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École polytechnique fédérale de Lausanne

February 9, 2016

Using Origami for Deployable Structures and Adaptable Metamaterials

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1. University of Illinois
at Urbana Champaign

Prof. Glaucio H. Paulino^{1,2}

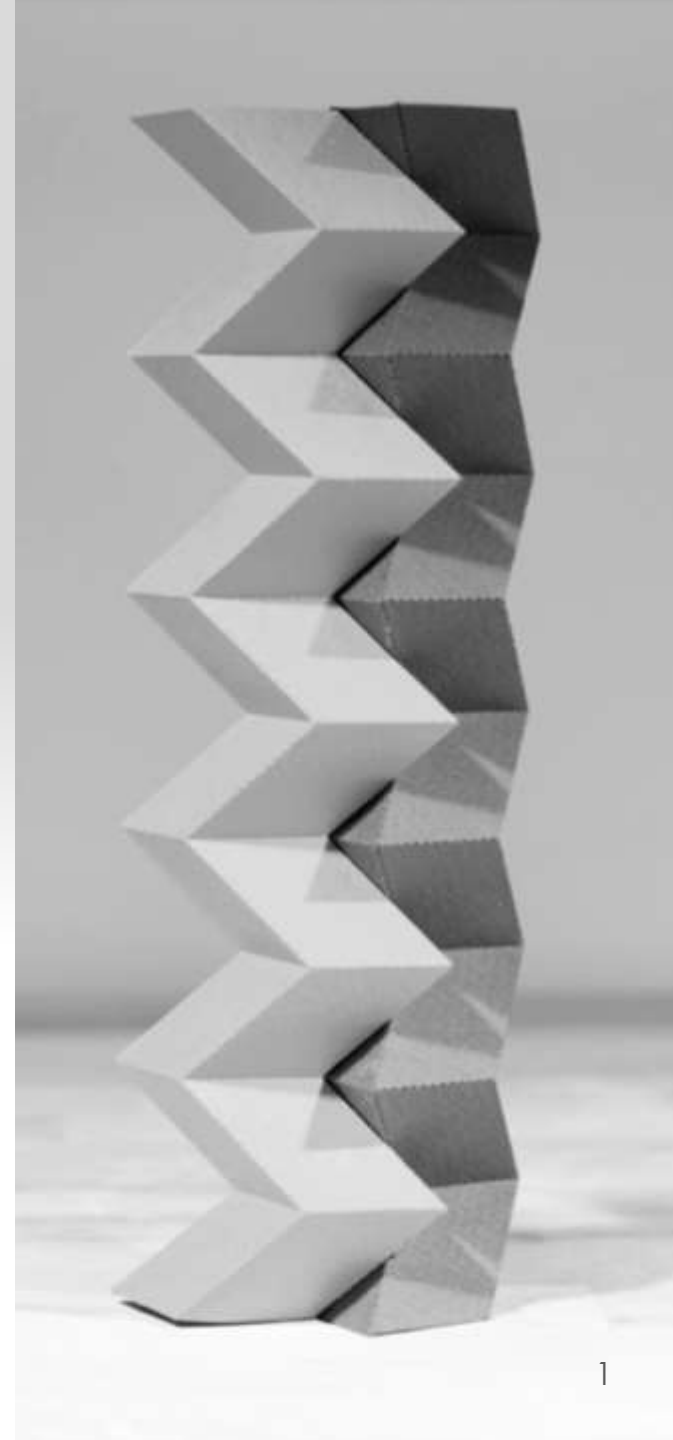


2. Georgia Institute
of Technology

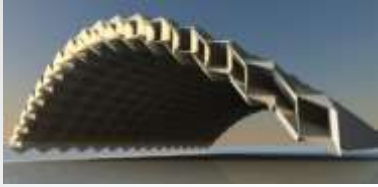
Prof. Tomohiro Tachi³



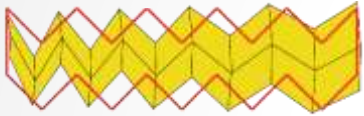
3. The University
of Tokyo



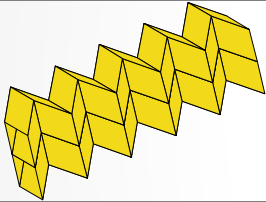
Presentation Outline



Origami in Engineering



Structural Analysis of Origami



Coupling of Origami Tubes



Cross-Section and Other Variations



Cellular Assemblages



Future Research Plans

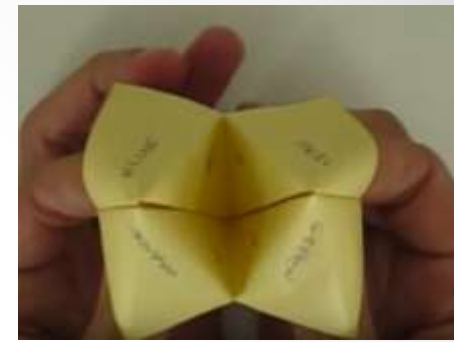
Origami as Art



Orchfani 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/

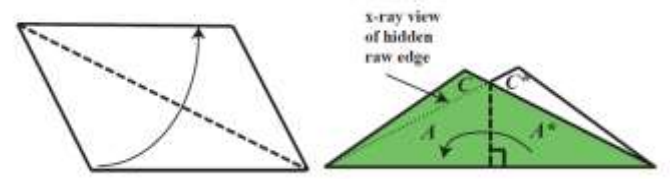
Origami as Fashion



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

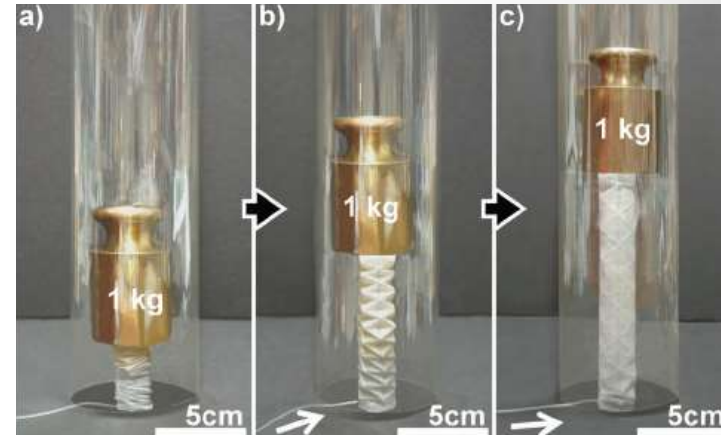
- Compact
- Deployable
- Pre-Fabricated
- Self-Assembly
- Tunable
- Multi-Functional
- Adaptable



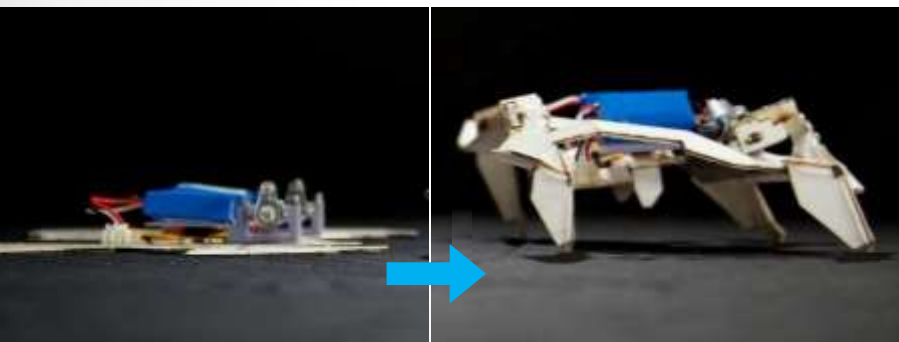
Kiefer Technic Showroom



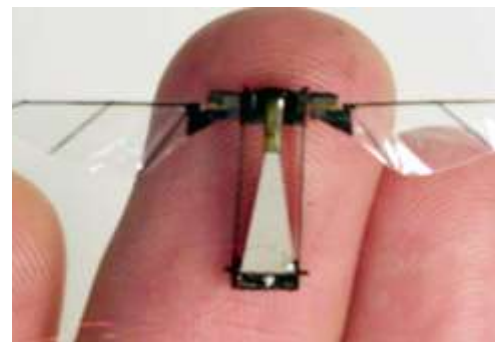
ISS – NASA 2011



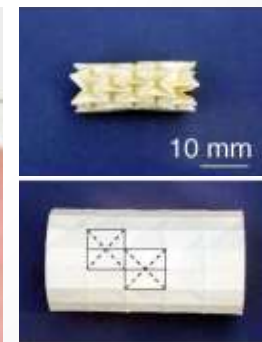
Martinez et al. (2012)



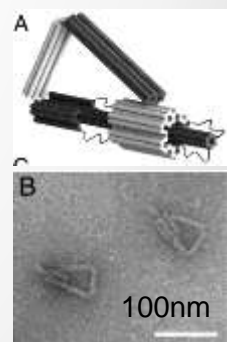
Felton et al. (2014)



Wood (2008)

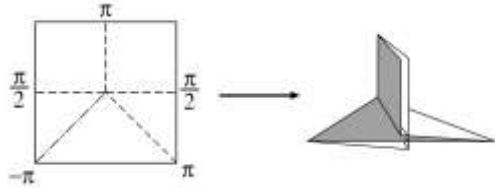


Kuribayashi et al. (2006)

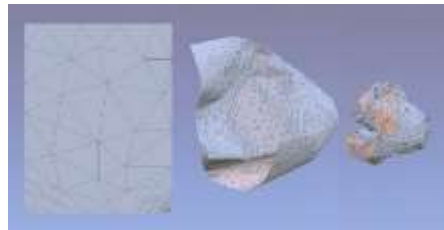


Marras et al. (2015)

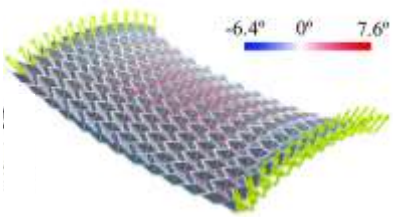
Theory and Analysis



Belcastro and Hull (2013)



Narain et al. (2013)

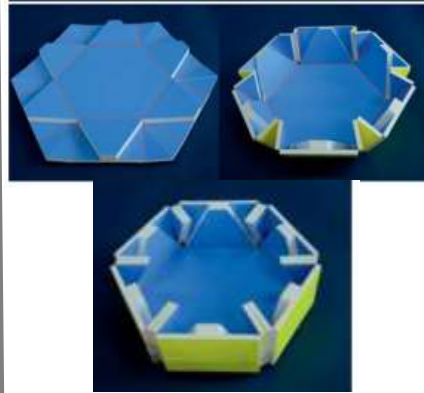


Wei et al. (2013)

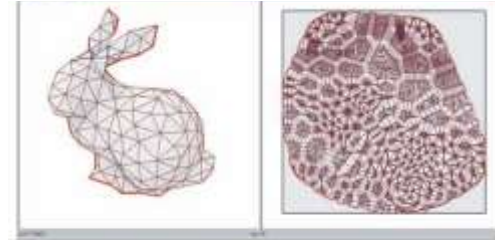


Demaine and Demaine (2012)

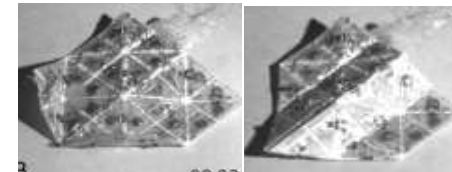
System Design



Chen et al. (2015)



Tachi (2010)



Hawkes et al. (2010)



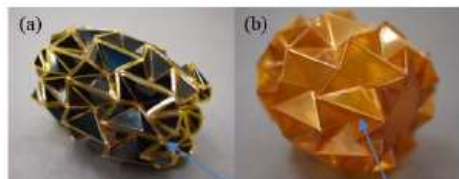
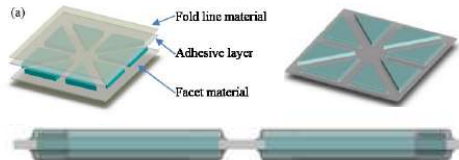
Origami Engineering Materials & Fabrication



Black LAB Architects (2014)



C. Hoberman (2012)



Lee et al. (2013)



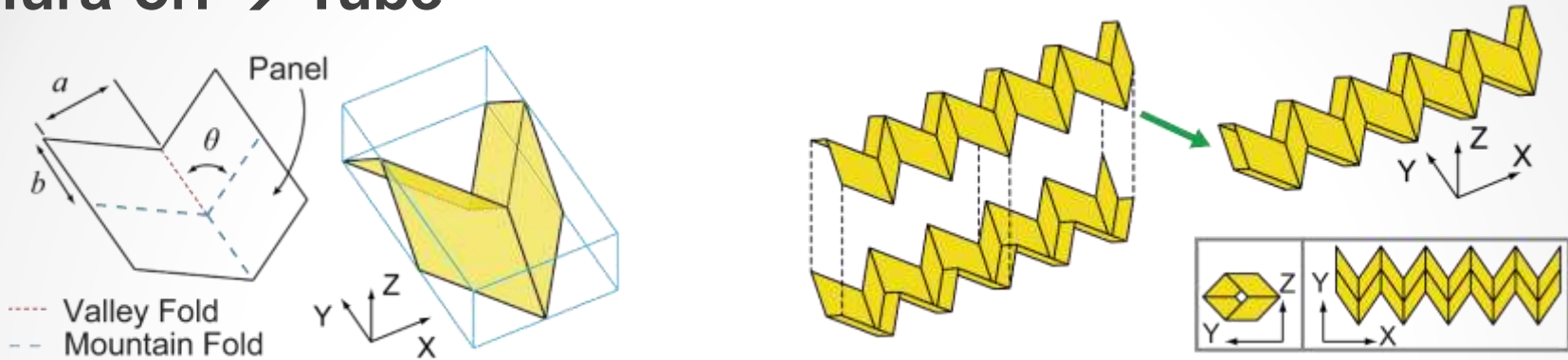
Living hinge



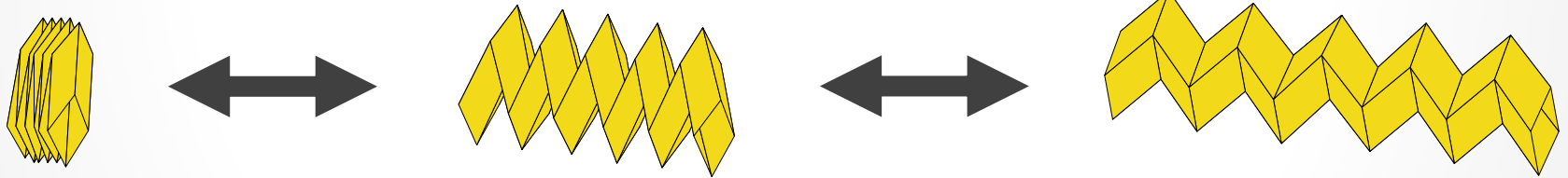
Graphene sheet

Miura-ori Tube Origami

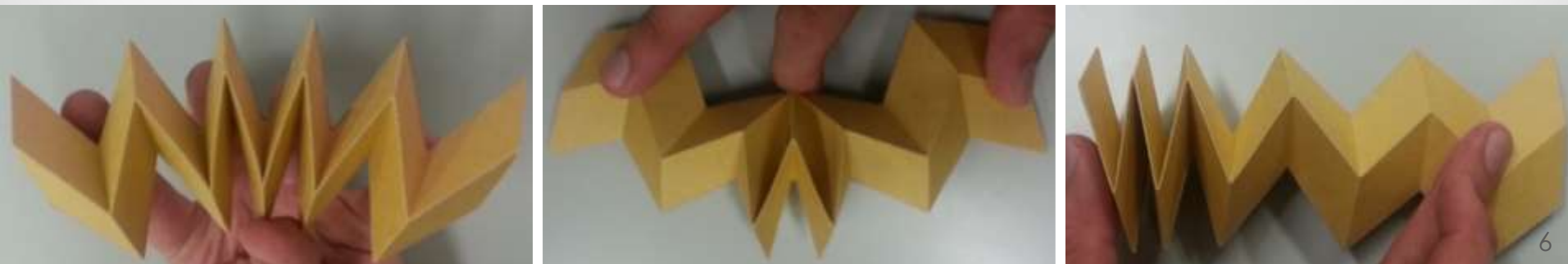
Miura-ori \rightarrow Tube



Kinematic “rigid” folding



Elastic deformations



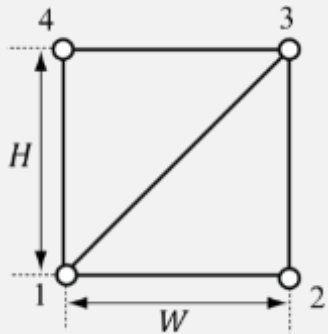
Elastic Modeling for Origami

S

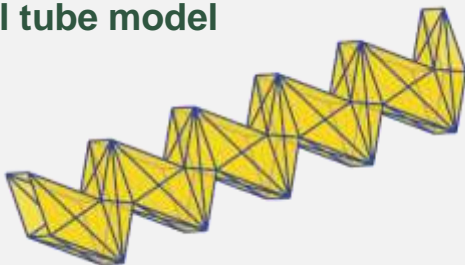
Panel Shear & Stretching



Model with bars elements

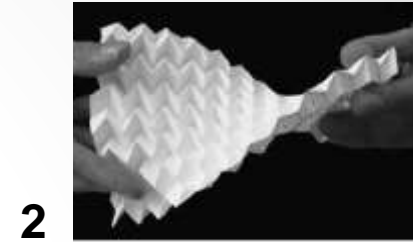
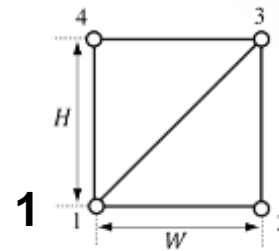


