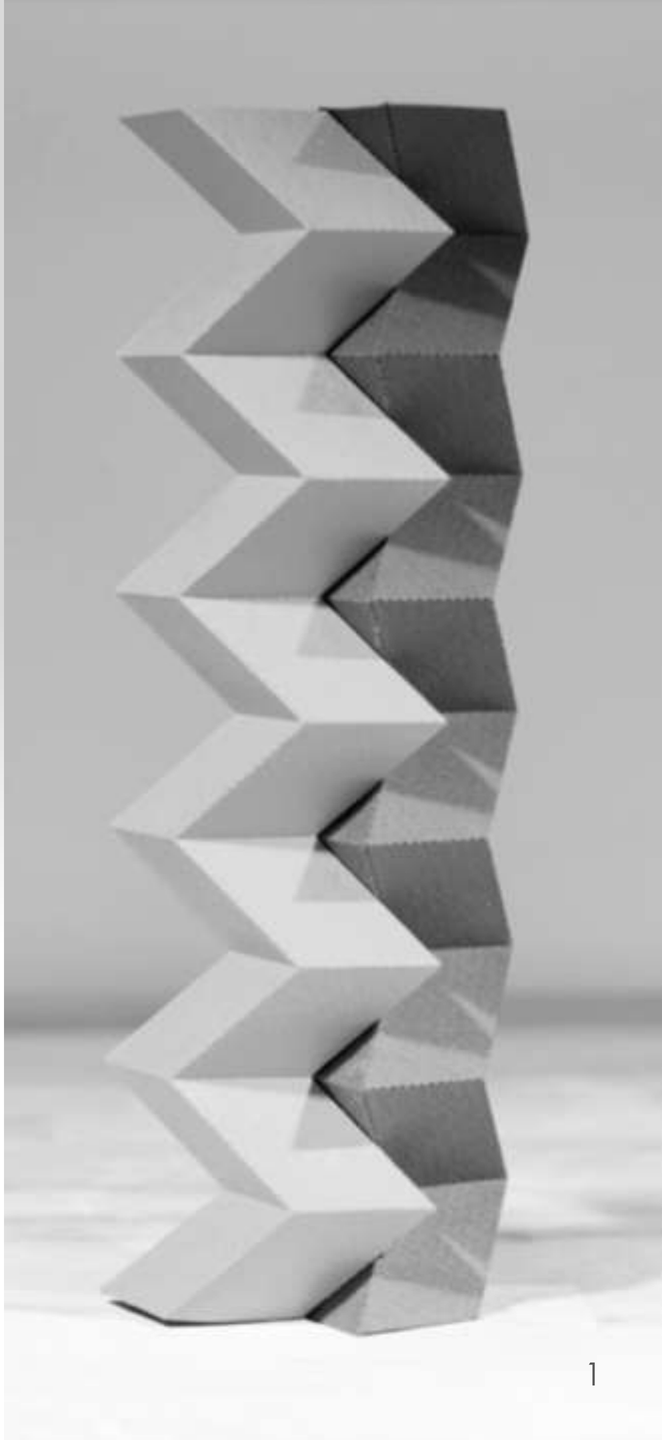
Department of Mechanical Engineering,
École polytechnique fédérale de Lausanne

February 9, 2016

Using Origami for Deployable Structures and Adaptable Metamaterials



Evgueni T. Filipov[1]

Prof. Glaucio H. Paulino[1,2]

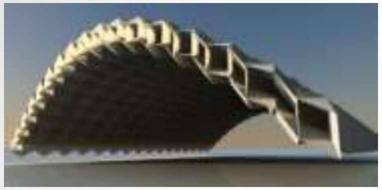
Prof. Tomohiro Tachi[3]

1. University of Illinois at Urbana Champaign

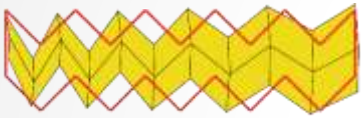
2. Georgia Institute of Technology

3. The University of Tokyo

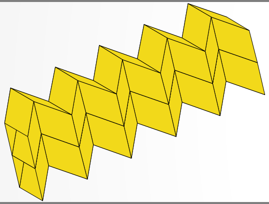
Presentation Outline



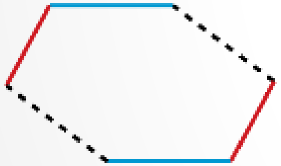
Origami in Engineering



Structural Analysis of Origami

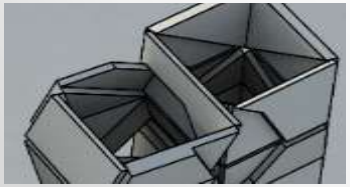


Coupling of Origami Tubes



Cross-Section and Other Variations

Cellular Assemblages



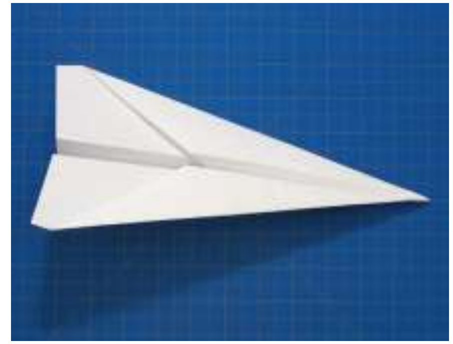
Future Research Plans

Origami as Art

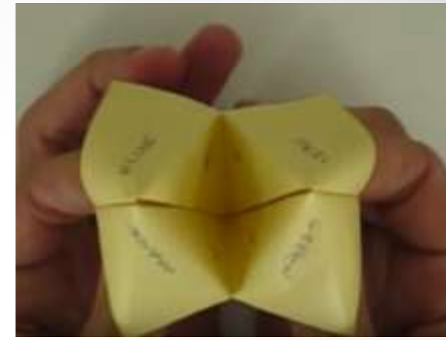
Orchfini by E. Joisel
www.ericjoisel.com/gallery.html

Elk 358 by R. Lang
http://www.langorigami.com/

Origami as Entertainment



Paper Airplane
http://www.foldnfly.com/



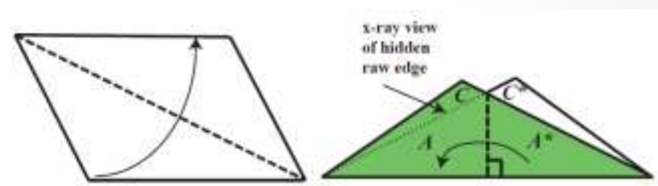
Origami Fortune Teller
www.origami-instructions.com/

Origami as Fashion

Origami Dress
http://www.julewaibel.com/

Origami Bracelet
www.tinederuysser.com/

Origami in Education



Geometry - A. Tubis *6OSME* 2014

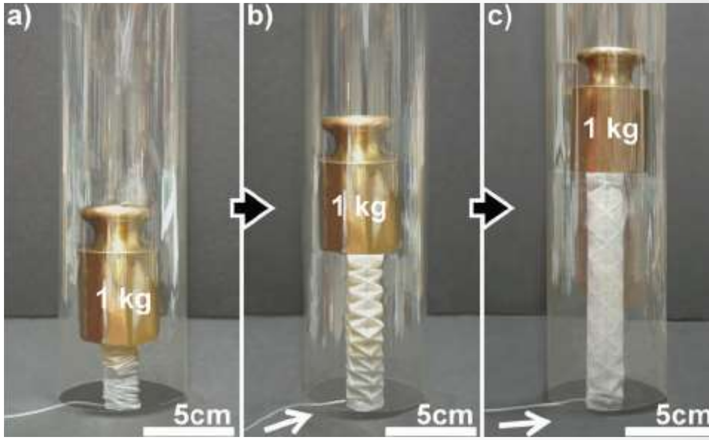
Gaussian Curvature - T. Hull 2012

Engineering Applications of Origami

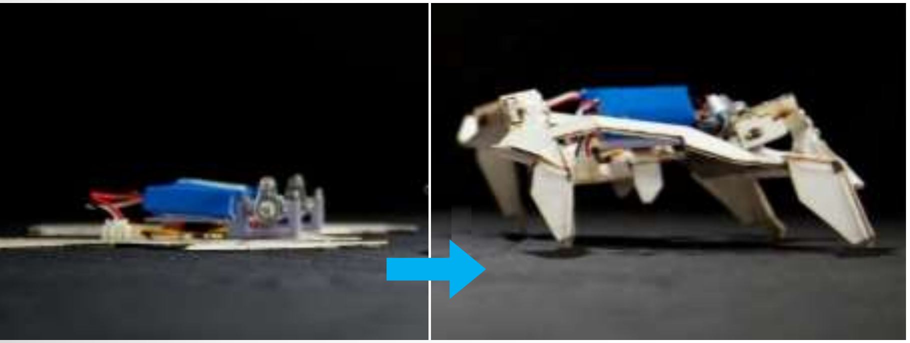
- Compact
- Deployable
- Pre-Fabricated
- Self-Assembly
- Tunable
- Multi-Functional
- Adaptable

Kiefer Technic Showroom

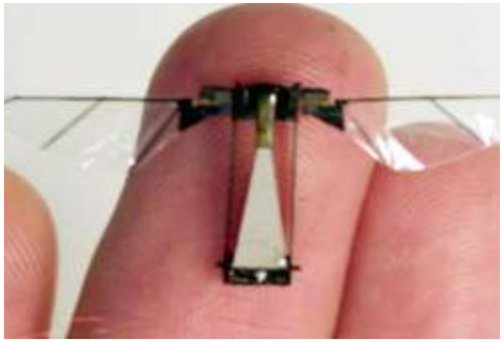
ISS – NASA 2011



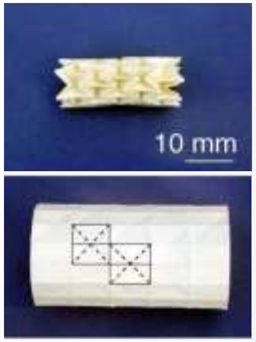
Martinez et al. (2012)



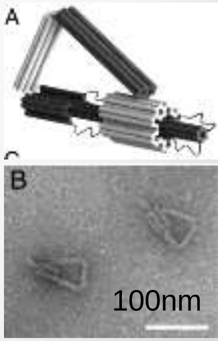
Felton et al. (2014)



Wood (2008)

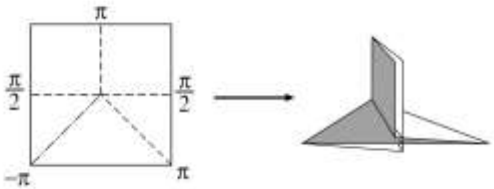


Kuribayashi et al. (2006)



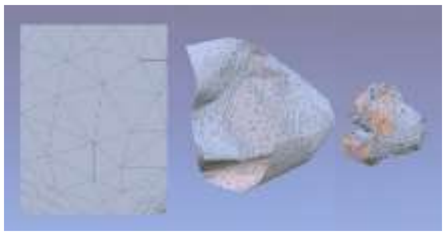
Marras et al. (2015)

Theory and Analysis

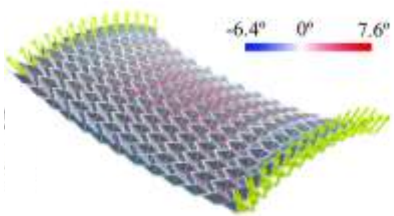


Belcastro and Hull (2013)

Demaine and Demaine (2012)

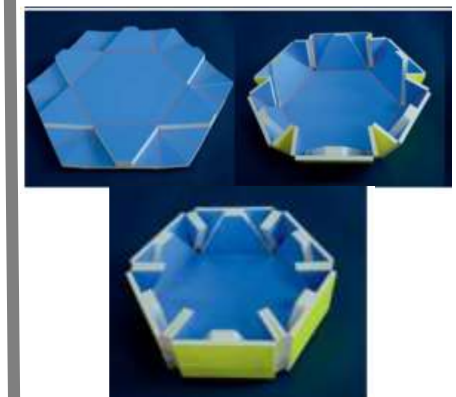


Narain et al. (2013)

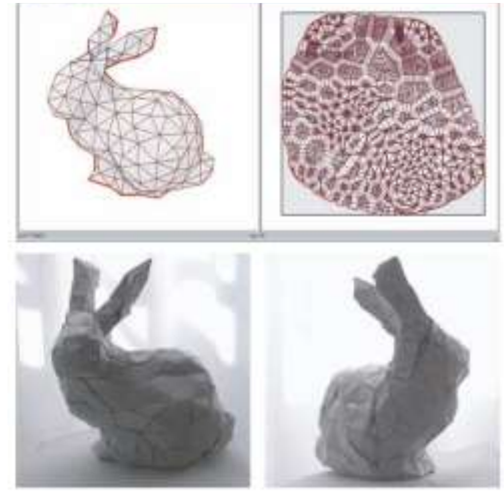


Wei et al. (2013)

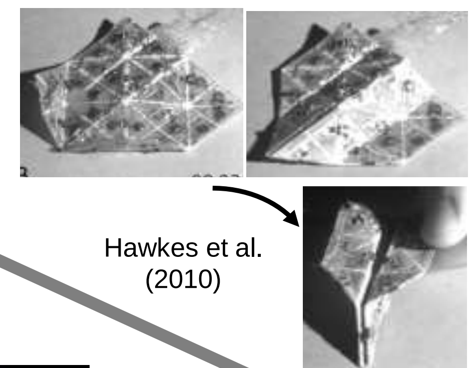
System Design



Chen et al. (2015)



Tachi (2010)



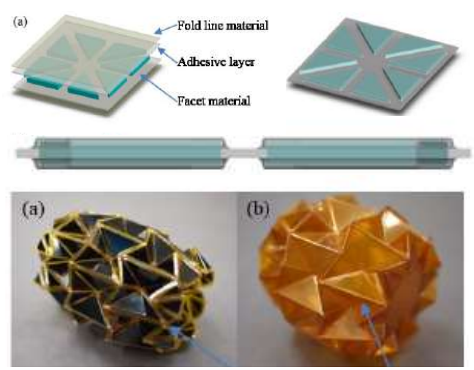
Hawkes et al. (2010)

Origami Engineering

Materials & Fabrication

Black LAB Architects (2014)

C. Hoberman (2012)



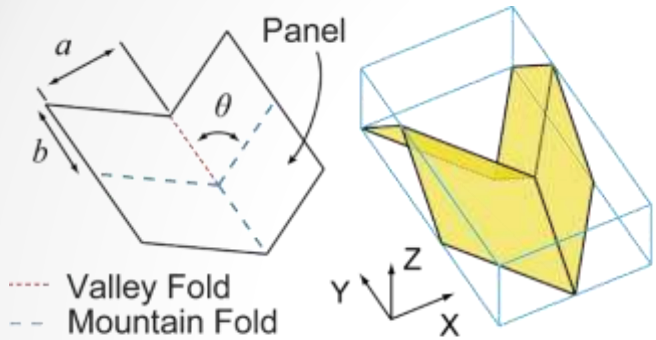
Lee et al. (2013)

