

Compliant Polymer Origami Bellows in Cryogenics

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Abstract

Mechanical applications for polymers at cryogenic temperatures are extremely limited due to decreased atomic mobility and ductility, resulting from glass transitions above the cryogenic regime (<120 K). As such, polymeric materials are known for cracking and low fatigue life. Early studies on the twist-flex behavior of polymer thin films in liquid nitrogen resulted in complete shattering of films after a few cycles. To improve upon this failure behavior, we fabricated thin-film origami bellows with Yoshimura and Kresling geometries to primarily restrict strain to below the elastic limit. We found the resulting bellows survived 100 full compression and extension cycles in liquid nitrogen. No tears or pinholes were detected in the bellows. These results indicate that restricting the strain modes in thin-film polymers via origami structures could lead to a new class of cryogenic technologies useful for liquid storage bladders, expandable seals, positive displacement fluid pumps, and flexible electronics.

Keywords: Compliant mechanisms, Polymers, BoPET, Bellows, Origami

1. Introduction

There is negligible use of polymeric materials at cryogenic temperatures for mechanical applications due to embrittlement. Cooling to cryogenic temperatures subjects polymers to primary, and potentially even secondary and tertiary glass transitions, where the mobility of progressively smaller portions of polymer chains is restricted. Below 100 K, the viscous molecular motion of polymer chains required for plastic deformation to occur is negligible under low-to-moderate loads [1, 2]. Tensile tests of common engineering plastics, biaxially-oriented polyethylene terephthalate (BoPET, Mylar™) and polyimide (PI, Kapton™), between room temperature and 77 K reveal 80 - 90% and 75% reductions in percent elongation under load, respectively [3, 4].

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Circumventing this brittleness of polymers has been attempted for mechanical actuation. Pope and Penner, and Weiderkamp constructed expulsion bladders from thin polymer films to manage liquid hydrogen propellant in a microgravity environment. These bladders, filled with hydrogen, can expel liquid when crumpled [5, 6]. Such complex crumpling of a polymer film concentrates stress along elemental 1-D and 0-D folds: ridges and vertices [7-9]. Reducing the thickness of polymer films utilized will mitigate stress, and thus pinhole formation, at these vertices. Locke reported this general behavior for Gelbo-flex tests of Mylar™ film at 77 K (Gelbo-flex tests characterize the fatigue life of polymer films to repeated cycles of crumpling and uncrumpling). While the 25.4 μm thick Mylar™ film survived approximately four times as many flex cycles as 50.8 μm Mylar™ before tearing, the former still only survived up to 20 cycles on average [10]. At cryogenic temperatures, any application that requires the crumpling of a polymer film similarly brittle as Mylar™ would see limited reuse.

An alternative method to crumpling for mechanical actuation is folding polymer films into kinematic origami (also called kinetic origami), a subset of compliant mechanisms [11, 12]. Compliant mechanisms primarily actuate through elastic deformation, and thus are subject to minimal friction during motion, do not require lubrication, and are resistant to fatigue. The preceding advantages make these devices ideal for a variety of fields, including microelectromechanical systems and spacecraft [13]. Kinematic origami structures are a particular type of origami still capable of motion even after the structure has been fabricated and folded into its final state. This motion is due to a network of panels/facets and creases. The creases bend like hinges, interacting with each other and the panels to produce the global deformation of the origami structure [12].

Creased sheets can be formed into a cylinder to create a variety of kinematic origami bellows capable of axial actuation. Reid et al. describe four classes of origami bellows, each constructed from a different unit cell of folds and panels: Kresling, Miura-Ori, Hexagonal, and Yoshimura unit cells. Actuation of these bellows with an Instron® test frame indicated that much of the energy applied to these bellows is recoverable (i.e. elastically stored) [14]. Butler et al. took actuation tests a step further: they characterized the fatigue life of bellows using the Kresling unit cell. Their origami bellows, constructed from materials including Mylar™ and Kapton™, all survived $\geq 10,000$ actuation cycles before pinholes in the polymer film developed. These bellows were more compressible (the collapsed length of a given bellows is $< 10\%$ of the deployed length) and less massive than traditional metal bellows [15]. In determining if the fatigue resilience of origami bellows extended from room temperature to 77 K, Reid actuated a Hexagonal bellows,

fabricated from 101 μm thick KaptonTM, for 500 cycles in liquid nitrogen without failure. However, compression of the bellows was limited to 86% of the deployed length [16].

