinge to move through its full 180-degree range of motion without experiencing material failure. Specific to this material's application in LOC hinge geometry, "the majority of these HSC laminate structures rely on the stored strain energy of the packaged configuration to attain a final deployed state" (Fernandez & Murphey, 2018, p. 1). Ultimately, the high strain composite material's ability to bend is the method of hinge deployment, so verifying the torque specification of the hinge is also evaluating the material properties of the high strain composite material. This material behavior is crucial to understand before designing a test fixture to evaluate the component's performance.

Previous Test Methods

Opterus R&D is ultimately evaluating the quality of the high strain composite (HSC) material by verifying the hinge torque specification. Therefore, "Accurate prediction of the strain and stress states of these flexural elements and their failure modes are necessary to develop HSC structures with improved packaging efficiency and deployed structural performance" (Fernandez & Murphey, 2018, p. 1). Opterus is innovating the field for these deployable spacecraft structures, so previous test methods for the hinge have flaws in their ability to evaluate the hinge behavior. So far, only "Three main tests have been developed or adapted over the last decade for understanding the behavior of HSC flexures, with each having their own challenges and limitations" (Fernandez & Murphey, 2018, p. 2). When considering three-point bending tests, "the elastic deformations, prior to failure of these thin elements, result in large configuration changes that cannot be accommodated by these test configurations" (Fernandez & Murphey, 2018, p. 1). Similarly, "Standard four-point-bending test approaches are not sufficient to measure the load-displacement behavior of thin laminates because they are limited to small curvatures" (Reynolds et al., 2013, p. 3). Observing the hinge under compression in a vertical test, "the moment-curvature relationship was obtained from the post-buckling behavior of the sample under compressive loads" (Fernandez & Murphey, 2018, p. 2). Finally, in a platen test, a "shear component results in unbalanced test configurations of the clamping plates (top and bottom) that experience different rotation angles to reach moment equilibrium in the system" (Fernandez & Murphey, 2018, p. 2). Overall, no test configuration easily accommodates the large deformations of the HSC material to accurately verify the torque specification.

Opterus developed a fourth type of test method to accommodate the deformation of their HSC material. They called it the Column Bending Test (CBT). It subjects a vertically mounted laminate "to a pure bending stress state" as the mounting interfaces are "driven downward, the carts are forced to rotate flexing the sample" (Fernandez & Murphey, 2018, p. 2). It combines the benefits of the platen test and four-point bending tests while allowing the bending moment to be applied as a rotational force. In addition to accommodating the material behavior and range of motion, "In the CBT, the stress state is mostly uniform, allowing a simple kinematic analysis to estimate moments and curvatures" (Fernandez & Murphey, 2018, p. 3). This method is not in operation at the Opterus R&D campus, but is the closest match to my team's approach to developing the test fixture. With the main constrains of accommodating the HSC material properties and the uniqueness presented by the LOC hinge geometry, my team developed a test fixture to function similarly to the CBT while mounting horizontally on a benchtop Mark-10 tensile tester.

Engineering Senior Design Project

Goals

The main goal of the project is to improve upon the current LOC hinge test fixture in operation at Opterus R&D. Figure 1 shows the apparatus, consisting of two floating pulley mounting interfaces and eight cables, which are placed in tension to bend the hinge in a multi-story tensile tester.

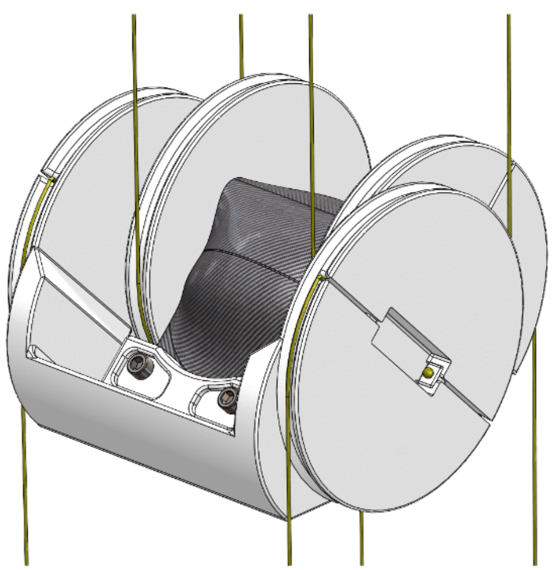

Figure 1. Opterus R&D's current LOC hinge test fixture.