Full tube model

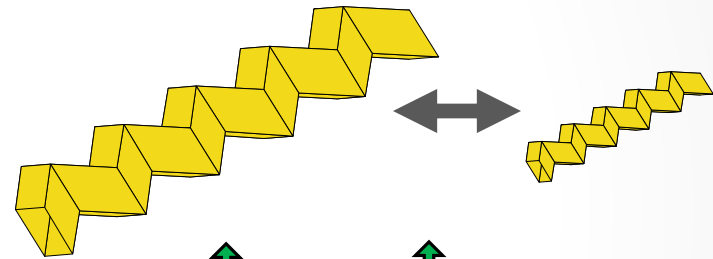


Benefits of the *Bar and Hinge Model*

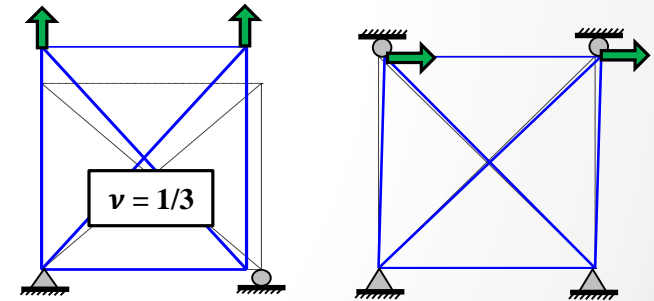
1. **Simplicity in the design and use**
2. **Insight on stiffness properties**
3. **Scalability**
4. **Model isotropy**
5. **Material properties**
 - Thickness t
 - Poisson's Ratio ν
 - Young's modulus E
 - Density ρ
6. **Large displacements**
7. **Elasto-plastic folds**



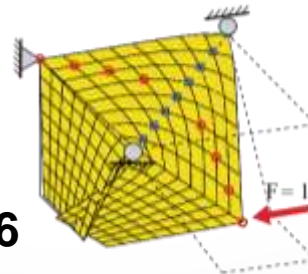
3



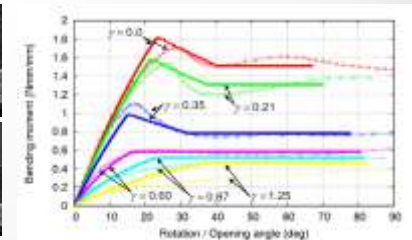
4, 5



6



7

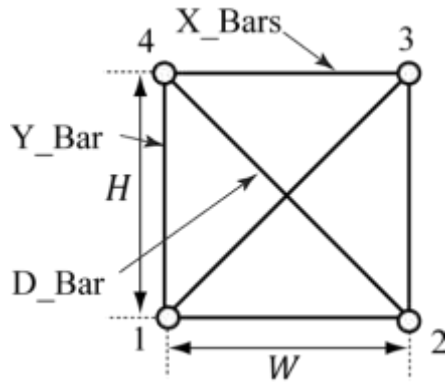


Nagasawa et al. (2003)

S

Bar Model for Panel Shear & Stretching

Bar stiffness definitions



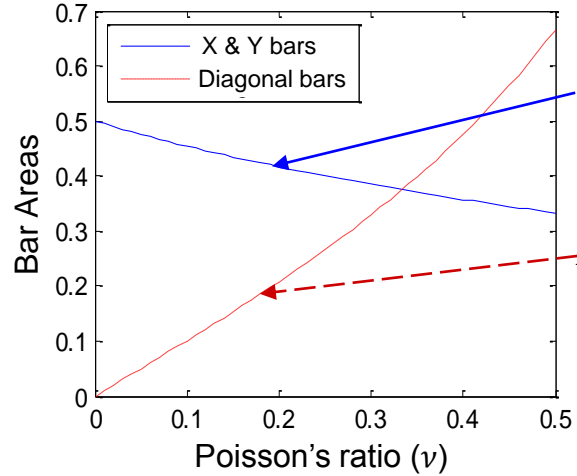
$$K_S = \frac{EA_{Bars}}{L}$$

Young's modulus: E

Thickness: t

Poisson's ratio: ν

Bar areas:

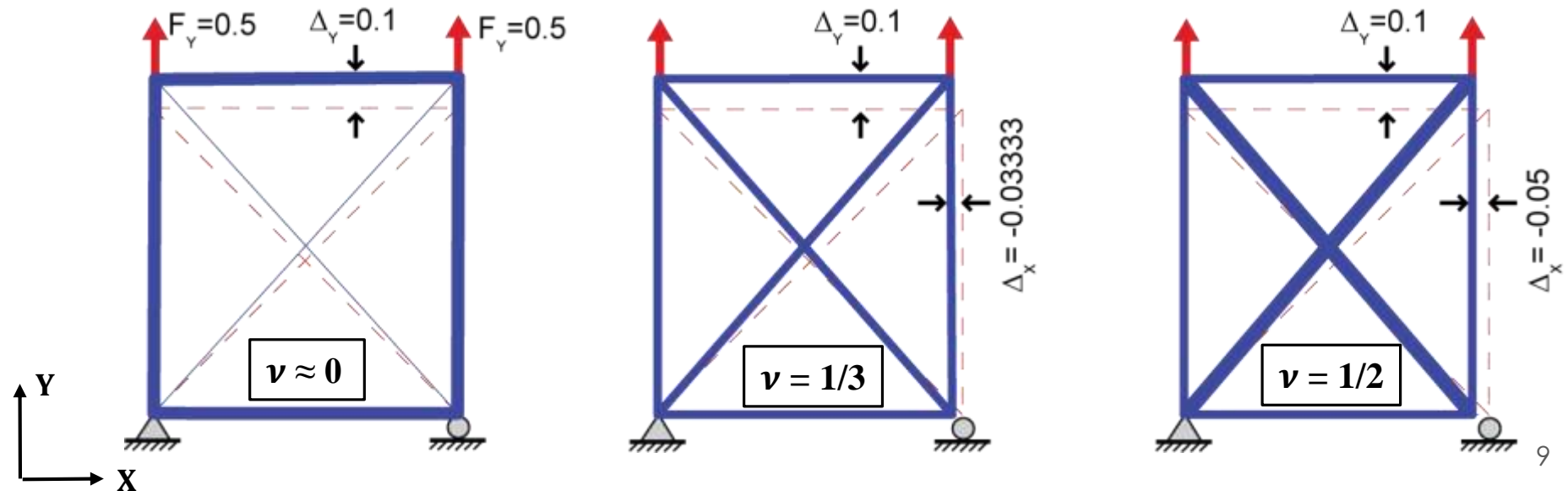


$$A_Y = t \frac{W^2 - \nu H^2}{2W(1 - \nu^2)}$$

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

Poisson effect

$$\epsilon_x = \nu * \epsilon_y$$

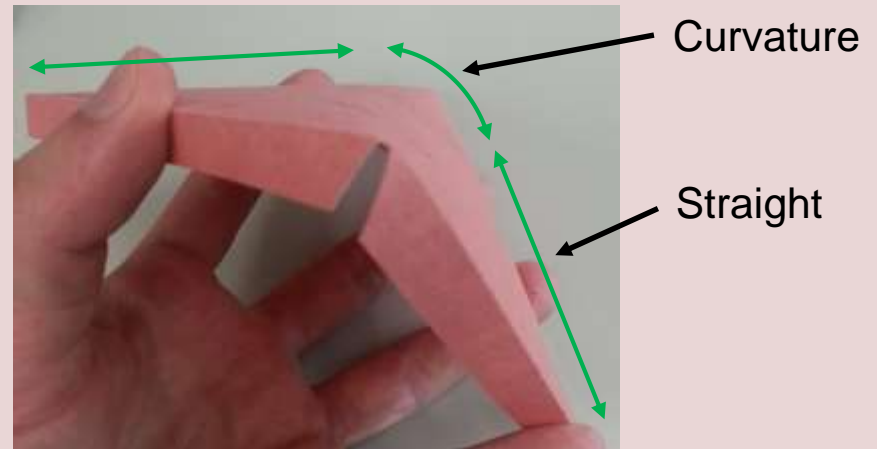


B Bending Thin Sheet with Restricted Edges

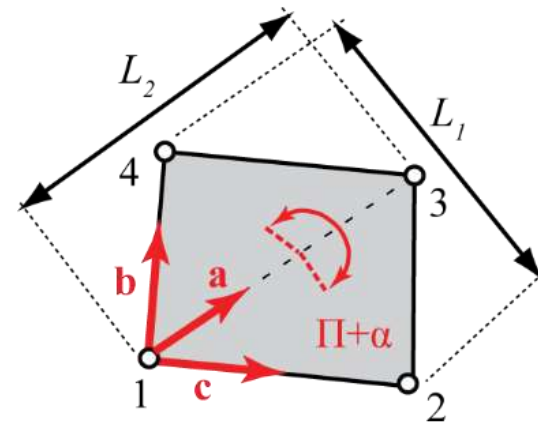
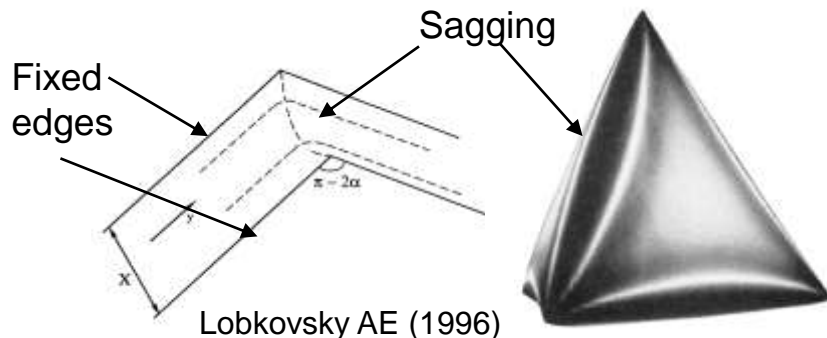
Constant curvature bending



Bending restricted at edges



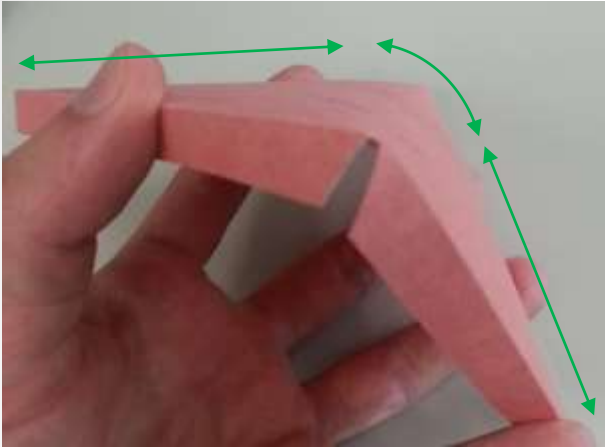
- Bending is localized in the center of span
- Stiffness is higher than with constant curvature bending



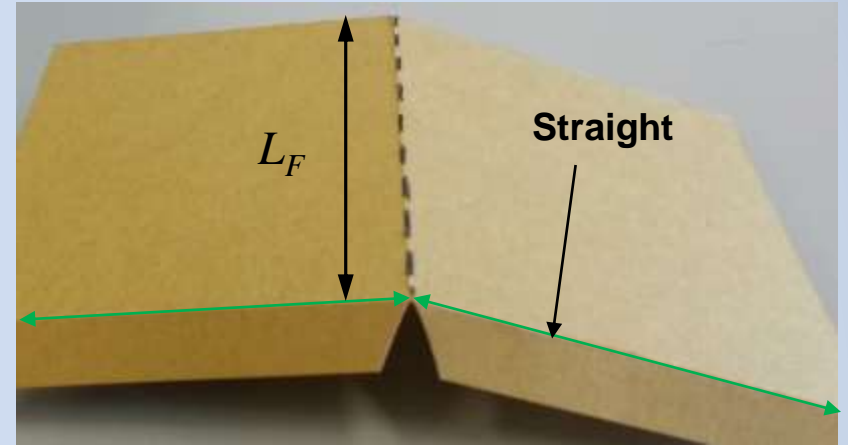
$$K_B = C_B \frac{Et^3}{12(1-\nu^2)} \left(\frac{L_2}{t}\right)^{1/3}$$

Modeling Prescribed Fold Lines

Bending restricted at edges

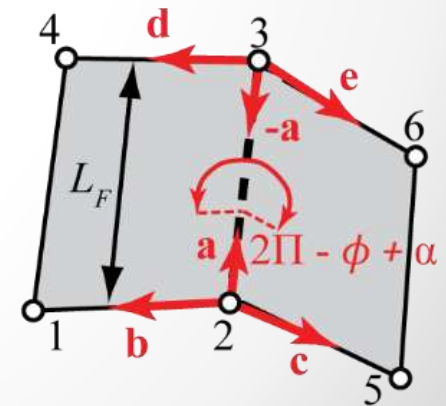


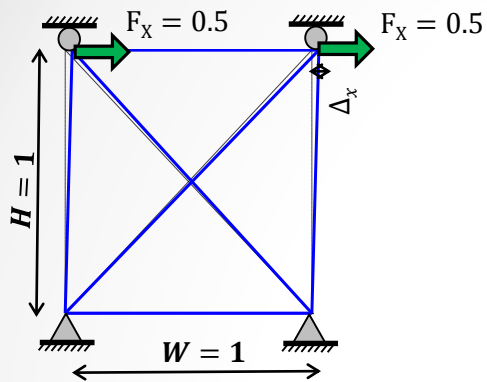
Bending at prescribed fold line



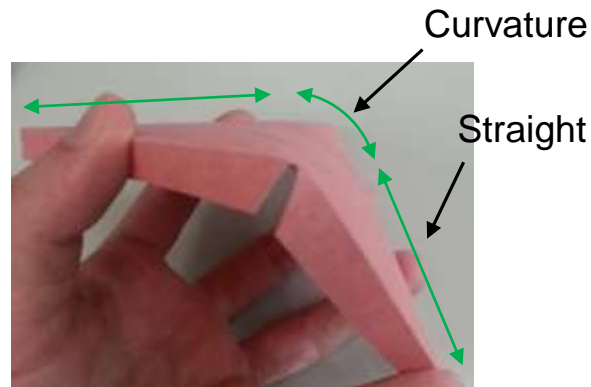
- $R_{FP} = 1/10$ relates panel to fold stiffness
- Stiffness scales with L_F
- R_{FP} may depend on physical and material properties

