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Residual Creases

mechanics of partly (un)folded structures

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Workshop: Folding and Creasing of Thin Plate Structures
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Introduction

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Work done at Surrey Space Centre
and University of Cambridge.

Talk outline

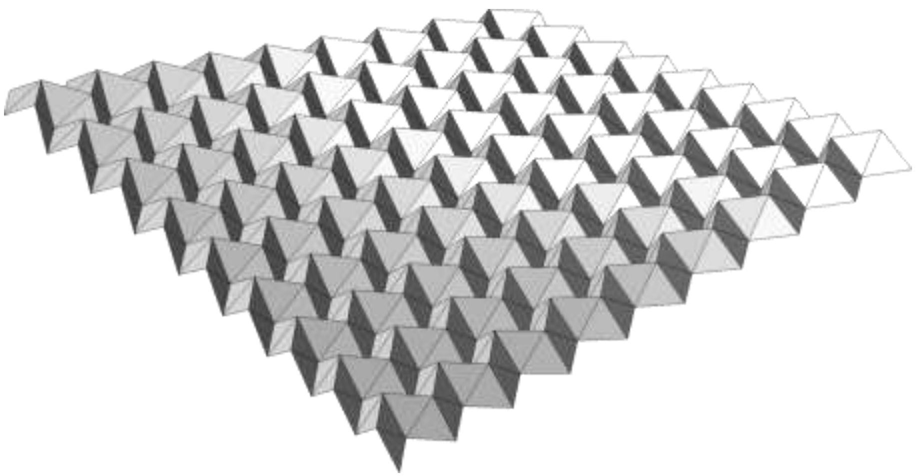
- brief history of mechanics of partly (un)folded structure
- case study of deployable structure with residual creases
- challenges and future directions

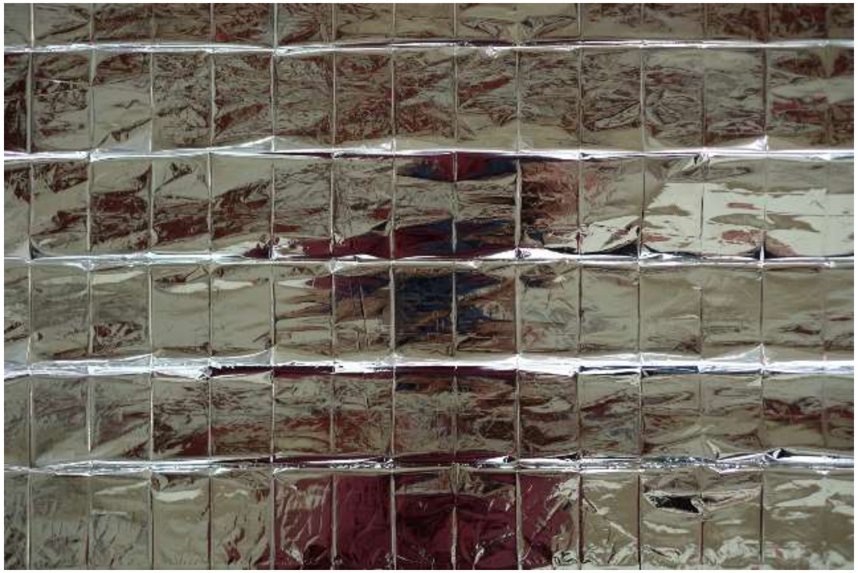
A brief history…

partly-folded or **partly-unfolded** structures

- effect of folds and creases on global structural properties
- dominated by folding kinematics, but requires structural mechanics

examples: morphing structures (compliant shell mechanisms), deployable structures with residual creases, *etc.*



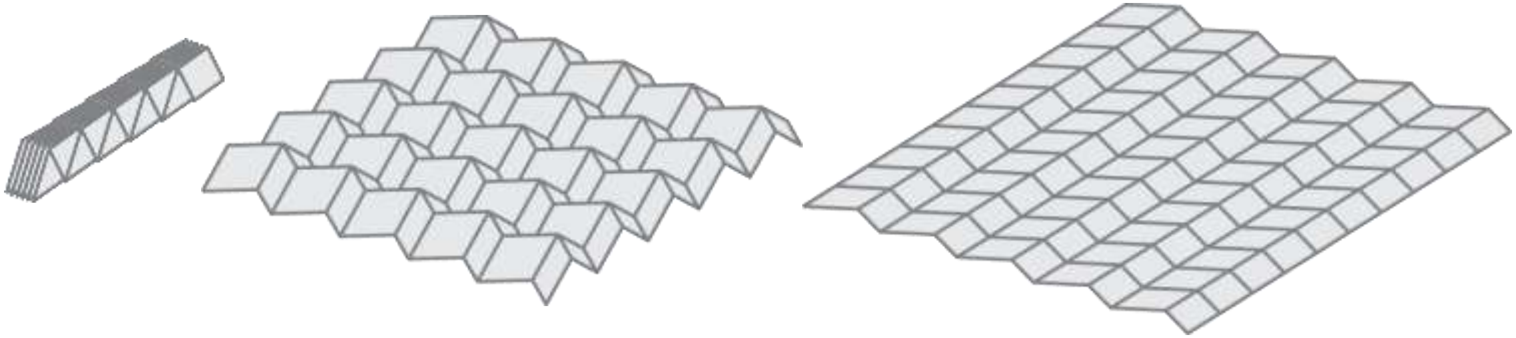


A brief history…

whistle-stop tour of mechanics of folded structures

kinematics

- rigid origami (rigid panels and frictionless hinges)
- quadrilateral meshes (Kokotsakis, 1933; Tachi, 2009; Stachel, 2010)
- curved creases (Huffman, 1976; Duncan and Duncan, 1982)



A brief history…

mechanics : kinematics + torsion springs at folds

- *linear* torsion springs

  structural analysis
  (Resch and Christiansen, 1971;
  Guest and Pellegrino, 1996;
  Okuizumi *et al*., 2011)

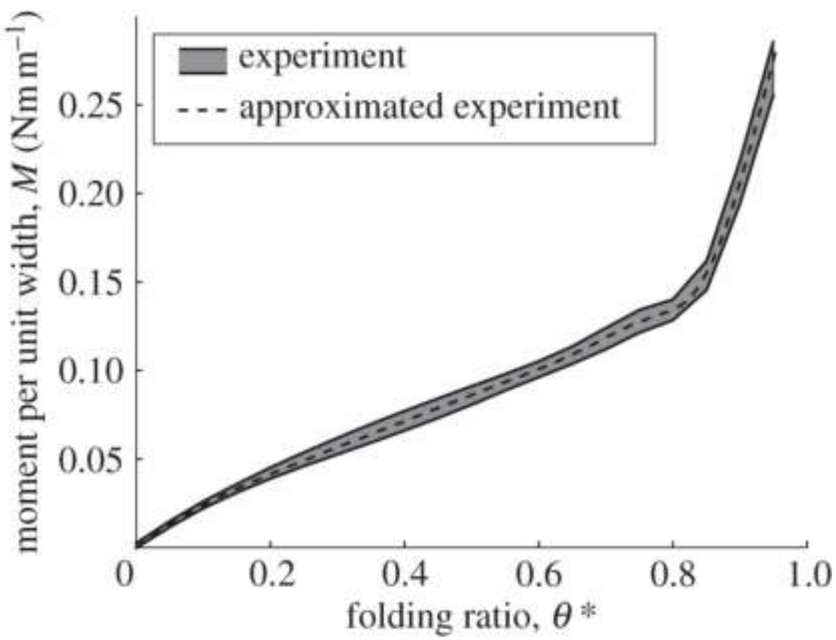
  equivalent stiffness of partly-folded sheets (Wei, *et al.* 2013)