The scale of the tensile tester allows this apparatus to employ small angle theorem. This theorem proves that changes in angle within a certain range are negligible, which simplifies kinematic solutions. The theorem originated fundamentally "as a mathematical result that may be used to understand the behaviour of the pendulum" (Bissell, 2023, p. 1). It's common to employ this theorem when an angle is less than fifteen degrees. However, "a mathematical model is typically only as good as its weakest assumption; […] ensuring accuracy in the linear approximation for the differential equation governing the simple pendulum is not necessarily the same thing as ensuring accuracy in the equation's solution" (Bissell, 2023, p. 6). Since measuring the torque specification for the hinge accurately is an important goal for this design, small angle theorem can be a valuable tool, but it must be implemented properly when applied to our fixture.

The main issues arise from the eight cables suspending the floating pulleys in the tensile tester. These cables are difficult to manage, tangle easily, and take a long time to set up. The main goals of this project can be summarized as improving the user interface while maintaining the degrees of freedom to accommodate the hinge's full range of motion. In addition, Opterus R&D manufactures various geometries of hinges, so the fixture needs to universally accommodate various lengths, widths, and mounting angles. Finally, the test fixture will need to accurately calculate the torque specification of a LOC hinge.

Design

For the first semester of the senior design project, my team focused on understanding the goals of the project and designing the test method. Our first step was to develop a problem statement for designing a solution. This project needed to provide a way for Opterus to validate a hinge torque specification to its desired value in order to ensure a level of quality to the consumer. Initially, we did not limit the solution to a fixed system, since Opterus's current test method used floating pullies to measure the bending moment. We created a house of quality to prioritize meeting specification goals and iterated through multiple prototype designs to begin understanding the hinge behavior. By unintentionally compressing the hinge, the team discovered that bending behavior could be created due to buckling. Non-centralized buckling of the hinge was observed in the first few prototype iterations, so this behavior had to be explored and understood. I took some time to research bifurcation buckling, which is an instability in the system where buckling can occur in multiple directions (Budiansky, 1974). In other words, the hinge can experience internal stresses that would encourage it to buckle in multiple directions if compressive forces were applied. However, due to the hinge's geometry, the hinge only seemed to buckle in one direction. We determined that Opterus's hinge geometry acted as a "bifurcation control, in which one uses a control input to modify the bifurcation characteristics and output performance of a parametrized nonlinear system" (Chen & Moiola, 1994, p. 846). While my team was not concerned with the direction in which the hinge would buckle, we still needed to figure out how to design the test fixture so the hinge bent at its center.

The team created a test fixture to mount onto a F505 Mark-10 static load frame. The fixture shown in Figure 2 converts force-displacement data to moment-angle data, verifying the hinge torque specification. Most of these components were machined by hand in the Colorado State University Engineering Manufacturing Education Center (CSU EMEC). The rest were sourced from manufacturers. The system converts a force to a moment by threading a string along the pulley attached to the shaft, which applies a moment in line with the mounting interface of the hinge. The bending angle was calculated through kinematic equations and verified with various testing methods.