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

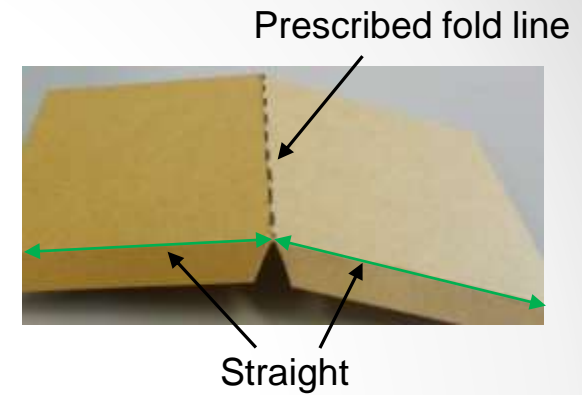


S**Panel Shear & Stretching**

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

B**Panel Bending**

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

F**Fold Bending**

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

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

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

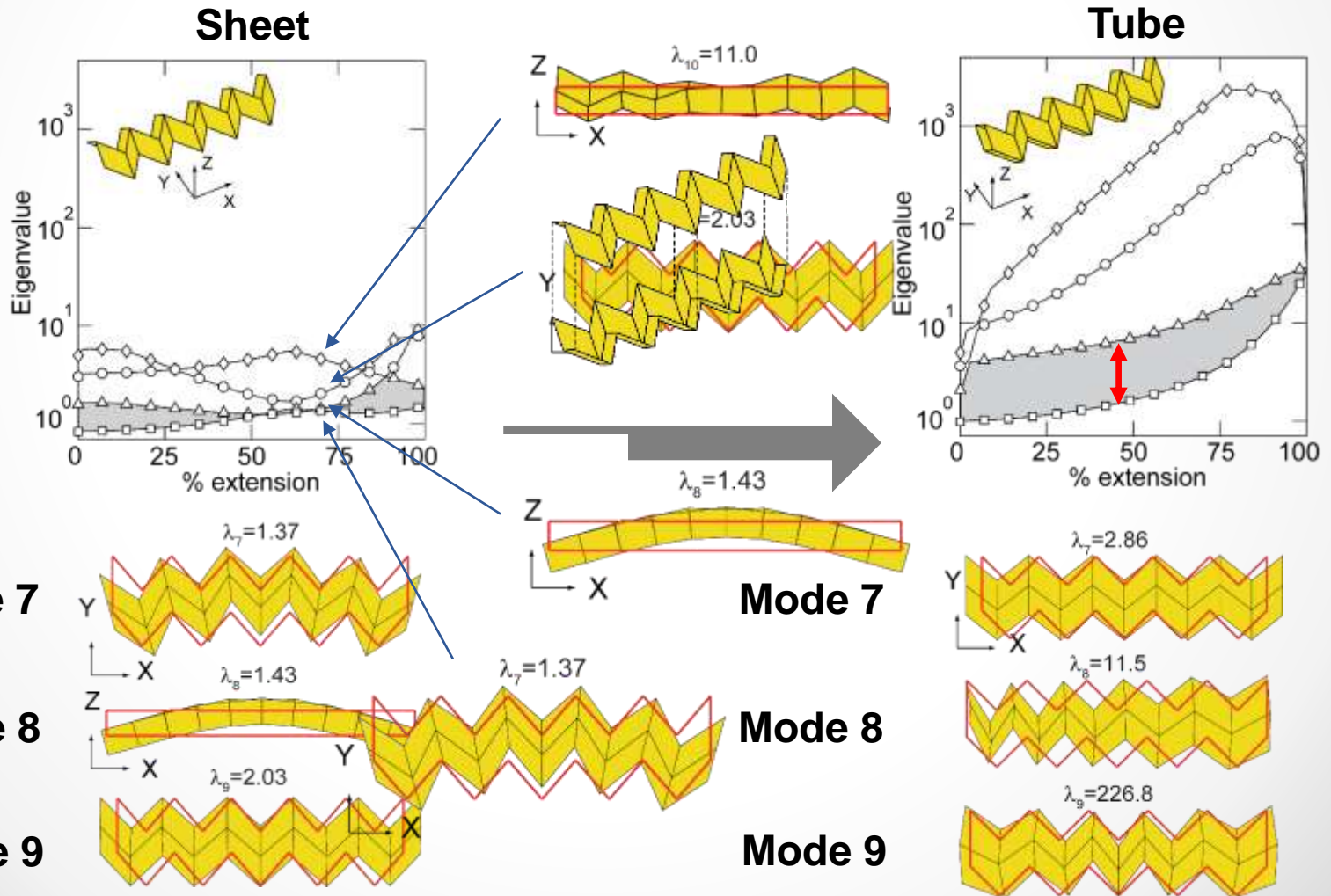
Eigenvalue Analyses

\mathbf{K} = Stiffness matrix

\mathbf{M} = Mass matrix

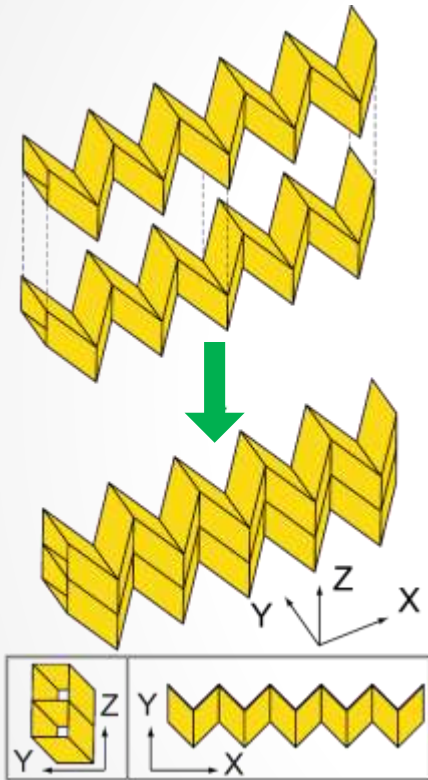
$$\mathbf{K}\mathbf{v}_i = \lambda_i \mathbf{M}\mathbf{v}_i \quad i = 1, \dots, N_{dof}$$

λ_i ← Eigenvalue \mathbf{v}_i ← Eigen-mode

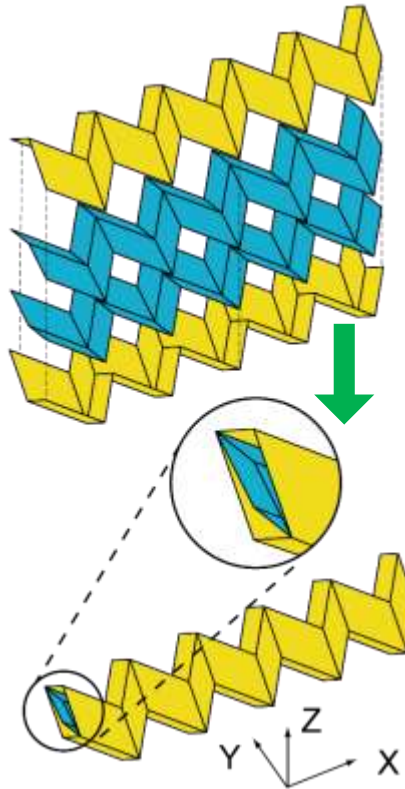


Tube Assemblages

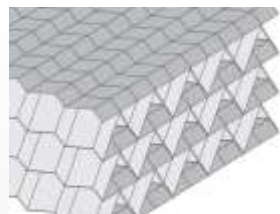
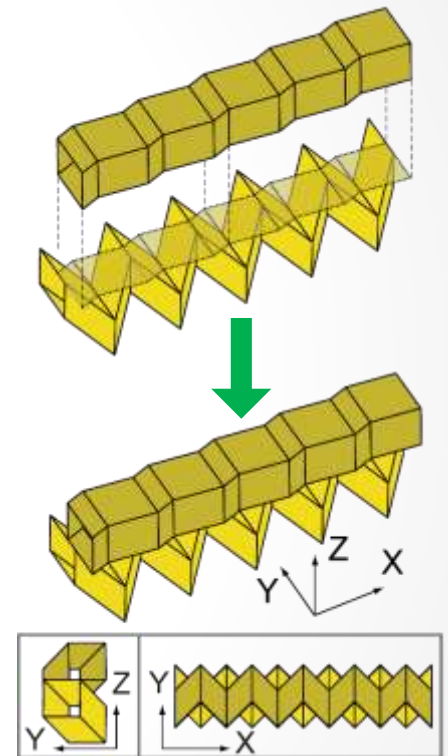
Aligned coupling



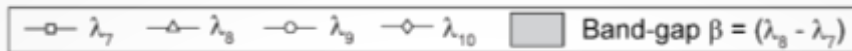
Internal coupling



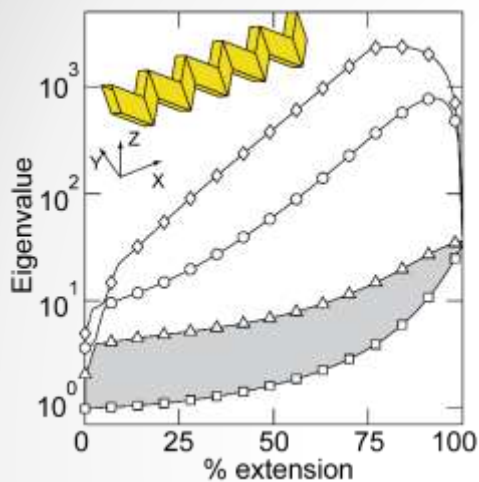
Zipper coupling



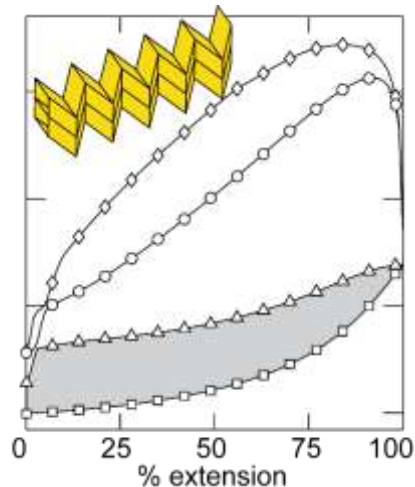
Schenk and Guest (2013)



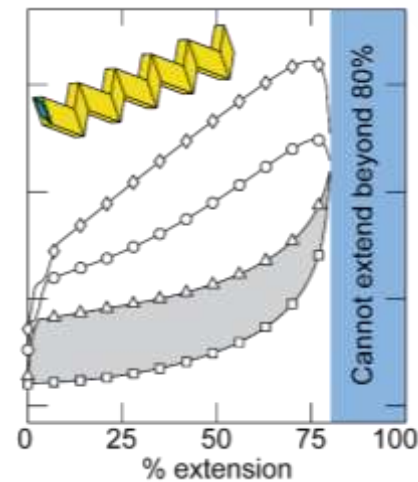
Single tube



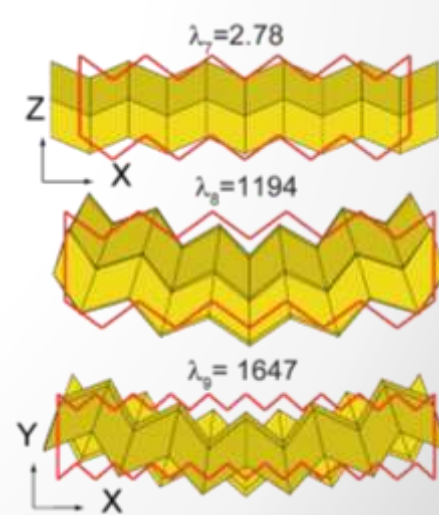
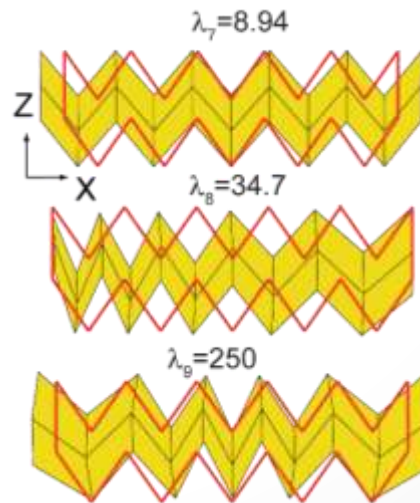
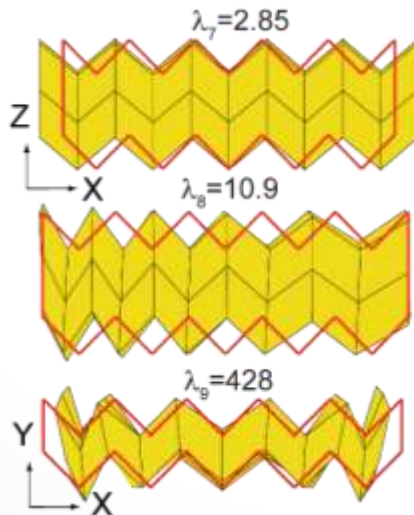
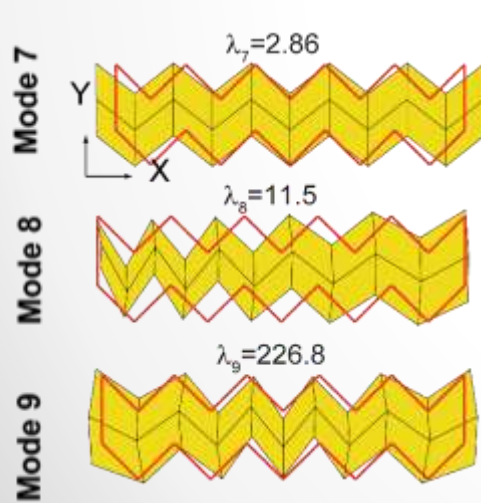
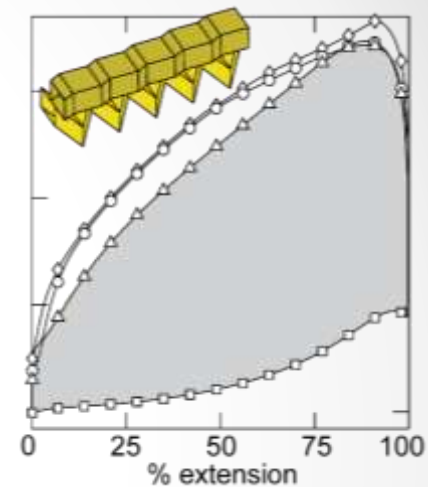
Aligned



Internal



Zipper



Origami tubes assembled into stiff, yet reconfigurable structures and metamaterials

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Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved August 7, 2015 (received for review May 14, 2015)

Thin sheets have long been known to experience an increase in stiffness when they are bent, buckled, or assembled into smaller interlocking structures. We introduce a unique orientation for coupling rigidly foldable origami tubes in a “zipper” fashion that substantially increases the system stiffness and permits only one flexible deformation mode through which the structure can deploy. The flexible deployment of the tubular structures is permitted by localized bending of the origami along prescribed fold lines. All other deformation modes, such as global bending and twisting of the structural system, are substantially stiffer because the tubular assemblies are overconstrained and the thin sheets become engaged in tension and compression. The zipper-coupled tubes yield an unusually large eigenvalue bandgap that represents the unique difference in stiffness between deformation modes. Furthermore, we couple compatible origami tubes into a variety of cellular assemblies that can enhance mechanical characteristics and geometric versatility, leading to a potential design paradigm for structures and metamaterials that can be deployed, stiffened, and tuned. The enhanced mechanical properties, versatility, and adaptivity of these thin sheet systems can provide practical solutions of varying geometric scales in science and engineering.

stiff deployable structures | origami tubes | rigid origami | thin sheet assemblies | reconfigurable metamaterials

Introducing folds into a thin sheet can restrict its boundaries, cause self-interaction, and reduce the effective length for bending and buckling of the material (3–4). These phenomena make thin sheets practical for stiff and lightweight corrugated assemblies (5, 6); however, such systems tend to be static, i.e., functional in only one configuration. For creating dynamic structures, origami has emerged as a practical method in which continuous thin sheet panels (facets) are interconnected by prescribed fold lines (creases). Existing origami patterns and assemblies can easily be deployed; however, they tend to be flexible and need to be braced or locked into a fixed configuration for a high stiffness-to-weight ratio to be achieved (7–10). The zipper-coupled system is different because it is stiff throughout its deployment without having to be locked into a particular configuration.

