2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #40224

# Origami in Materials Engineering

**Dr. Anuja Kamat, Wentworth Institute of Technology**

Anuja Kamat is an Associate Professor in the Civil Engineering Department at Wentworth Institute of Technology, Boston. Prof. Kamat received her Ph.D. in Civil Engineering from the University of Arizona, Tucson, and MS in Civil Engineering from the University of Illinois, Urbana Champaign

# Origami in Materials Engineering

In the author's university, Wentworth Institute of Technology, Boston, a newer elective and a lab-based class were offered. With the school being online, there was a need to look at innovative ways to find hands-on labs for students which would be related to civil engineering. In this effort, a new model of Origami in materials engineering was developed. Origami is a traditional Japanese art or technique of folding paper into a variety of decorative or representational forms. Typically, origami is thought of as the art of folding paper into animals or flowers. In recent years, origami has been useful in large- and small-scale engineering applications, from large solar arrays in space to tiny medical devices. Origami has also found applications in structural engineering. For our module, the students were expected to fold regular printer paper using the Miura ori fold which demonstrated interesting material properties like the negative Poisson's ratio. In addition, the students predicted and then tested the strength of the folded paper. The teaching module is presented here. In this course, the students are usually exposed to different materials every week. They then pick one material and study it in-depth in the last few weeks of class as their project. Three of the nine students in the class picked this topic. Details of the projects are also presented here. Additionally, what worked, what did not work, and why, is then discussed in this paper, along with suggestions for improvement.

Introduction:

Origami has been used for several years as works of art, but in recent years has been used for car airbags, space systems [1], and bio-medical devices. It is also considered a therapeutic exercise [2]. Researchers at the University of Illinois and Georgia Tech have been doing research on the use of origami for civil engineering [3]. When Civil Engineering Materials became an online class for Fall 2020 semester, the authors decided to reimagine the content of the class while teaching in an online format instead of simply replicating the in-person content in an online format. The author's university is known for hands-on learning and the students come to the school for this experience. So, adding hands-on content was important.

The course is called "Advanced Civil Engineering Materials". It is a part of the Structural minor. The materials are taught with a focus on Structural Engineering. Since the prerequisite course, "Civil Engineering Materials", does not have a lab component, all the labs for that course are included in the "Advanced Civil Engineering Materials" course as well and the "Advanced Civil Engineering Materials" course is a (1/4/3) course. This means that it is a 3 credit course with one hour of lecture and 4 hours of lab every week.

Students learn a new topic/ material every week. This includes self-healing concrete, shear design around the world, Aggregate Labs, Asphalt labs, Concrete labs, design an experiment, finite element analysis, to name a few. The final project is a big part of the course. Students usually build on any topic studied in the weekly readings/topic and carry out a lab based experiment. It is expected that the students would complete a student poster or paper suitable to be presented at the ASEE -Regional Conference.

Considering the limitations, the authors set out to build a lab module which would be educational, innovative and inspiring. Inspired by the work of Professor Paulino from Georgia Tech, who does graduate level research in this area, the authors thought that it would be valuable to build a one week module for undergraduate students.

