ESEP-G 2025
Origami-Inspired Deployable Space Structures with Programmable Bistability

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Introduction

Origami in Engineering

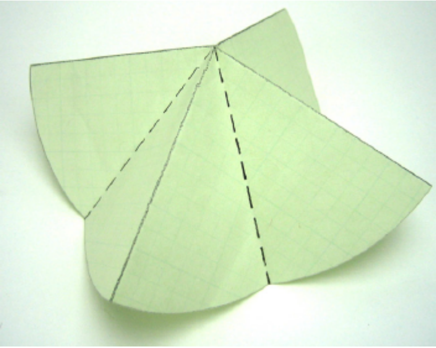
Origami, the traditional Japanese art of paper folding, has found a new role in modern engineering applications, especially in aerospace and robotics. We shall focus on rigid origami i.e. only the hinges/folds (creases) are allowed to rotate without significant deformation of faces (facets)

Applications:

- Morphing structures
- Vibration isolation systems
- Deployable space structures

Focus of this study: Waterbomb base

A simple, bistable origami unit for application in space deployable structures



Waterbomb base unit geometry

What is the Waterbomb Base?

- Geometrically simple and easy to manufacture
- Naturally bistable (has two stable equilibrium states)
- Can form large structures using tessalations
- Usually has 8 creases, 4 mountain (solid lines) and 4 valley (dotted lines)

Goal: Understand and control its bistable behaviour to enable applications that require shape retention without continuous actuation or supports

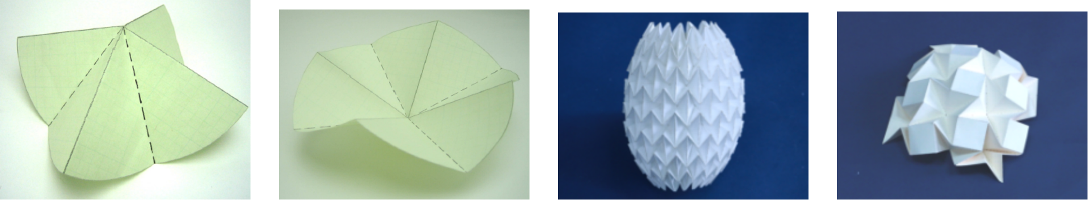


Figure: First two images(from left) showing two stable configrations of waterbomb base, next two images showing two possible tessalations

Background and Literature

- **Miura-ori** is well studied in deployable origami systems, used in The **Space Flyer Unit** (SFU), a spacecraft which was launched by Japan on March 18, 1995
- Bistable Composite Tape-Spring Booms are also begin used to deploy space structures like solar arrays (ISS Roll-Out Solar Array (**iROSA**)). **Don't require actuators to deploy, use strain energy!**
- Not much literature on waterbomb base

Figure: Space Flyer Unit

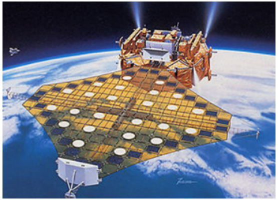
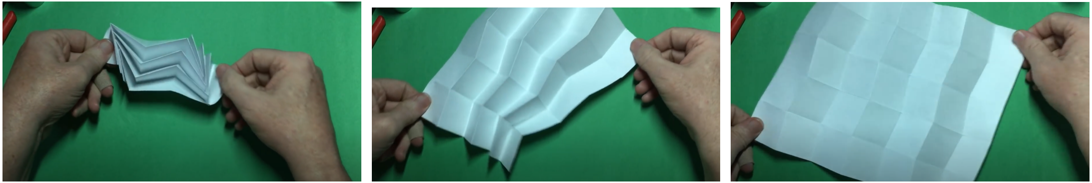


Figure: 2D deployable solar cell array on SFU

Figure: ROSA at the ISS

1-DoF Miura-Ori

If we hold two corners of the sheet, and pull it in opposite directions, the miura-ori fold open up and it deploys to a sheet like structure.



Challenges

- Miura-ori 2D solar array needs supports to hold it in place post deployment
- Bistable booms can hold it in place, but are limited to 2D arrays and can't roll back once deployed

Why waterbomb base?