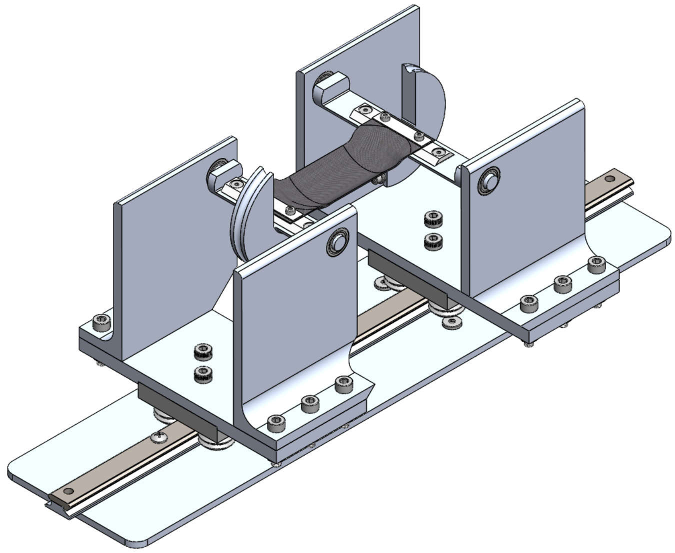

Figure 2. Final 3D model of the test fixture.

This test fixture exhibits similarities to the Column Bending Test (CBT) developed by Opterus R&D. For the measured variables of the CBT, “the only independent variables that require measurement during the test are the linear displacement of the fixture arms, δ, and the load acting on the fixture from bending the coupon” (Fernandez & Murphey, 2018, p. 5). My team’s fixture similarly measures force and displacement, but ours applies the load through tension in a cable rather than compression, and calculates the angle based on kinematic equations. One advantage of our team’s mounting orientation is that gravity can be neglected in the main motion equations. When the CBT motion equations were derived, it was noted that “The simple kinematic equations of motion aforementioned are only applicable to cases where gravity-induced loading is not present, which is true in weight-balanced or horizontal test configurations” (Fernandez & Murphey, 2018, p. 5). The orientation of the CBT requires gravity to be accounted for. The similarities and advantages of our test fixture compared to the CBT create the same centralized buckling behavior with less assumptions, allowing for a more reliable evaluation of the hinge torque specification.

Fabrication

During the second semester of the senior design project, we focused on manufacturing and testing of our final design concept. Modifications were made to simplify manufacturing steps, saving time and minimizing complexity. To integrate the bearings into the final assembly, I performed tolerance calculations for the housing and shaft dimensions. We determined that the bearings would require somewhere between a locational clearance fit and a medium drive fit to reliably secure the bearings (Budynas et al., 2020). After calculating maximum and minimum tolerances for these dimensions, the range was equivalent to the reliable resolution on the EMEC machines. We machined to the limits of the machine, then supplemented the shaft fit with a liquid adhesive during assembly. I tested various tooling to create the bearing housing hole by drilling into scrap stock, and selected tooling that created a snug fit that was still able to be assembled by hand. Referencing the CAD in Figure 2, I manufactured the four L-shaped brackets to mount the hinge, as well as one of the plates between these brackets and the sliding mechanism. All critical dimensions were machined to meet tolerances of 0.005” or less.

The team ran into the most issues when creating the base plate component that interfaced with the Mark-10 static load frame. This component shown in Figure 2 is the large, thin, rectangular plate mounted to the rail, which has four holes not shown in that image to secure it to the base of the Mark-10. The team machined this component correctly according to the initial drawings, but realized the measurements were for a different Mark-10 model. We ordered extra stock to account for mishaps in the machining process, so the final product now interfaces perfectly with the base of the Mark-10 static load frame at Opterus R&D. Figure 3 shows the final assembled product.