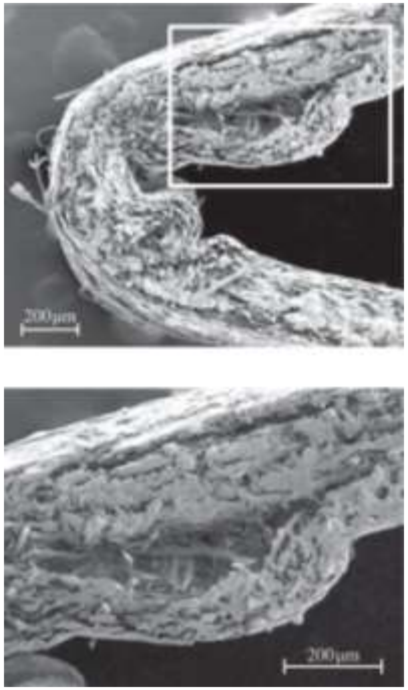
  analysis of multi-stability
  (Hanna, *et al.* 2014; Silverberg, *et al.* 2014; Waitukaitis, *et al.* 2015)

A brief history…

mechanics : kinematics + torsion springs at folds

- non-linear torsion springs (Yasuda, *et al.* 2013)

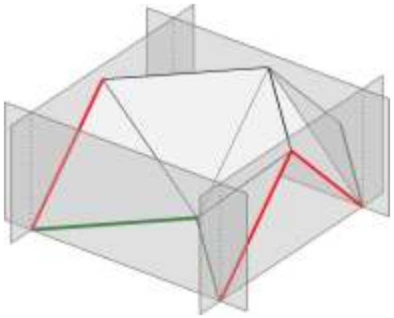


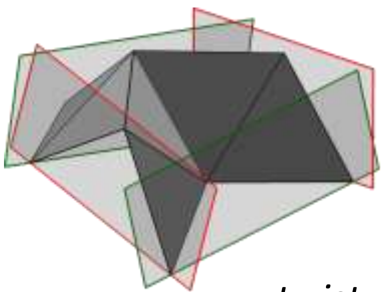


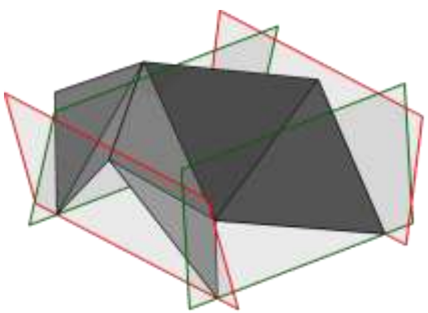
A brief history…

mechanics: deformation between the creases

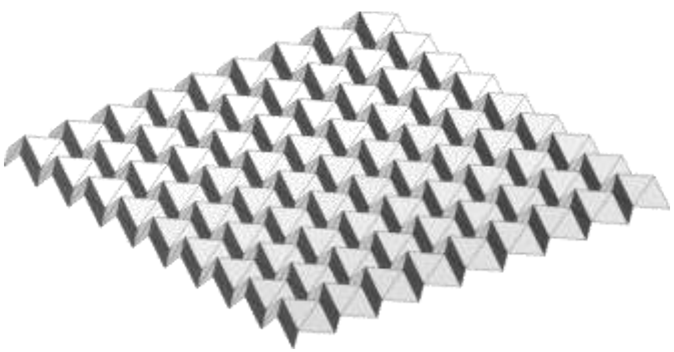
- bending along diagonals of quadrilateral elements
  (Schenk and Guest, 2010-2013; Wei *et al.*, 2013)
- introduces additional degrees of freedom