- Shows **bistable** nature, potential for holding itself in place after deployment
- Allows for **3D structures** (deployable radar dishes, inflatable habitats, 3D light shields like JWST)
- Has **1-DOF** (like Miura-ori), ease of deployment
- Limited study on waterbomb base for space structures

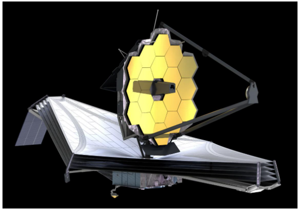


Figure: JWST with its curved solar shield

Motivation and Goal

Goal: To make a **multistable** 3D space structure, with compact 1st stable state(less energy for storage) and deployed 2nd stable state (self locking)

Focus of this study:

- Study bistable nature of single waterbomb base (WB) unit
- Program its bistable nature i.e. designing a WB with desired 1st and 2nd stable equilibrium configurations (θ_1 and θ_2) and energy required for transition
- Study the non-square (rectangular) variation of WB

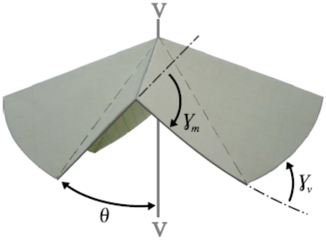


Figure: θ is the angle between valley crease and vertical and γ_m and γ_v are parameters to characterize mountain and valley angles

Methodology

Simulation Pipeline (FEA)

- CAD created using SolidWorks
- **Shell elements** used for facets
- Creases modeled with wire elements **CONN3D2** (elastic hinge behaviour)
- Automated geometry generation using Abaqus Python scripting
- **Riks static** solver used to capture snap-through events
- Downward tip displacement is applied to trigger **snap-through** transition

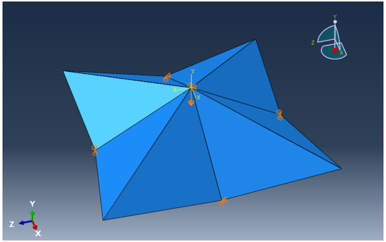


Figure: Waterbomb model setup in Abaqus CAE

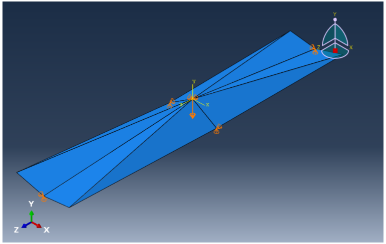
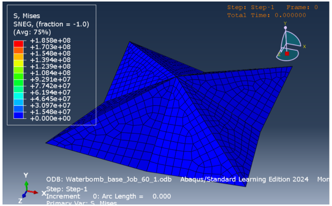


Figure: reactangulaar variation of Waterbomb in Abaqus CAE

Simulation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+1.548e+08
+1.394e+08
+1.239e+08
+1.084e+08
+9.291e+07
+7.742e+07
+6.194e+07
+4.645e+07
+3.097e+07
+1.548e+07
+0.000e+00
Step: Step-1 Frame: 0
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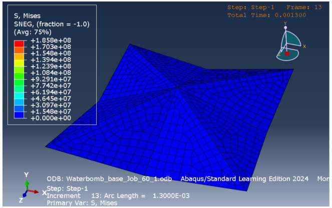
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Step: Step-1
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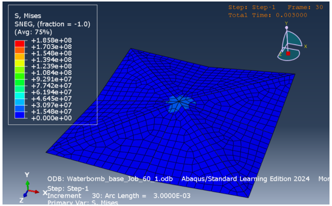
Primary Var: S, Mises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+3.097e+07
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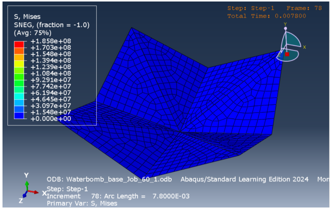
Step: Step-1
Increment 30: Arc Length = 3.0000E-03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+0.000e+00
Step: Step-1 Frame: 78
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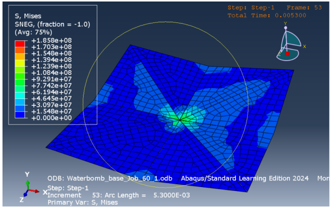
Step: Step-1
Increment 78: Arc Length = 7.8000E-03
Primary Var: S, Mises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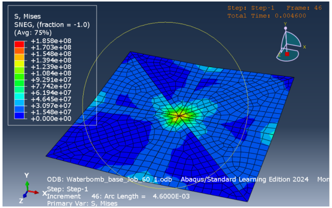
S, Mises
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Step: Step-1
Increment 46: Arc Length = 4.6000E-03
Primary Var: S, Mises

Validation with Literature

- Validated our FEA simulation results against plots and data from prior research
- Decent agreement in strain-energy energy profiles using our FEA and experimental study by *B H Hanna et al*