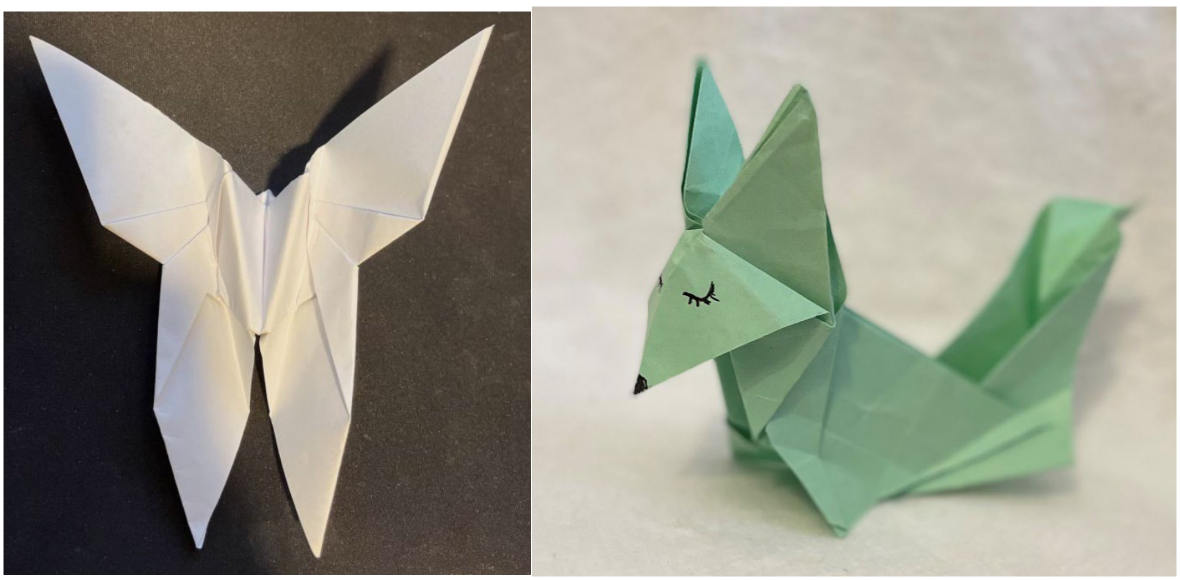


Fig 1. Origami used as works of art

Lesson Plan:

Objective: To build a structure using Origami which can carry a large amount of weight and to learn about material properties of the model

Application in Civil Engineering: Origami bridges, building, structures would soon be possible.

Hands on experience: Folding a printer paper and making a basic miuri ori fold: The instructor demonstrated the miuri-ori fold and the students followed. It is a relatively challenging fold to master and students needed a couple of hours to complete the fold.

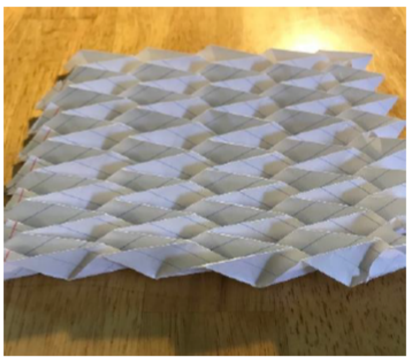
Test: The students stacked books on the folded paper and tested to see when it would fail. This was done on zoom and students cheered as others tested their structure.

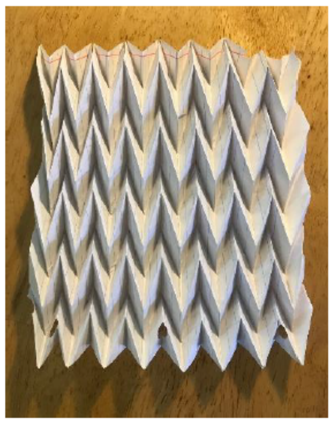
Analysis and Discussion: There was a discussion on why some of the structures could hold up to 7 lbs. Other concepts were demonstrated like

1. Poisson's ratio was negative.

**Summary**:

Origami in civil engineering has been a new topic in and around the field of structural engineering. The geometry of different origami folds at both the macro and microscopic scale presents numerous advantages. Similar to the way an I-beam is efficiently shaped to provide structural support without using a solid rectangular steel beam, origami uses the same theory. The ability to construct structures by making precise origami folds in materials gives impressive amounts of strength because of the unique way space is used to support existing members, like also done with I-beams. Using folds founded in origami could also allow for less material to be used during the construction process, thereby giving structures an even more impressive strength to self-weight ratio because of their overall improved efficiency rating. The ways columns, beams, girders, and other components of civil engineering projects could be further improved by using different origami folding techniques should be explored because of the new and innovative ways materials can be fabricated and arranged to support structures more efficiently.





**Reflection**:

I enjoyed the processes of learning more about origami and how it could be used in the field of civil engineering. Although complex, observing how the folds on a paper sheet began to weave together to form an arrangement which expanded in both directions of the x-y plane was fascinating. Making the folds themselves was difficult at times, but this only added to the overall experience of making such a structure that was able to support three of my textbooks while only being made out of one sheet of loose-leaf paper. It was even more interesting when deformations were introduced. The folded material that we had created became even stiffer than before and could support even more weight. Although, its failure would have most likely occurred more suddenly than when there were no deformations present. Overall, I liked doing this assignment because it acted as an educational model to show how materials react with deformations introduced. I also found it very beneficial to observe how origami can turn what was once a two-dimensional object into one with three that could support hundreds of times its self-weight.