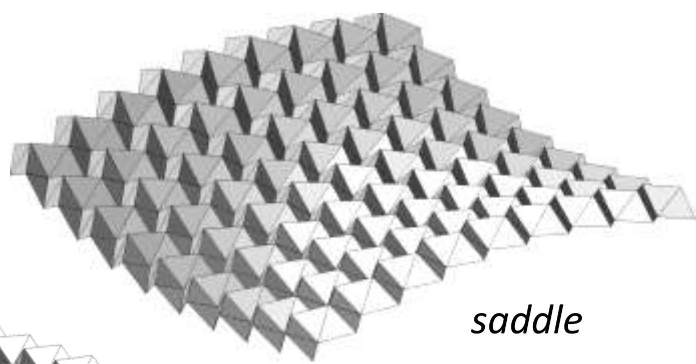




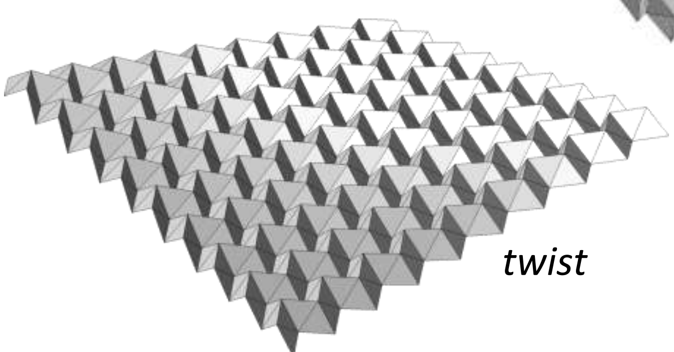
twist



saddle



twist

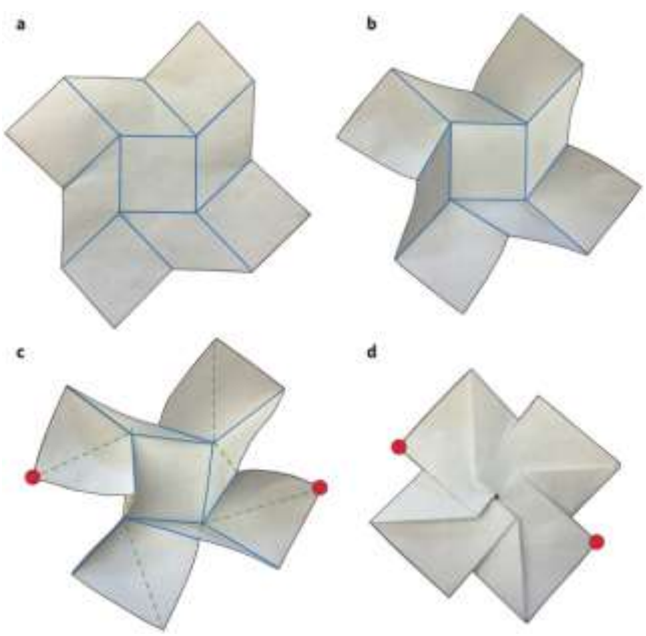


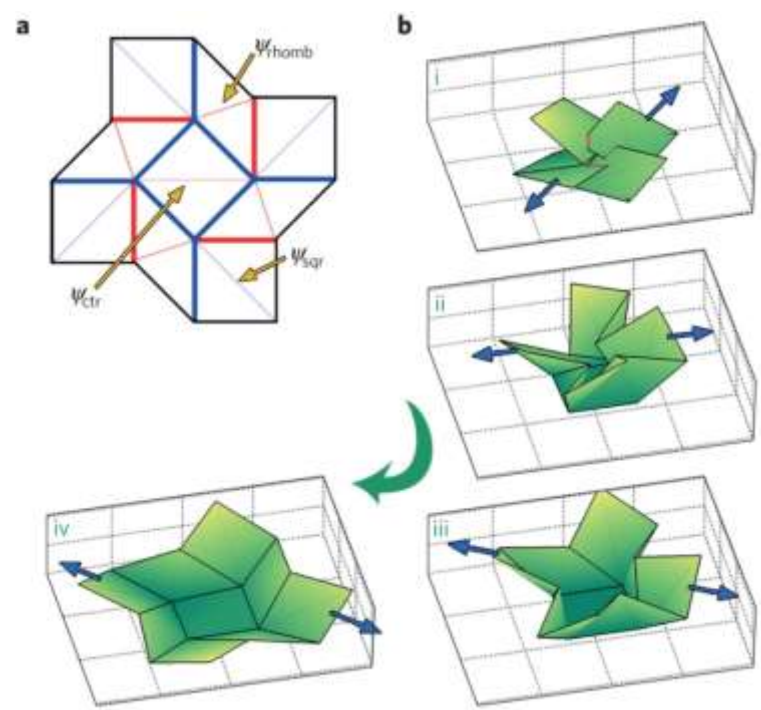
saddle

A brief history...

mechanics: deformation between the creases

recently published work: bending of facets provides additional degrees of freedom and multi-stability (Silverberg *et al.*, 2015)

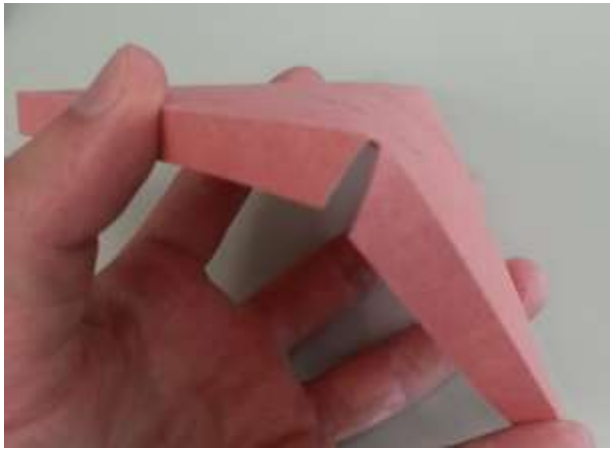




A brief history…

mechanics: deformation between the creases

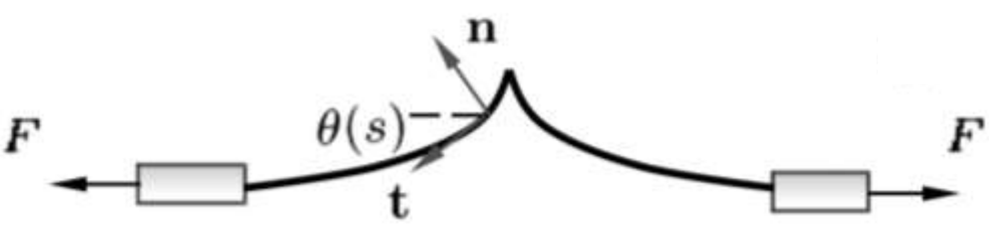
- <u>discrete</u> deformations
  - triangulating quadrilateral panels & linear springs
    (Schenk and Guest, 2010-2013; Silverberg, *et al.* 2014-2015)
  - folding of constrained facets
    (Lobkovsky *et al.*, 1995-1996;
    Filipov *et al.*, 2014)



A brief history…

mechanics: elastic deformation between the creases

- continuous deformations : linear hinges with elastic facets
  - engineering beams (Papa and Pellegrino, 2008; Furuya *et al.*, 2005)
  - elastica (MacNeal and Robbins, 1976; Lechenault *et al.* 2014)



- necessity for curved creases (Dias *et al.*, 2012-2014)

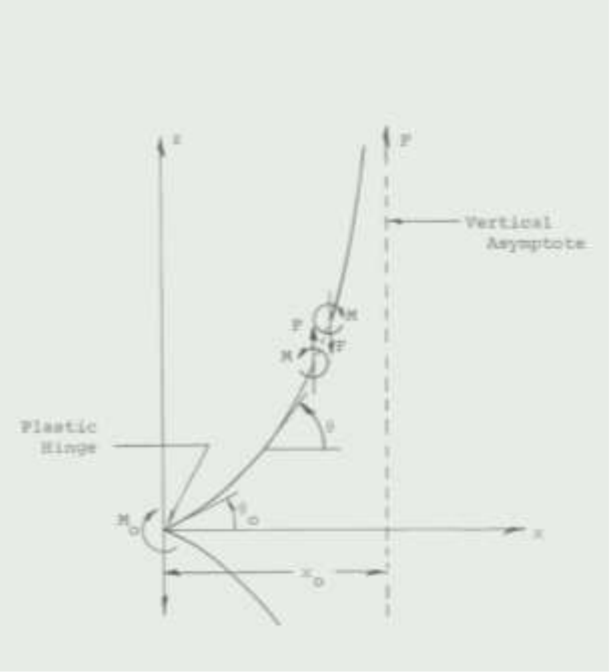
A brief history…

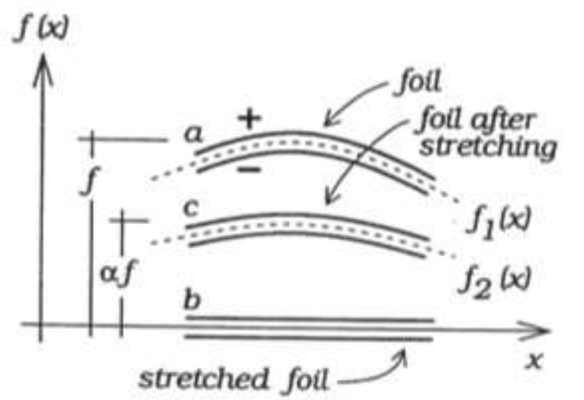
mechanics: elasto-plastic modelling

- plastic hinges : manufacturing
  (Duncan and Duncan, 1981; Schenk *et al*., 2011)

- **plastic** hinges and **elastic** facets
  (MacNeal and Robbins, 1967; Hedgepeth, 1981)

- plastic deformation of a smoothly deformed foil (Greschik, 1996)





A look towards the future…

A brief look towards the future:

- **elasto-plastic** modelling of the creases and interlying material
- **detailed modelling** of fold lines : moving away from mechanical trends, to accurate (surrogate-)models
- interactions between creases: **vertices**!