The objective of this work is to determine if origami bellows could possess both axial fatigue resistance and high compressibility at 77 K, and compare the results to Gelbo-flex tests. This comparison will quantify any increase in fatigue life a polymer mechanical actuator formed from origami may have over actuating a polymer film through crumpling.

2. Experiment

2.1 Overview

Three specimens of 76.2 μm thick BoPET film were flex-tested for 5 cycles in liquid nitrogen at 77 K, as this was the number of cycles comparably survived by films in historic tests [10]. Origami bellows fabricated from BoPET, including a single Yoshimura bellows and three Kresling bellows, were each linearly actuated for 100 cycles at 77 K. All of the above tests are tabulated in Table 1. The sections below describe the design and operation of the Gelbo flex-tests, the fabrication of the origami bellows, and how the linear actuation tests of the bellows were completed.

Table 1 Test matrix of fatigue tests for samples.

Origami Fold	Film Thickness (μm)	Fatigue Test	Fatigue Test Cycles	Number of Tested Samples
-	76.2	Twist-Flex Test	5	3
Yoshimura	76.2	Linear Actuation [†]	100	1
Kresling	76.2	Linear Actuation	100	3

2.2 Gelbo-Flex Tests

Gelbo-flex tests, also termed twist-flex tests, are traditionally used to characterize the capacity of a polymer film to resist cyclic crumpling. A Gelbo-flex tester was adapted from standard ASTM F392/F392M-11 for operation within an open-mouth liquid nitrogen dewar to cycle samples at 77 K (see Fig. 1) [17]. The key components for the Gelbo-flex tester include two mandrel mounting surfaces for a 203.2 mm (8 inch) by 279.4 mm (11 inch) polymer sample. Several clamps were tested with for mounting samples to the mandrels, before settling on a hook-and-loop fastener

[†] Note that the linear actuation test for the Yoshimura origami bellows was less rigorous than tests completed for the Kresling fold-based bellows.

and low-profile Nylon cable tie for clamping the sample to the upper mandrel and lower mandrel, respectively. Dimensions for the mandrels are a diameter of 88.9 mm (3.5 inch), and a thickness of 12.7 mm (0.5 inch). A 304.8 mm (12 inch) grooved shaft fixtured to the upper mandrel guides the test through a prescribed actuation path, subjecting the polymer film to two phases of deformation: 1) the first phase simultaneously twists and compresses the polymer film by 440 degrees and 90 mm, and 2) the test further compresses the film by another 65 mm. Reversal of the process completes a cycle. The movement of the grooved shaft was completed manually.



Fig. 1 a) Gelbo flex test apparatus after testing, with a film secured to the mandrels. b) Test apparatus in the midst of twist-flex testing.

2.3 Bellows Fabrication and Linear Actuation Tests

In a preliminary test, an origami bellows constructed from a Yoshimura fold pattern was actuated 100 times in liquid nitrogen to determine if such a bellows would quickly fracture at cryogenic temperatures, using pliers and a ruler to linearly compress and expand the bellows (see Fig. 2). Visual inspection of the bellows after such testing revealed no pinhole formation. For more rigorous testing, the Kresling-based origami bellows was selected, as its fatigue behavior at room temperature is better characterized than the Yoshimura pattern. As such, the Kresling fold template provided by Butler et al. was printed out and affixed to a desk [14, 15]. Samples of BoPET were cut to fit the template, folds pre-scored with a flat-head screwdriver, and then hand-folded into shape. 3M 3311 silver aluminum

foil tape joined a seam running along the side of each origami bellows. Though the lack of two or more circumferentially positioned seams introduces asymmetry in the stiffness of the bellows, only one seam was used to simplify fabrication (see Fig. 3). After fabrication, Kresling fold bellows stood ~81 mm (3 ¼ inch) in height, and possessed an outer diameter of ~76 mm (3 inch).

