Crashworthiness of Filament Wound Composite Origami Thin-Walled Tubes

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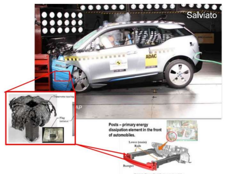
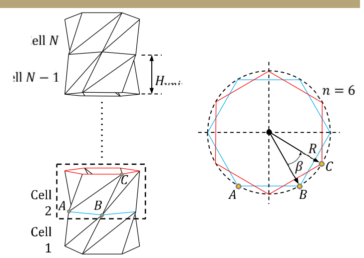
Introduction \ Problem Statement

- Straight-walled tubes traditionally utilized for energy absorption in crash scenarios
- Large initial forces and fluctuations – can be detrimental to passenger safety
- Kresling origami proposed as geometric improvement to improve safety
- J. O'Neil, M. Salviato, J. Yang, "Energy absorption behavior of filament wound CFRP origami tubes pre-folded in Kresling pattern," *Composite Structures* (under review).



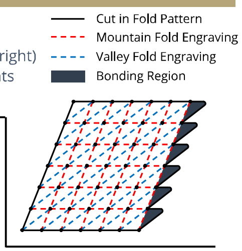
Geometrical Definitions

- β – Twist angle of unit cell
- H_{unit} - Unit cell height
- n – Number of cross-sectional sides
- N – Number of unit cells in a tube
- R – Circumscribed radius of cross-section

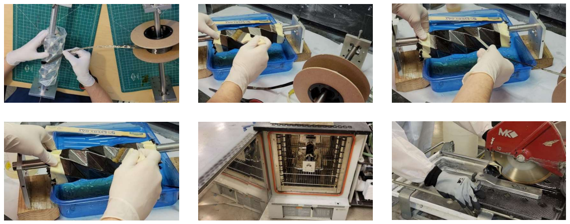


Manufacturing Process

- Mandrel material is PET plastic
- Mandrel is folded as described by fold pattern (right)
- Surface coated with double-sided tape – prevents fiber slippage



- Carbon fibers placed parallel to valley creases along convex region
- Room temp epoxy resin applied with bristle brush
- Cured in oven for six hours
- End cells cut off with wet tile saw



Previous Work

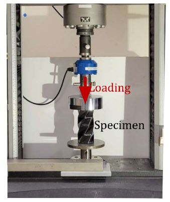
- Numerical studies with metal materials

Zhao, Xilu, Yabo Hu, and Ichiro Hagiwara. "Shape optimization to improve energy absorption ability of cylindrical thin-walled origami structure." *Journal of Computational Science and Technology* 5.3 (2011): 148-162.

- Papers exploring potential manufacturing methods for metal Kresling

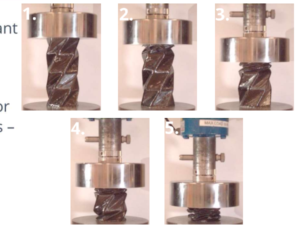
Kong, C. H., X. L. Zhao, and I. R. Hagiwara. "A new local thickening reverse spiral origami thin-wall construction for improving of energy absorption." *IOP Conference Series: Materials Science and Engineering*. Vol. 307. No. 1. IOP Publishing, 2018.

Experimental Procedure



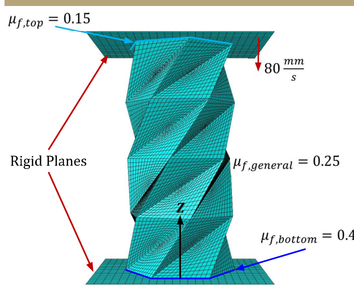
Experimental quasi-static compression setup

- $IPCF$ is the initial peak crushing force at failure – want to minimize
- $SEA = \frac{\int_0^{\delta_{total}} F(s)ds}{m}$ is the specific energy absorption or energy absorption per mass – want to maximize
- $CFE = \frac{\int_0^{\delta_{total}} F(s)ds}{IPCF}$ is the crushing force efficiency, measures variation in force response – want as close to one as possible