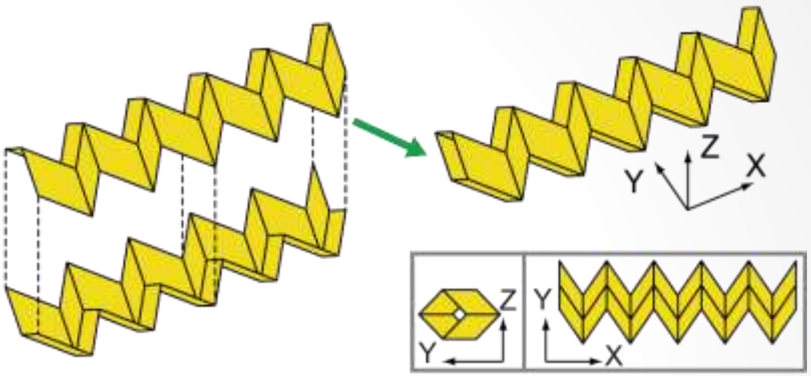
Living hinge

Graphene sheet

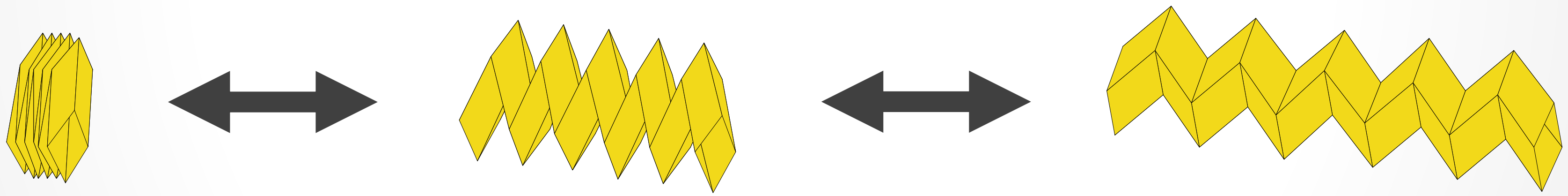
Miura-ori Tube Origami

Miura-ori → Tube





Kinematic “rigid” folding

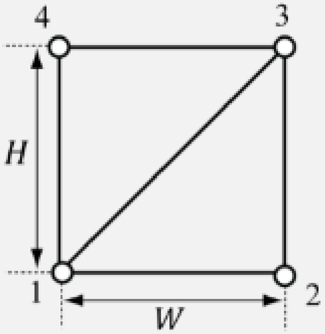


Elastic deformations

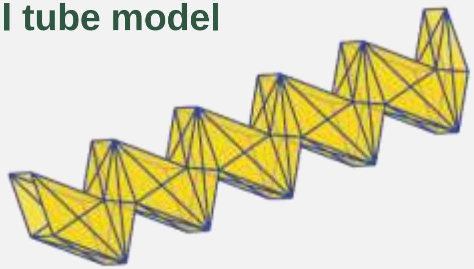
Elastic Modeling for Origami

S Panel Shear & Stretching

Model with bars elements



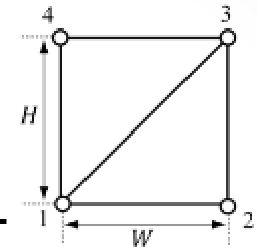
Full tube model



Benefits of the *Bar and Hinge* Model

Schenk and Guest (2010)

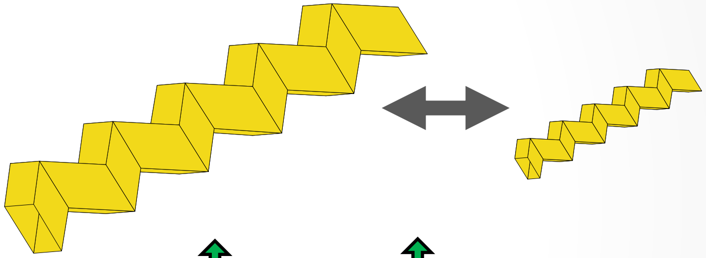
1. **Simplicity in the design and use**
2. **Insight on stiffness properties**

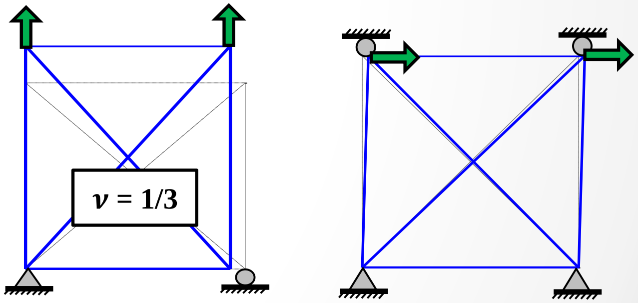
1


2


Filipov, Tachi, Paulino (2016) *Origami 6*

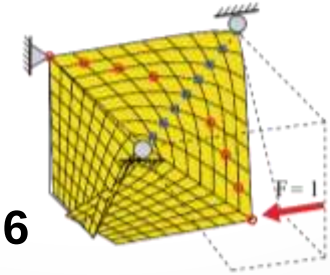
3. **Scalability**
4. **Model isotropy**
5. **Material properties**
   - Thickness t
   - Poisson's Ratio ν
   - Young's modulus E
   - Density ρ

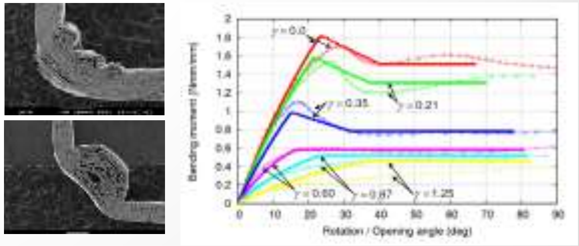
3


4, 5


Filipov, Liu, Tachi, Paulino (2016) In Preparation

6. **Large displacements**
7. **Elasto-plastic folds**

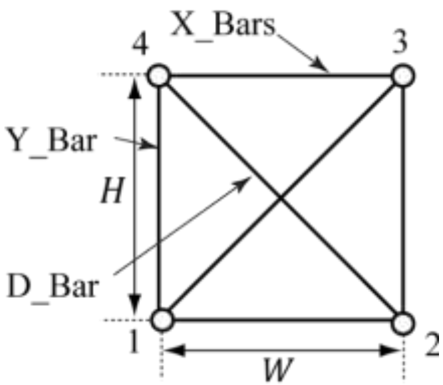
6


7


Nagasawa et al. (2003)

S Bar Model for Panel Shear & Stretching

Bar stiffness definitions



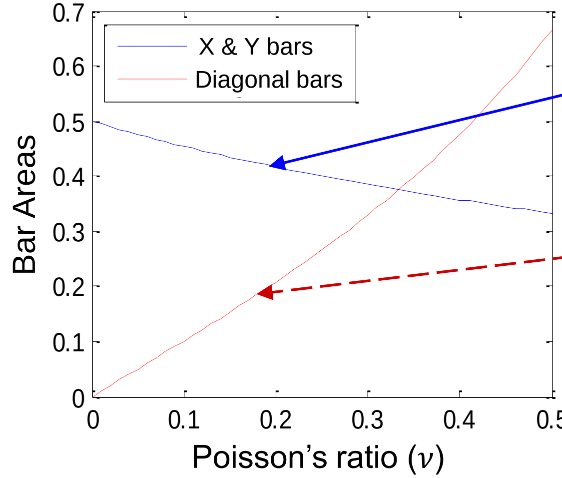
$$K_S = \frac{EA_{Bars}}{L}$$

Young's modulus: E

Thickness: t

Poisson's ratio: ν

Bar areas:

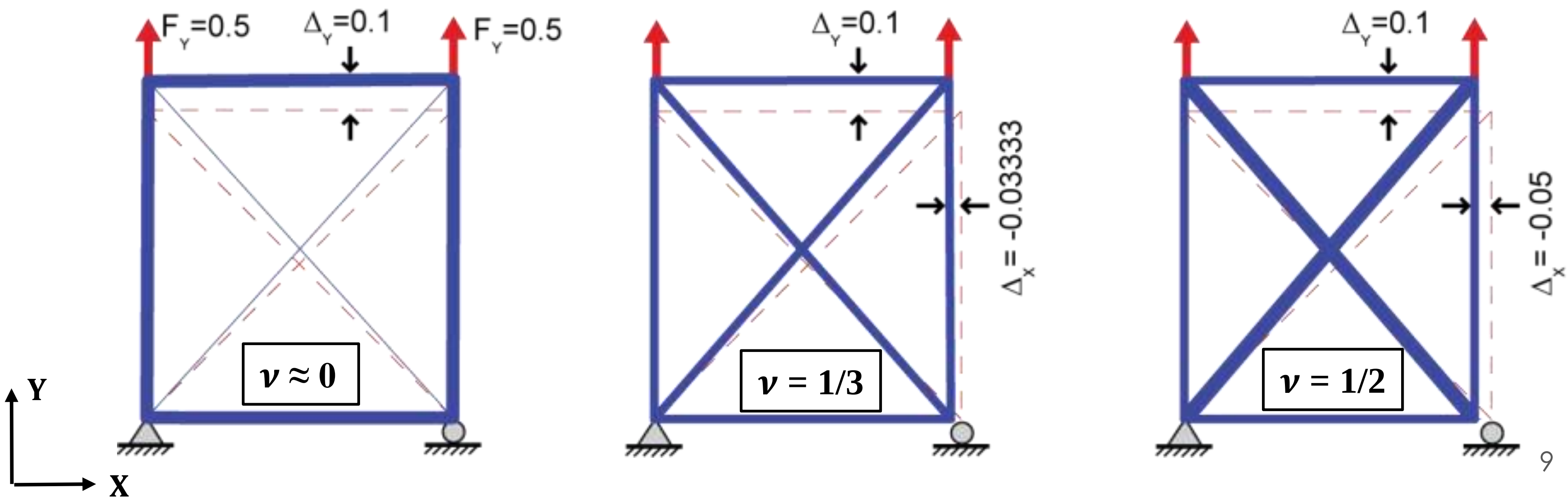


$$A_Y = t\frac{W^2 - \nu H^2}{2W(1-\nu^2)}$$

$$A_D = t\frac{\nu(H^2 - W^2)^{3/2}}{2HW\,(1-\nu^2)}$$

Poisson effect

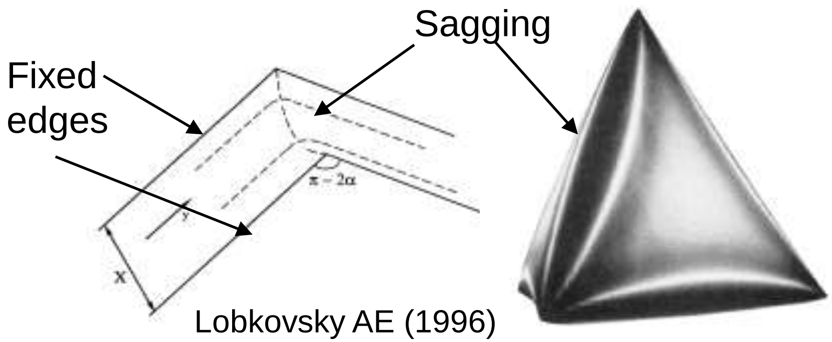
$$\varepsilon_x = \nu * \varepsilon_y$$



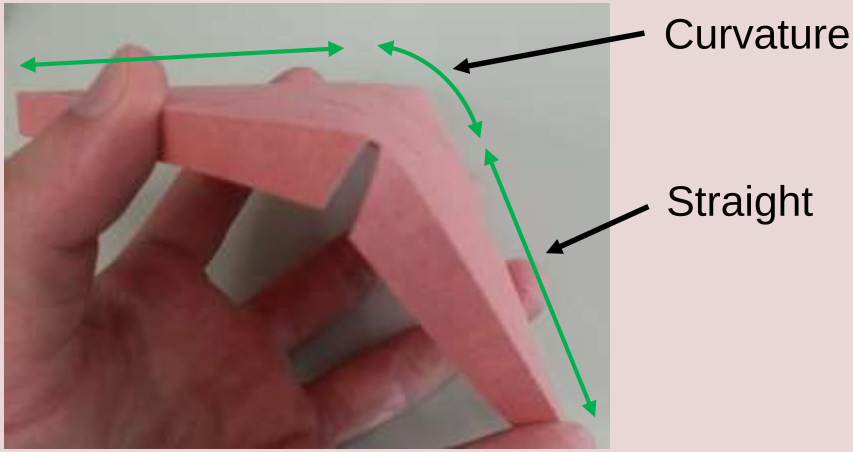
B Bending Thin Sheet with Restricted Edges

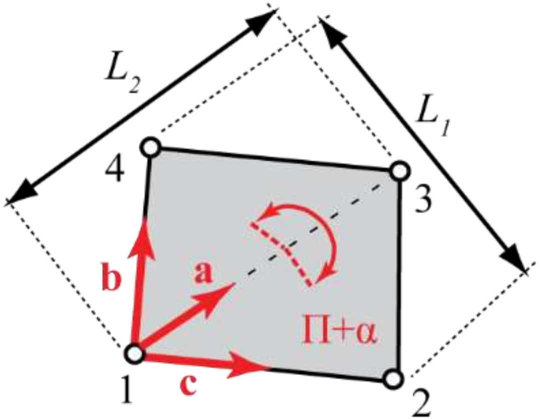
Constant curvature bending

- Bending is localized in the center of span
- Stiffness is higher than with constant curvature bending



Bending restricted at edges

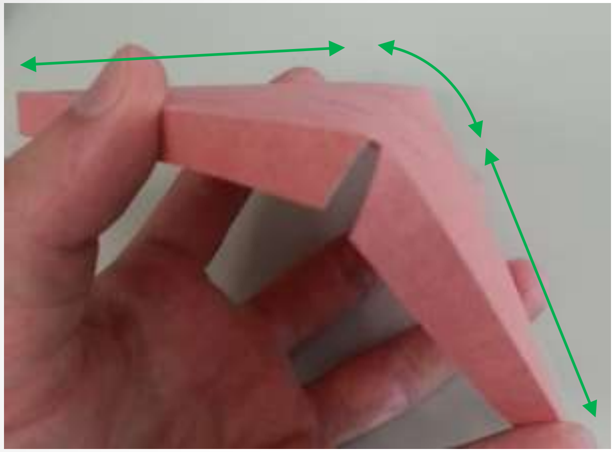




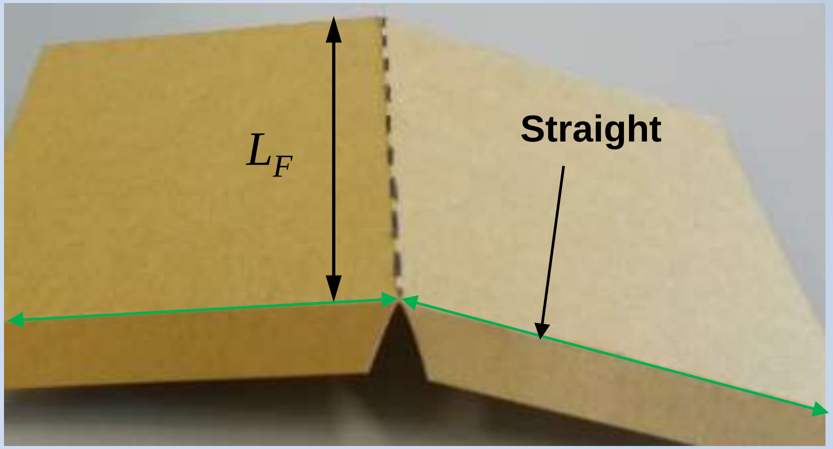
$$K_B = C_B \frac{Et^3}{12(1-\nu^2)}\left(\frac{L_2}{t}\right)^{1/3}$$