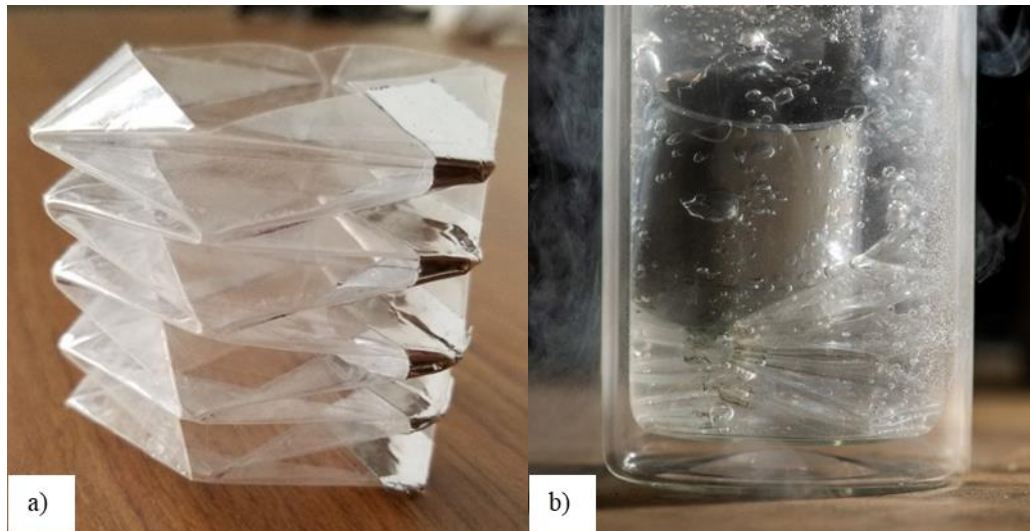


Fig. 2 a) Bellows constructed from a Yoshimura fold pattern. b) Actuating the bellows in liquid nitrogen using pliers and a large socket tool.

To fatigue test the Kresling-fold bellows, the Gelbo-Flex tester was modified for purely vertical actuation by removing the top plate and guideposts. Bellows were taped to the bottom mandrel, inserted into liquid nitrogen, and manually actuated with the upper mandrel (see Fig. 3). Samples were visually inspected and subjected to dye penetrant testing, also known as liquid penetrate inspection, after fatigue testing to determine if there were any microtears. Often this test process is used to detect cracks or defects on metal surfaces, and is described in ASTM standard (ASTM E1417/E1417M-16) [18]. This standard was adapted to identify tears in the bellows. A given bellows sample was pulled apart at the seam, and unfolded such that the global topology of the sample was now planar. Purple dye and white developer were then sprayed on separate sides of the sample: any dye wicking onto the developer would indicate the presence of a pinhole the dye progressed through.

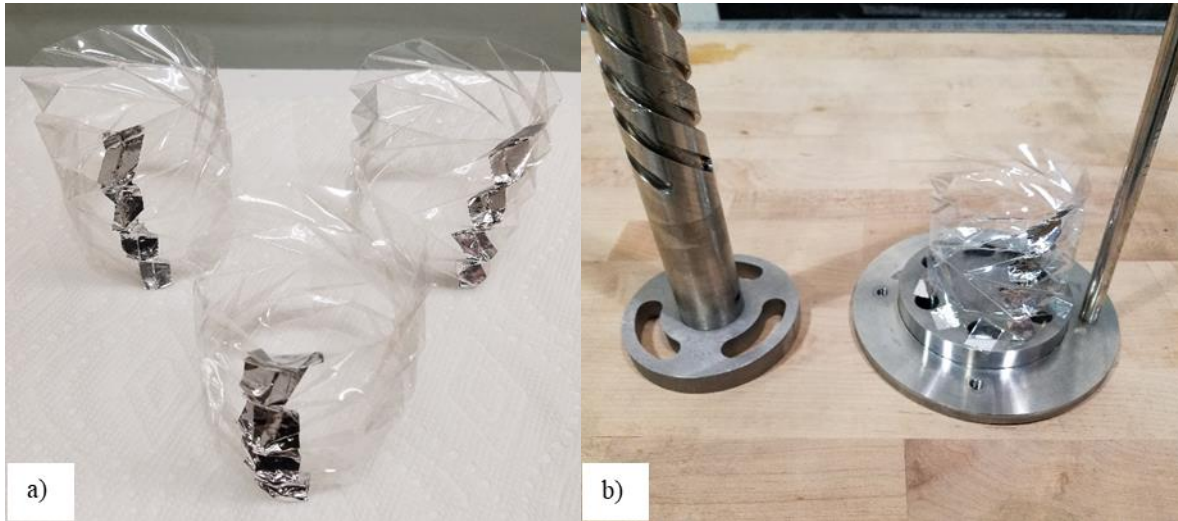


Fig. 3 a) Three Kresling fold bellows fabricated from 76.2 μm BoPET. b) Modified gelbo-flex tester for axial compression of bellows.

