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Fatigue life characterization of hand folded and vacuum formed Kresling origami bellows at 77K

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Abstract. Propellant migration in microgravity is a critical challenge for in-space fuel storage and transfer. Origami fuel bladders are a new design solution to prevent cracking in polymeric materials within the cryogenic regime. This paper explores manufacturing techniques for producing origami bladders as well as the limits of possible thicknesses for origami bladders. Origami bladders are manufactured from polyvinylidene fluoride (PVDF) and polyethylene terephthalate glycol (PETG). Hand folded bladders follow a Kresling bellows origami pattern while the thermoformed samples are prepared using a mold of the Kresling bellows and an EZFORM LV 1827 thermoformer is used to shape the polymeric film. Compressive fatigue testing is carried out within liquid nitrogen to confirm the sample can survive deformation at cryogenic temperatures. Hand folded origami bellows specimens survived 3300+ cycles with minimal signs of degradation, while similar PVDF specimens cracked in fewer than 10 cycles.

1. Introduction

Bladders offer a potential solution to cryogenic fuel management issues that have persisted in aerospace for decades [1]. Most specifically propellant migration in microgravity. Microgravity causes fuel to become de-stratified and migrate within the ullage as fuel is expelled [2]. In contrast, bladders work by collapsing or crumpling to expel fuel. As a bladder compresses, the internal volume is also reduced. This reduces the chances for propellant to migrate or form bubbles. Recently the HYPER lab at Washington State University demonstrated a polymeric origami fuel bladder to solve this issue [3].

Polymeric materials have historically seen limited cryogenic application due to brittle mechanical properties below glass transition temperatures. Embrittlement is associated with loss of polymer chain mobility as temperature decreases. Generally speaking, though, plastics offer potentially important advantages for fuel bladders when compared to metal or ceramic materials including low density, high specific strength, low thermal conductivity and diffusivity, electronic resistivity, low Young's moduli, and high ductility [4]. However, the biggest advantage polymers may have been the novel manufacturing techniques recently developed for these materials.

To expand upon our preliminary results for the origami bladders [3] this work seeks to identify suitable bladder manufacturing methods and materials. The suitability of the manufactured bladders is tested via repeated mechanical cycling in liquid nitrogen (LN2). The results offer insight into both the fatigue characteristics of origami bladders to thousands of cycles, as well as investigates possible manufacturing techniques to produce scalable and leak-tight structures.

2. Materials and Experimental Methods

The bladders formed in the initial proof of concept work were manufactured via hand folding following a pattern [3]. Increasing the repeatability and scalability of bladder manufacture is important for the long-term viability of this concept. The best manufacturing methods depend on material and thickness, which were both un-investigated. To address this issue, a simplified single fold geometry was tested while varying film thickness. This most simplified case was then compared to a hand-folded full bladder origami structures that served as a repeatability test to the initial proof of concept. 3D printing and vacuum forming were then tested to compare both single the single fold and the full bladder origami structures.

Increasing the thickness of fuel bladders has the added advantage of maintaining higher pressure differentials before loss of structural integrity. To reduce the manufacturing time and inconsistencies of the sample's, simplified creases were made to study the effects of thickness. The pattern applied for sample preparation utilizes triangular indentions along the edges to stiffen the panels. This helps to limit the amount of panel stretching due to shear forces (see Fig. 1). The triangular folds help isolate the limits of the crease. The dashed lines indicate valley folds while the solid lines indicate mountain folds.