Origami principles have broad and varied applications, from solar arrays (11) and building facades (12) to robotics (13), mechanisms in stent grafts (14), and DNA-stored boxes (15). The materials and methods used for fabricating, actuating, and assembling these systems can vary greatly with length scale. On the microscale, metals and polymer films are, more often, layered composites consisting of stiff and flexible materials that can be folded by inducing current, heat, or a chemical reaction (16, 17). Large-scale origami structures can be constructed from thickened panels connected by hinges and can be actuated with mechanical forces (11, 18, 19). The kinematic motion, functionality, and mechanical properties of the origami are governed largely by the folding pattern geometry. For example, rigid origami systems are defined as those having a kinematic deformation mode in which movement is concentrated along the fold lines, whereas the panels remain flat (20, 21). Among various rigid folding patterns, the Miura-ori has attracted attention for its folding characteristics (22, 23); elastic

stiffness properties beyond rigid folding (24, 25), geometric versatility (26, 27), and intrinsic material-like characteristics (28, 29).

The zipper-coupled tubes introduced here are derived from the Miura-ori pattern and can undergo the same type of rigid kinematic deployment. All other deformations are restrained as they require stretching and shear of the thin sheets. Thus, the structure is light and retains a high stiffness throughout its deployment. It has only one flexible degree of freedom and can be actuated by applying a force at one point (Fig. 1 and Movie S1). To explore unique mechanical properties of the zipper tubes, we introduce concepts of eigenvalue bandgaps and cantilever analyses to the field of origami engineering. Zipper assemblies can be fabricated with a variety of materials and methods. We envision applications of these assemblies will range in size from microscale metamaterials that harness the novel mechanical properties to large-scale deployable systems in engineering and architecture (Movies S2–S4).

This paper is organized as follows. First, the Miura-ori pattern is introduced, and the geometries of three fundamental coupling orientations are discussed. Next, we demonstrate how the system stiffness changes as we assemble two sheets into a tube and then two tubes into the unique zipper-coupled tubes. The fundamental coupling orientations are then studied as deployable cantilevers that can carry perpendicular loads. Next, we discuss cellular assemblies, geometric variations, and practical applications that can be created from coupled tubes, and we conclude with some final remarks.

Geometric Definitions

A Miura-ori cell consists of four equivalent panels, defined by a height a , width b , and vertex angle α (Fig. 2A). For our analytical investigation, we use a cell with $a = b = 1$ and $\alpha = 55^\circ$ as the basis for all structures unless otherwise noted. A sheet is created by repeating this cell N ($N=5$) times in the X direction (Fig. 2B). We

Significance

Origami, the ancient art of folding paper, has recently emerged as a method for creating reconfigurable and reconfigurable engineering systems. These systems tend to be flexible because the thin sheets bend and twist easily. We introduce a new method of assembling origami into coupled tubes that can increase the origami stiffness by two orders of magnitude. The new assemblies can deploy through a single flexible motion, but they are substantially stiffer for any other type of bending or twisting movement. This versatility can be used for deployable structures in robotics, aerospace, and architecture. On a smaller scale, assembling thin sheets into these tubular assemblies can create metamaterials that can be deployed, stiffened, and tuned.

Author contributions: E.T.F., T.T., and G.H.P. designed research, performed research, contributed new reagent/materials/tools, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

See Commentary on page 12334.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1508011112/-DCSupplemental.

Transforming architectures inspired by origami

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Paper folding is found across cultures for both aesthetic and functional purposes, with its most widely recognized exponent being the ancient art form of origami. More recently, it has become an inspiring source for translating origami designs into mathematics, natural sciences, engineering, and architecture. Across these different fields, origami is becoming a frontier of inspiration for the new reconfigurable and multifunctional materials and structures. However, the use of origami designs at engineering scales is typically compromised by limitations in structural performance. A new study by Filipov et al. (1) presents an innovative approach for the design of uniquely rigid deployable structures. Their strategy is based on

new structural mechanics that are commonly used in civil and mechanical engineering and port them to this new emerging field of origami-inspired design.

Much of the recent research inspired by origami spans across fields, from mathematics, physics, and computer science to materials engineering, nanotechnology, aerospace, and architecture in mathematics and computational origami, for instance, to modify stiffness by considering rigid panels (also known as rigid foldable origami), with a focus on geometry and topological considerations (2–5). There is a substantial body of literature in this domain (6) and powerful simulation tools have been developed to predict a remarkably complex, coarse pattern for origami (7). A drawback of these approaches is that they tend to exclude considerations on mechanical properties, which are required if we are to predict the mechanical response of origami structures. With the goal of understanding the coupling of the mechanics and geometry of origami, the physics and mechanical characteristics far beyond the field with great interest. The essence of the activity is reconfigurable based on the Miura-ori pattern and retains primarily around issues related to the strong geometrically nonlinear behavior with bistability (8), tunable metamaterials (9), and self-assembled structures at different scales (10). On the robotics and fabrication front, there have also been significant advances in programmable foldable sheets (11), printable self-folding robots (12), and self-folding microstructures and microsystems (13), to mention just a few examples.

Starting from a structural mechanics viewpoint, Filipov et al. (1) take their study on techniques originally developed for frame structures (14) that have been adapted to study the mechanics of foldable structures by relaxing the conditions of rigidity of the planar faces (15). Here, origami are studied as a pin-jointed truss structure and each fold represented by a flat, abutted,

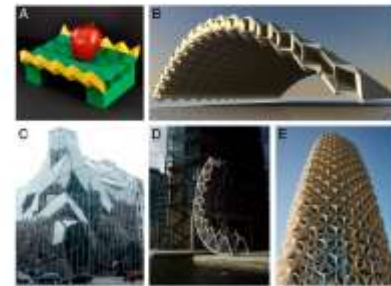
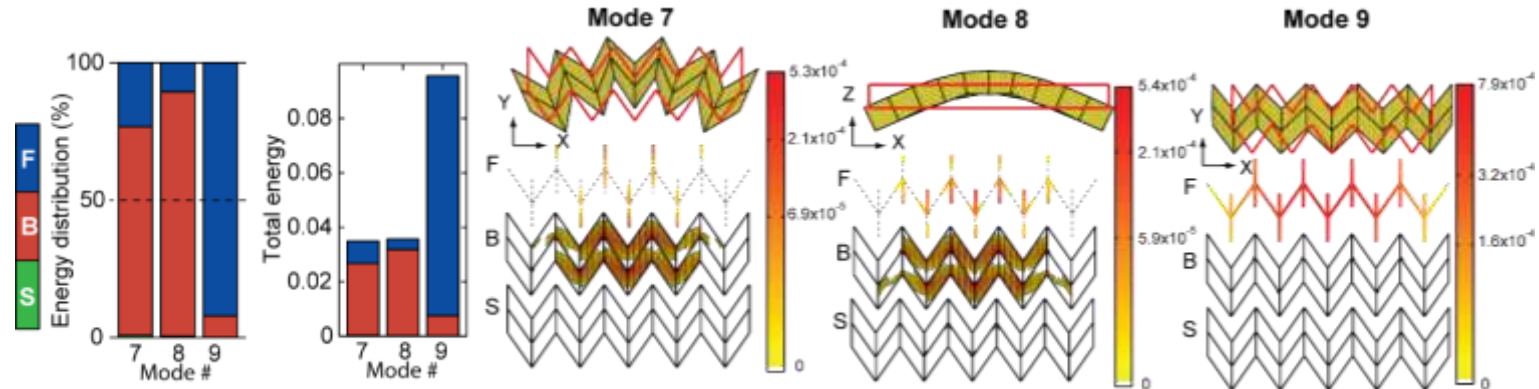
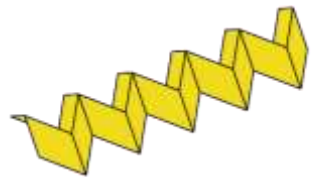


Fig. 6. (A) Origami-inspired engineering. (B) Metal bridge designed by Filipov et al. (1) employing a series of deployable tubes. (C) Curved origami structure. (D) Origami structure of the Boston Health Department, Boston, MA. (E) The Tokyo Bridge, London. (B)–(E) Images courtesy of the authors. (A) Image courtesy of the authors. (C)–(E) Images courtesy of the authors. (A)–(E) Images courtesy of the authors.

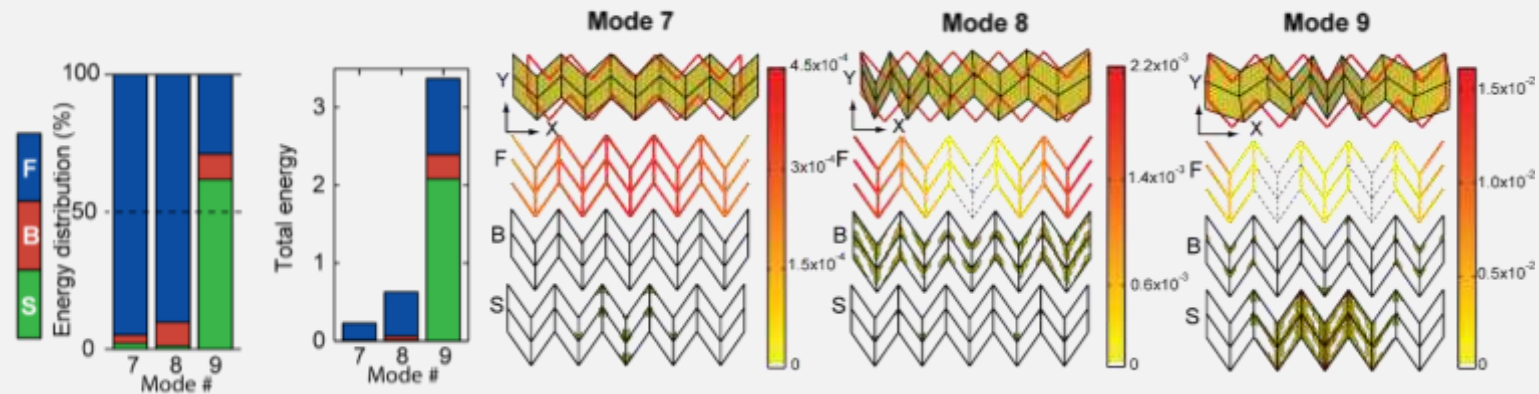
Commentary by:
Reis PM, López Jiménez F,
and Marthelot J

Energy Distribution

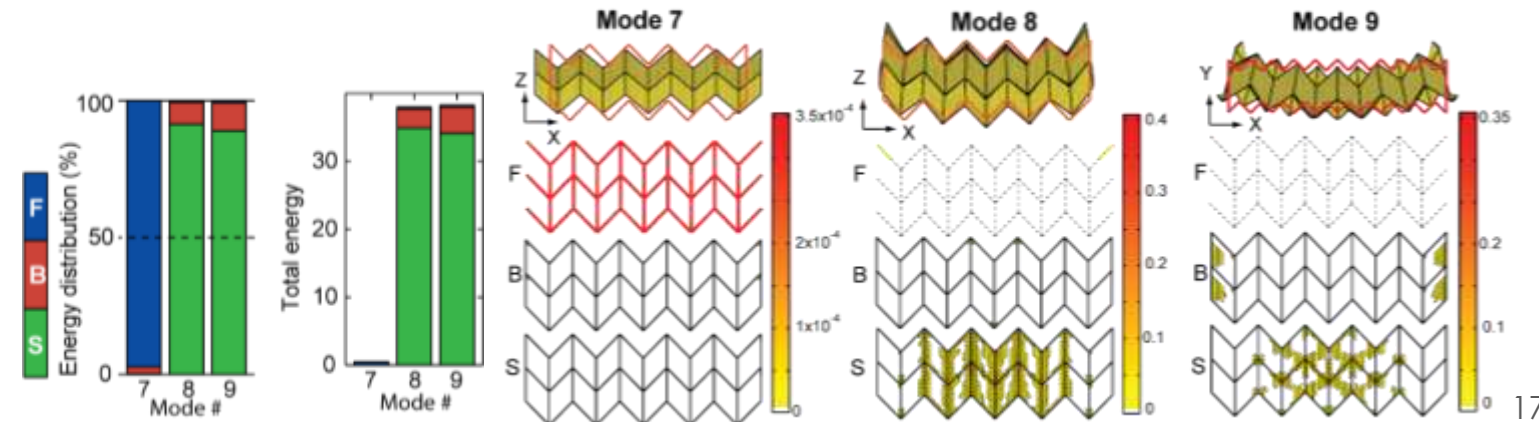
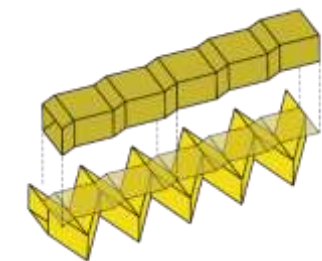
Sheet