Fig 2. Summary and Reflection Assignment -Student 1

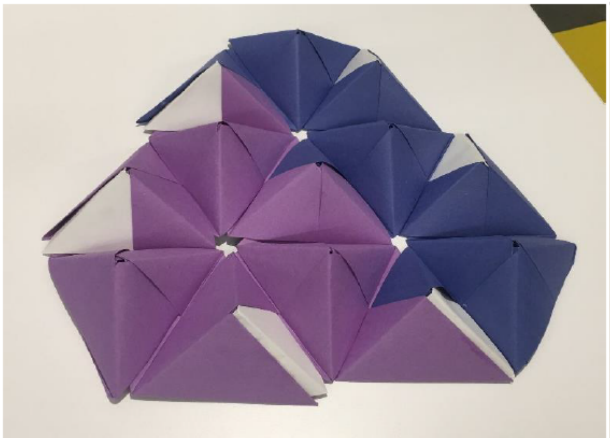


*Figure 1 View of the top*

*Figure 2 View of the bottom*

Summary of Origami in Civil Engineering:

Civil engineering plays a role in the world's day to day functioning with its great influence on infrastructure and has been around for thousands of years. An interesting topic that has recently presented itself in the world of civil engineering is origami. Origami, a method of paper folding, is being used to look at specific materials, shapes, and angles that present strong structures that can hold loads. Many researchers are using it as a form of material science and apply it to a larger scale and design methods after analysis.

Currently a large study of origami is being led by Professor Glaucio Paulino at Georgia Tech. It is at Georgia tech where he studies (as well as teaches) how tubes can be made of paper and folded and weaved together to form even stronger shapes and structures. These designs of paper folding can help influence the way civil engineers design structures in the real world and introduce new, more sustainable, and long-lasting infrastructure in today's world.

Reflection:

I found this origami project interesting. When it was first introduced, I thought it was fascinating because it seemed so new to me as well as the field of civil engineering. I had not really learned about origami in civil engineering until now.

With everything being online this semester, I also liked how we were able to do a "hands-on" lab after a while of just theoretical lectures about the labs. One of the main things I liked about it was that I could put my ideas/thoughts about it into a model that I could build and touch with my hands. Also the trial and error of the folding was a fun challenge that was not highly taxing on my brain, but rather my physical abilities and the translation of my ideas to real life. One thing that I think would be better next time, online or not, is to maybe start with a quick beginner's fold. I was having a hard time learning how to fold correctly on the more advanced fold we started and ended with. Maybe if there is an introductory (quick too, nothing too long) fold to start with for beginners that would help with the more advanced folds.

Fig 3. Summary and Reflection Assignment -Student 2

Origami originated in Japan in early ages for ceremonial purposes, but the unique folding techniques that have stemmed from it have become useful in engineering and has been the topic of research for many in the past few decades. Origami is unique in the way that folding the thin material in a certain way can increase its strength significantly. Folding the paper causes deformations that in some forms can cause flexibility but can also provide bending stiffness. The origami Herringbone Tessellation offers another a different into structural insight. Poisson's Ratio is the amount of transverse elongation divided by the amount of axial strain. The value of Poisson's Ratio can range from 0.0 to 0.5. In materials science, poisons ratio can never be negative, and likewise there is no common construction material that can achieve this. This is due to the fact that the increase in transverse elongation always results in the decrease of the cross-sectional area. However, origami folds such as the herringbone tessellation result do demonstrate a negative poison's ratio. This is because transvers elongation does result in the increase of a area. This is a result of a specific arrangement of folds. When connected together, origami can provide great resistance to compression, and yet and be folded for storage or transportation. While individually flexible, consecutive patterns of the same structure together can provide rigidness.

Overall, this project fit perfectly into the curriculum of advanced materials, where the class investigates unique engineering and construction applications. Folding the paper was proven to be rather difficult, and it took the student a significant number of tries to develop a herringbone relation that was defined. With that being said, the completion of this project allowed the student to view the causes of a negative poison's ratio. It also helped to connect prerequisites for the course into the current curriculum. It was also interesting learning about applications of origami in structural engineering.

**Origami in Relation to Structural Engineering**

Fig 4. Summary and Reflection Assignment -Student 2

2. Effect of deformations – when a deformation is introduced in the patterned tessellation, the properties of the structure changes.
3. Ductility and strength are related inversely to each other.

Lab Report/ Assignment: The lab report had 3 parts.

1. Photographs of the miuri-ori fold
2. Photographs taken during testing
3. Summary of the lab
4. Reflection about the lab.

Student summary, photographs and reflection are given in Fig 2 -4.