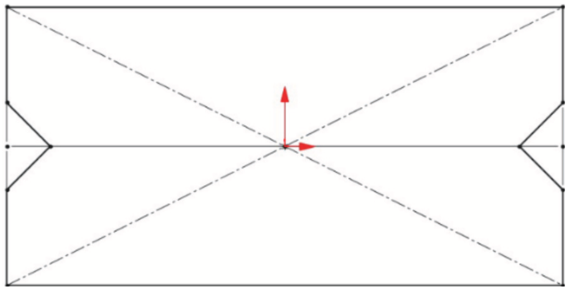

Figure 1. *Crease pattern for thickness study*

Fully origami bladder specimens were manufactured for this work for comparison to the proof of concept [3] and as a reference for repeatability. For fuel bladder applications, the Kresling pattern is promising due to large internal volumes compared to other bladder geometries. A total of 5 bladders were constructed using hand folding techniques and sealed by using Mylar tape along the open seam. The pattern used was a slightly modified Kresling pattern which was originally taken from Schenk M. et al [5]. The blue lines denote valley folds in which the vertex of the folds are recessed when viewed straight on. The red lines denote mountain folds in which the vertices are protruding from the surface. The modification made to the original pattern was alternating the fold direction halfway up the bladder (measured from the vertical axis, see Fig. 2). For extended fatigue cycling, bladders were constructed out of three different material thicknesses: 76.2 μm, 127 μm , and 177.8 μm Mylar. To hand fold the bladder, first the template was printed out and fixed to the table. Then, a sheet of bi-axially oriented Mylar fixed onto the surface. The transparency of Mylar allows simple tracing of pattern lines onto the Mylar using a straight edge. Next, the valley folds (solid lines) are folded individually until none remain. The material is then flipped, and all the mountain folds (dashed lines) are then folded. This process may need to be repeated multiple times to get stiff creases in the material. This process results in the material forming the shape of the desired bellows. Finally, metallized Mylar tape is placed along the seam to hold the structure in place.

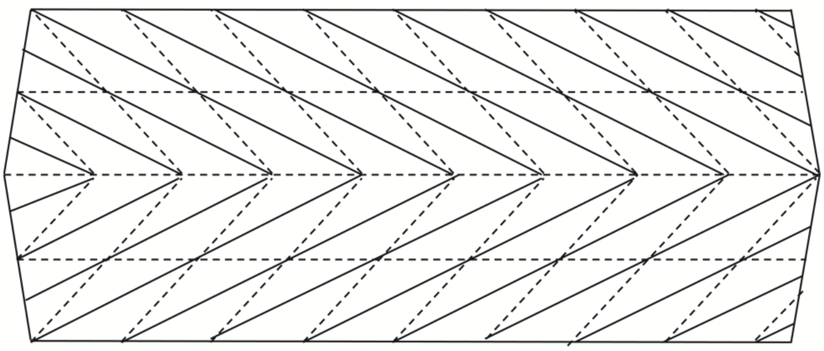

Figure 2. *Modified Kresling Pattern, solid lines indicate valley folds and dashed lines indicate mountain folds*

3D printing and vacuum forming are evaluated as alternative manufacturing methods to improve the repeatability, scalability, and cost of bladder manufacture. Various 3D printing processes were explored such as selective laser sintering (SLS) and MultiJet fusion (MJF). Polyurethane (TPU), polyamide (PA), and polylactic acid (PLA) were among the candidate materials for the 3D printing experiments. Three-point bending specimens with a living hinge geometry (see Fig. 3) were produced along with a Kresling pattern bladder.

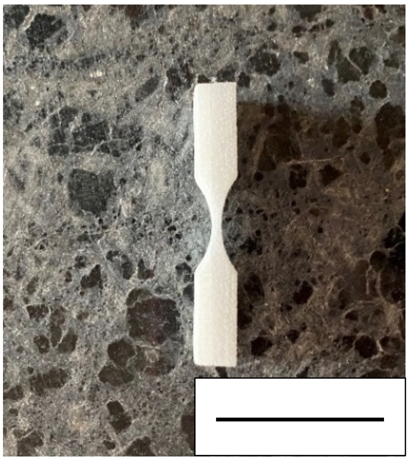

Figure 3. *3D printed living hinge sample used for 3 point bending experiment (1/4" thick on the ends, 0.03" thick in center, 1 inch scale bar)*

Vacuum forming involves heating a polymeric film close to its melting temperature and then forming the film around a mold. Vacuum is used to help pull the heated film around the mold to improve the definition of more complex parts. An EZFORM LV 1827 was used as the vacuum former for the experiment. Previously Wang et al demonstrated a vacuum forming approach to forming origami bellows [7]. A different vacuum forming method was used in which the entire structure was formed at one time rather than formed in halves and then spliced together. To ensure that the mold and part could be separated after forming, a 5-part, modular mold was 3D printed out of PLA (see Fig 4). The mold is comprised of a center cylinder which has 4 slots that the remaining pieces slide into place with. After the forming process is complete, the center piece can be pressed out and then the outer diameter parts collapse in towards the center to free the part from the mold.