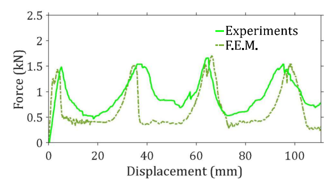


Example compression

Finite Element Modelling



Finite Element Mesh

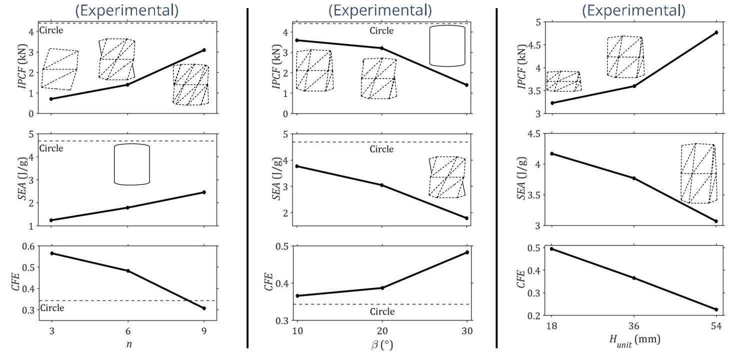


$n = 6$, $H_{unit} = 36$mm, $R = 36$mm, $\beta = 40°$, $N = 4$

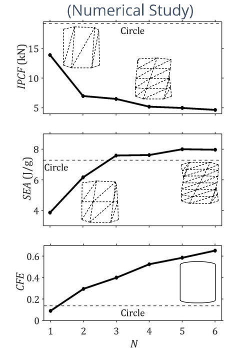
- Abaqus Explicit
- Two parts – PET and composite layers meshed with S4R elements (top left) of global size 3-5 mm
- Mass scale of 100 applied
- Cohesive contact interaction between parts
- Three friction contact interactions (top, bottom, general)
- Micromechanics for material properties
- Hashin failure criteria for composite damage initiation
- Built-in damage ductile scheme for PET
- Crack band model used for fracture
- Works well for predicting qualitative behavior (top right)

Parametric Study

Effect of number of sides (Experimental) | Effect of twist angle (Experimental) | Effect of unit cell height (Experimental)



Effect of unit cell count (Numerical Study)



- Adding more sides to a tube increases initial peak force while increasing specific energy absorption and sacrificing efficiency
- Increasing twist decreases initial peak force and energy absorption but increases efficiency
- Taller unit cells have larger initial peak forces and smaller efficiencies and can reduce energy absorption per mass
- Adding more unit cells in a tube can reduce initial peak force, improve specific energy absorption as well as crushing force efficiency
- To compete with straight-walled tubes: need smaller twist, a reasonable number of cross-sectional sides, and more than one unit cell

Kresling tubes show potential to outperform cylindrical (a straight-walled configuration) tubes in terms of all three axial indicators. Further improvements can be made with proper tuning of geometry.

Future Work, References, and Acknowledgments

- Investigation on the effects of geometric imperfections from manufacturing and how to mitigate them
- Exploration of a Kresling origami tube as the number of sides approach infinity
- Dynamic crash simulations and experiments

Collaborators: Professor Marco Salviato
Faculty: Bill Kuykendall
Graduate Students: Seunghyun Ko, Yasuhiro Miyazawa, Koshiro Yamaguchi, Xiaotian Shi, Shuaifeng Li, and Chun-Wei Chen

Other References:

1) Li, Jiaqiang, et al. "Computational Modeling and Energy Absorption Behavior of Thin-Walled Tubes with the Kresling Origami Pattern." Journal of the International Association for Shell and Spatial Structures 62.2 (2021): 71-81.
2) Zhao, Xilu, and Ichiro Hagiwara. "Designing and manufacturing a super excellent and ultra-cheap energy absorber by origami engineering." *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2019.

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