Case Study:

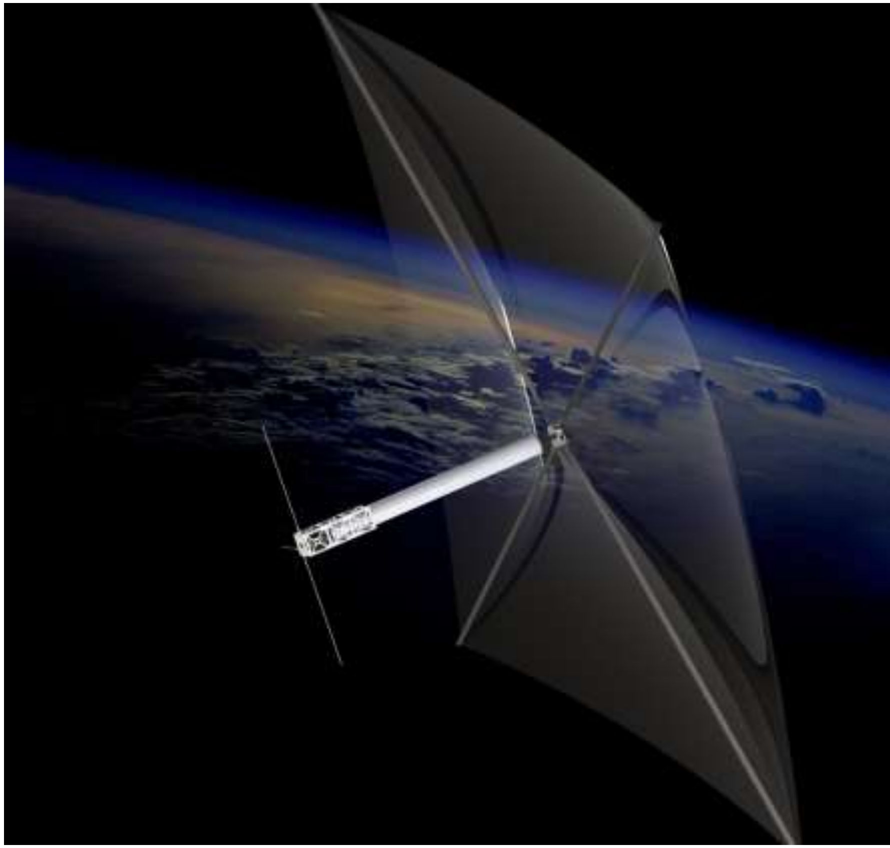
Deployable Space Structures

InflateSail

InflateSail: technology demonstration mission

3U CubeSat (100 x 100 x 340 mm)

- deploy 10 m^2 gossamer sail
- deploy 1 m long inflatable mast



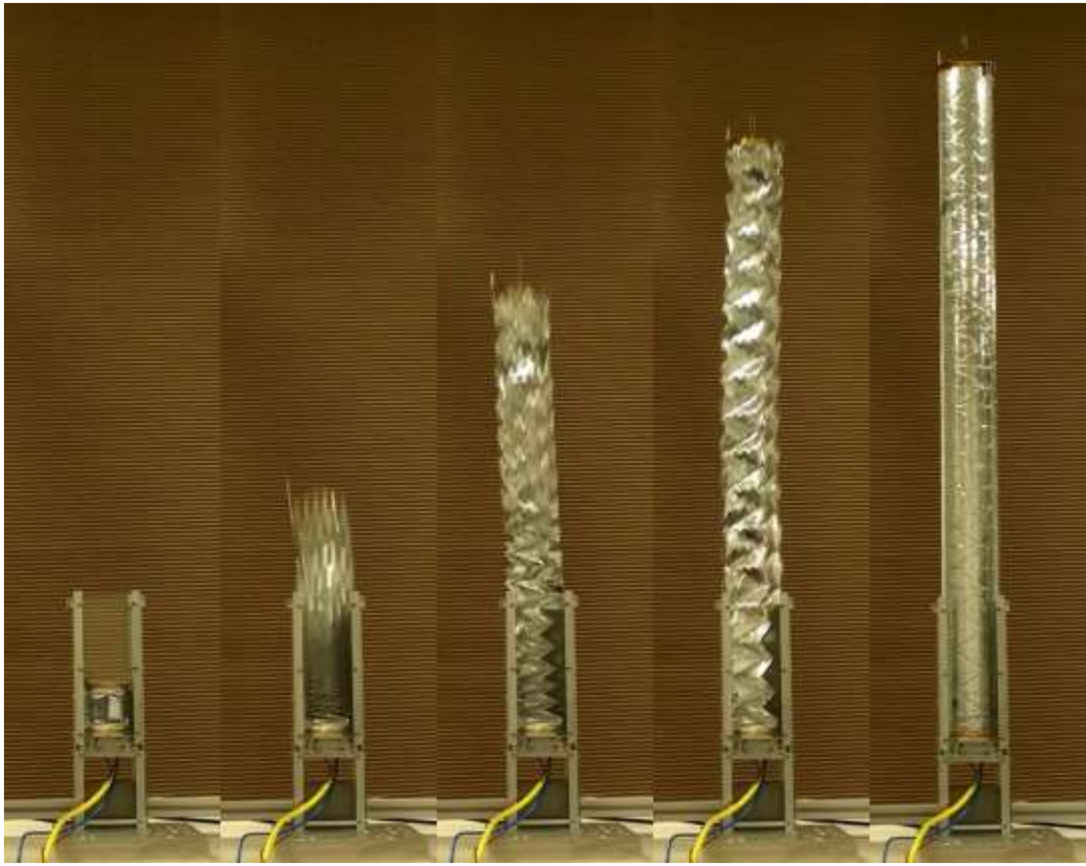
Objective: demonstrate feasibility of drag augmentation to de-orbit satellites from LEO

EU FP7 funding / QB50 launch

PI: Prof. Vaios Lappas

Inflatable Origami Mast

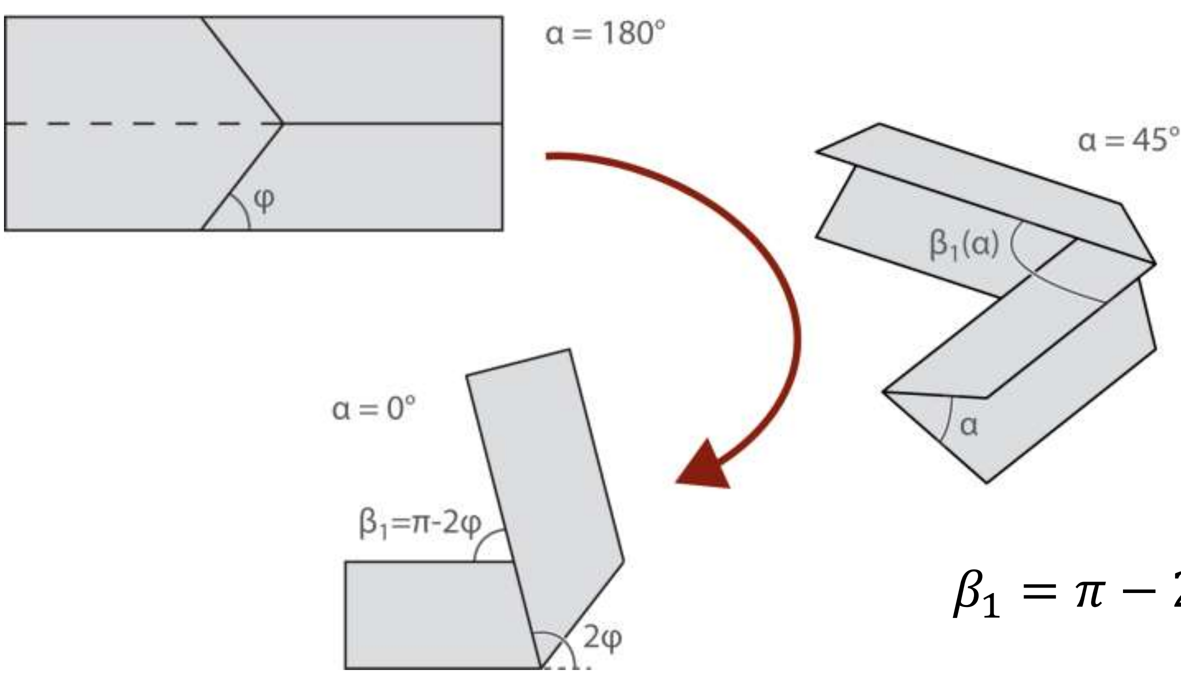
Deployable Origami Mast (video)