Vacuum forming shows promising results for several reasons. First, vacuum forming is a natural fit for working with thin films. Thin films take very little time to heat to their respective melt temp and are easy to form once heated. In addition, the vacuum forming process leaves a part that is fully sealed around the circumference as well as fully sealed on the one end of the bladder (see Fig. 4). This leaves one face still to be sealed on the bladder. Figure 4b shows the final part from using the modular mold with 25.4 μm thick PVDF.

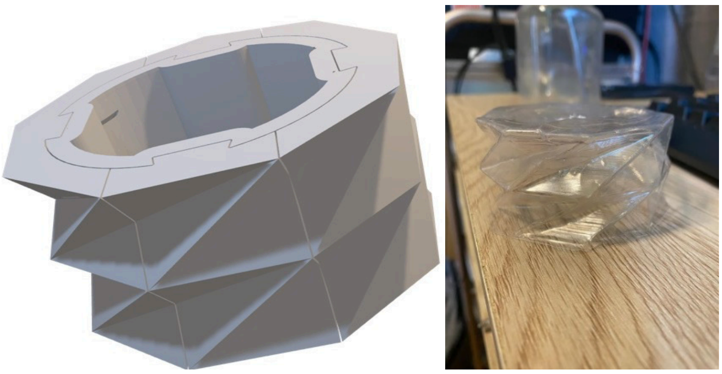

Figure 4. *a) Modular mold and b) Vacuum formed bellows*

3. Experiment

To explore the limits of the bellows and the various manufacturing techniques within the cryogenic temperature regime, an automated fatigue testing setup was adapted from an existing gelbo-flex testing apparatus. To automate the fatigue testing apparatus, a stepper motor was controlled using an Arduino Uno. This Arduino enabled control over the distance and rate at which the actuator traveled. Samples are fixed to a mandrel which is driven by a stepper motor to compress the sample at a precise rate (0.5 Hz) and distance while fully submerged in LN_2. It is expected that thickness is the most critical metric for determining polymer fatigue life in cryogenic conditions, due to the increased tensile and compressive loading on the creases [9]. To confirm this theory, the simplified creases (see Fig. 5) were affixed to the testing apparatus and repeatedly flexed until failure was observed.

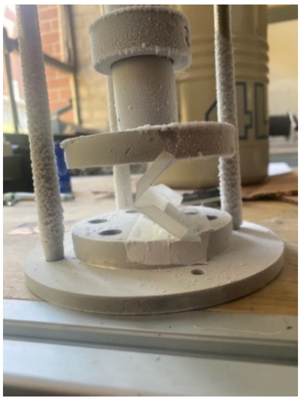

Figure 5. *76.2 thick Mylar Crease Experiment after testing in LN_2*

Testing the Kresling bellows structures followed a similar procedure as used in the simplified crease test. The bellows are fixed to the bottom of the LN_2 flask (see Fig. 6 b), and the mandrel is lowered onto the specimen. One cycle is defined to be a compression and expansion of the bellows; 90% compression for each cycle was achieved via markings on the testing shaft. A cycle rate of 0.5 Hz was kept consistent throughout the testing procedure. It has been documented that strain rate is not a critical factor in the mechanical properties of polymers at cryogenic temperatures and this variable was not controlled beyond the 0.5 Hz cycle frequency [10]. Due to the lack of visibility within the testing chamber, there is some uncertainty with the precise amount of compression being achieved. In addition, the lack of visibility also requires that the tests are stopped periodically to inspect the status of the sample. Inspection of the bellows was typically done every 400 cycles, but there was some slight deviation from this standard periodically. Any visible cracking or hole formation is considered a failure given that these structures are potential fuel tanks.