Some more student comments:

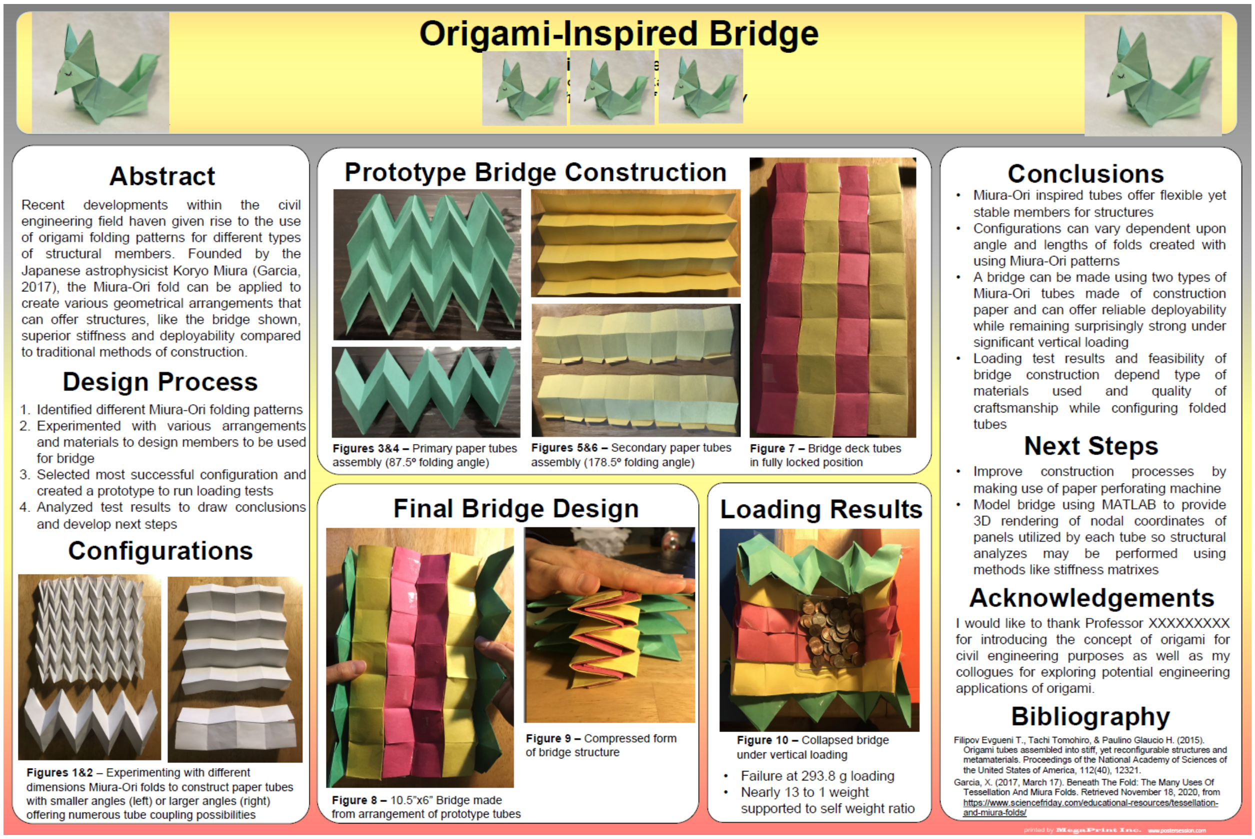
*"The process of folding was very stressful and took four pieces of paper. This origami project was something new and different. I learned a lot from researching more into origami and how Engineers are planning on using the concept. China had created the paper, Japan started the origami and todays Engineers are origami to be able to produce a light weight, fast assembling structures. The technology improves by the day and in the future origami designs will be more common."*

*"The attempt took me about two tries as I am not very arts and crafty with paper especially. The project was overall satisfying, setting out to do something I am not good at and seeing the process as I made the object come into fruition with its result. I can see why engineers use this method to hand create their project to have a visual of what the result might be and go from there if they want to make any adjustments. The project was overall fun, and stress relieving and would do it again if there was any need to do so."*

*"Origami is an interesting topic in the structural sense, using paper as an example, the paper can hold objects significantly heavier than the sheet of the origami model. My reflection on this assignment is that I am bad at folding paper and it took many tries and hours to complete the model. My theory is that the printer paper I was using was not thick enough and it became difficult to continue folding the model due to the crumbled form and texture of the model, but after trying a different brand of paper I was able to come close.. All in all the integration of origami from paper folding into civil engineering is very interesting."*

Project:

The students are required to submit a paper or poster at the end of the semester on a topic of their choice. Students usually connect one topic to a prior knowledge and build on it. Usually students are given a lot of flexibility and the university supports reasonable cost to build the project. This year three out of 9 students picked this topic. This clearly shows that the students found the topic interesting. One student built the model in Matlab while others made with paper and tested the strength of the model bridge. The student posters and part of the student paper are presented in Fig. 5 and 6.