Inflatable Origami Mast

Kinematics : Rigid Origami

building block: reverse fold



$\alpha \in [0, \pi]$

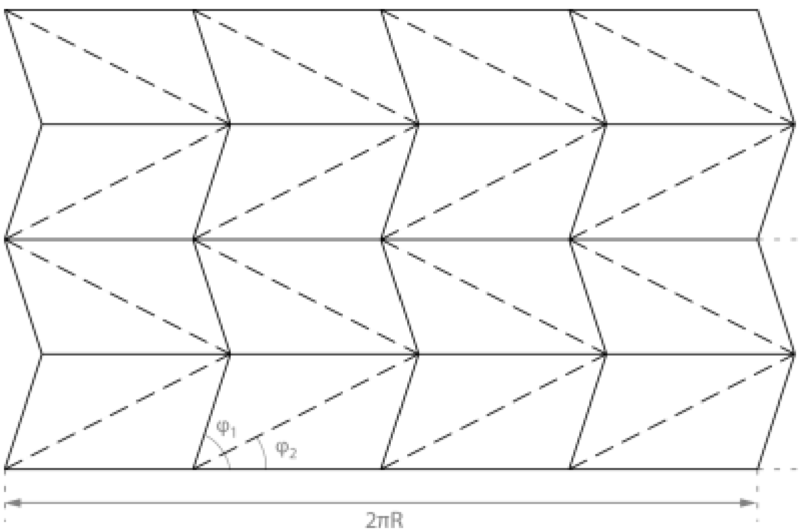
$\beta \in [\pi - 2\varphi, \pi]$

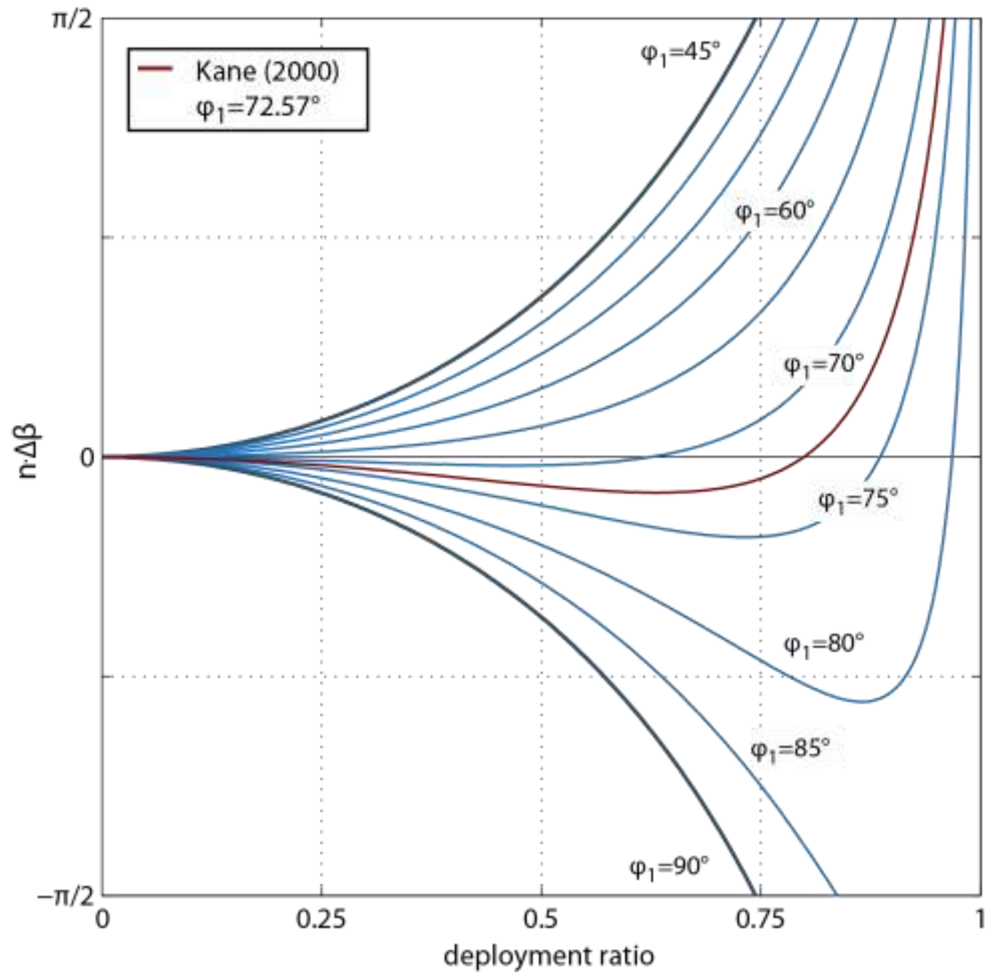
$$\beta_1 = \pi - 2 \cdot \operatorname{atan}\left(\cos\frac{\alpha}{2} \cdot \tan\varphi\right)$$