F Modeling Prescribed Fold Lines

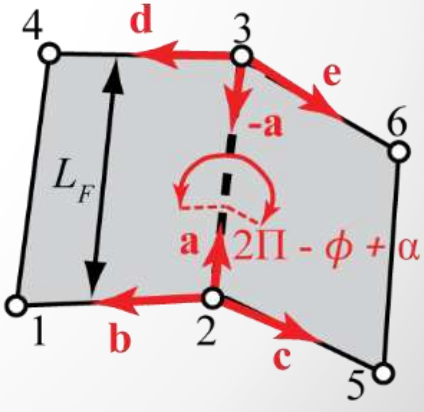
Bending restricted at edges



Bending at prescribed fold line

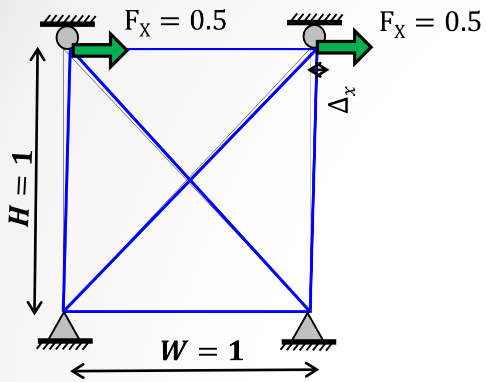


- R_{FP} = 1/10 relates panel to fold stiffness
- Stiffness scales with L_F
- R_{FP} may depend on physical and material properties



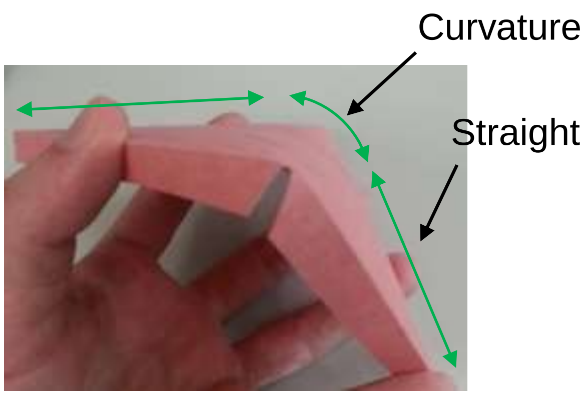
$$K_F = R_{FP} C_B \frac{L_F}{2} \frac{E t^3}{12(1-\nu^2)} \left(\frac{1}{t}\right)^{1/3}$$

S Panel Shear & Stretching



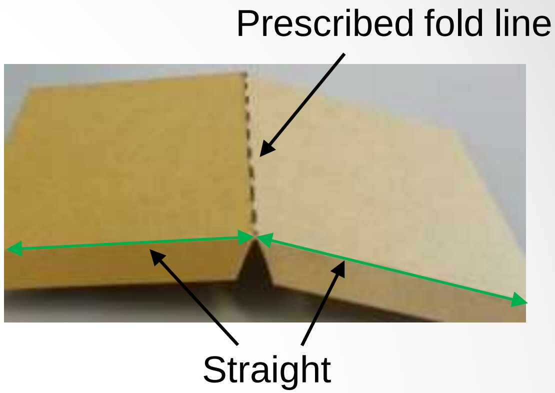
$$K_S = \frac{E A_{Bars}}{L}$$

B Panel Bending



$$K_B = C_B \frac{E t^3}{12(1-\nu^2)} \left(\frac{L_2}{t}\right)^{\frac{1}{3}}$$

F Fold Bending



$$K_F = R_{FP} C_B \frac{L_F}{2} \frac{E t^3}{12(1-\nu^2)} \left(\frac{1}{t}\right)^{\frac{1}{3}}$$

- Scalability
- Model isotropy
- Material properties t, E, and ν

$$\mathbf{K} = \begin{bmatrix} \mathbf{C} \\ \mathbf{J}_B \\ \mathbf{J}_F \end{bmatrix}^T \begin{bmatrix} \mathbf{K}_S & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_B & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K}_F \end{bmatrix} \begin{bmatrix} \mathbf{C} \\ \mathbf{J}_B \\ \mathbf{J}_F \end{bmatrix}$$

Filipov E, Tachi T, and Paulino GH (2016) *Origami 6*

Filipov E, Liu K, Tachi T, and Paulino GH (2016) In Preparation

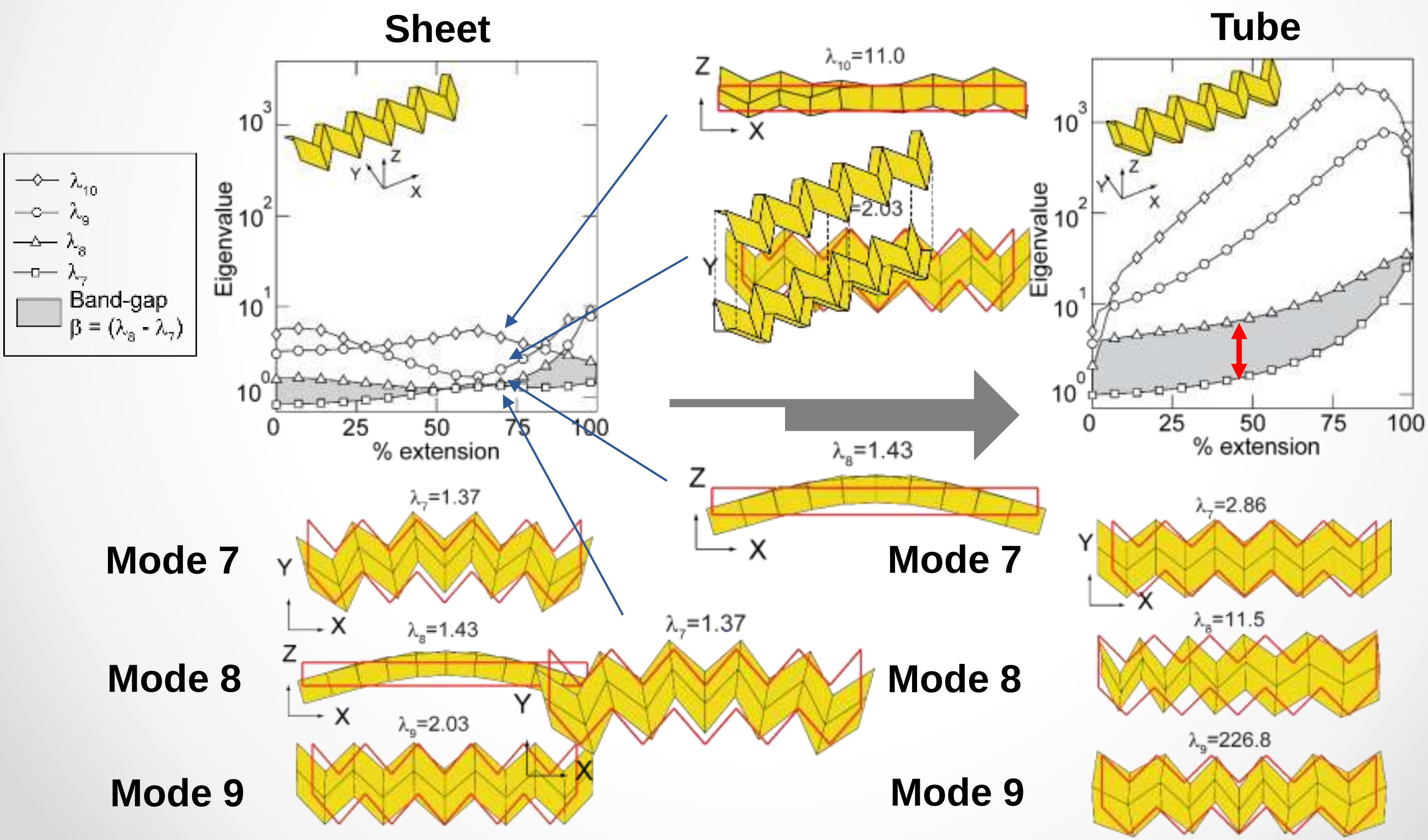
Eigenvalue Analyses

K = Stiffness matrix

M = Mass matrix

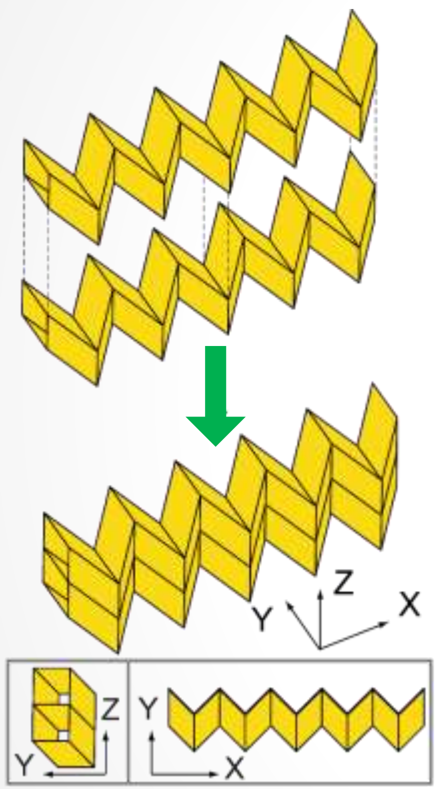
$$\mathbf{K}\mathbf{v}_i = \lambda_i \mathbf{M}\mathbf{v}_i \qquad i = 1, \dots, N_{dof}$$

Eigenvalue Eigen-mode

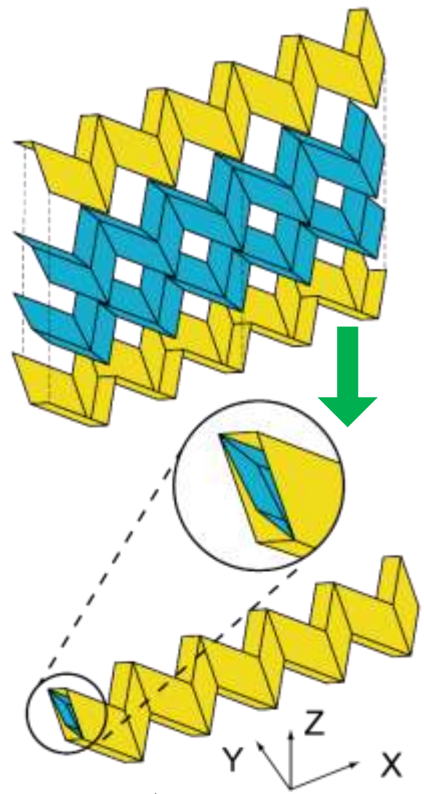


Tube Assemblages

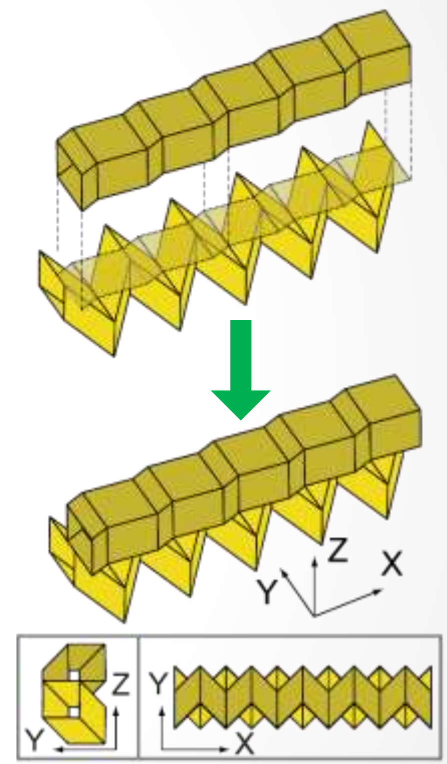
Aligned coupling

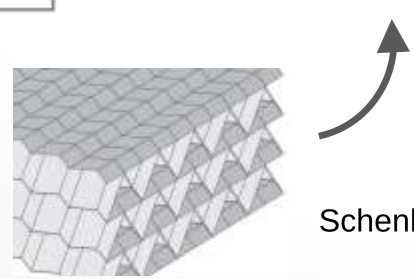


Internal coupling

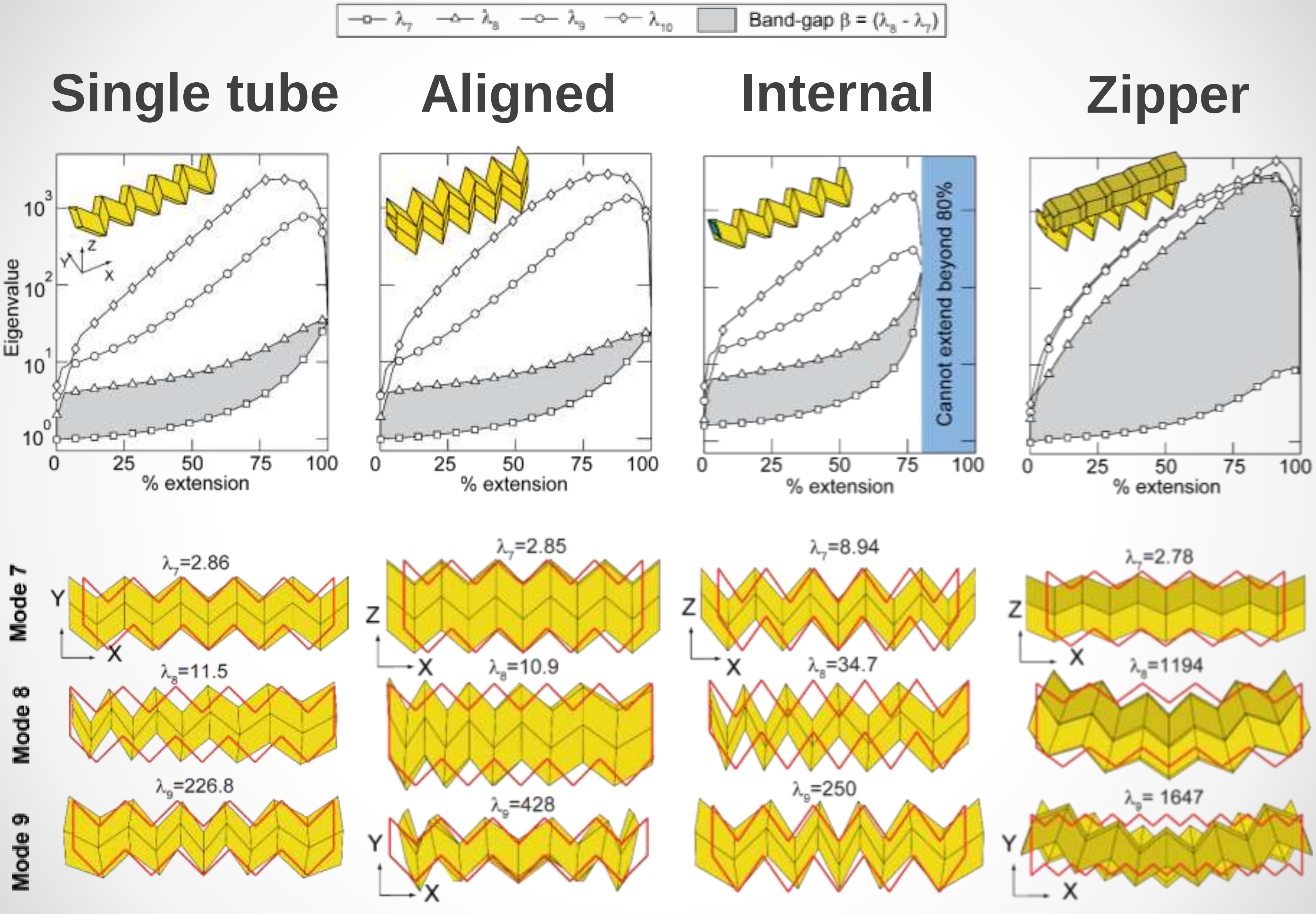


Zipper coupling





Schenk and Guest (2013)