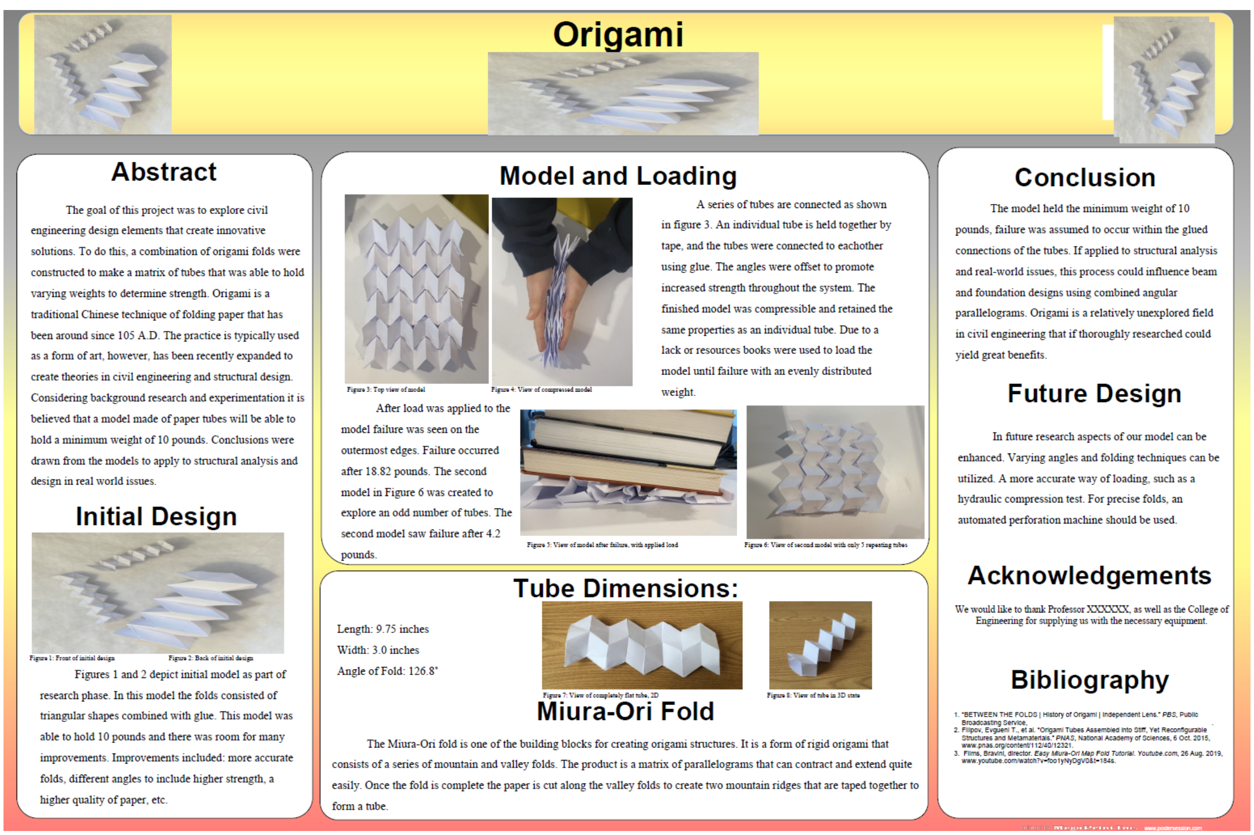




Fig 7. Student Project Posters

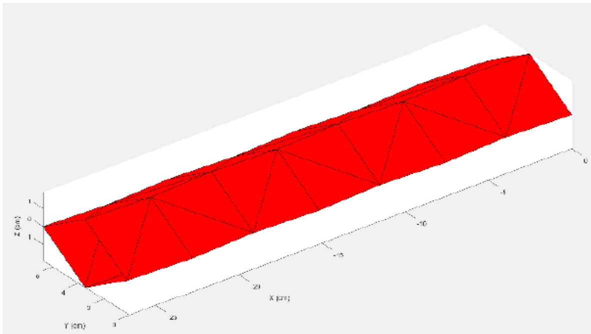


*Figure 11: Modeled red tube member at full extension*

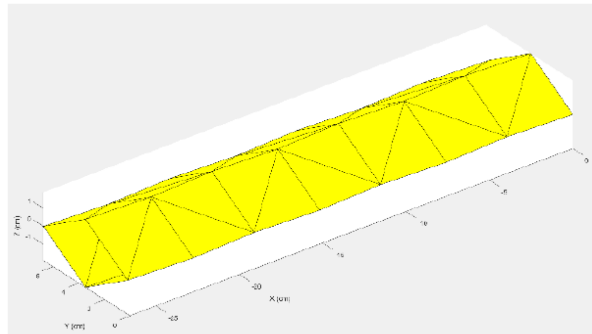


*Figure 12: Modeled yellow tube member at full extension*

Explorations of the Miura-Ori fold lent a new and interesting perspective on structures designed within the civil engineering field. The geometric analysis of tubes created from tessellations of Miura-Ori folded sheets showed how different origami-inspired structural members can be from traditional steel I-beams. The negative Poisson's ratios found for tubes made described how the action of the tubes was different from those of metals, like steel, because of the translational growth experienced when tubes were strained axially. The unique deformations of tubes offered enhanced deployment capabilities. The modeling of tube geometry, using nodal coordinates of Miura-Ori panels making up the tubed members, allowed optimizations to be made and compatibility relationships to be defined for zipper tube formations. The proposed configurations of tubes with two different folding specifications were successful in constructing a bridge made from folded paper that could be reshaped from fully compressed to fully deployed positions while maintaining respectable stiffness based on those load tests performed. Potential improvements to the bridge design were plentiful and consisted of possibly using stronger material for folding tubes, added cross bracing to ends of tube members, as well as extensions of deck members to prevent sidesway failure of the structure upon vertical loading.

Fig 5. Part of student project paper

Psycological Benefits

In these unpresented times of COVID and quarantine, when the students were so stressed, an engineering education module which is a stress reliver is great. The psychological effects were not planned. It was surprising when the students in the class reported the stress relief provided by this lab in the reflection assignment. Then, the authors looked at resources and realized the research that has already been done and proven benefits.

Lessons learned:

The students found the advanced fold very challenging. It would have helped to give a pre-lab assignment with some videos with basic folds. 1 out of 9 students found the assignment very difficult. It is possible to but a perforating device which helps with accurate folding. This could be introduced after the first week. It is important to fold the first miuri ori fold by hand so that the pattern and properties start to make sense. However, after the first week, it can be beneficial to use the computer for help.

It is possible to make this lab modue into a full semester course with interdisciplinary students including computer science, engineering, architecture and industrial design so that each group could build, program and apply the origami principles and be on the forefront of this research.

Conclusion:

The origami lab module had a successful run in the Fall 2020 semester. It showed material properties like Poisson's Ratio, introducing deformations to increase strength and modifying properties of a material. It also showed structural properties like increase in load carrying capacity and application in bridges. The student reflection as well as one question in the final exam showed that the students benefitted from this lab. There were only 9 students in the class and so a robust assessment to prove the success and benefits of this lab. However, student reflections and student work give a good insight to encourage the continuation of this lab in the in-person mode.

References:


[1] S. Zirbel, "Compliant Mechanisms for Deployable Space Systems," *Theses Diss.*, Nov. 2014, Accessed: Mar. 09, 2021. [Online]. Available: https://scholarsarchive.byu.edu/etd/5612.

[2] C. Edwards and S. Hegerty, "Where It's Cool to be Kitty: An Art Therapy Group for Young People with Mental Health Issues Using Origami and Mindfulness," *Soc. Work Groups*, vol. 41, no. 1–2, pp. 151–164, Apr. 2018, doi: 10.1080/01609513.2016.1258625.

[3] P. P. Pratapa, K. Liu, and G. H. Paulino, "Geometric Mechanics of Origami Patterns Exhibiting Poisson's Ratio Switch by Breaking Mountain and Valley Assignment," *Phys. Rev. Lett.*, vol. 122, no. 15, p. 155501, Apr. 2019, doi: 10.1103/PhysRevLett.122.155501.