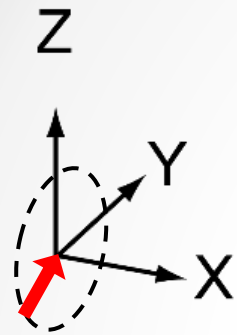
Tube



Zipper

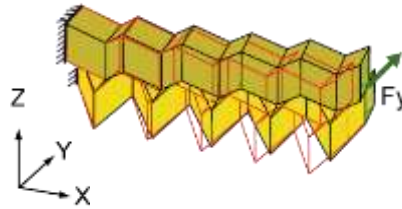


Stiffness in Y-Z Plane

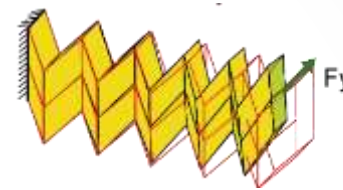


Load applied perpendicular to X axis

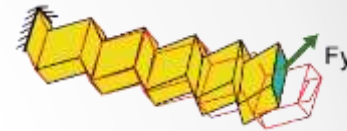
Zipper



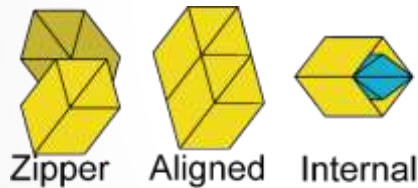
Aligned



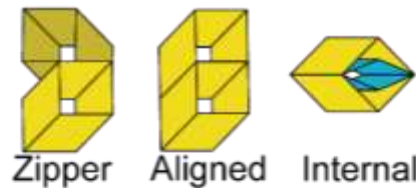
Internal



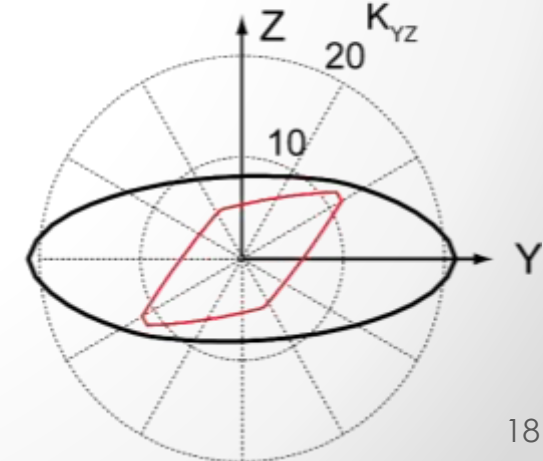
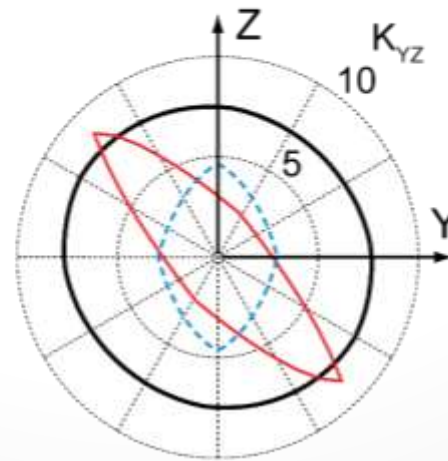
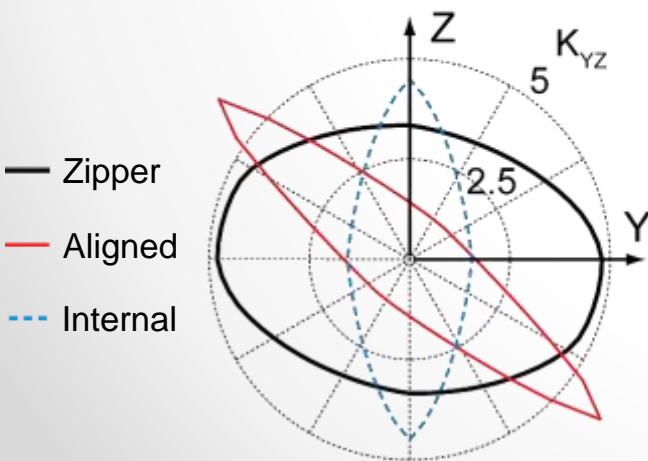
At 40% extension



At 70% extension

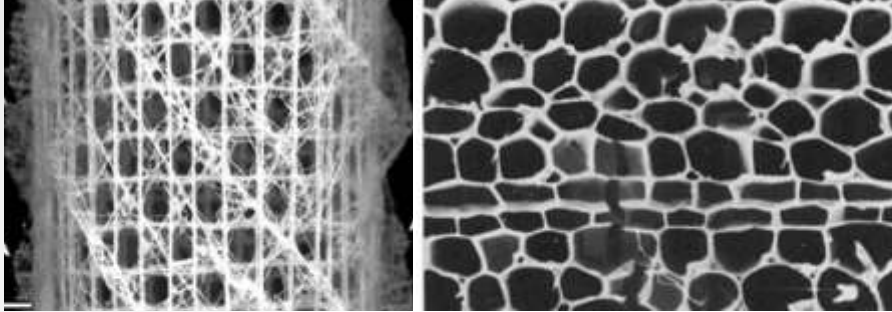


At 95% extension



Cellular Assemblages as Metamaterials

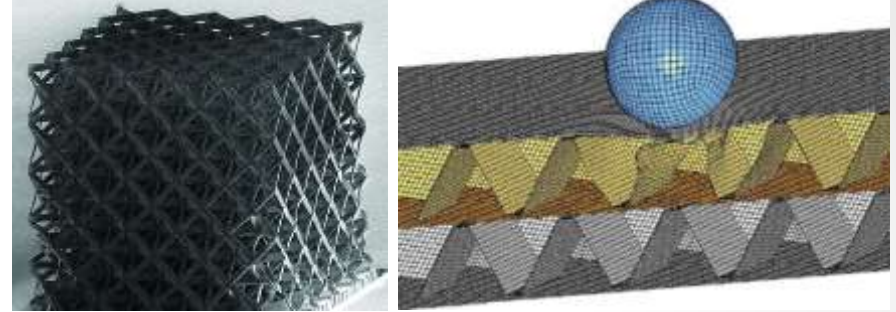
Nature



Aizenberg et al. (2005)

Ashby et al. (1985)

Engineering



Meza et al. (2014)

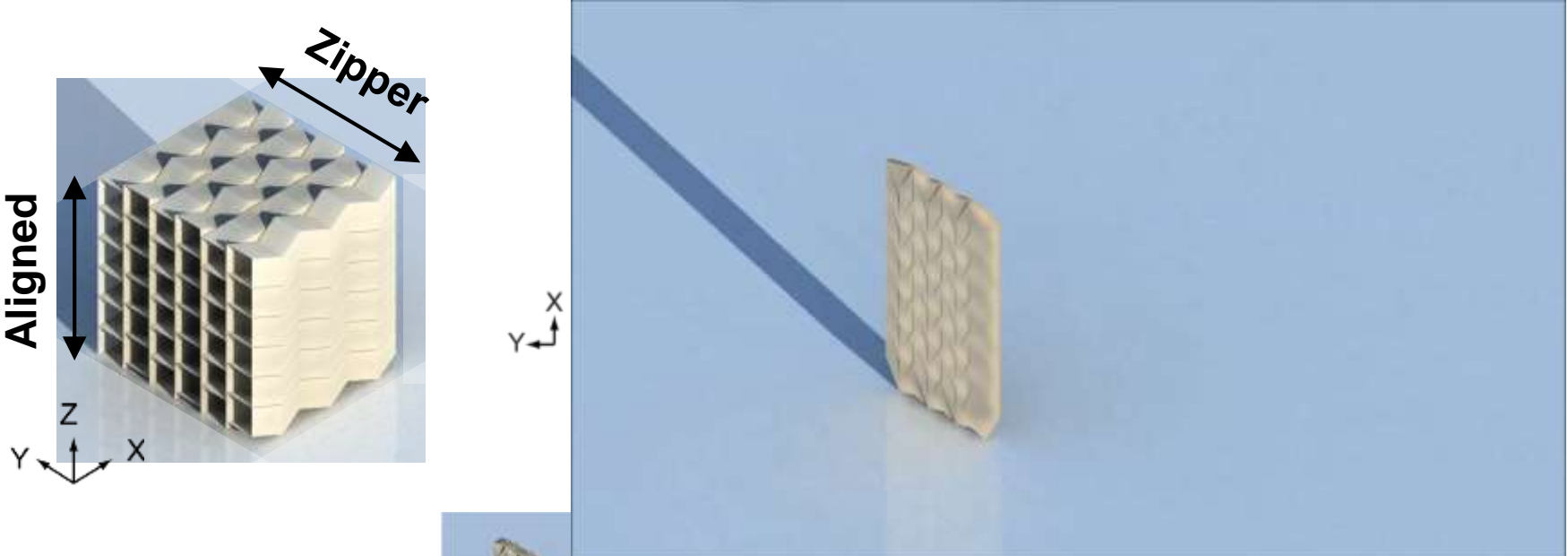
Heimbs (2013)

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

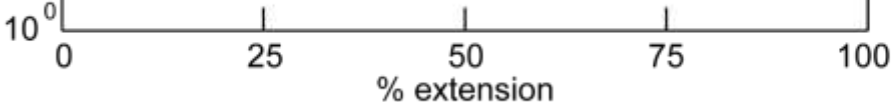
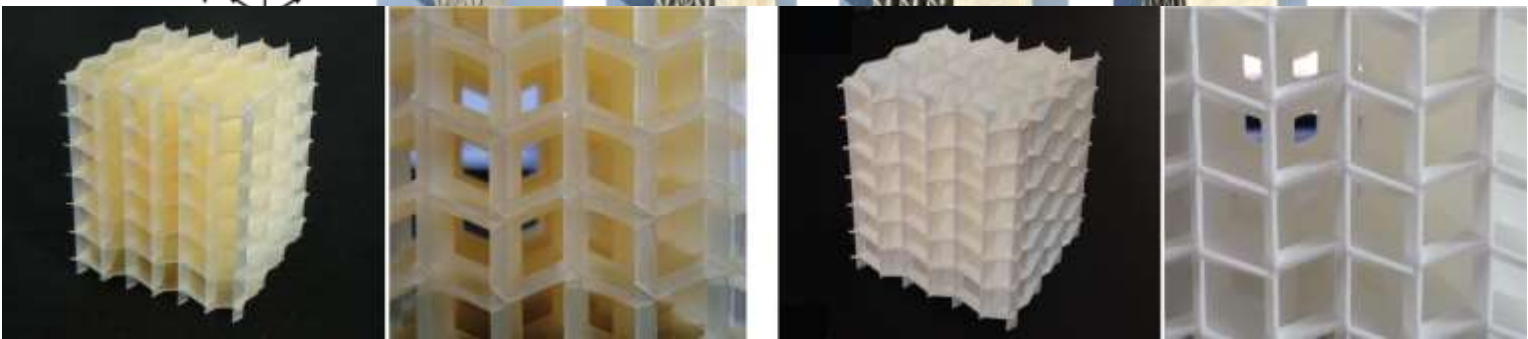
With origami:

- Self-assembly
- Deployable
- Tunable characteristics

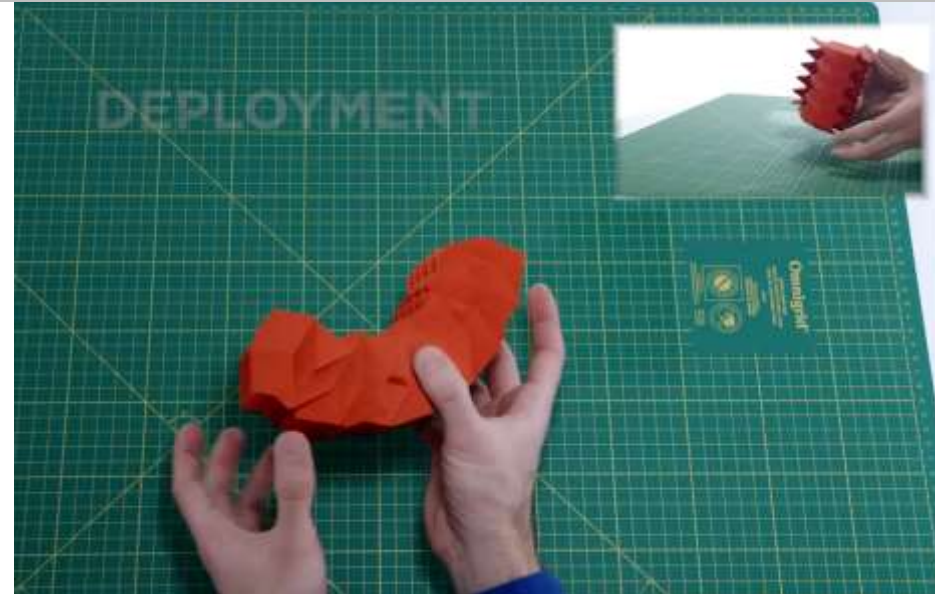
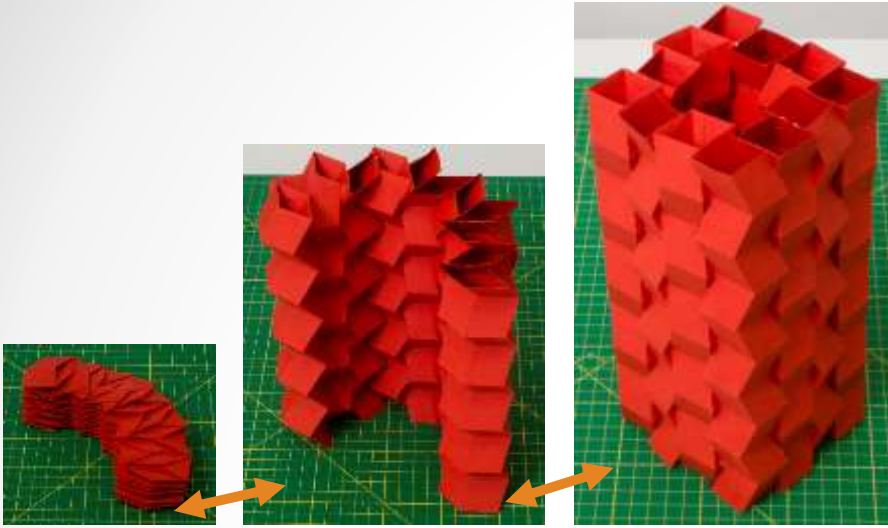
Zipper + Aligned Assemblage



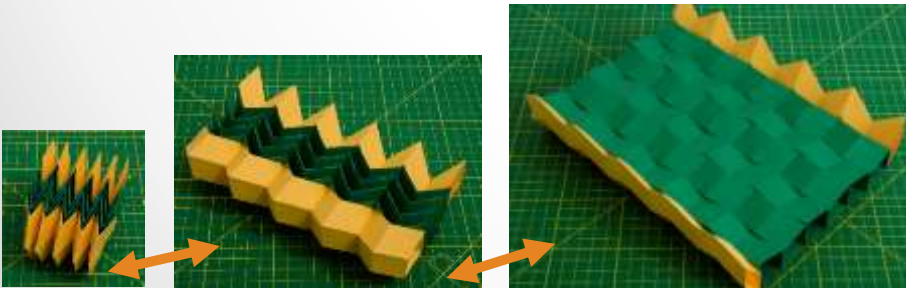
3D Printed Metamaterials



Self-Interlocking Structure

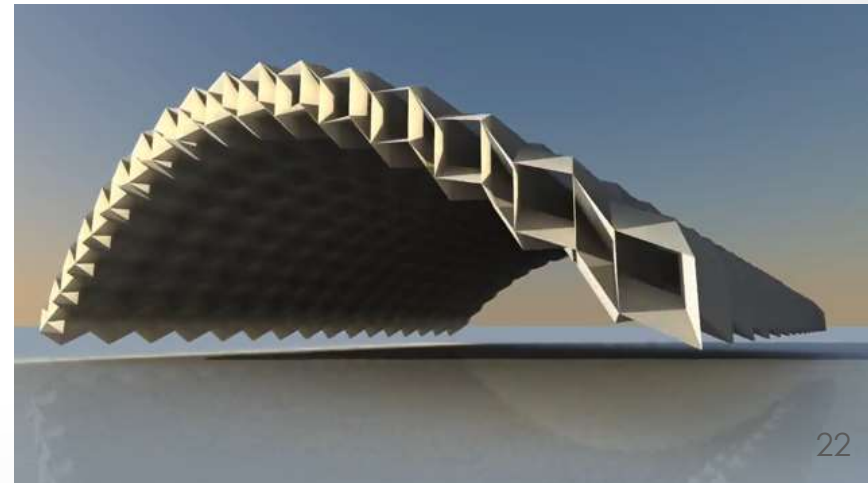
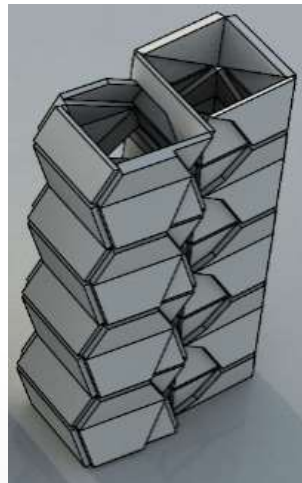
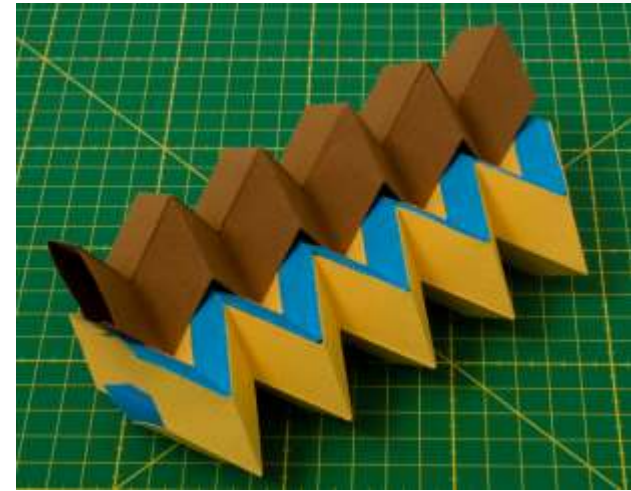
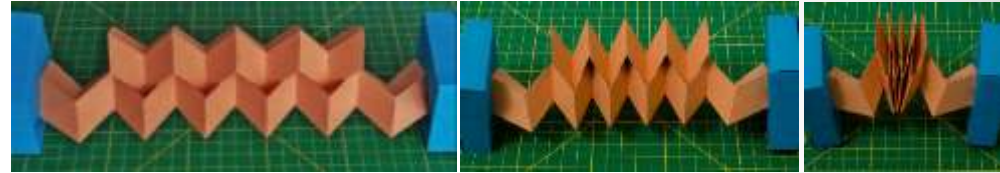