the enclosed angle β_1 is a strictly increasing function of α

Inflatable Origami Mast

Kinematics : Compatibility

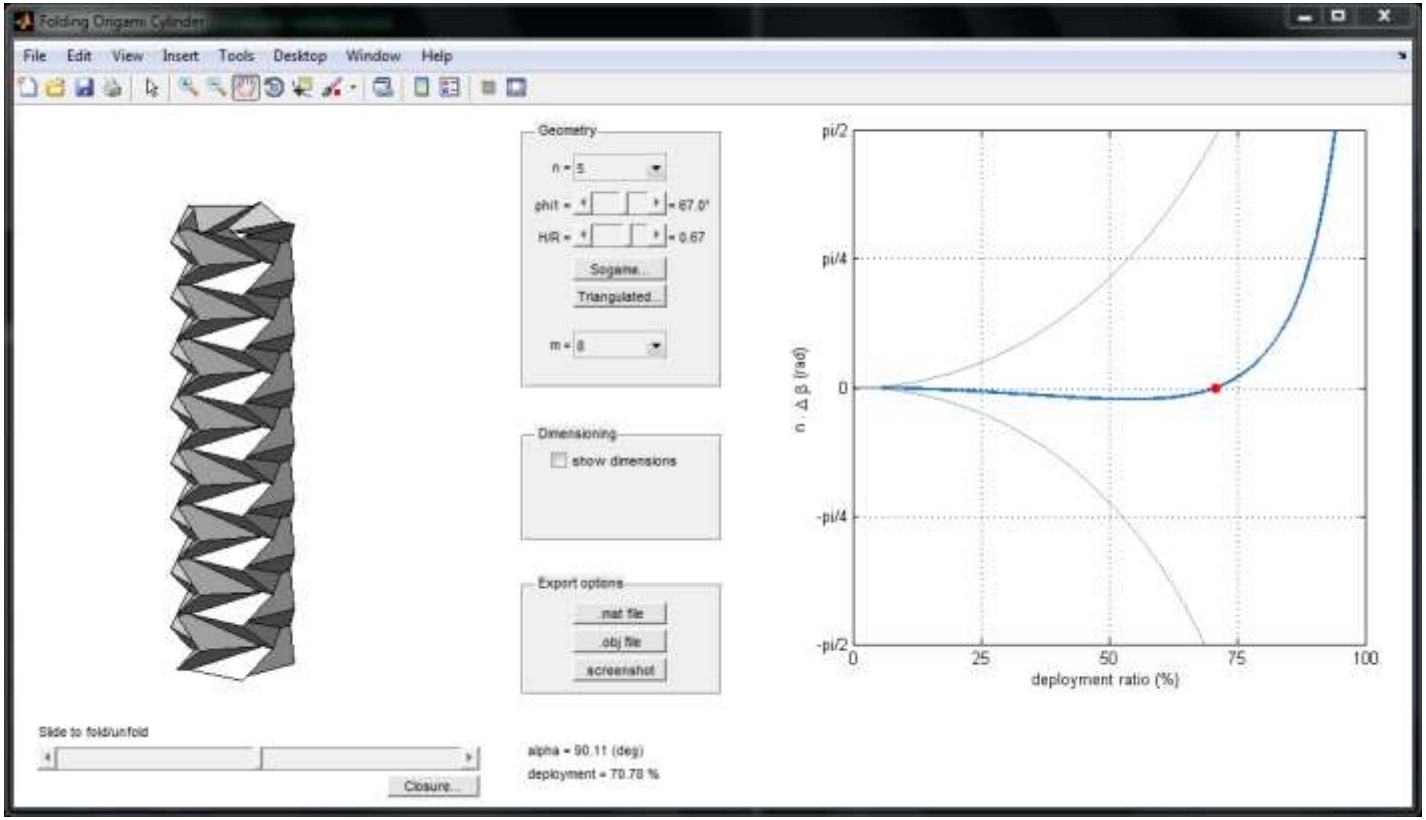




Deployment ratio: $\frac{L}{L_{max}} = \sin\frac{\alpha}{2}$

Inflatable Origami Mast

Parametric Design Tool



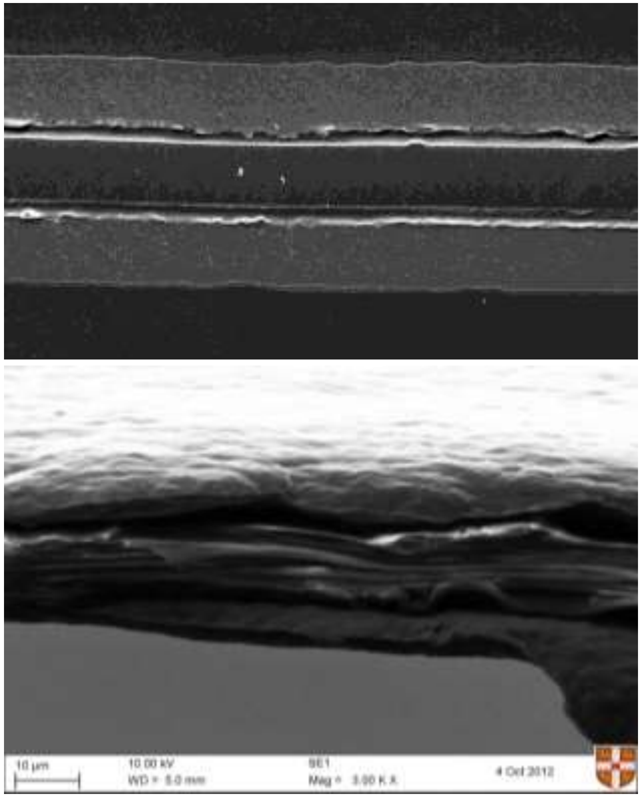
http://www.markschenk.com/research/#software

Schenk, M., Kerr, S., Smyth, A.M. & Guest, S.D. (2013), "*Inflatable Cylinders for Deployable Space Structures* " Proceedings of the First Conference Transformables 2013, 18—20th September 2013, Seville, Spain.

Inflatable Origami Mast

Inflatable Boom : Membrane Material

- laminate of Aluminium-Mylar-Aluminium (14.5/16/14.5 ≈ 45μm)
- the Aluminium layers provides stiffness, and polymer layer adds toughness
- limited thickness of membrane due to plastic deformation (folding and rigidisation)

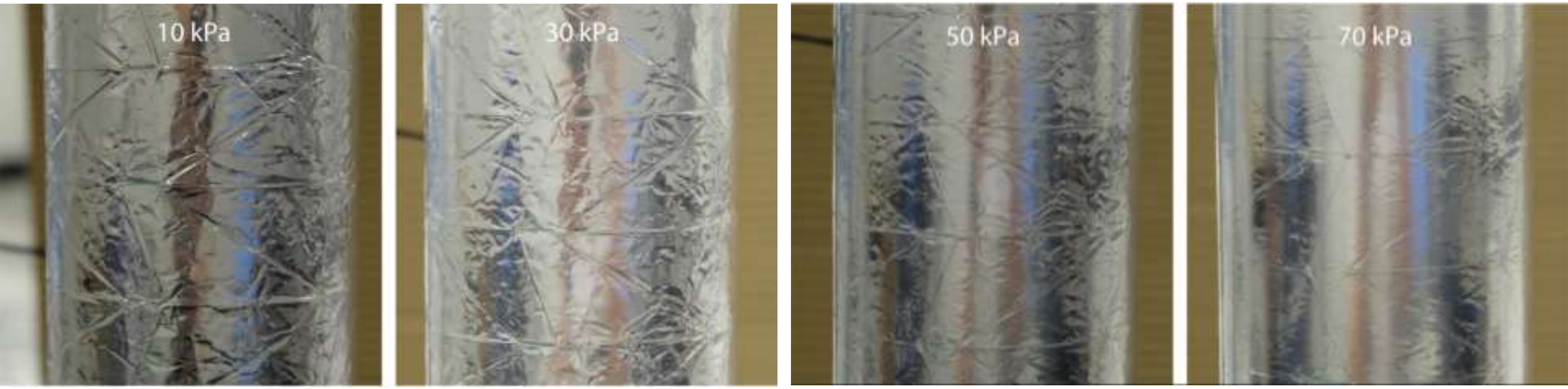


Inflatable Origami Mast

Inflatable Boom : Strain-rigidisation

- ensure long-term structural performance after deployment

- <u>strain-rigidisation</u> : permanently remove folding creases by plastic deformation of aluminium-polymer laminate