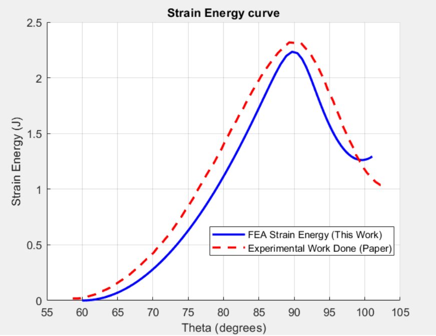


Figure: Strain energy vs θ comparison: FEA vs Literature

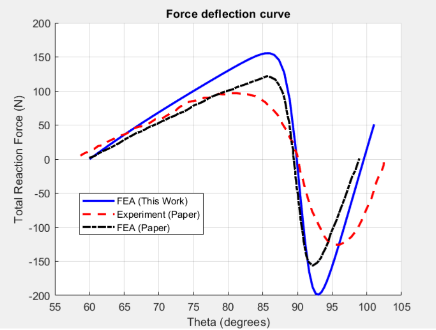


Figure: Force vs θ comparison: FEA vs Literature

Interesting Observation

- In the prior work done on waterbomb base unit study by *B H Hanna et al*, it was observed that if we keep different elasatic stiffness at mountain and valley crease, then we can shift the 2nd stable position for a given 1st stable position.
- k_{γ_m} and k_{γ_v} denote stiffness at mountain and valley crease repectively
- Can use this for programming bistable behaviour!

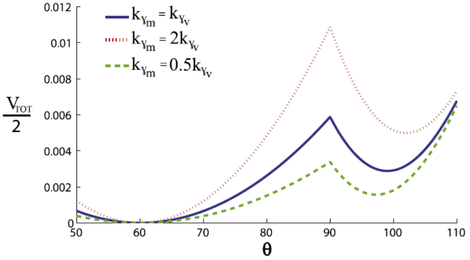


Figure: θ_2 variation with varying k_{γ_m} and k_{γ_v} for a given θ_1 (here 60^o)

Tuning Bistability

Goal: Given desired θ_1, θ_2, and energy barrier ΔE, determine stiffnesses k_{γ_m}, k_{γ_v}.

1. **Step 1:** Fix θ_1, assume $k_{\gamma_m} = 1$, $k_{\gamma_v} = 1$, we get some θ_2, most probably, not the desirable one
2. **Step 2:** Tune $\alpha = k_{\gamma_v}/k_{\gamma_m}$ to shift θ_2 to desired value
3. **Step 3:** Scale k_{γ_m} to achieve desired energy barrier

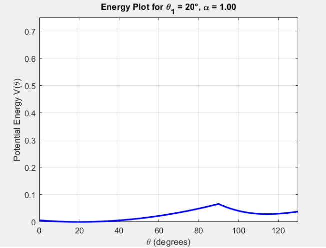


Figure: Step 1

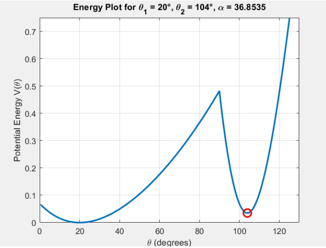


Figure: Step 2

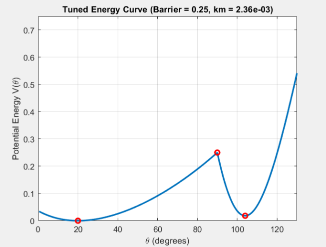


Figure: Step 3

Results

Validation of Programmable Behavior

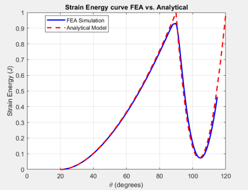


Figure: $\theta_1 = 20^o, \theta_2 = 104^o, \Delta E = 1$J

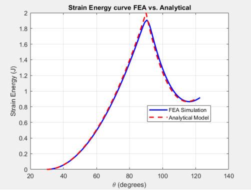


Figure: $\theta_1 = 30^o, \theta_2 = 115^o, \Delta E = 2$J

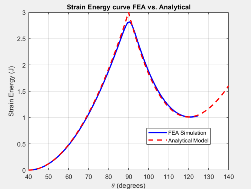


Figure: $\theta_1 = 40^o, \theta_2 = 120^o, \Delta E = 3$J

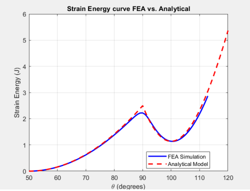


Figure: $\theta_1 = 50^o, \theta_2 = 100^o, \Delta E = 2.5$J

Programmability Map

Caution: Not all θ_2 are possible given any θ_1!

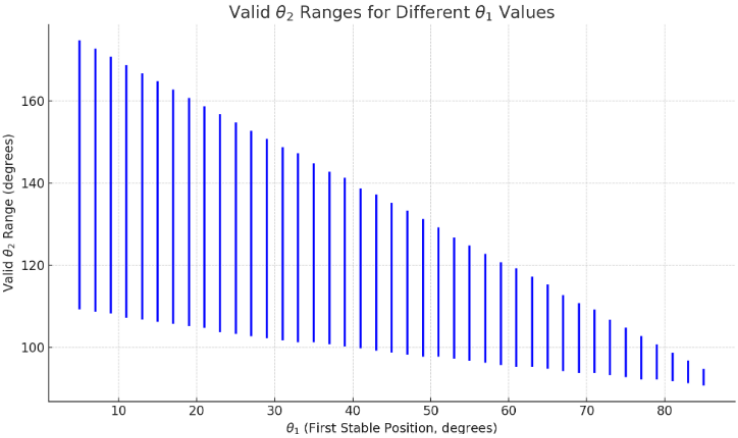


Figure: Feasible θ_2 range for given θ_1

Effect of Non-Square Geometry

- Studied rectangular base units (aspect ratio $\neq 1$)
- Aspect ratio is denoted by n, where $\mathrm{n} = \text{length}/\text{breadth}$
- Observed changes in force-displacement and bistable behaviour