Bridge Structure

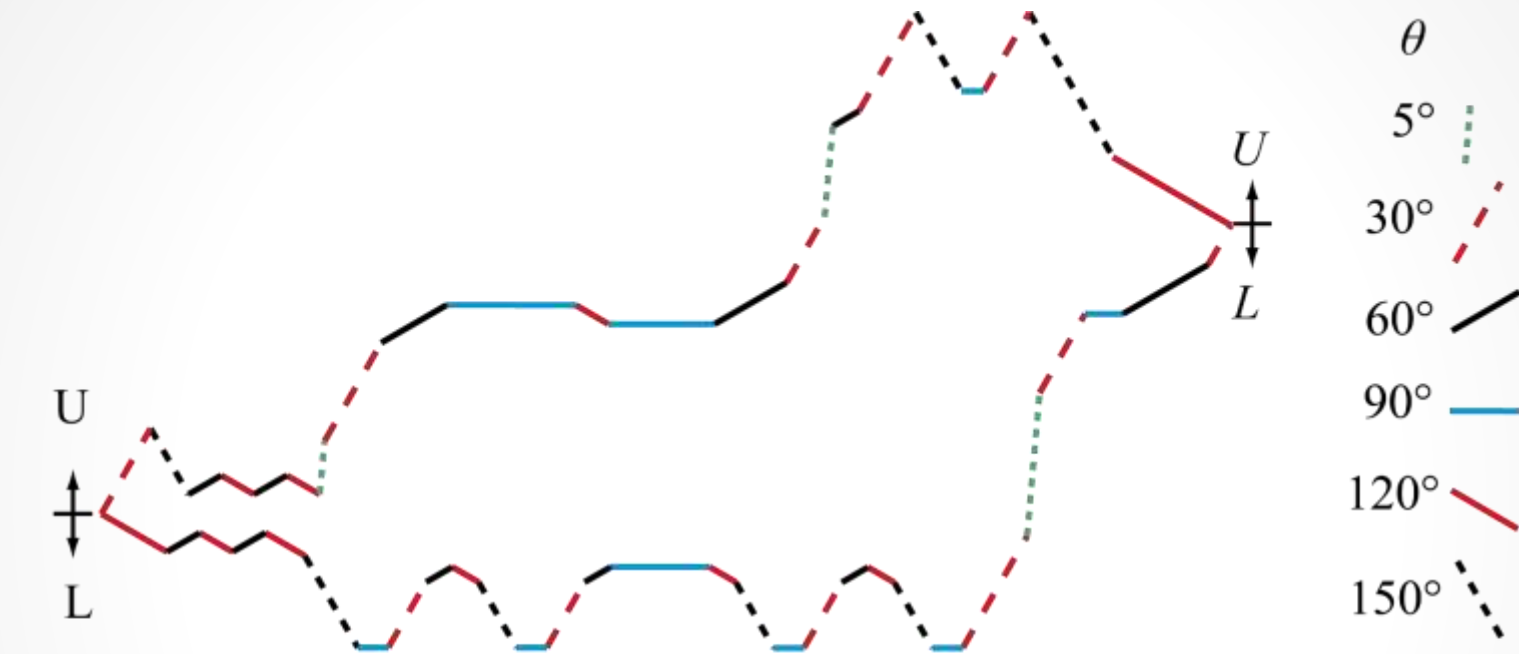


Extensions and Future of Zipper Tubes

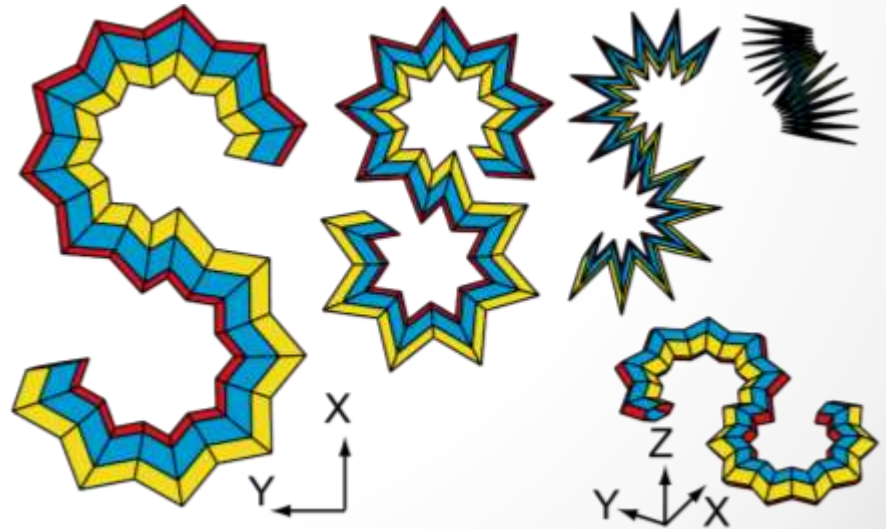
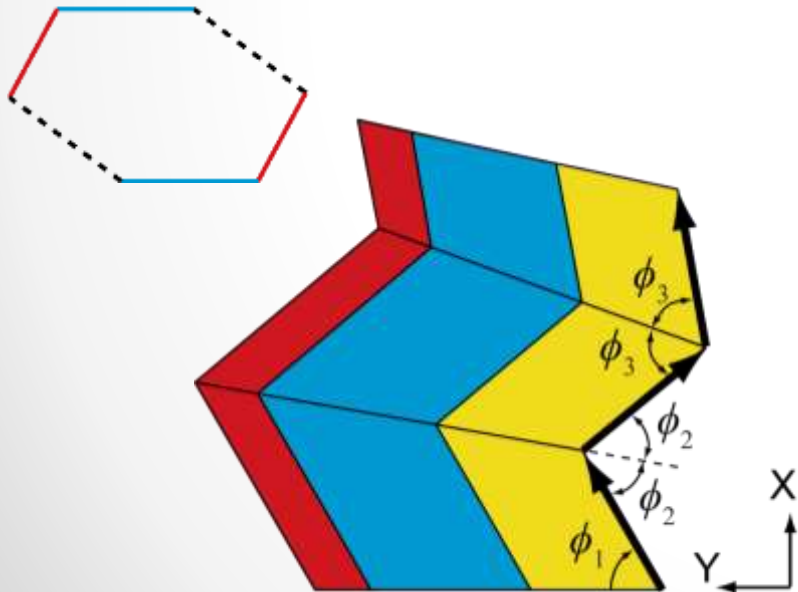
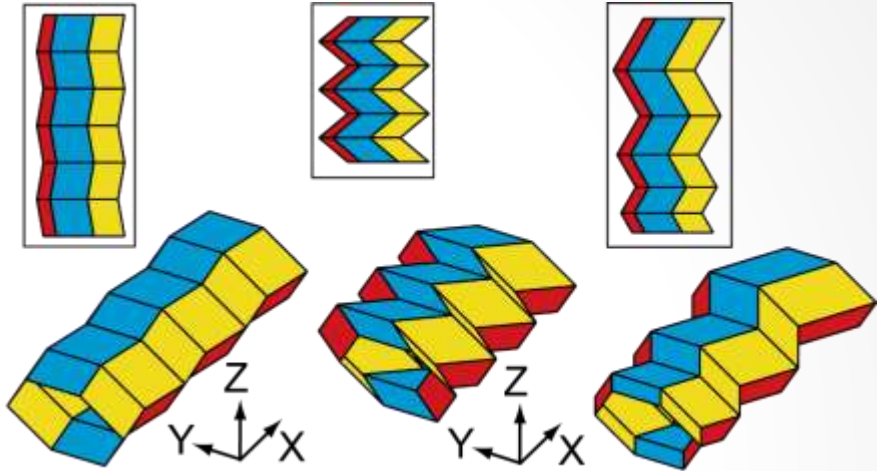
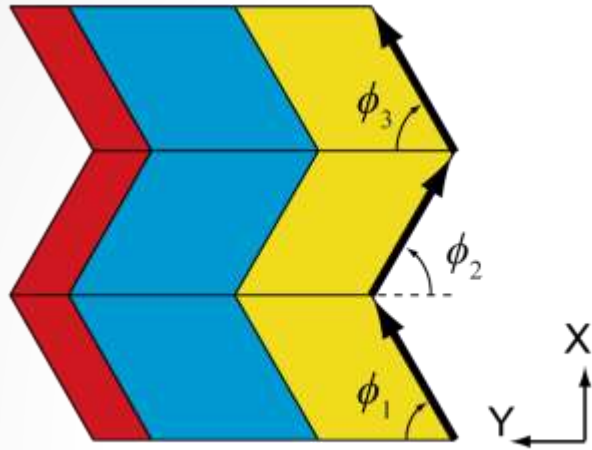
- **Localized adaptations**
- **Geometric variations**
- **Tailored applications at different scales**
 - Thickness
 - Material
 - Fabrication
 -



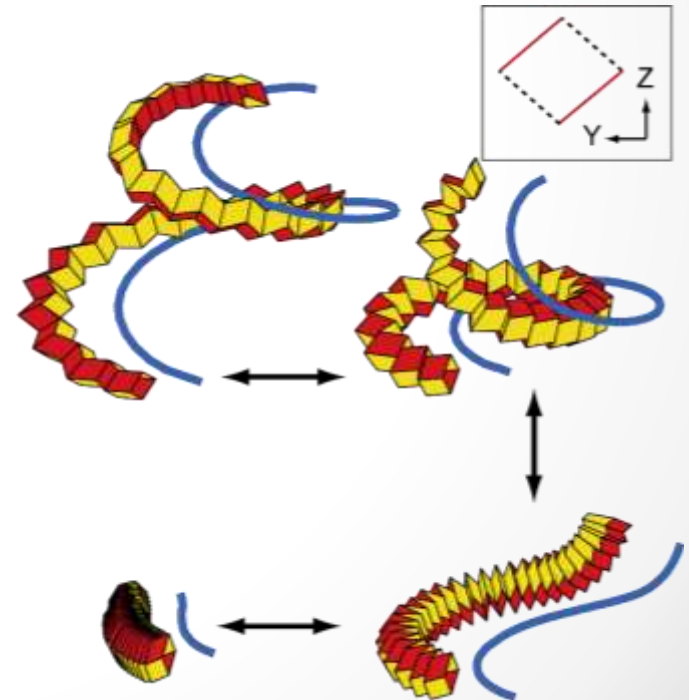
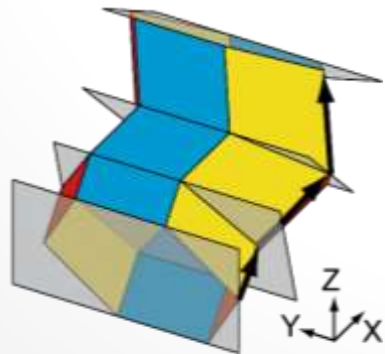
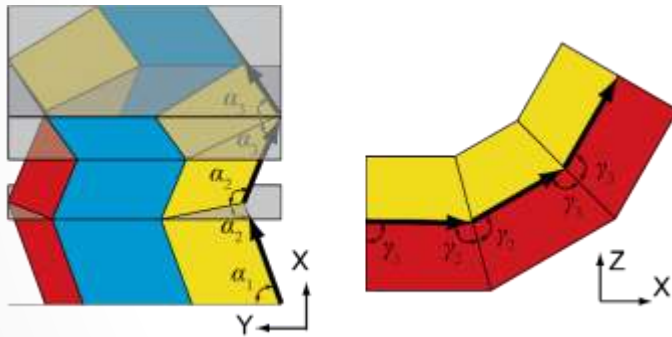
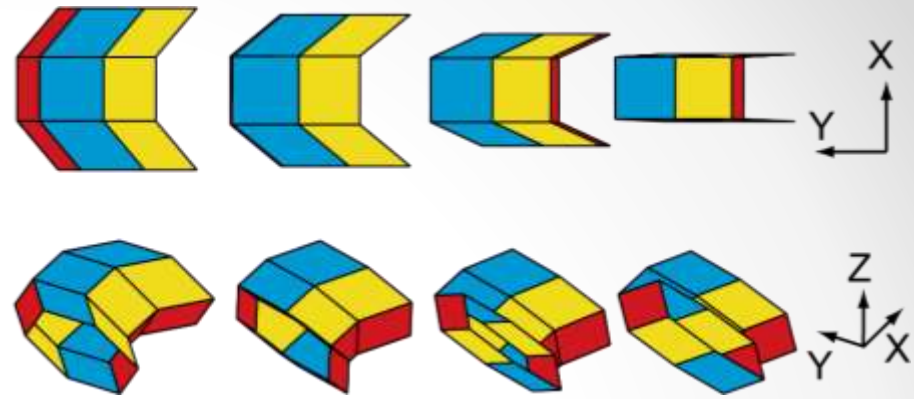
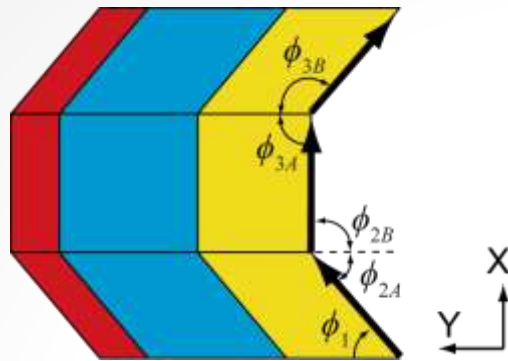
Any Section w/ Translational Symmetry