Inflatable Origami Mast

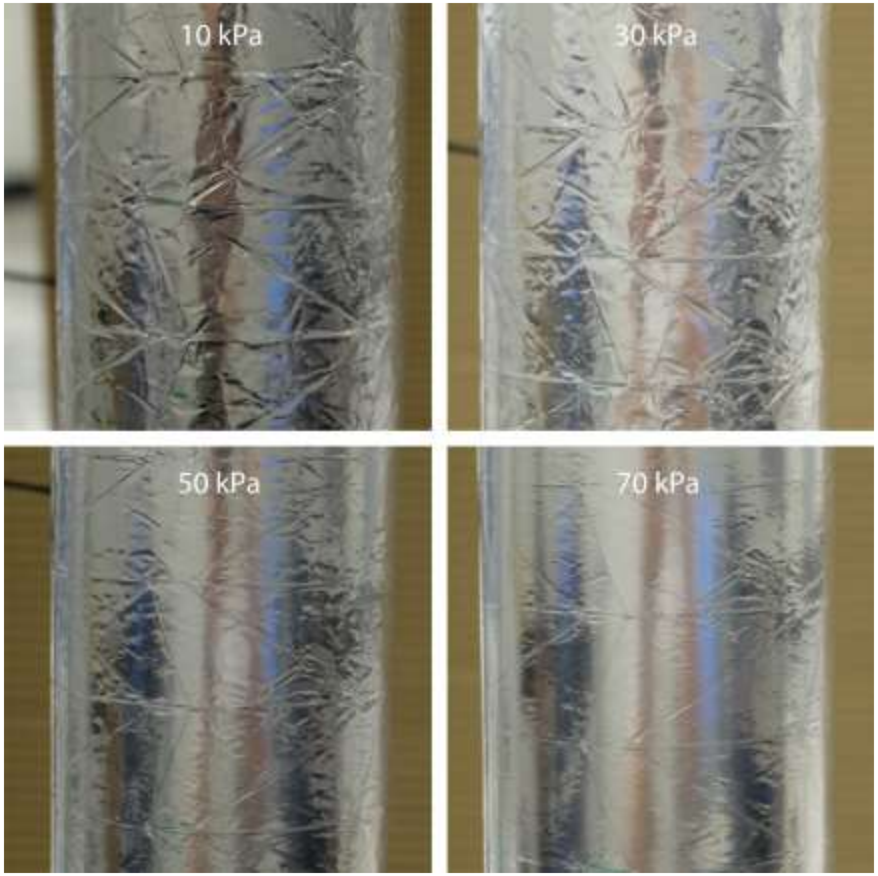
Inflatable Boom : Strain-rigidisation

- investigate efficacy : measure boom against inflation pressures

- first natural frequency as indication of stiffness: $EI \propto \omega_n^2$

- theoretical rigidisation pressure

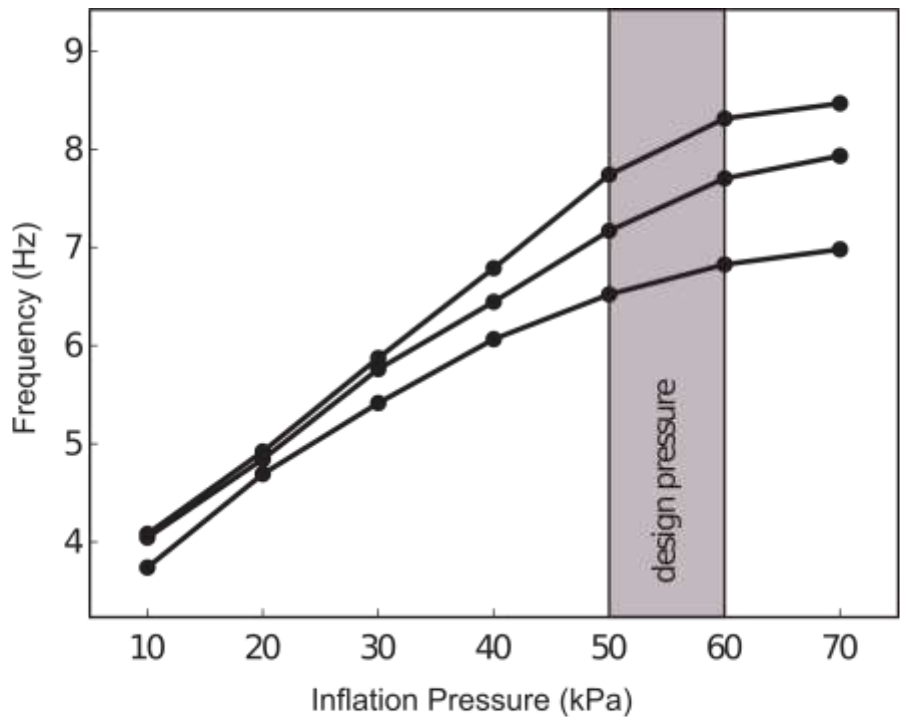
$$P = \sqrt{\frac{4}{3}\frac{\sigma_y t}{R}} \approx 50 - 60\,kPa$$



Inflatable Origami Mast

Inflatable Boom : Strain-rigidisation

- recovery up to approximately 50% of theoretical stiffness
- Experimental! No predictions of stiffness (or strength) due to residual creases



- numerical prediction, *e.g.* feed imperfections into FEM?

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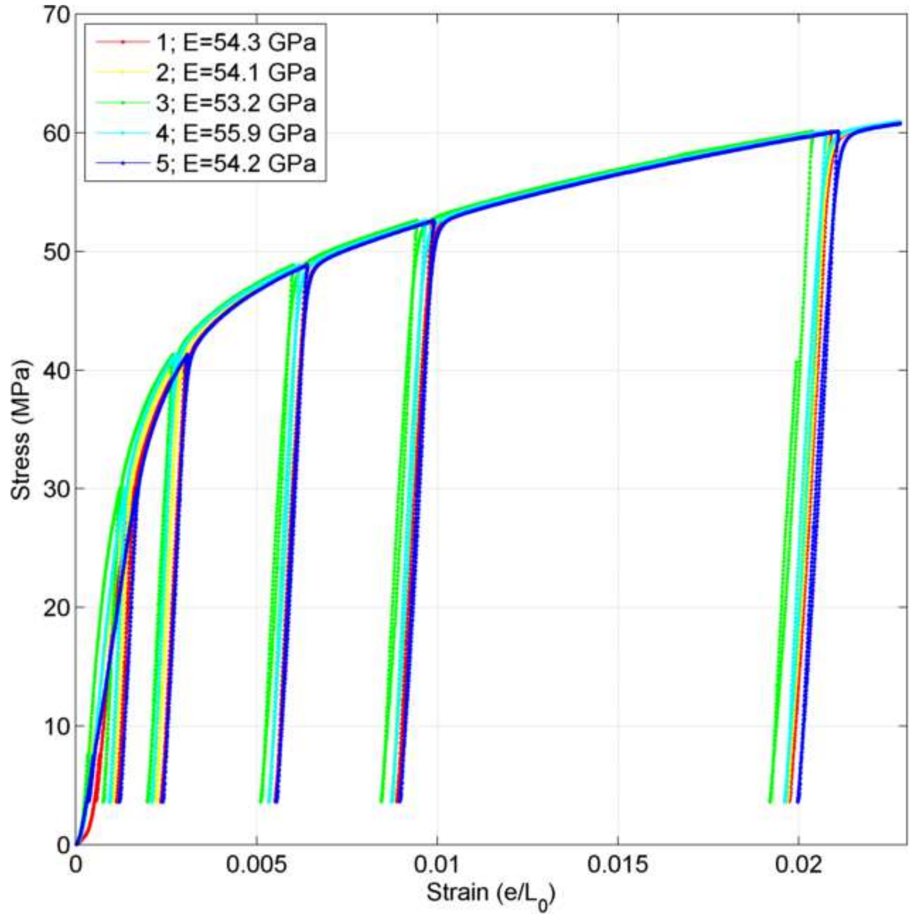
Inflatable Origami Mast