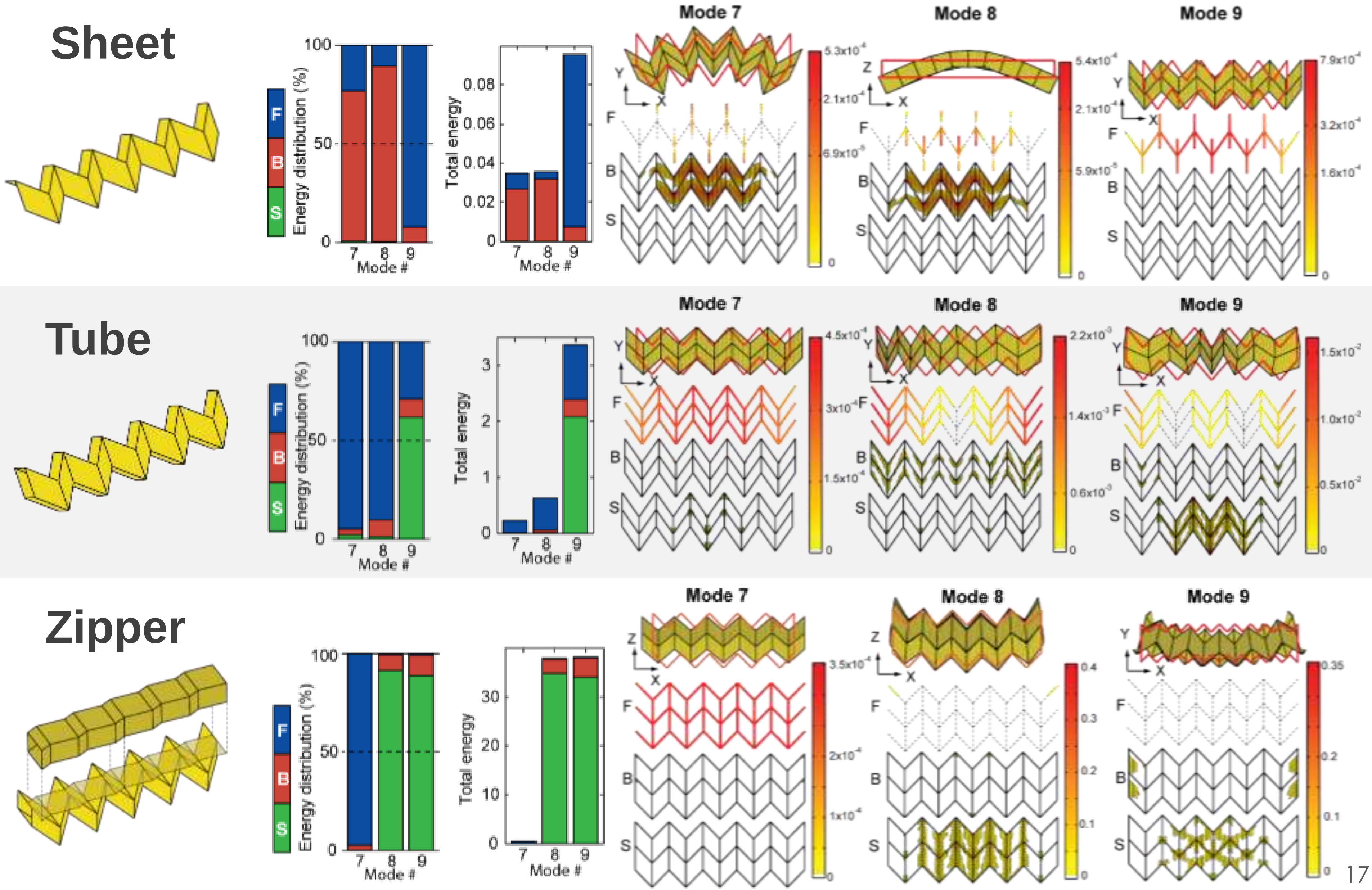


λ7 λ8 λ9 λ10 Band-gap β = (λ8 - λ7)
Single tube
Aligned
Internal
Zipper
Eigenvalue
% extension
Cannot extend beyond 80%
Mode 7
Mode 8
Mode 9
λ7=2.86
λ7=2.85
λ7=8.94
λ7=2.78
λ8=11.5
λ8=10.9
λ8=34.7
λ8=1194
λ9=226.8
λ9=428
λ9=250
λ9= 1647

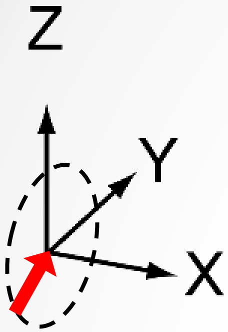
Filipov EF, Tachi T, and Paulino GH (2015) *PNAS* Vol. 112, No. 40

Commentary by:
Reis PM, López Jiménez F, and Marthelot J

Energy Distribution

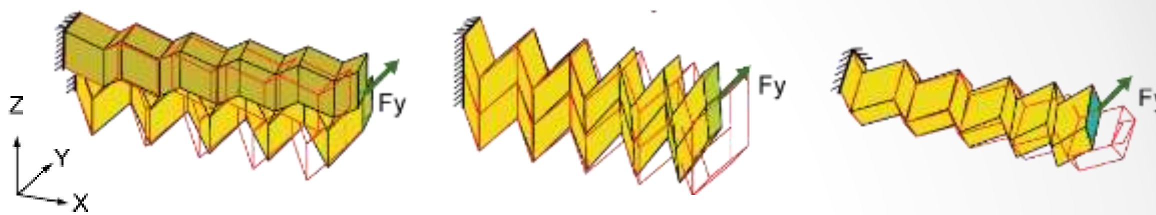


Stiffness in Y-Z Plane

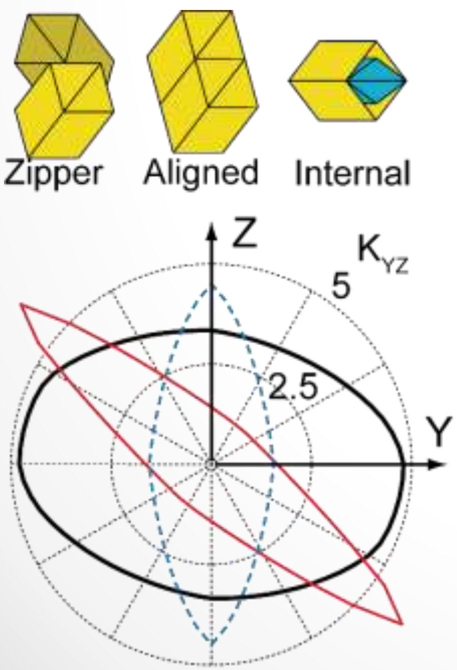


Load applied perpendicular to X axis

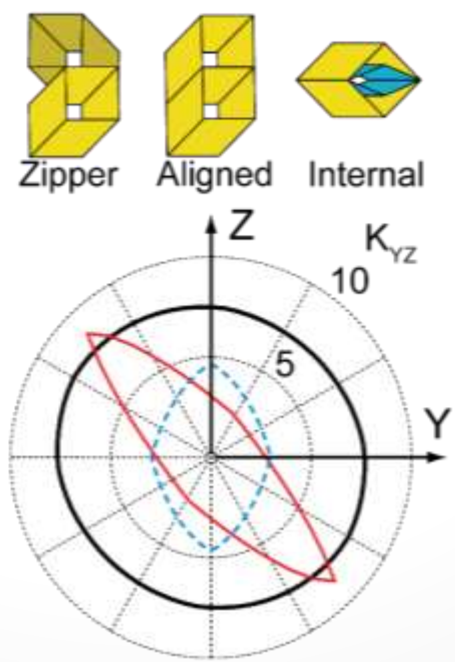
Zipper Aligned Internal



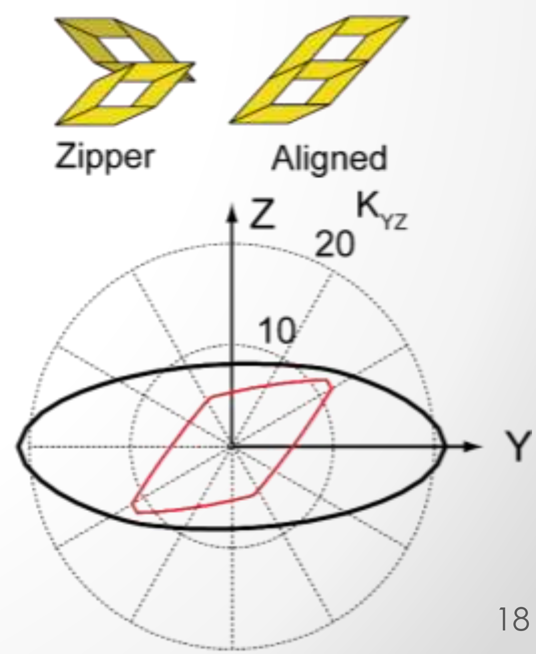
At 40% extension



At 70% extension



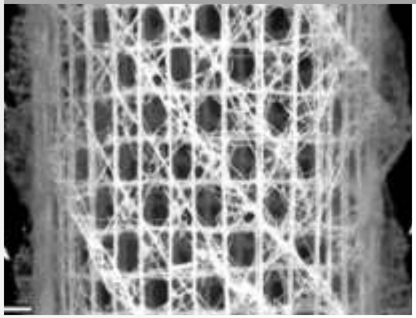
At 95% extension



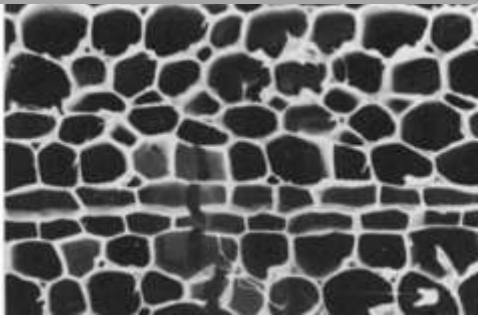
Zipper
Aligned
Internal

Cellular Assemblages as Metamaterials

Nature

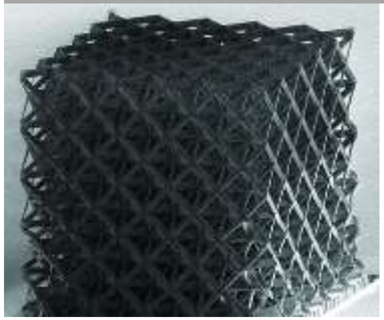


Aizenberg et al. (2005)

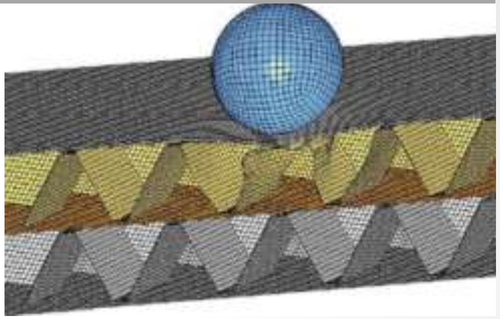


Ashby et al. (1985)

Engineering



Meza et al. (2014)



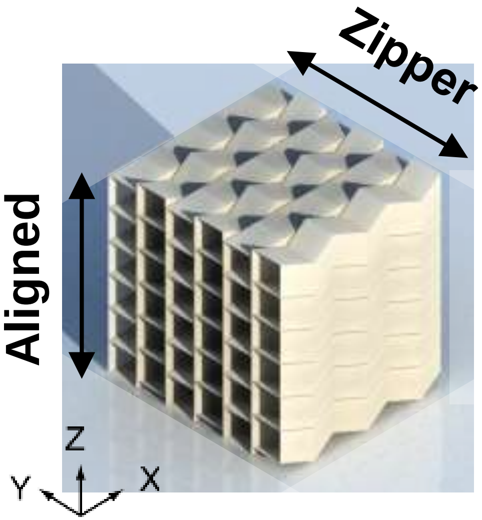
Heimbs (2013)

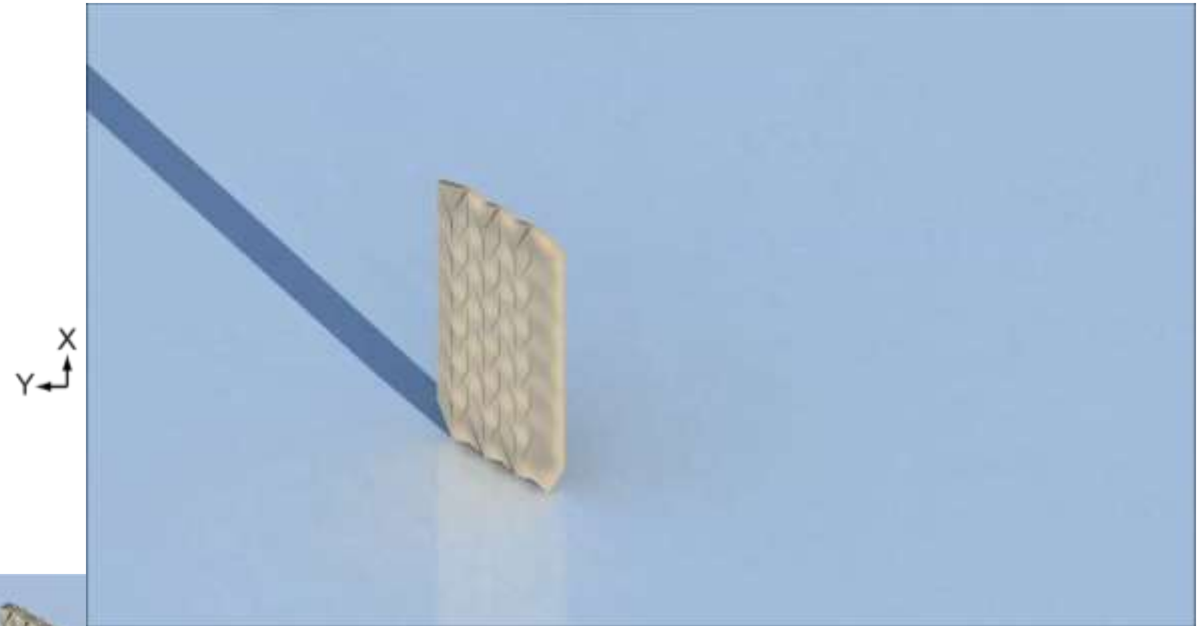
- Hierarchical properties (e.g. lattice systems)
- High stiffness to weight ratios
- Novel properties (auxetics or asymmetry)

With origami:

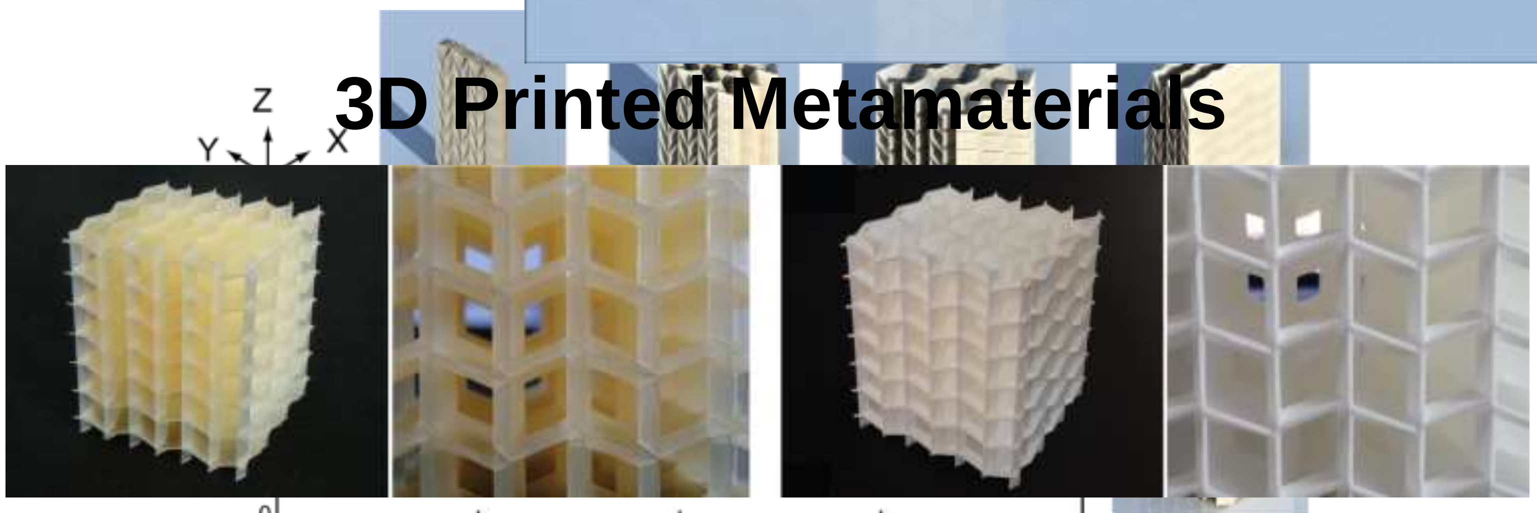
- Self-assembly
- Deployable
- Tunable characteristics

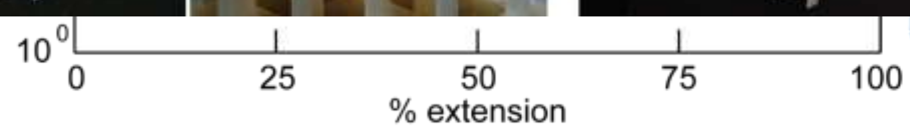
Zipper + Aligned Assemblage



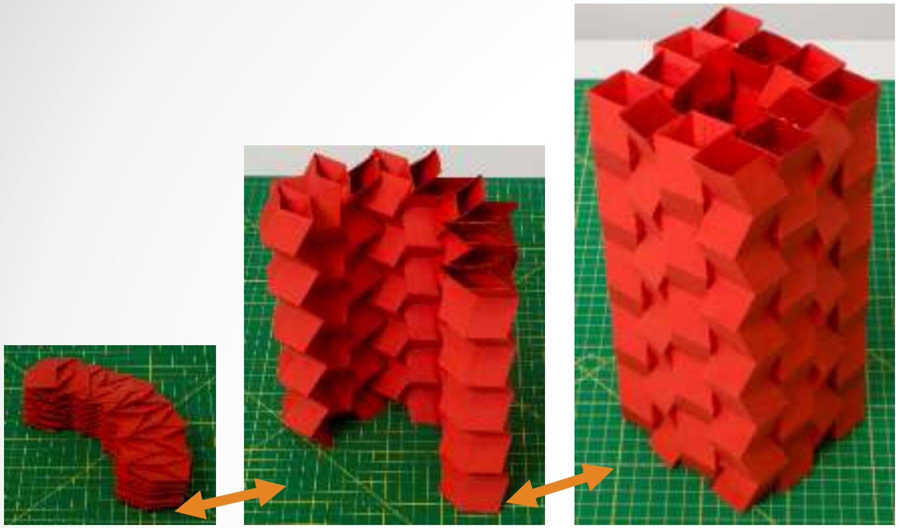


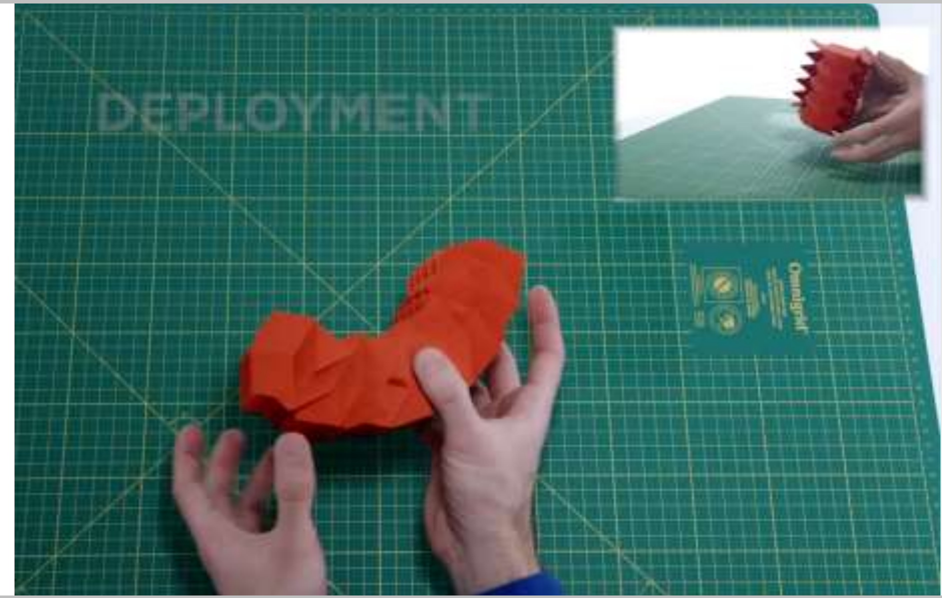
3D Printed Metamaterials



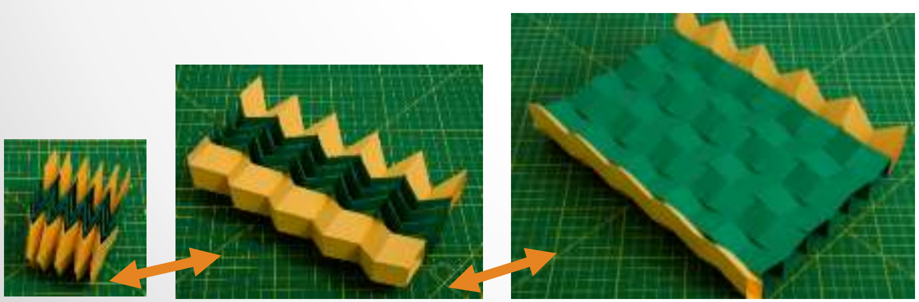


Self-Interlocking Structure



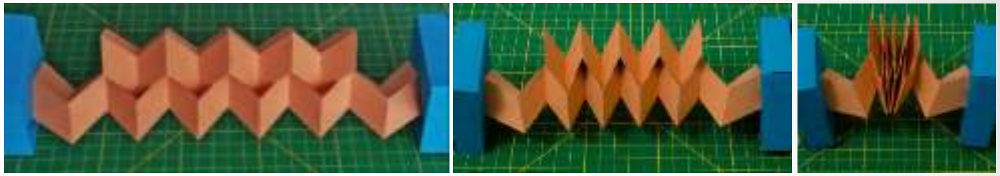


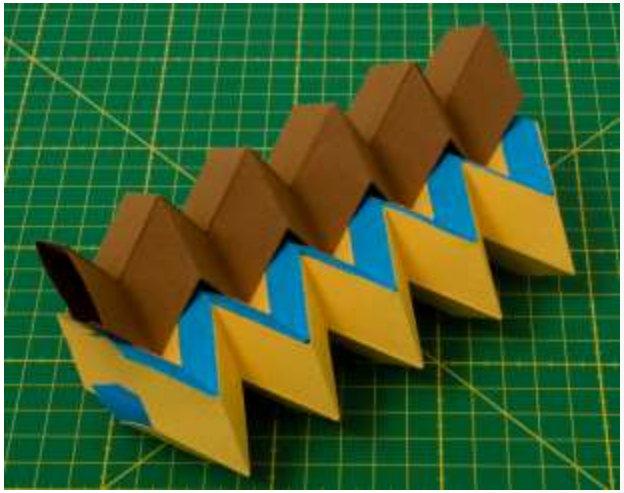
Bridge Structure

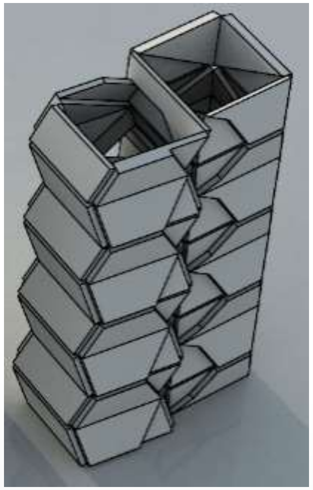


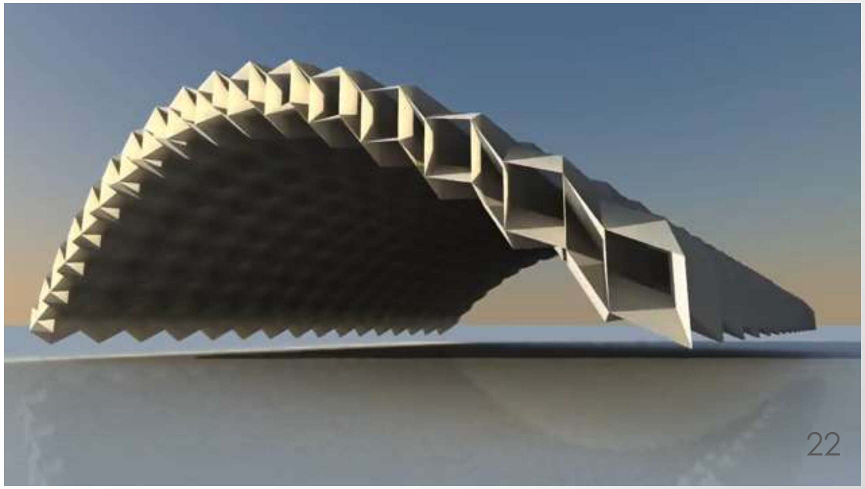
Extensions and Future of Zipper Tubes

- **Localized adaptations**
- **Geometric variations**
- **Tailored applications at different scales**
  - Thickness
  - Material
  - Fabrication
  - ….

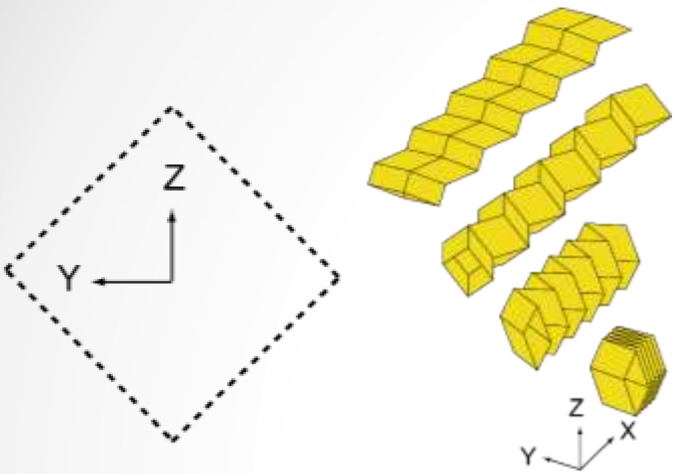




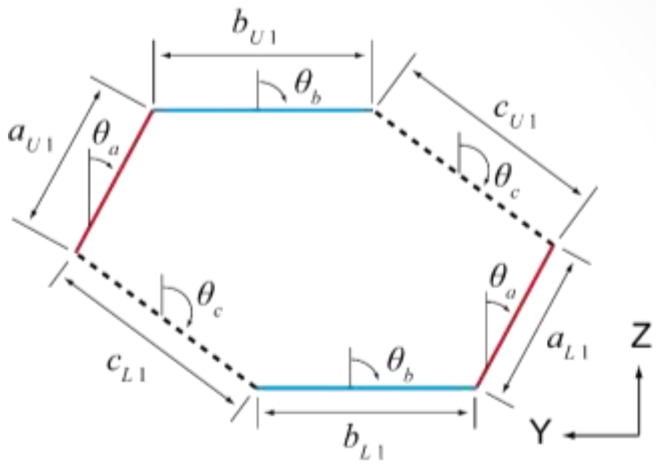


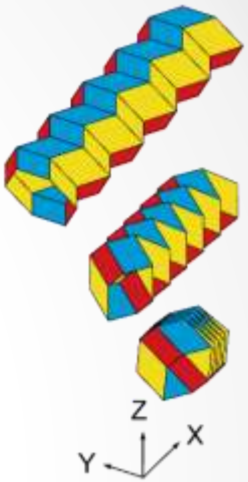


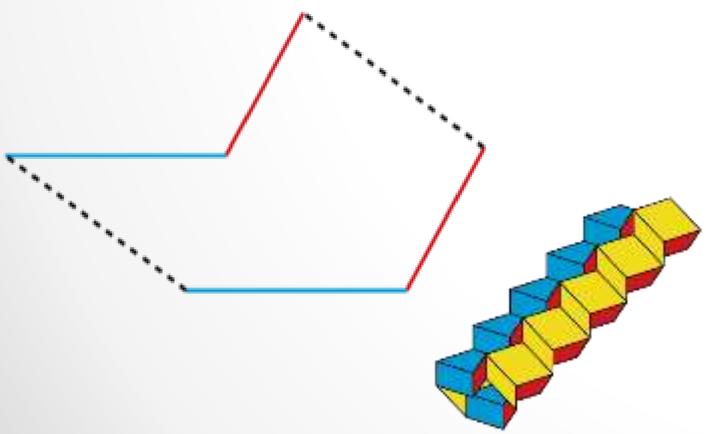
Foldable Polygonal Tubes

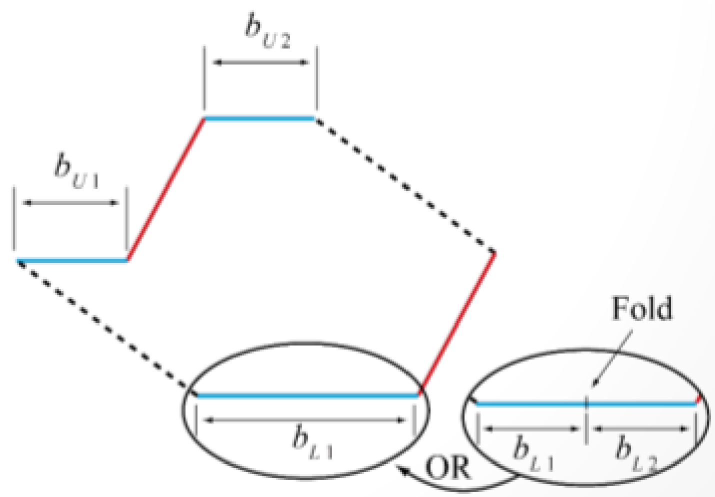


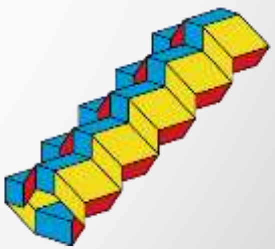
Tachi and Miura (2009)