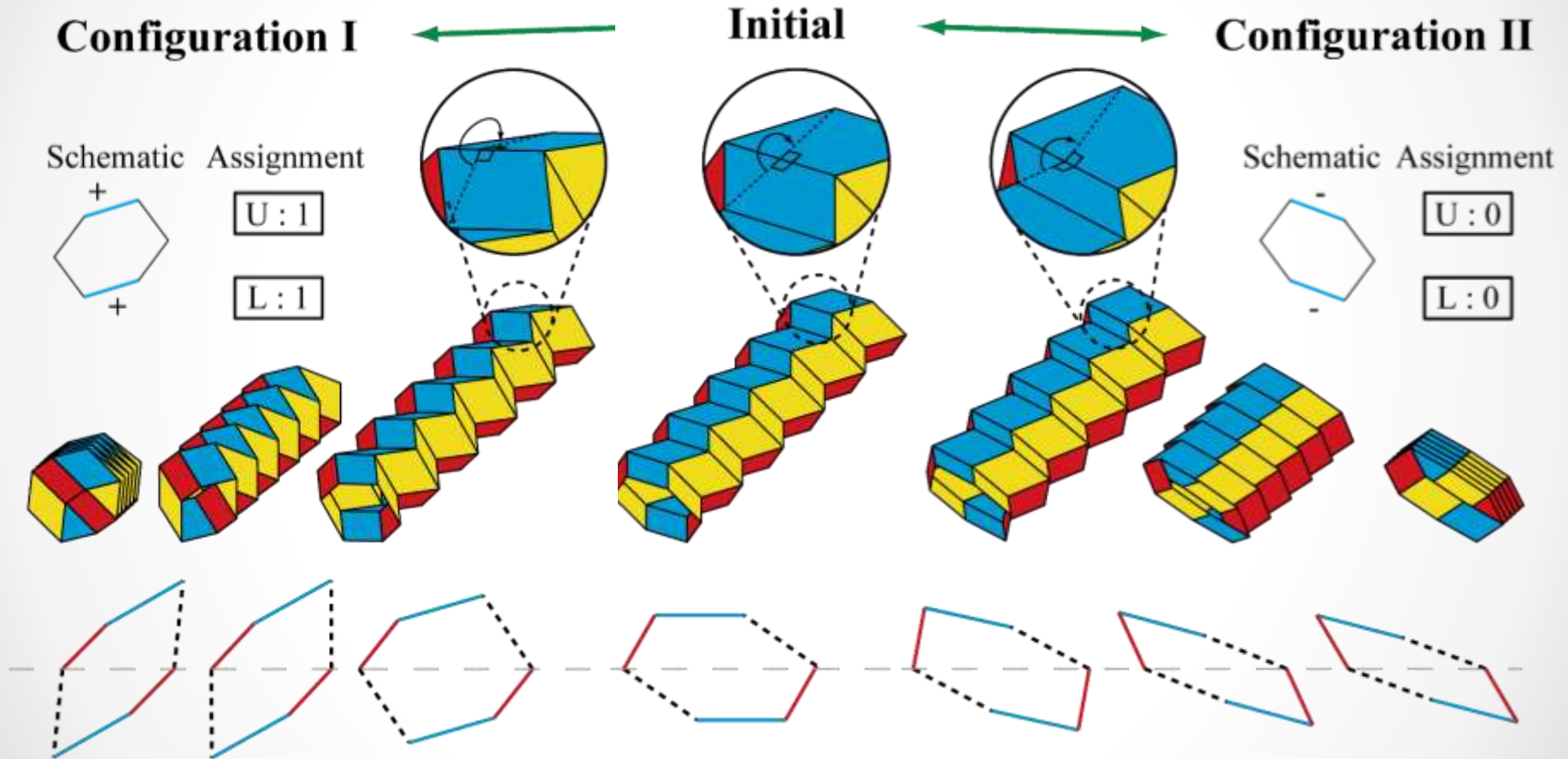
Projection Definitions



Non-symmetric X-Y

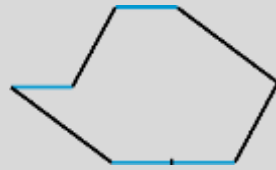


Reconfiguration

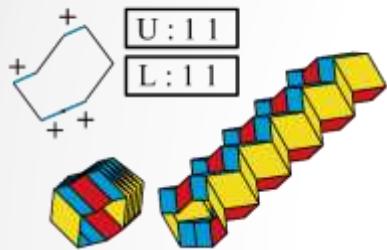


Reconfiguration with $n = 2$ Switches

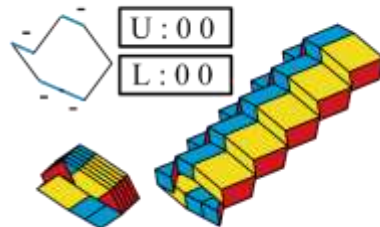
$n = 2$
switches



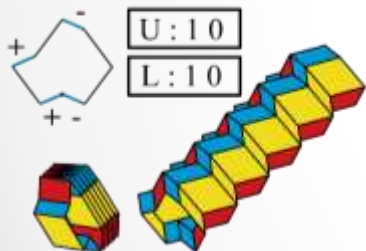
Configuration I



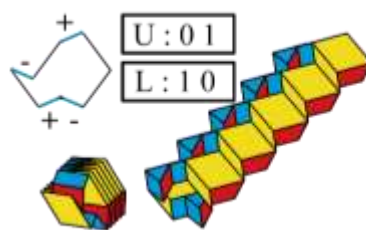
Configuration II



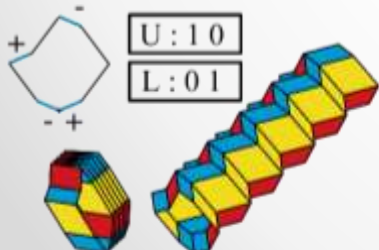
Configuration III



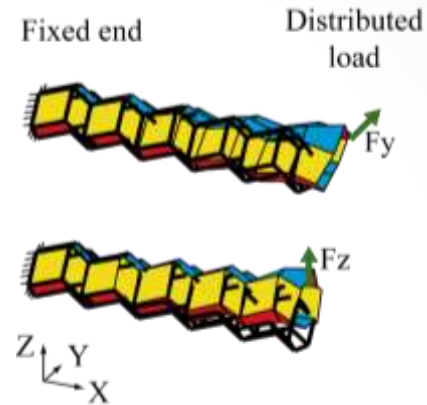
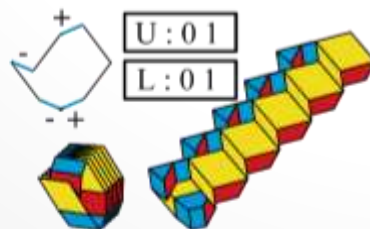
Configuration IV



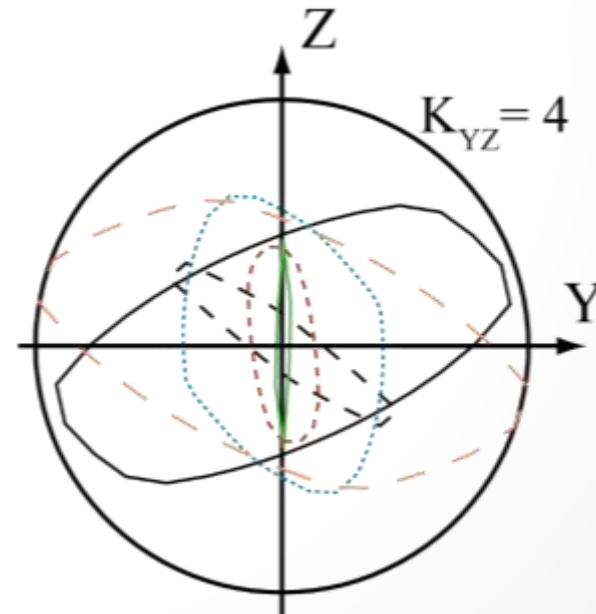
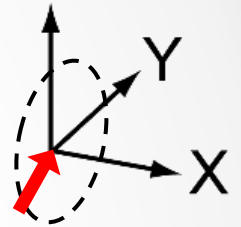
Configuration V



Configuration VI



Z



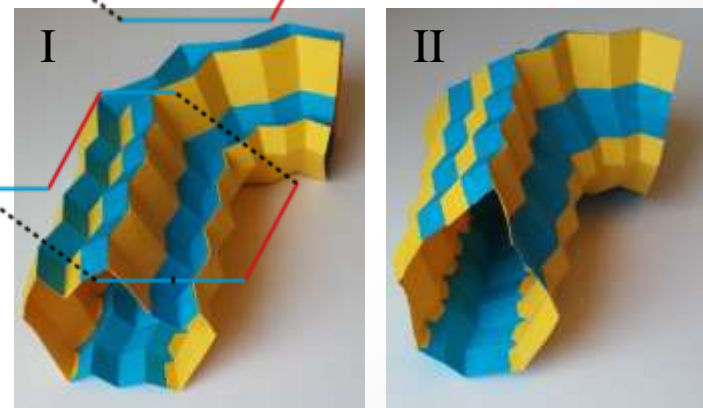
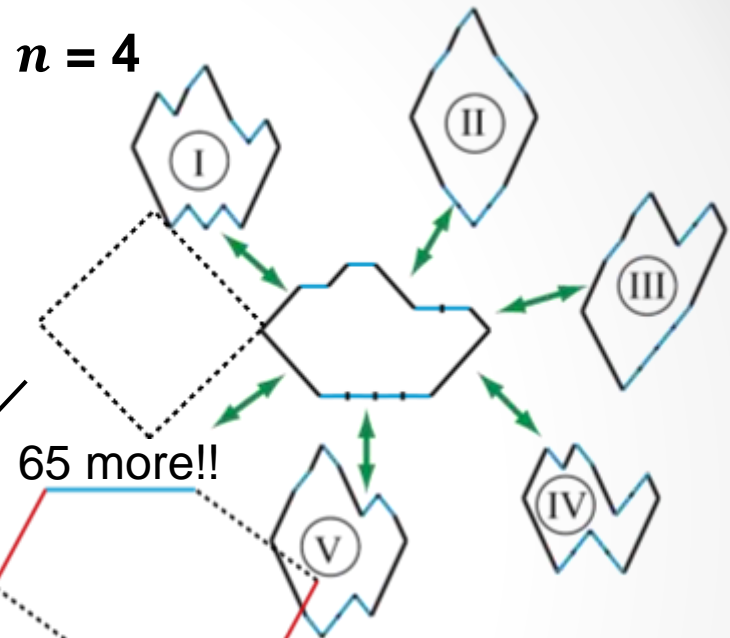
- I ———
- II - - -
- III ·····
- IV ———
- V - - -
- VI ·····

Reconfiguration with More Switches

Central Binomial Coefficient

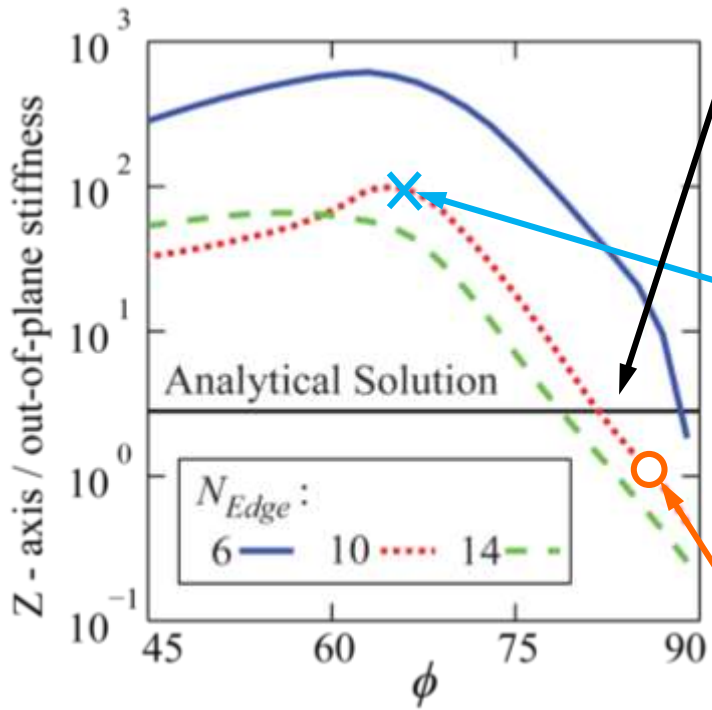
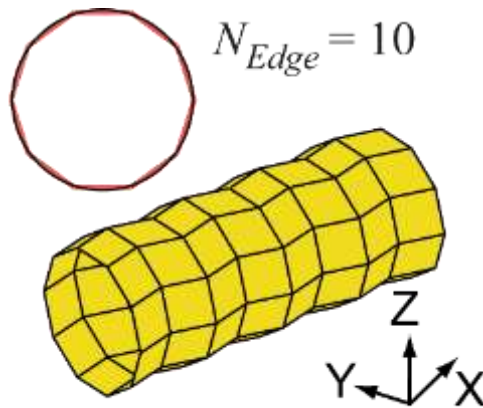
$$\# \text{ Configurations} = \frac{(2n)!}{(n!)^2}$$

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

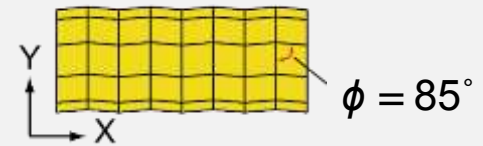
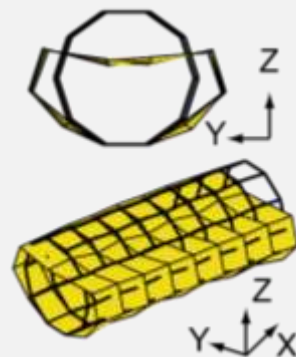
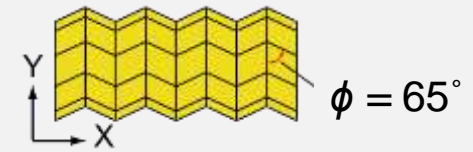
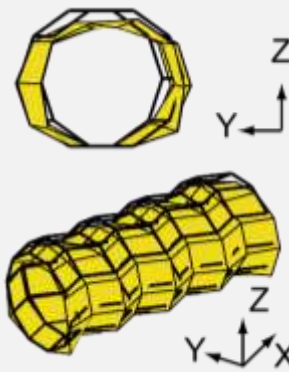
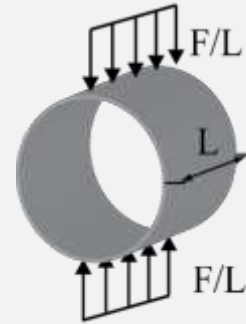
Out-of-Plane Compression of a Pipe