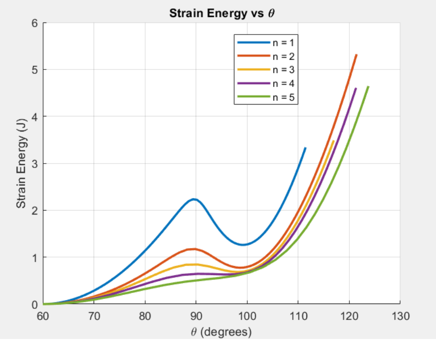


Figure: Strain energy vs θ for different aspect ratio

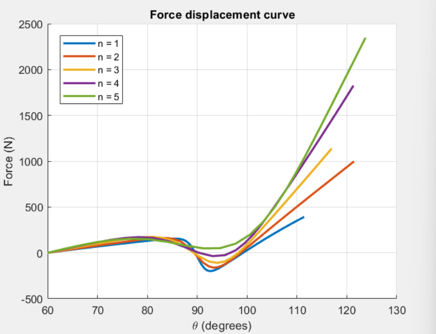
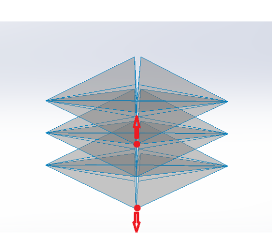
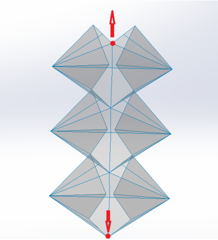
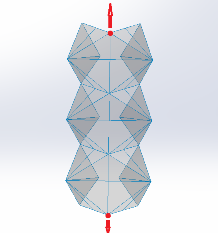


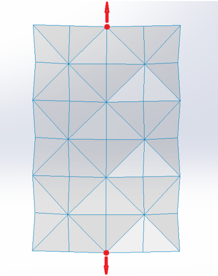
Figure: Force vs θ for varying aspect ratio

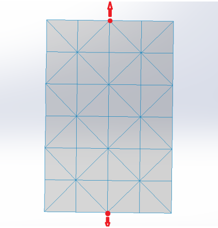
Waterbomb tessellation structure

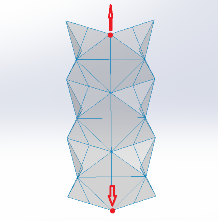




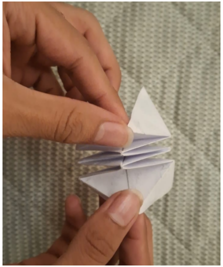
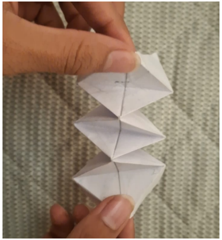
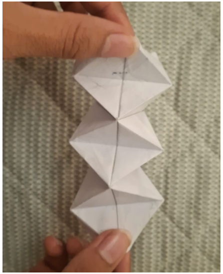


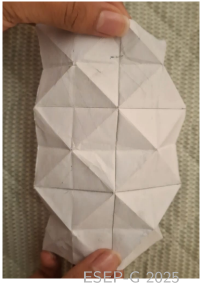
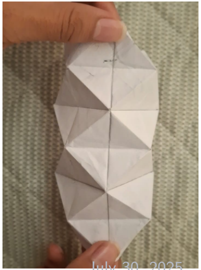






Waterbomb tessellation structure

Conclusion

Conclusion and Future Work

- Developed formulation to program bistable behaviour via stiffness tuning
- Validated using FEA simulations and literature
- Observed a dip in bistable behavior on increasing aspect ratio, with $n = 1$ showing most bistable characteristics

Future work

- Analyse other variation of WB (4 mountain + 2 valley) popular in tessellations
- Simulate the multistable structure made of waterbomb base units

Acknowledgement

I would like to express my heartfelt gratitude to my project advisors, Prof. Higuchi Ryo and Prof. Lu Xin, for their unwavering guidance, encouragement, and invaluable feedback throughout the course of this work. I am also deeply thankful to all the members of the lab for their support with the lab PC setup and for always being so accommodating and respectful.

Thank you!

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