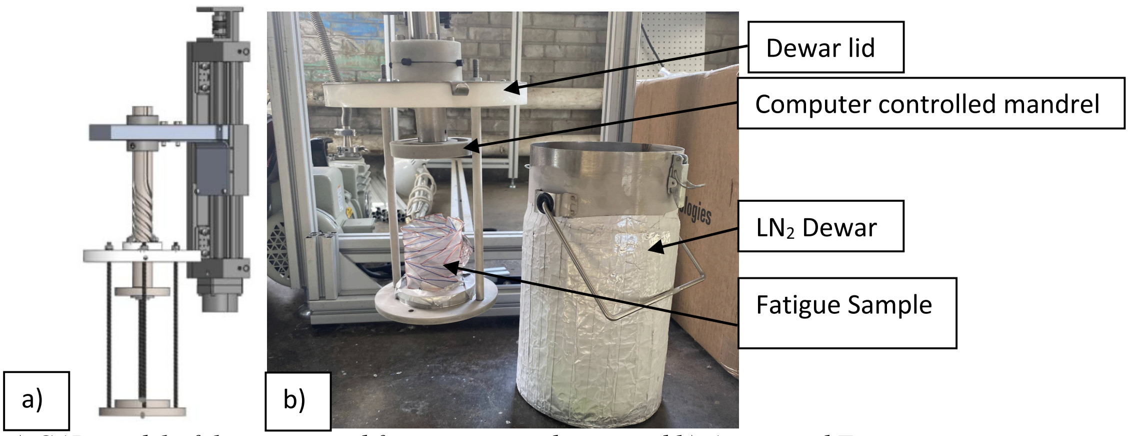

Figure 6. *a) CAD model of the automated fatigue testing design and b) Automated Testing setup and LN2 Flask with a 3" diameter Kresling bellows fatigue sample*

Finally, to test the 3D printing methods and material, a testing apparatus, which followed ASTM standard D7774, was machined to perform a 3-point bending tests in LN_2. One notable change from the ASTM standard involved the addition of the upper portion of the fixture to prevent the specimens from shifting while immersed in the LN2. The sample is tested by lowering the point load (see Fig 7. b) onto the sample. Then a computer controls the number of cycles and displacement that the living hinge samples undertake.

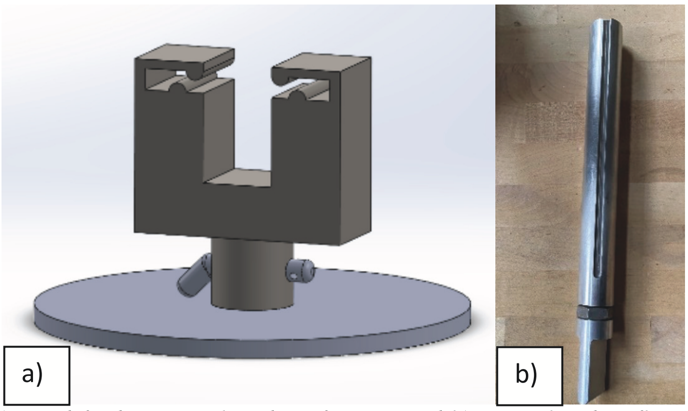

Figure 7. *a) Modified 3-point bending fixture and b) point load to flex the samples*

4. Results and Discussion

4.1. Thickness Study

Table 1 shows the compression fatigue results for the Mylar simplified creases. The Mylar results confirm how critical thickness is to determining bellows survivability at cryogenic temperatures. Doubling the thickness from 177.8 μm to 355.6 μm thick Mylar reduced the lifespan of the samples by two orders of magnitude. Given that the cycling goal of the fuel bladder is 100 cycles, the next step should be to construct a Kresling bellows out of 254 μm thick Mylar and confirm survival beyond 100 cycles.

