# Buckling-induced Functionalities in Origami Tubes

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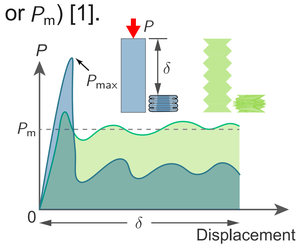
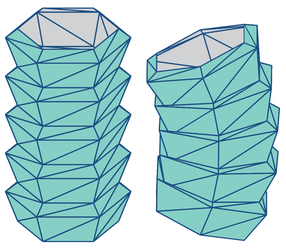
## Project Objectives and Goals

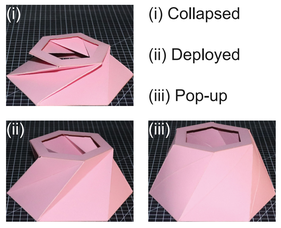
- Buckling brings new functions to Origami tubes
- Improve the energy-absorbing performance
- Uncover the geometric effects on multi-stability
- Create tunable mechanical properties by buckling

## Background

- Patterned tubes can decrease the peak force $P_{max}$ while absorb similar energy ($P_m \cdot \delta$, or $P_m$) [1].
- Local snap-throughs lead to multiple stable states corrugated tubes [2].
- Multi-stable structures show tunable mechanics, e.g., stiffness.





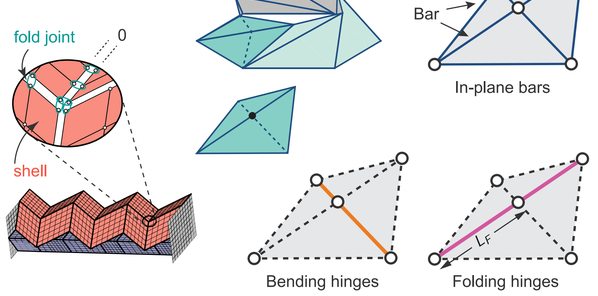

(i) Collapsed

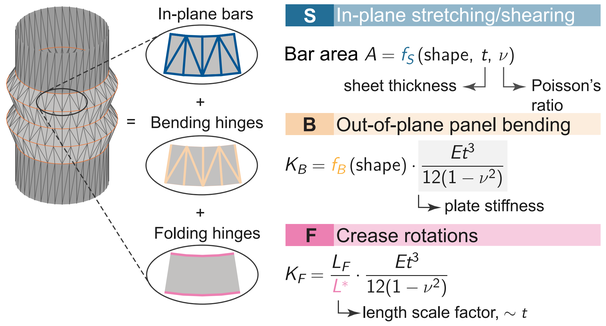
(ii) Deployed

(iii) Pop-up

## Methods

- *A reduced-order bar and hinge model [3]*
- Finite-element analysis
- Experimental test




**S** In-plane stretching/shearing

Bar area $A = f_S(\text{shape}, t, \nu)$

sheet thickness, Poisson's ratio

**B** Out-of-plane panel bending

$K_B = f_B(\text{shape}) \cdot \frac{Et^3}{12(1-\nu^2)}$

plate stiffness

**F** Crease rotations

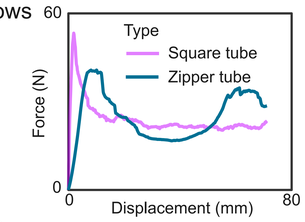
$K_F = \frac{L_F}{L^*} \cdot \frac{Et^3}{12(1-\nu^2)}$

length scale factor, $\sim t$

## Results

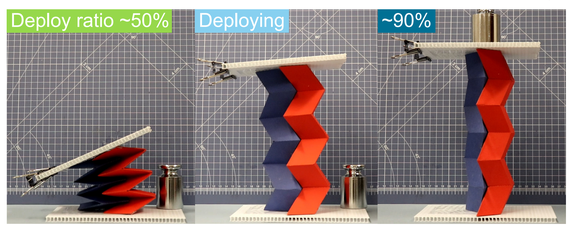
### (1) A deployable Origami tube with tunable energy absorption

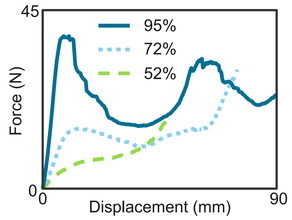
- As compared to the square tube, the Origami tube shows lower peak force and similar energy absorption.
- The energy-absorbing performance can be tuned as the Origami tube deploys along the axial direction.




Less energy (lower $P_m$) — More energy (higher $P_m$)

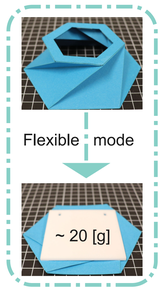
Less damage (lower $P_{max}$) — More damage (higher $P_{max}$)

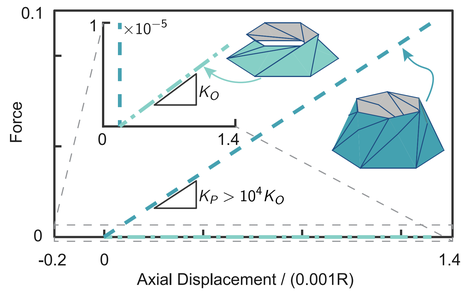



### (2) Stiffen multi-stable Origami tubes by crease buckling

- The Kresling cone can be popped to a dome-like shape by valley-crease buckling.
- The stiffness can be increased by up-to-four orders of magnitude after the shape-morphing.