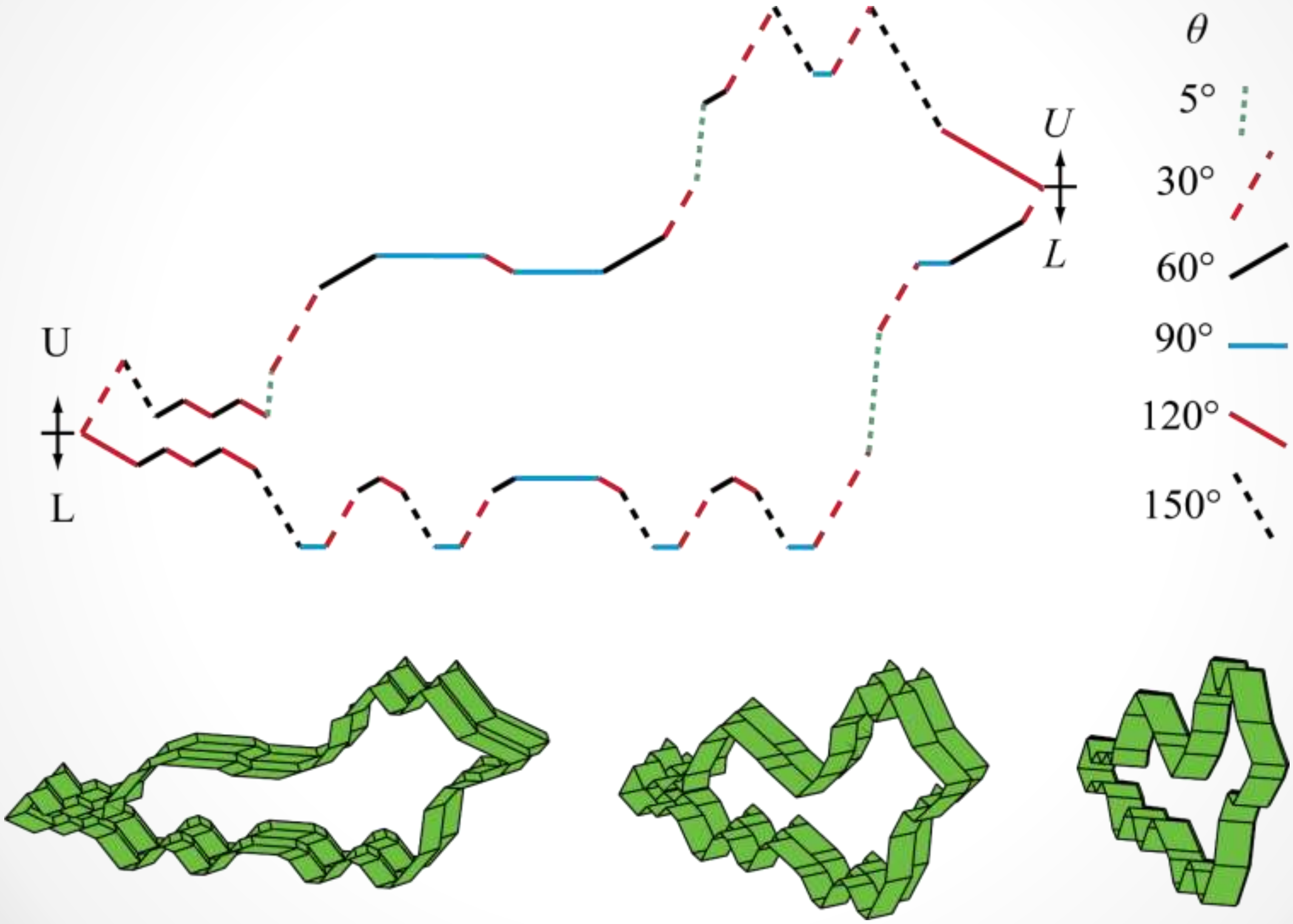






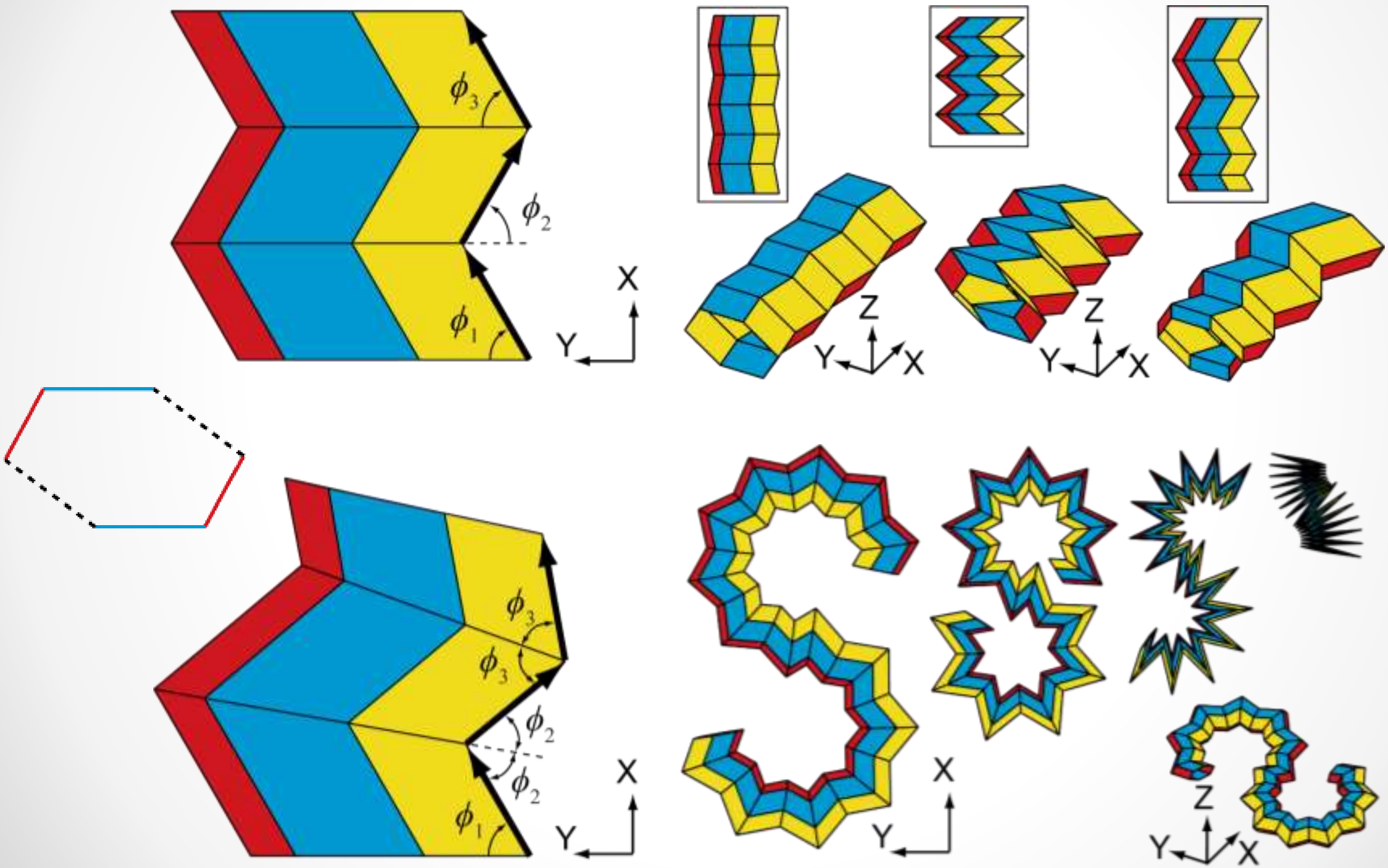
Filipov, Tachi, and Paulino (2016) *Proceeding of the Royal Society – A,* Vol. 472, No. 2185