The PVDF simplified creases performed much worse when compared to the Mylar samples. The 76.2 μm samples were not able to survive more than 5 cycles before failure. This data helped guide fatigue testing of the Kresling bellows shown in table 2, in which only very thin PVDF of 25.4 μm was tested because thicker samples would fail. Fatigue failure is a unique phenomenon compared to maximum stress. However, in previous work, D.H. Weizel et al reported that the maximum bending radius for plastics is defined by $r_m = \frac{E_y t}{2\sigma_u}$, where E_y is the Young's modulus, t is thickness and σ_u is the ultimate tensile strength. This suggests that ultimate tensile strength and young's modulus are the two most important material properties for long lasting, and robust bellows structures [9].

Table 1. *Simple Mylar Crease Fatigue Results*

Mylar Thickness Study							
Thickness		177.8 μm		254 μm		355.6 μm	
Sample #	Cycles Before Failure	#1	1000+	#1	90-110	#1	0-10
		#2	1000+	#2	140-160	#2	0-10
		#3	1000+	#3	140-160	#3	20-30

4.2. Bellows Fatigue Testing

The Mylar bellows fatigue results are tabulated in Table 1. It is critical to note that each of the Mylar samples tested did not break due to cycling. All the samples are still intact and could be put through additional cycling to find their fatigue limits. The bellows start to show some signs of crazing marks, indicated by increased opacity, along the crease lines. However, it is unknown how many more cycles the bellows could undergo. These preliminary results were the foundation for studying how thickness effects the survivability. Given that the initial cycle goal was for the bellows to survive 100 cycles at cryogenic temperatures, the Mylar bellows exceed expectations. The PVDF had drastically different results compared to the Mylar samples. Further work is needed to understand what material properties are critical for determining survivability at cryogenic temperatures.

Table 2. *Kresling Bellows Fatigue testing results (ND= Not Done)*

	Thickness			
Hand folded Material	25.4 μm	76.2 μm	127 μm	177.8 μm
Hand folded Mylar	ND	1500	3300	1500
Hand folded PVDF	ND	ND	0	ND
Vacuum Formed PVDF	100	ND	ND	ND

4.3. 3D Printed Living Hinges (3-Point Bending)

The 3D printed samples had several manufacturing constraints including thickness and surface finish. Regardless of the material, the 3D printed samples failed with deformation as small as 2.5 mm from resting position. The minimum thickness of 3D printed specimens is primarily to blame. The SLS printed samples had a lower limit of 508 μm thick while the MJF samples had a lower limit of 762 μm thick. For reference, that is an order of magnitude greater than the films that have shown success flexing in liquid nitrogen.

In addition to the issues with print thickness, each method of 3D printing had an additional flaw. MJF printed parts are not watertight which makes them incompatible for fuel bladder applications. SLS printing showed very poor thermal cycling performance, most likely caused from voids left in the sample. After 2 thermal cycles from 77K to room temperature, the samples would crack without the presence of any load. These various issues in addition to challenges associated with scaling the size of bellows, quickly deterred further research in this manufacturing process.

5. Conclusion

Various bellows fabrication techniques such as 3D printing and vacuum forming were explored and compared. Three point bending tests were performed on the 3D printing samples to test their flexural performance. Through this experiment, it was found that 3D printing cannot produce thin enough parts to survive in LN_2. Vacuum forming seems to be a promising manufacturing technique for future fuel bladder applications due to the compatibility with thin films as well as the ability to produce a sealed bellows. A simple study on how thickness affects fatigue performance was performed and verified the hypothesis that small changes in material thickness drastically impact the fatigue life. Additionally, the simplified crease test confirmed that material properties such as ultimate tensile strength and elastic modulus are important factors in fatigue life. Finally, extended fatigue testing was carried out into the thousands of cycles in which the Mylar samples showed promising results. In future work, the HYPER lab plans to connect this relationship back to physical theory to develop a predictive design solution for polymeric thin films at cryogenic temperatures.

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