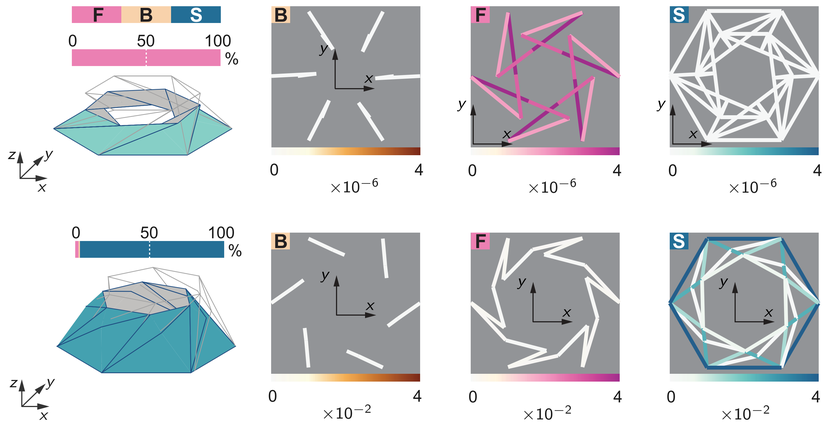


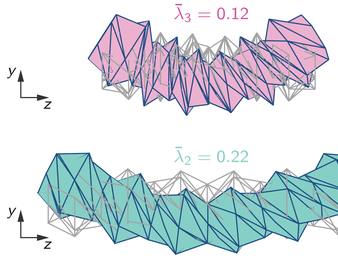





> 500 times self weight

The flexible deformation mode is dominated by crease folding, while the stiff mode requires more panel stretching.

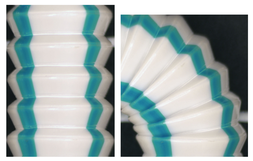


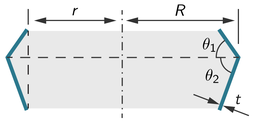

Bending stiffness (reflected by the eigenvalue) of the Kresling tube can be tuned as the constituent units switch among different stable states.

### (3) Geometry-controlled multi-stability of straws

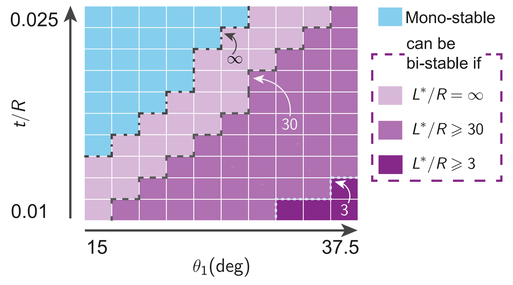
A straw can be multi-stable when bent.



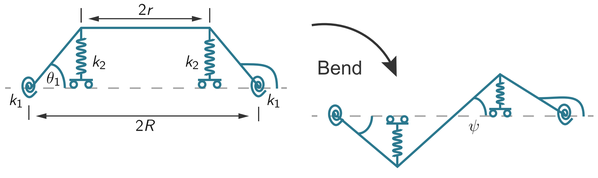
Geometry of the unit is defined with five parameters.

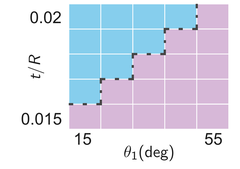



To achieve multi-stability, a straw needs:
- thinner shells (smaller $t$)
- steeper cones (greater $\theta_1$)
- weaker creases (greater $L^*$)




Such geometric influences can also be captured by a four-bar linkage model.




## Conclusion & Future Studies

- Proposed a tunable energy absorber using a rigid-foldable Origami tube.
- Understood how geometry affects the straw multi-stability.
- Created tunable stiffness in Origami tubes by buckling valley creases.
  - Deployment and untethered control (e.g., pneumatic).
  - An inverse design framework for targeted performances.

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## Publications

Wo, Z. et al., "Stiffen Multi-stable Origami Tubes by Crease Buckling", *Extreme Mechanics Letters.* **2022**, (submitted).

Wo, Z. et al., "Bending Stability of Corrugated Tubes With Anisotropic Frustum Shells", *ASME J. Appl. Mech.* **2022**, 89 (4): 041005.

Wo, Z. et al., "Locking Zipper-Coupled Origami Tubes for Deployable Energy Absorption", *ASME J. Mech. Rob.* **2022**, 14 (4): 041007.

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[1] Ma, J. et al., *ASME J. Appl. Mech.* **2013**, 81(1): 011003

[2] Bende, N. et al., *Soft Matter.* **2018**, 14(42): 8636-8642

[3] Filipov, E. T. et al., *IJSS.* **2017**, 124: 26-45