Any Section w/ Translational Symmetry



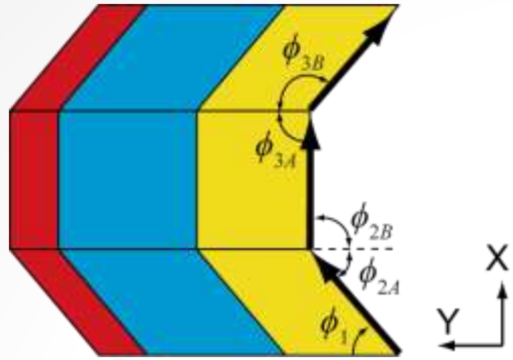
Filipov et al. (2016) *PRSA*

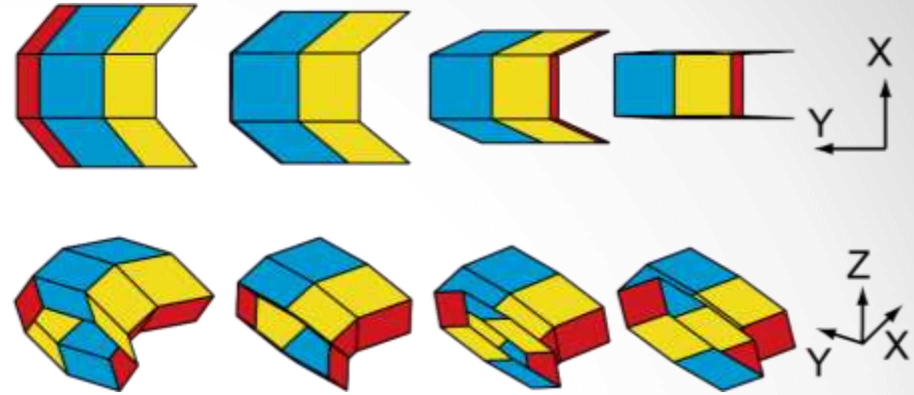
Projection Definitions

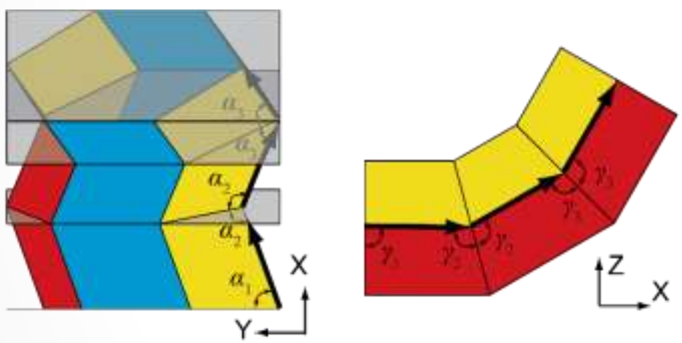


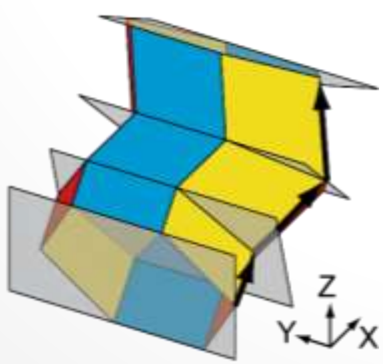
Filipov et al. (2016) *PRSA*

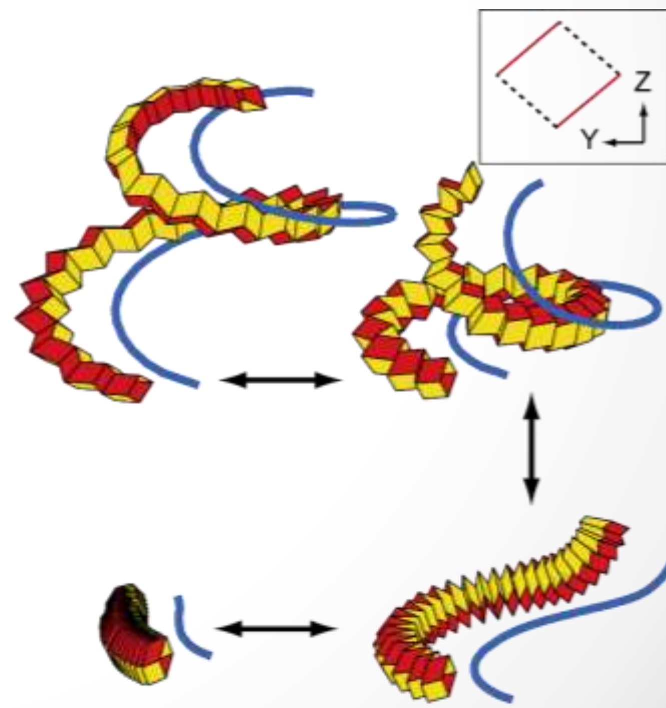
Non-symmetric X-Y





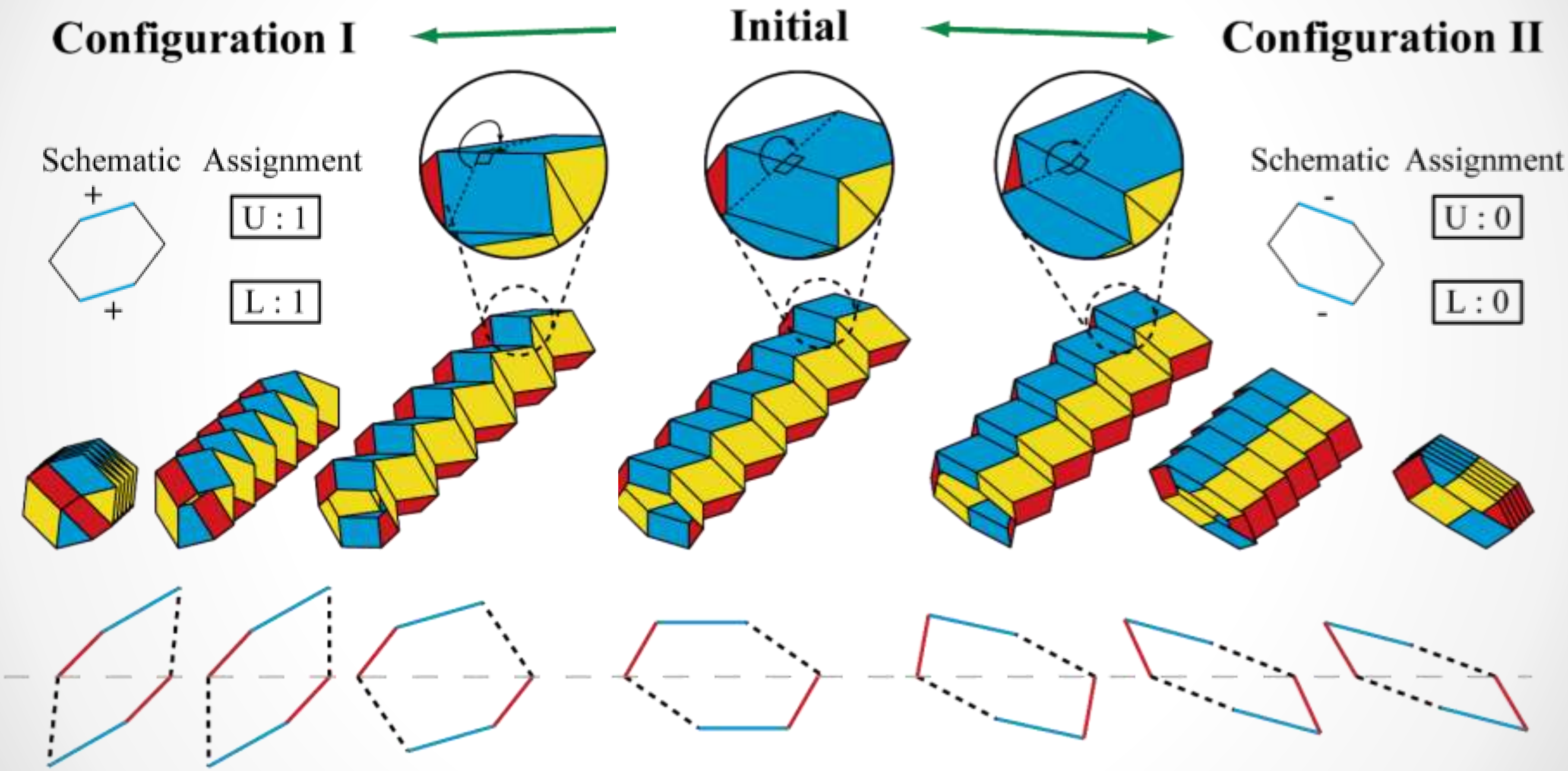






Filipov et al. (2016) *PRSA*

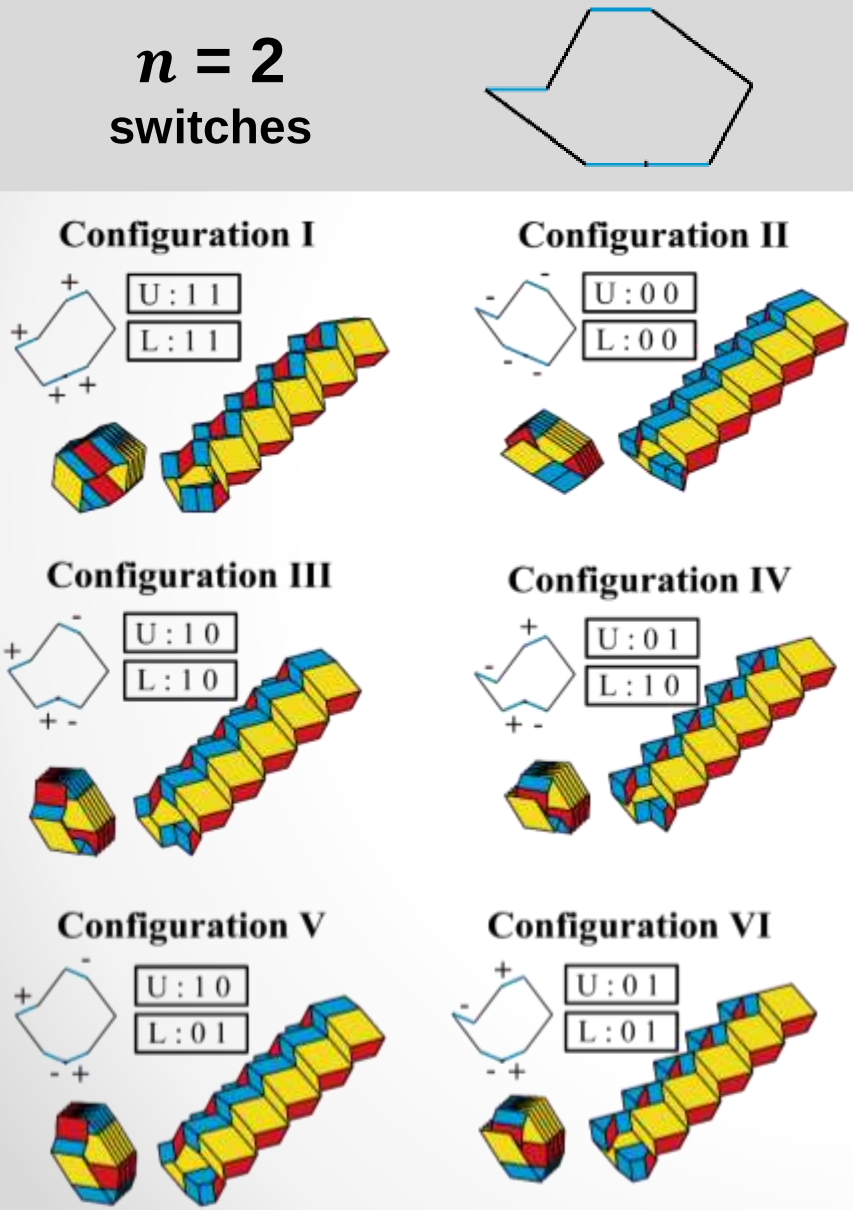
Reconfiguration

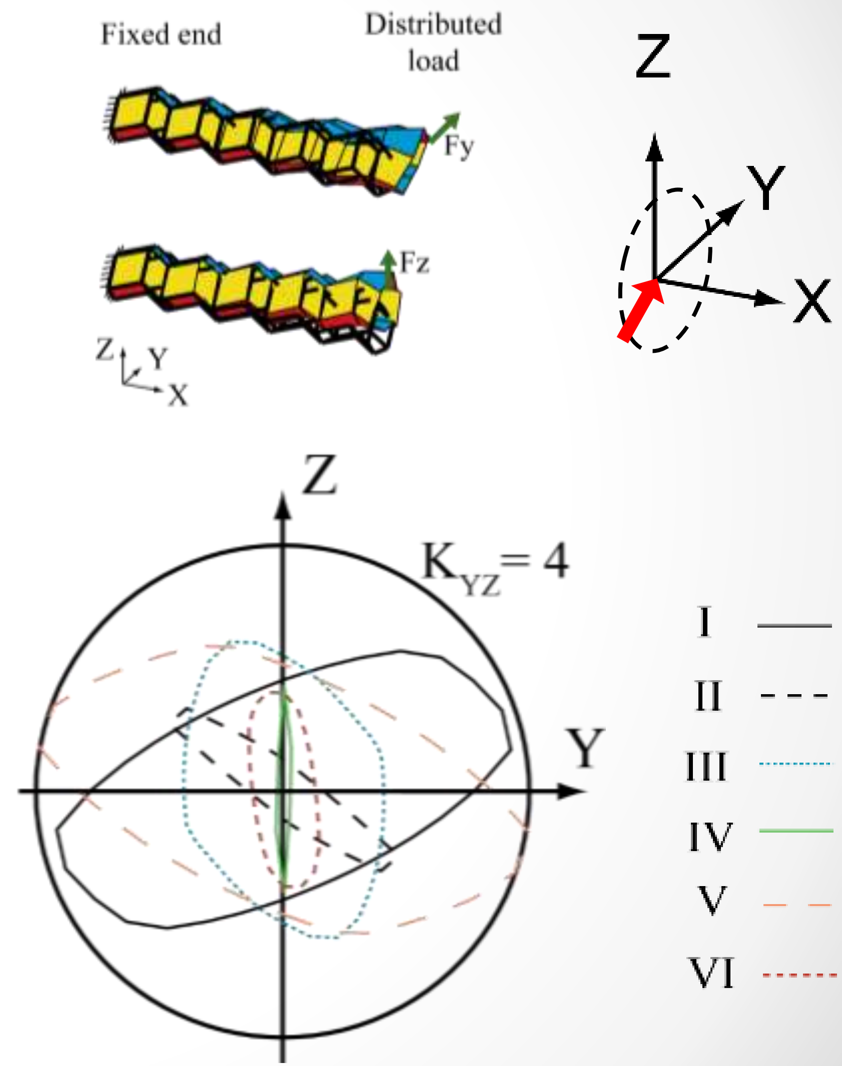


Filipov et al. (2016) *PRSA*

Reconfiguration with n = 2 Switches

n = 2 switches





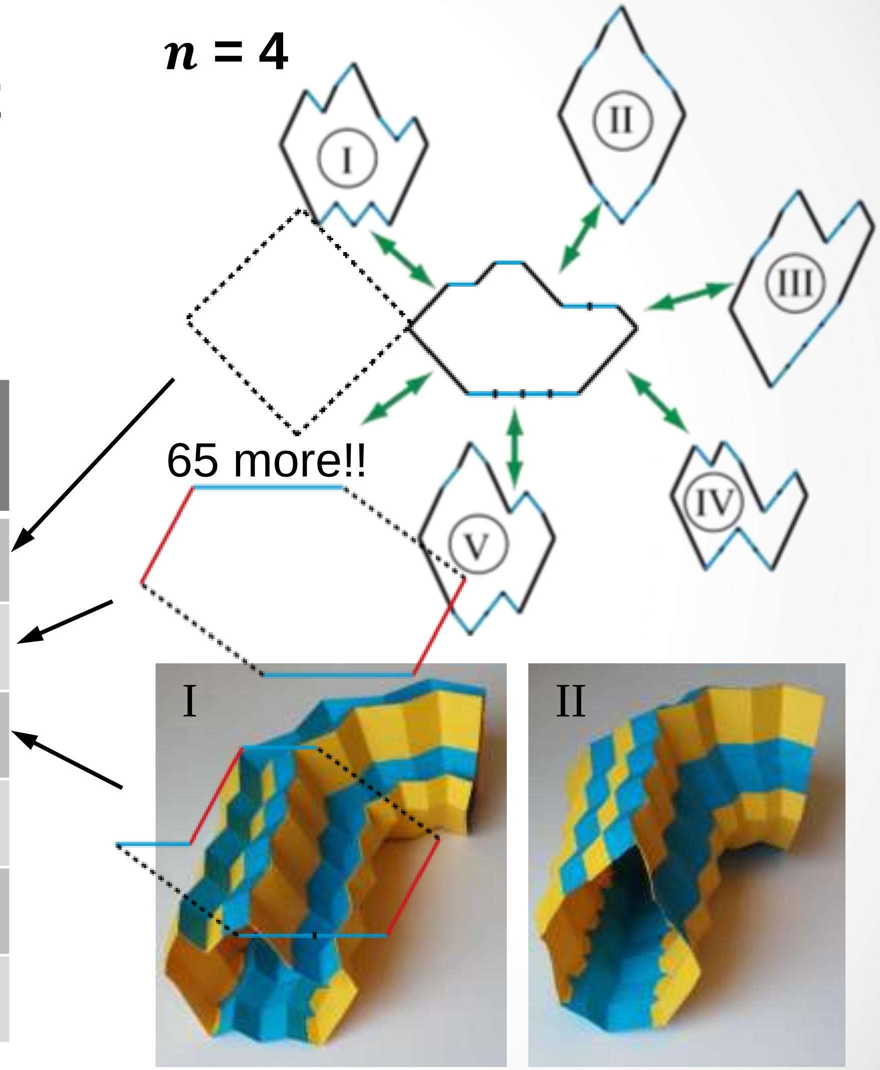
Filipov et al. (2016) *PRSA*

Reconfiguration with More Switches

Central Binomial Coefficient

$$\text{\# Configurations} = \frac{(2n)!}{(n!)^2}$$

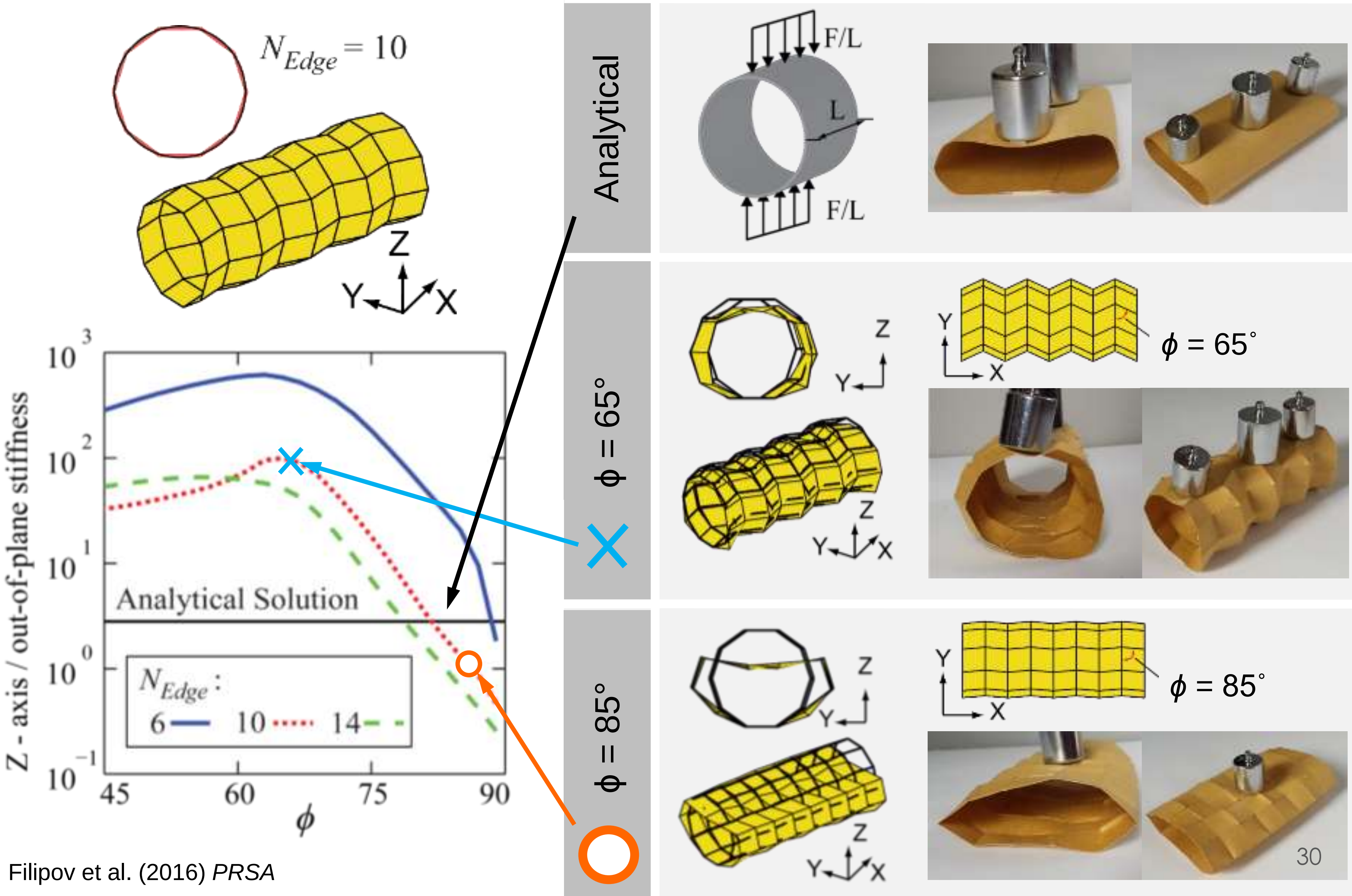
Switches	# Configurations
$n = 0$	1
$n = 1$	2
$n = 2$	6
$n = 3$	20
$n = 4$	70
$n = 5$	252



Physical model, n = 4 switches

Filipov et al. (2016) *PRSA*

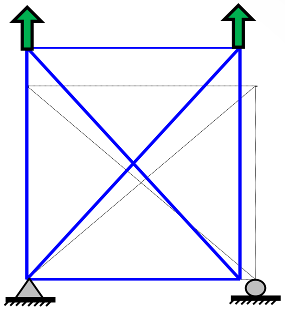
Out-of-Plane Compression of a Pipe

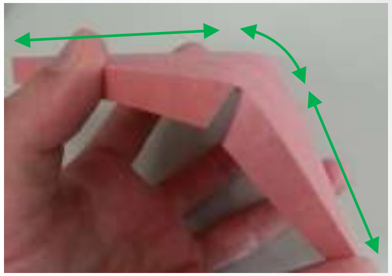


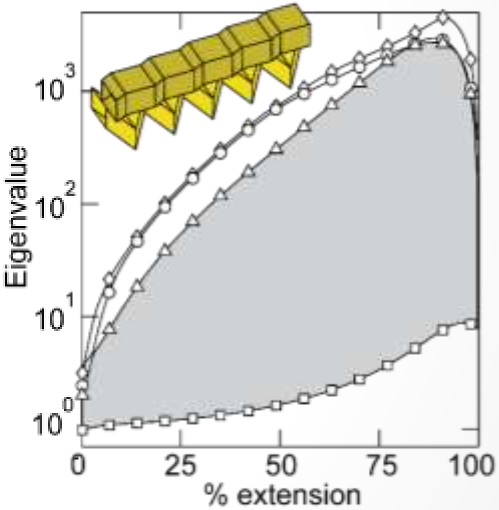
Filipov et al. (2016) *PRSA*

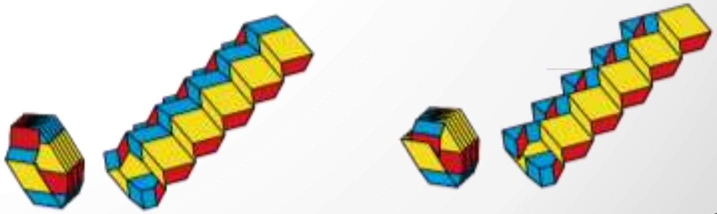
Summary of E. Filipov Ph.D. Research

- **Improved structural analysis for origami**
- **Zipper-coupled systems *engage thin sheet in shear/stretching***
- **A variety of cellular systems**
- **Polygonal cross-sections and curved profiles**
- **Structural tuning through reconfiguration**