Analytical

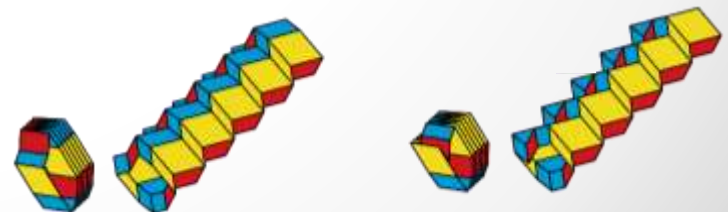
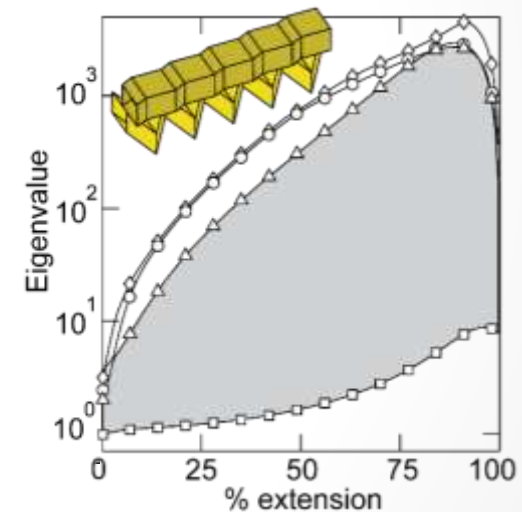
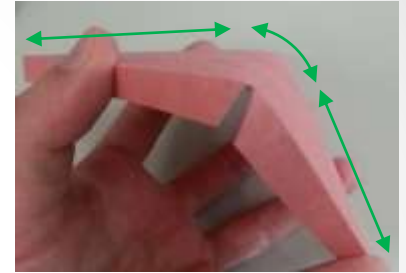
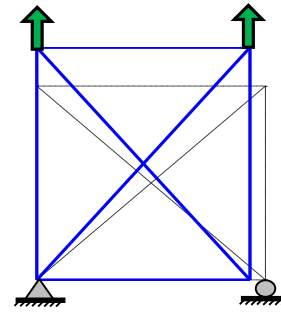
$\phi = 65^\circ$

$\phi = 85^\circ$




Summary of E. Filipov Ph.D. Research

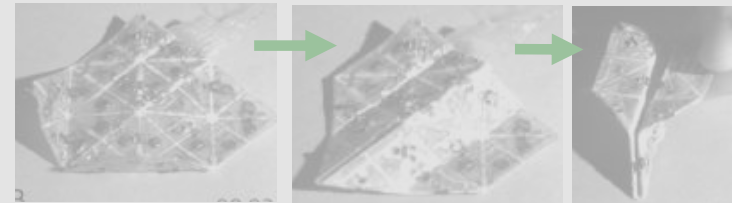
- Improved structural analysis for origami
- Zipper-coupled systems *engage thin sheet in shear/stretching*
- A variety of cellular systems
- Polygonal cross-sections and curved profiles
- Structural tuning through reconfiguration

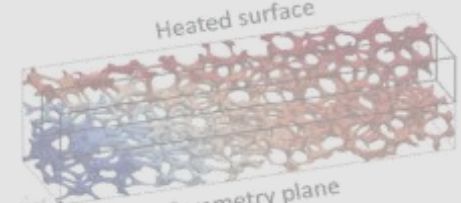


Future Research Directions

1 Analytical Methods for Folding Structures

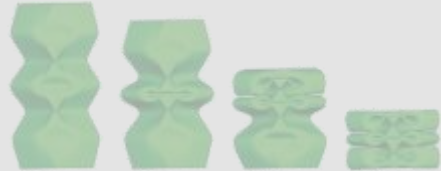
Nonlinearity

Silverberg et al. (2015)

Actuation & Assembly

Hawkes et al. (2010)

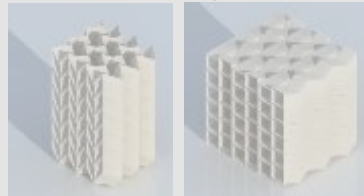
Multi-Physical

Heated surface
Symmetry plane
Bianchi et al. (2015)

2 Cellular Assemblages

Mechanical Function **Tunable Systems**



Ma and You (2014)



Design and Manufacturing



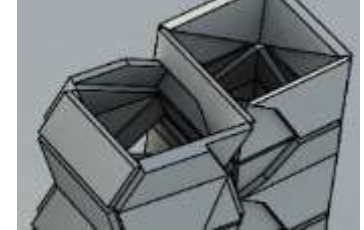
3 Hinged Structures

Deployment

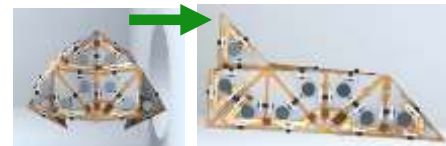


Zirbel et al. (2013)

Thickness



Multi-Functional



Paik et al. (2011)

Hinges

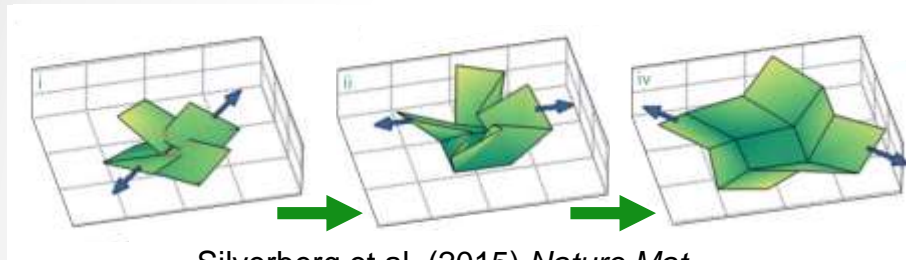


Hobermban (1990)

1 Analytical Methods for Folding Structures

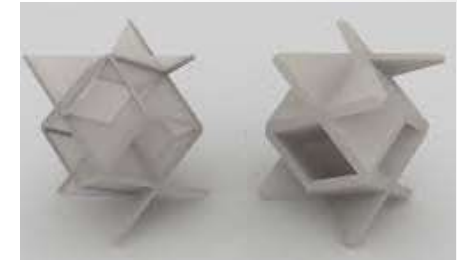
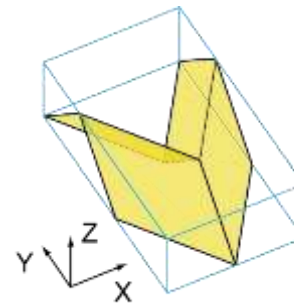
- Large Displacements
- Energy Dissipation
- Instabilities
- Nonlinearities
- Hinge Eccentricity
- Stress Concentrations

Bistable Square-Twist



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

Parametric Unit-Cell Analyses

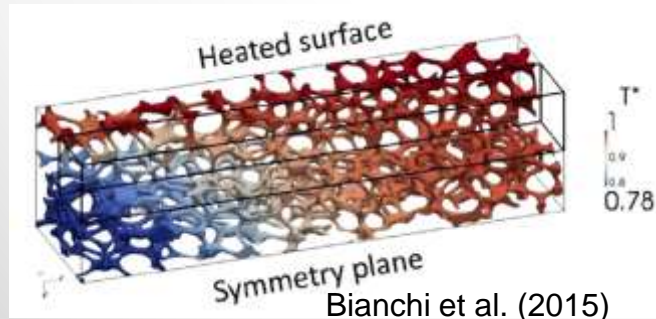


Cheung et al. (2014)

Multi-Physical Models

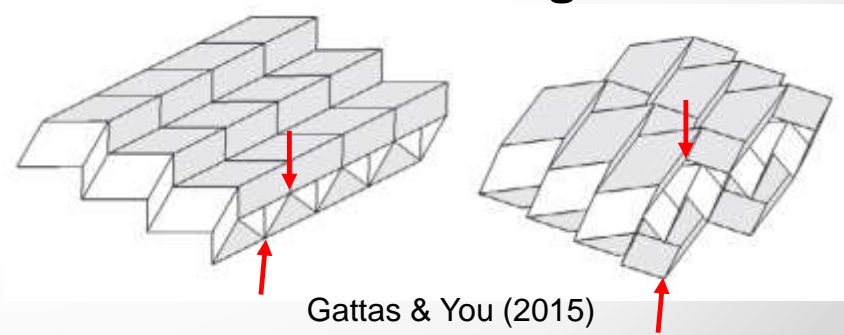
- Thermo-Mechanical
- Acoustics
- Thermodynamics
- Electromagnetics
- Fluid-Structure

Heat Transfer / Heat Effects



Bianchi et al. (2015)

Cellular Reconfiguration



Gattas & You (2015)

2 Metamaterials from Cellular Assemblages

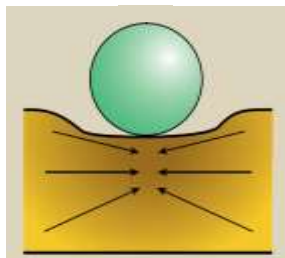
Mechanical Metamaterials

Blast Resistance

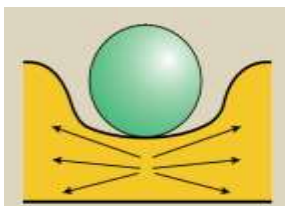


Schenk et al. (2014)

Auxetic



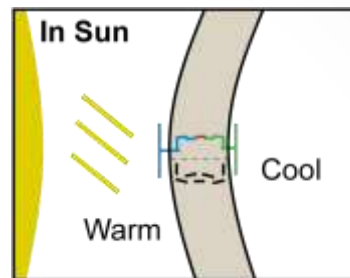
Non-auxetic



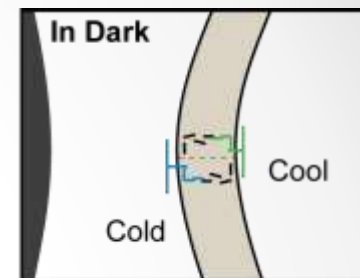
Alderson (1999)

Variable Thermal Conductivity

In Space

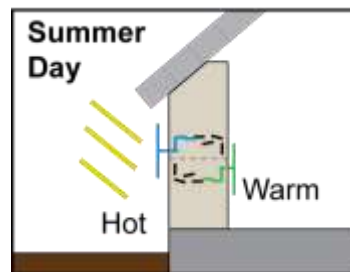


Thermal Bridging

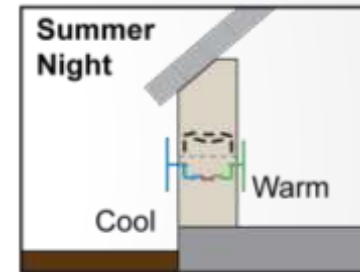


High Insulation

On Earth

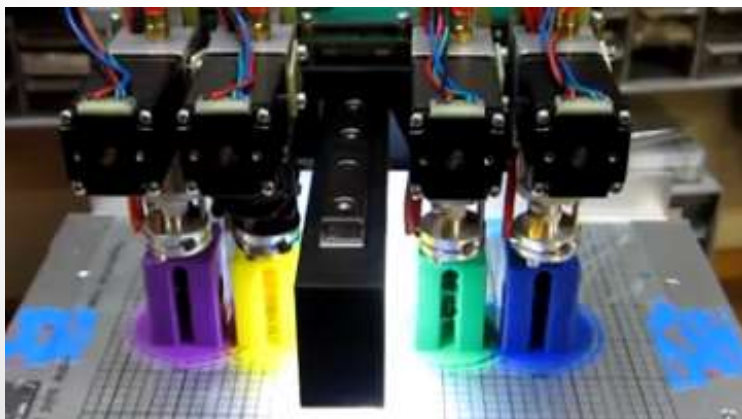


High Insulation



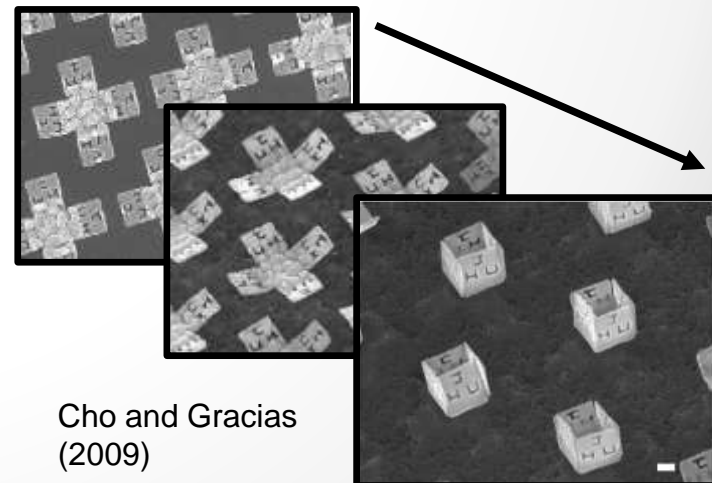
Thermal Bridging

Additive Manufacturing



HyRel 3D Printers (2016)

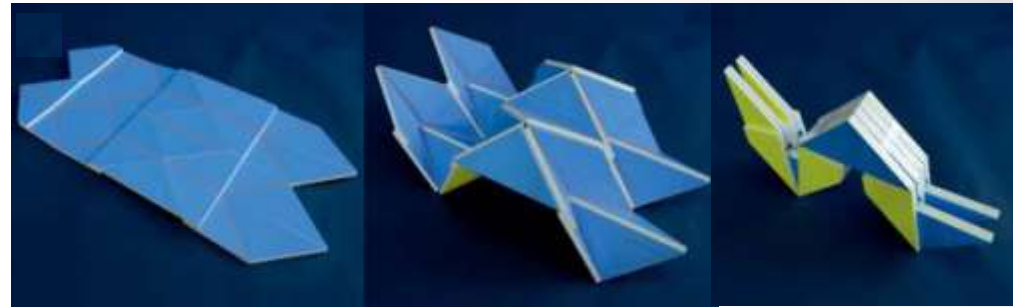
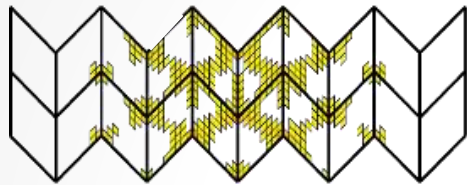
Self-Assembly of Perforated Sheets



Cho and Gracias (2009)

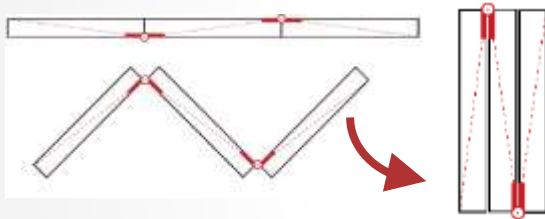
3 Hinged Systems with Thickness

- Optimal packing and panels with varying thickness



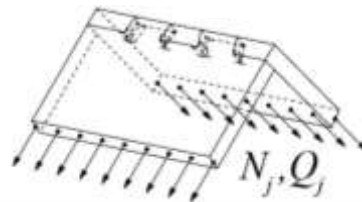
Chen et al. (2015) *Science*

- Hinge packing



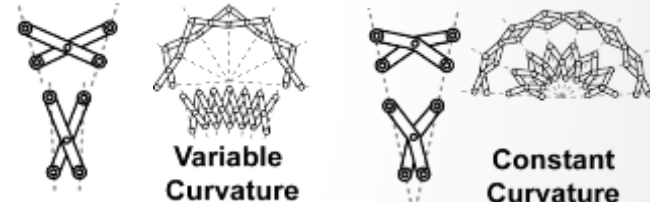
Tachi (2010)

- Hinge design



Roche, Mattoni & Weinand (2015)

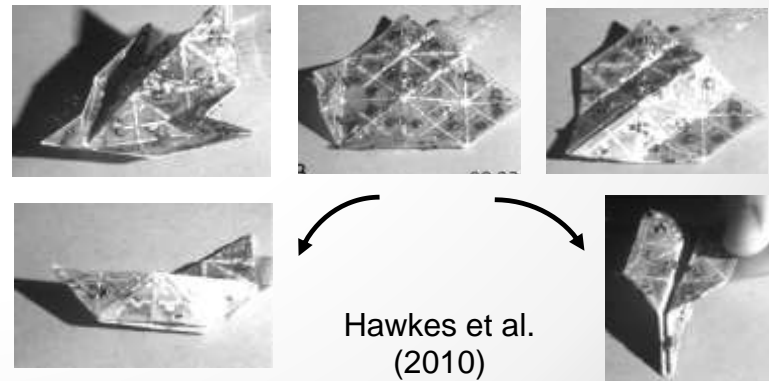
- Added function with hinges



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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