3. Results and Discussion

Visual inspection of the three samples of BoPET film subjected to cryogenic twist-flex tests found that all samples tore significantly enough to separate samples into pieces, as seen in Fig. 4. It is not known though during which cycle each sample failed. These results are comparable to the number of twist-flex cycles (≤ 10) completed by 50.8 micron thick BoPET in liquid nitrogen [10]. In contrast, each of the Kresling fold bellows linearly actuated for 100 cycles exhibited no obvious cracking under visual inspection and dye penetrant testing (see Fig. 4), a ≥ 20 times increase in fatigue performance from the twist-flex tests. The aluminum tape adhesive along the seams of the Kresling bellows performed more poorly, falling off the seams from the third bellows tested.



Fig. 4 a) Tear in sample. b, c) Kresling bellows subjected to dye penetrant testing.

The lack of identified pinholes within the tested bellows supports the notion that deformation is primarily elastic, and as such, origami bellows may be useful as mechanical actuators at cryogenic temperatures. An origami bellows could be used as a foldable substrate for electronics [19]. Capping and sealing one end of a highly compressible origami bellows may allow the device to be used as a positive displacement fluid pump, expulsion bladder, or expandable burst disk. One implementation of the above fluid technologies that could be explored is a multi-layer bellows to enable circulation of refrigerant between layers for zero-boil-off liquid storage. Washington State University has filed a provisional patent application, under patent serial number 62/972,745, for such a device. As much of these applications primarily manage fluids, they must remain seal-tight (i.e. no pinholes or leak-paths must form). Other tests, including helium leak tests with a mass spectrometer, may rigorously quantify if pinholes form in

origami bellows after actuation in liquid nitrogen. Fatigue tests of origami bellows should also be extended to thousands of cycles to evaluate the range of suitable applications.

The viability of different fabrication techniques could also be explored at cryogenic temperatures. Stitching, epoxy, or a thermal weldment can replace the use of adhesive tape for joining the seam along the origami bellows [15, 20]. Thermal weldments are particularly desirable, as thermal contraction mismatches should then not arise between materials. Seams could be abandoned altogether through use of other fabrication techniques, such as vacuum forming or robotic additive manufacturing [21].

4. Conclusions

A Gelbo-flex tester, adapted from ASTM F392/F392M-11 for operation at 77 K, was used to cyclically crumple 76.2 μm BoPET, tearing the samples into pieces after ≤ 5 cycles. These results contrast with the linear actuation of Yoshimura and several Kresling origami bellows, also fabricated from 76.2 μm thick BoPET, for 100 cycles at 77 K. No pinholes or tears in bellows were identified with visual inspection and dye penetrant testing. Origami bellows formed from polymers could be implemented in a suite of cryogenic technologies, including liquid storage bladders, expandable burst disks, positive displacement fluid pumps, and flexible electronics. Helium leak tests of the origami bellows after cryogenic actuation may be required to rigorously determine no tears were produced. Extending fatigue tests into the thousands of cycles, and the exploration of different fabrication techniques for the origami bellows should also be explored.

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References

- [1] Hartwig, G. *Polymer Properties at Room and Cryogenic Temperatures*. Springer Science & Business Media, New York, 1994, pp. 1-17, 117-172.
doi: 10.1007/978-1-4757-6213-6