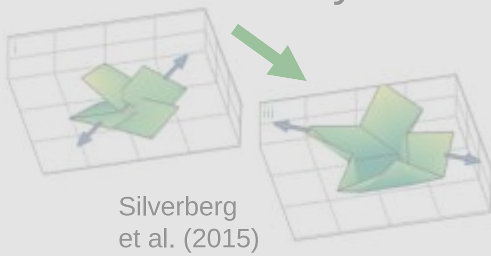




Future Research Directions

1 Analytical Methods for Folding Structures

Nonlinearity

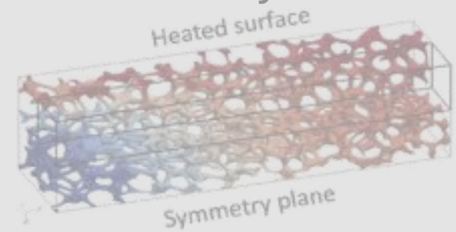


Silverberg et al. (2015)

Actuation & Assembly

Hawkes et al. (2010)

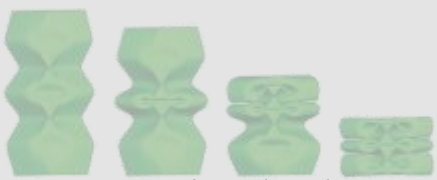
Multi-Physical



Bianchi et al. (2015)

2 Cellular Assemblages

Mechanical Function



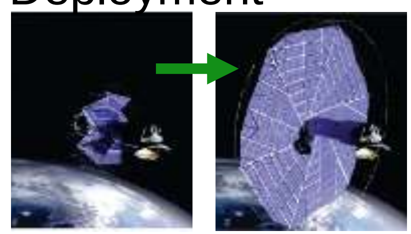
Ma and You (2014)

Tunable Systems

Design and Manufacturing

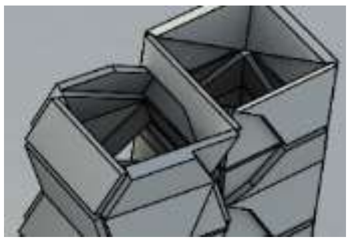
3 Hinged Structures

Deployment

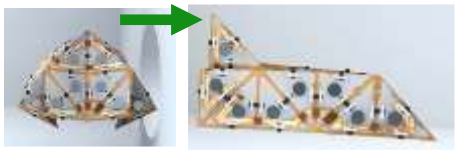


Zirbel et al. (2013)

Thickness

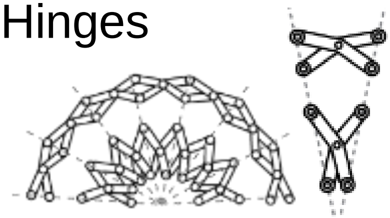


Multi-Functional



Paik et al. (2011)

Hinges



Hobermban (1990)

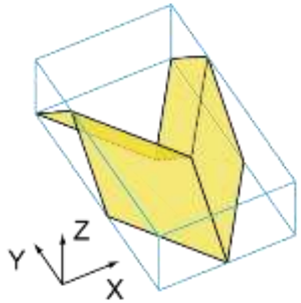
1 Analytical Methods for Folding Structures

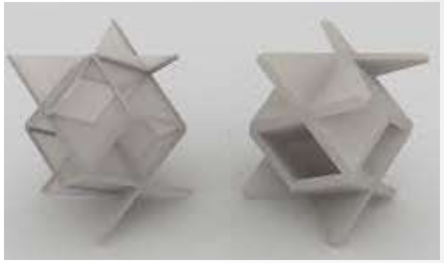
- Large Displacements
- Energy Dissipation
- Instabilities
- Nonlinearities
- Hinge Eccentricity
- Stress Concentrations

Bistable Square-Twist

Silverberg et al. (2015) *Nature Mat.*

Parametric Unit-Cell Analyses



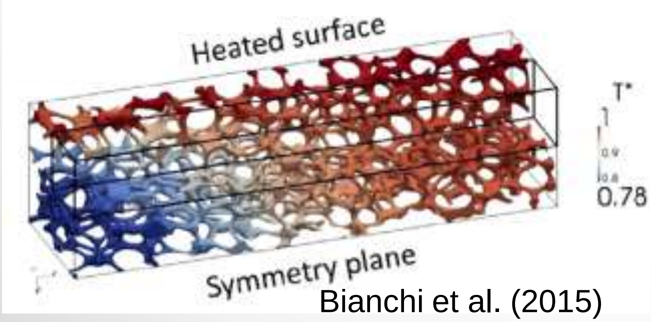


Cheung et al. (2014)

Multi-Physical Models

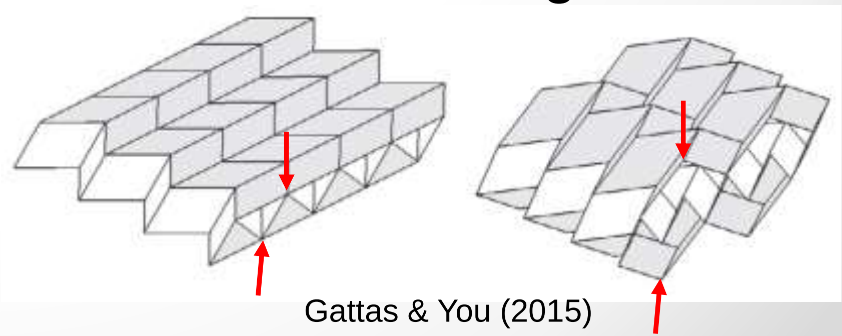
- Thermo-Mechanical
- Acoustics
- Thermodynamics
- Electromagnetics
- Fluid-Structure

Heat Transfer / Heat Effects



Bianchi et al. (2015)

Cellular Reconfiguration



Gattas & You (2015)

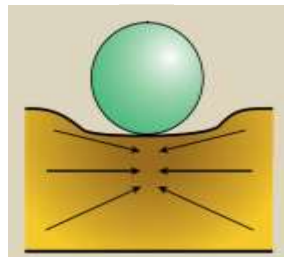
2 Metamaterials from Cellular Assemblages

Mechanical Metamaterials

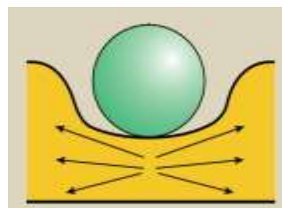
Blast Resistance

Schenk et al. (2014)

Auxetic



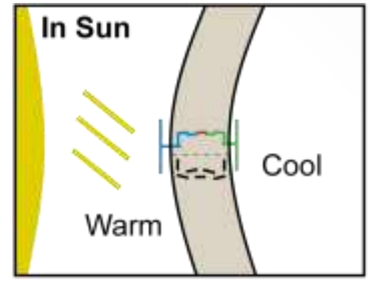
Non-auxetic



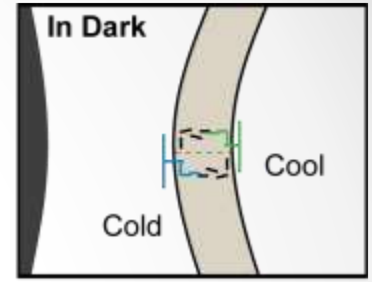
Alderson (1999)

Variable Thermal Conductivity

In Space

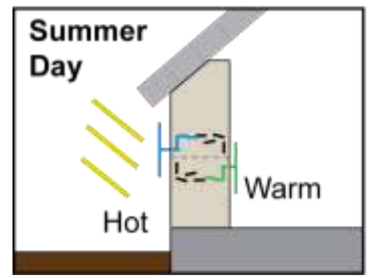


Thermal Bridging

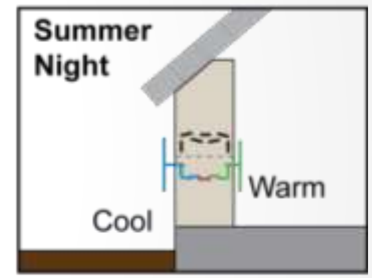


High Insulation

On Earth

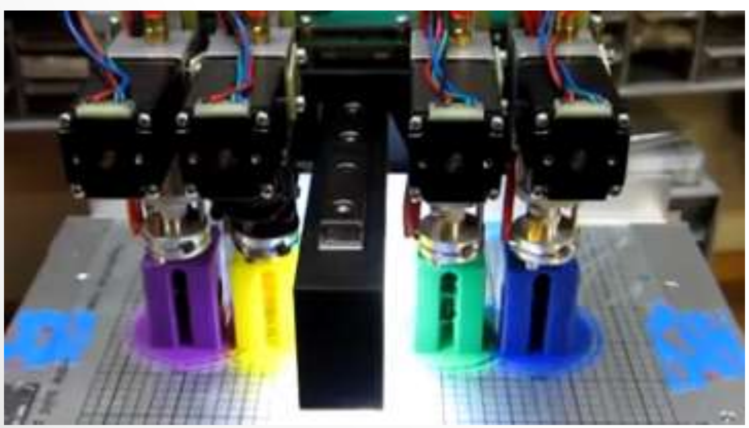


High Insulation



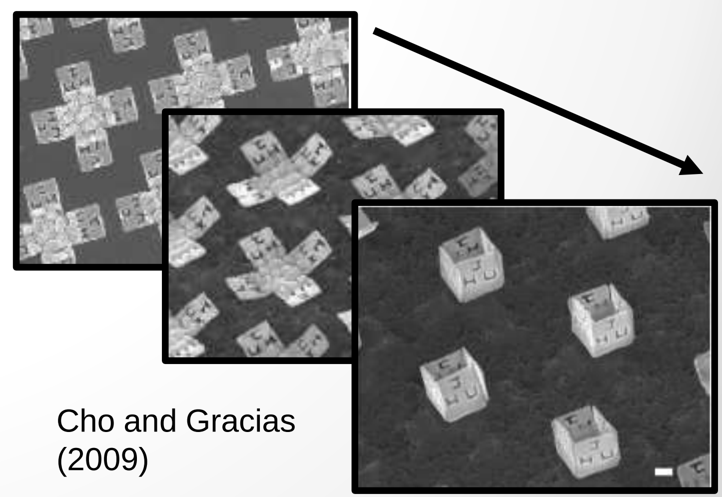
Thermal Bridging

Additive Manufacturing



HyRel 3D Printers (2016)

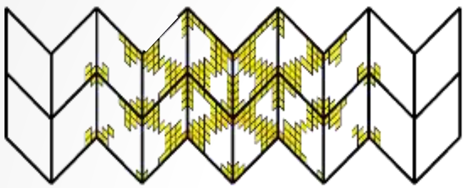
Self-Assembly of Perforated Sheets

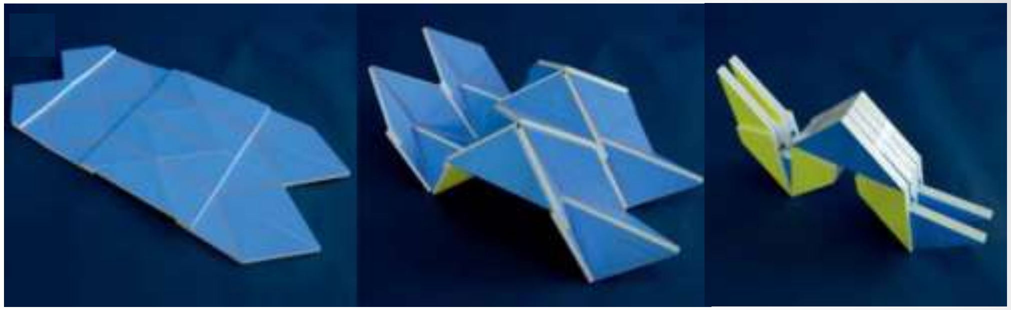


Cho and Gracias (2009)

3 Hinged Systems with Thickness

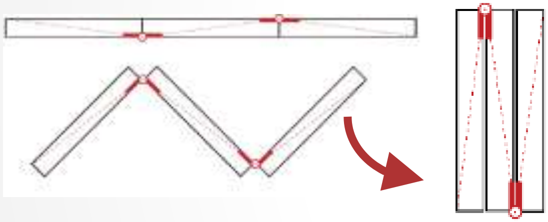
- Optimal packing and panels with varying thickness





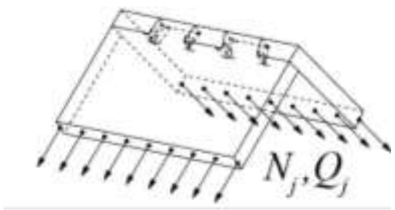
Chen et al. (2015) *Science*

- Hinge packing



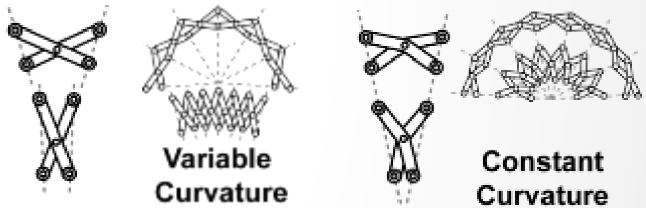
Tachi (2010)

- Hinge design



Roche, Mattoni & Weinand (2015)

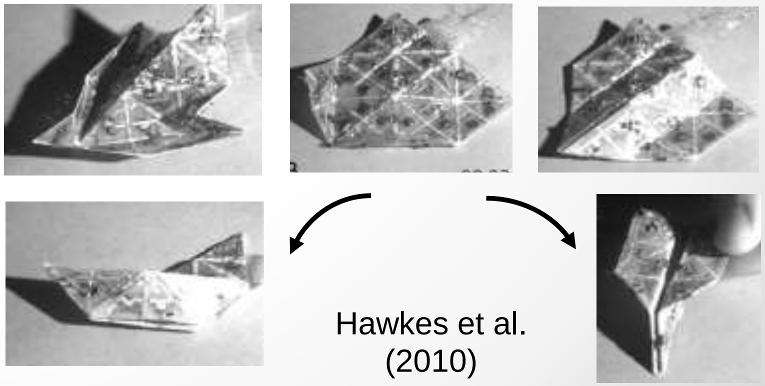
- Added function with hinges



Hobermban (1990)

System Design for:

- Efficient and safe deployment/motion
- Multi-functional reconfiguration
- Pre-fabrication and modular systems



Hawkes et al. (2010)

Thank you!

Acknowledgments:

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www.efilipov.com