Inflatable Boom : Material Characterisation

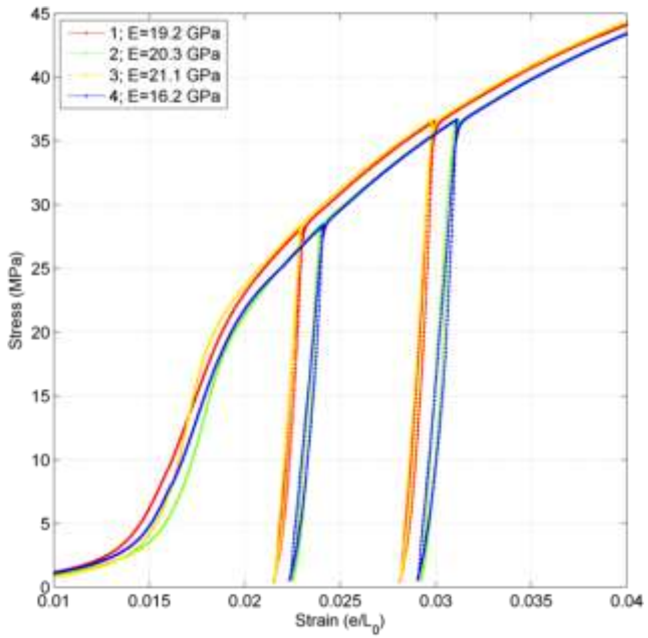
- accurately measuring the material properties (E and σ_Y) was challenging!
- ASTM E-345 : *"Standard Test Methods of Tension Testing of Metallic Foil"*
- define a yield point by 0.2% proof stress σ_Y; however, tensile tests gave inconsistent results and a <u>very low</u> E for Aluminium foils: <u>15-25 GPa</u>

Inflatable Origami Mast

cause: (negligibly) non-flat material!



	Young's Modulus	Yield Strength
elastic unloading	**55.4** ± 5.63 GPa	49.3 ± 6.50 MPa
Initial linear region	**24.8** ± 6.13 GPa	N/A

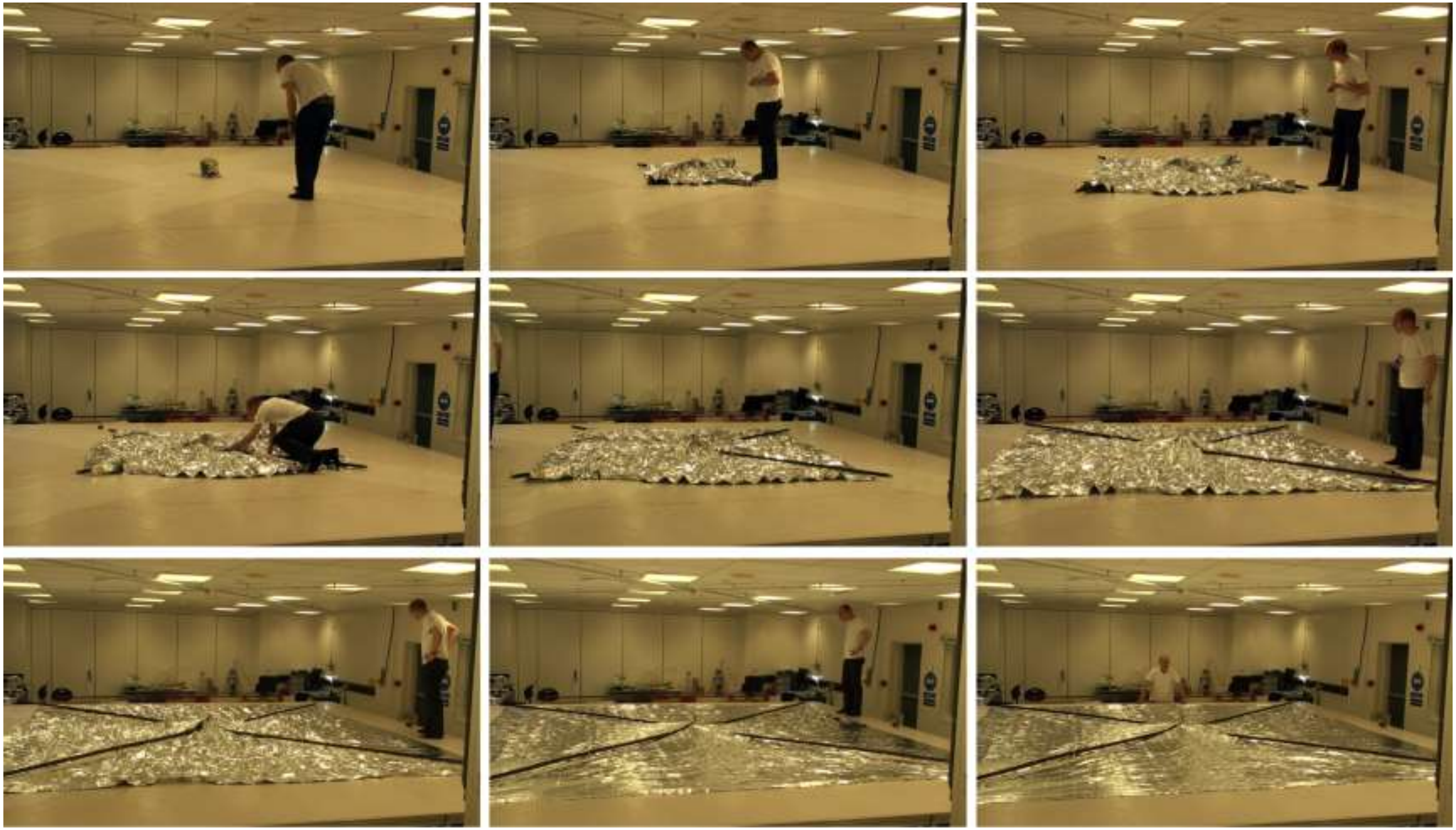


Charly Knight (2014)

Inflatable Origami Mast

- Lessons learned:
  - measuring material properties of thin membranes is tricky!
  - easy to find trends that give good approximations (power laws, *etc.*) but hard to get accurate numbers.
  - account for non-flatness of the base material (low effective E)
  - common measurement techniques for the hinge stiffness

Gossamer Sails



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Gossamer Sails

Residual creases in membranes:

- flatness vs reflectivity
- low in-plane modulus
- uncertain deployed dimensions

- increased bending stiffness (IKAROS mission)

Conclusions

Conclusions & Future Work

- elasto-plastic deformations (folds *and* facets)
- interactions between creases (vertices)

- accurately measuring the hinge stiffness (not order of magnitude) : develop common measurement techniques

- incorporating low-level analysis into high-level models

Questions

Thank you!

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