- [2] Yano, O., and Yamaoka, H. "Cryogenic Properties of Polymers," *Progress in Polymer Science* Vol. 20, No. 4, 1995, pp. 585-613.
doi: 10.1016/0079-6700(95)00003-X
- [3] Armeniades, C., Kuriyama, I., Roe, J., and Baer, E. "Mechanical Behavior of Poly (Ethylene Terephthalate) at Cryogenic Temperatures," *Journal of Macromolecular Science, Part B* Vol. 1, No. 4, 1967, pp. 777-791.
doi: 10.1080/00222346708212361
- [4] Yamaoka, H., Miyata, K., and Yano, O. "Cryogenic Properties of Engineering Plastic Films," *Cryogenics* Vol. 35, No. 11, 1995, pp. 787-789.
doi: 10.1016/0011-2275(95)90915-3
- [5] Pope, D., and Penner, J. "Development of Cryogenic Positive Expulsion Bladders," NASA-CR-72115, 1968.
- [6] Wiederkamp, K. "Liquid Hydrogen Positive Expulsion Bladders," NASA-CR-72432, 1968.
- [7] Witten, T. A. "Stress Focusing in Elastic Sheets," *Reviews of Modern Physics* Vol. 79, No. 2, 2007, p. 643.
doi: 10.1103/RevModPhys.79.643
- [8] Cerda, E., and Mahadevan, L. "Conical Surfaces and Crescent Singularities in Crumpled Sheets," *Physical Review Letters* Vol. 80, No. 11, 1998, p. 2358.
doi: 10.1103/PhysRevLett.80.2358
- [9] Lobkovsky, A., Gentges, S., Li, H., Morse, D., and Witten, T. A. "Scaling Properties of Stretching Ridges in a Crumpled Elastic Sheet," *Science* Vol. 270, No. 5241, 1995, pp. 1482-1485.
doi: 10.1126/science.270.5241.1482
- [10] Lark, R. F. "Cryogenic Positive Expulsion Bladders," *Journal of Macromolecular Science, Part B* Vol. 1, No. 4, 1967, pp. 623-637.
doi: 10.1080/00222346708212353
- [11] Greenberg, H., Gong, M. L., Magleby, S. P., and Howell, L. L. "Identifying Links between Origami and Compliant Mechanisms," *Mechanical Sciences* Vol. 2, No. 2, 2011, pp. 217-225.
doi: 10.5194/ms-2-217-2011
- [12] Bowen, L. A., Grames, C. L., Magleby, S. P., Howell, L. L., and Lang, R. J. "A Classification of Action Origami as Systems of Spherical Mechanisms," *Journal of Mechanical Design* Vol. 135, No. 11, 2013.
doi: 10.1115/1.4025379
- [13] Howell, L. L. "Compliant Mechanisms," *21st Century Kinematics*. Springer-Verlag, London, 2013, pp. 189-216.
doi: 10.1007/978-1-4471-4510-3_7

- [14] Reid, A., Lechenault, F., Rica, S., and Adda-Bedia, M. "Geometry and Design of Origami Bellows with Tunable Response," *Physical Review E* Vol. 95, No. 1, 2017, p. 013002.
doi: 10.1103/PhysRevE.95.013002
- [15] Butler, J., Morgan, J., Pehrson, N., Tolman, K., Bateman, T., Magleby, S. P., and Howell, L. L. "Highly Compressible Origami Bellows for Harsh Environments," *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2016.
doi: 10.1115/DETC2016-59060
- [16] Reid, A. R. "Helium-3 Polarization and Origami Folded Cryogenic Actuators and Metamaterials," Ph.D. Dissertation, Department of Physics, North Carolina State University, 2018.
- [17] International, A. "Astm F392/F392m-11(2015) Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability." ASTM International, West Conshohocken, PA, 2015.
doi: 10.1520/F0392_F0392M-11R15
- [18] International, A. "Standard Practice for Liquid Penetrant Testing." ASTM International, West Conshohocken, PA, 2016.
doi: 10.1520/E1417_E1417M-16
- [19] Hester, J. G., Kim, S., Bito, J., Le, T., Kimionis, J., Revier, D., Saintsing, C., Su, W., Tehrani, B., and Traille, A. "Additively Manufactured Nanotechnology and Origami-Enabled Flexible Microwave Electronics," *Proceedings of the IEEE* Vol. 103, No. 4, 2015, pp. 583-606.
doi: 10.1109/JPROC.2015.2405545
- [20] Butler, J., Magleby, S., Howell, L., Mancini, S., and Parness, A. "Highly Compressible Origami Bellows for Microgravity Drilling-Debris Containment," *AIAA SPACE and Astronautics Forum and Exposition*. 2017, p. 5341.
doi: 10.2514/6.2017-5341
- [21] Wang, H., Guo, C., Li, Y., Liu, Y., Wang, M., You, Z., and Zhao, D. "Structural Design and Forming Method of Single-Curved Surface Structure Based on Miura-Origami," *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection, 2016.
doi: 10.1115/DETC2016-59155