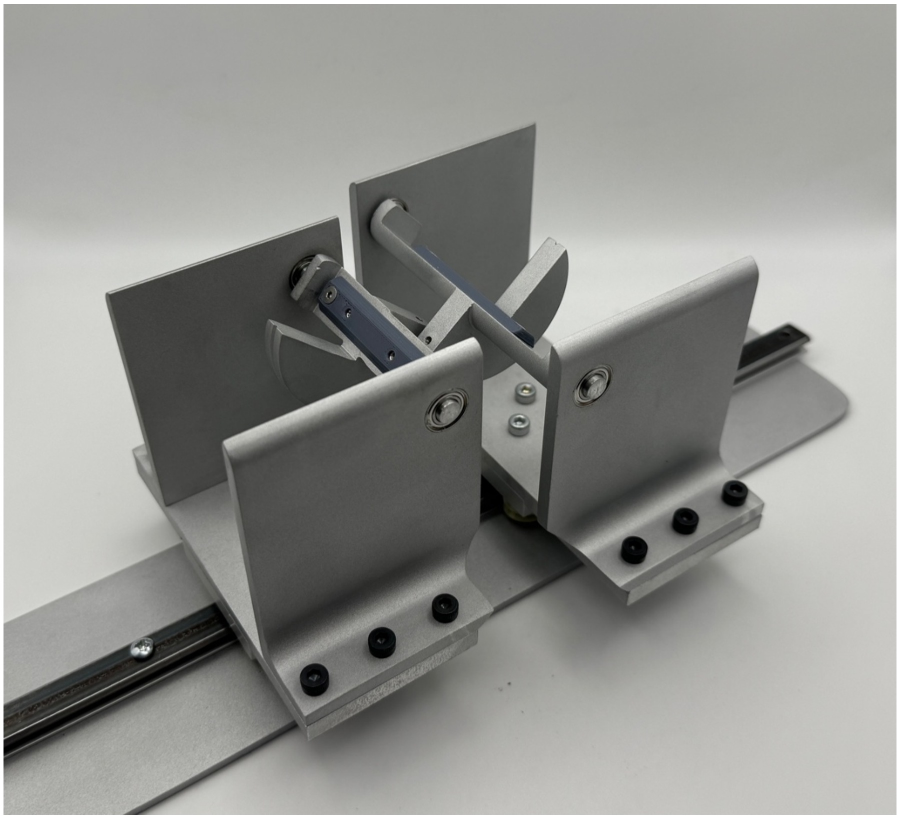

Figure 3. Final assembled product to be mounted in a F505 Mark-10 static load frame.

The final deliverable of the project is mainly an aluminum test fixture, with the exception of various fasteners and a 3D printed interchangeable versatility place to accommodate the hinge widths. A cable is threaded on the aluminum pulley components to apply a moment at the center of the shaft. This bends the hinge at the center by applying an equal moment at both mounting points.

Results

Opterus R&D provided a hinge to perform calibration testing. The team avoided bending the hinge unless it was mounted in the fixture for testing, since “the folding process can degrade tensile strength and buckling strength” (Murphey et al., 2012, p. 5). The team took a similar approach to the CBT to understand the motion of the pulley related to the linear translation of the carriages, as “a piece of paper with a random speckled patterns was taped to one side of the upper fixture arm to track its rotation throughout the test” (Fernandez & Murphey, 2018, p. 8). My team performed a visual analysis of the system to track the relation between the rotation of the hinge and the displacement of the carriage, and determined it to be linear. This allowed the team to derive kinematic motion equations of the system to solve for the position angle and the moment applied to the hinge throughout its range of motion.

We achieved the goals we set at the beginning of this project. This test fixture improved the user interface when compared to the current method in use at Opterus R&D. In addition, an interchangeable plate mounted onto the shaft can be switched out for various hinge widths, and the rails can accommodate the range of lengths. The moment-angle data mimics the behavior of the HSC material, demonstrating that we can validate a LOC hinge torque specification.

I learned a lot by completing this year-long project. My main role was to manage the schedule and logistics of the project, but I was also responsible for half of the custom manufactured components. When we moved into the manufacturing phase of the project, I realized I focused more on the components I needed to make rather than the trajectory of the project, which caused some detail oversights when we moved into the testing phase. One way I exceled was by recognizing my teammates’ strengths so we could complete the project to the best of our total combined abilities. This project gave me the opportunity to reflect on how I operate under pressure, how I engage with both teammates and professionals, and how my values align with my work. I gained experience that I couldn’t have learned in a traditional classroom, so these lessons will be extremely valuable to take into my future career. I am grateful that I had the opportunity to complete this engineering senior design project as a capstone for my degree program and enrich the experience with this context and reflection. By orienting myself to the field of deployable spacecraft structures, developing an understanding of the LOC hinge material behavior, and successfully managing the project to design and create a test fixture, I've grown confidence in my ability to pursue my career as an engineer and explore future prospects in engineering project management. I'm excited to see what my future career holds at the completion of this honors thesis in conjunction with the CSU Mechanical Engineering Department and Opterus R&D.

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