Design of Origami-based Actuators*

Minoru Taya, Director
Center for Intelligent Materials and Systems
Nabtesco Endowed Chair Professor
University of Washington
Email: tayam@uw.edu
http://depts.washington.edu/cims/
Collaborators: Profs. Miura, Tachi, University of Tokyo
* This work was supported by a AFOSR grant and Nabtesco contract to University of Washington

November 26, 2013

Contents of my talk

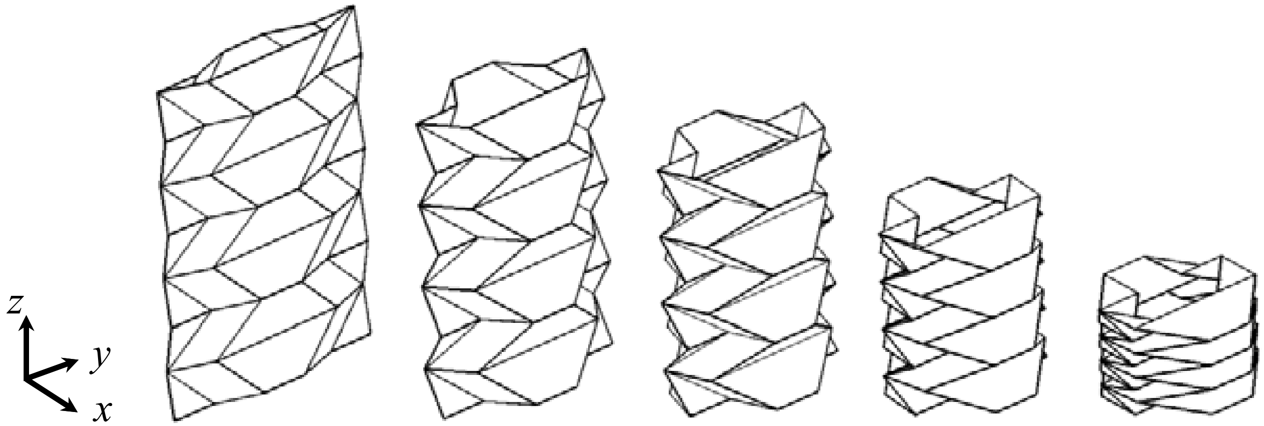
- 1. Tachi-Miura Bellow under compressive force
- 2. Bellow actuator based on FSMA composite
- 3. Bioinspired design of SMA actuator for beetle wing folding/unfolding
- 4. free-falling MAV made of origami

1. Introduction

Goal: Applying "Origami" to engineering application such as actuators and developable space structures

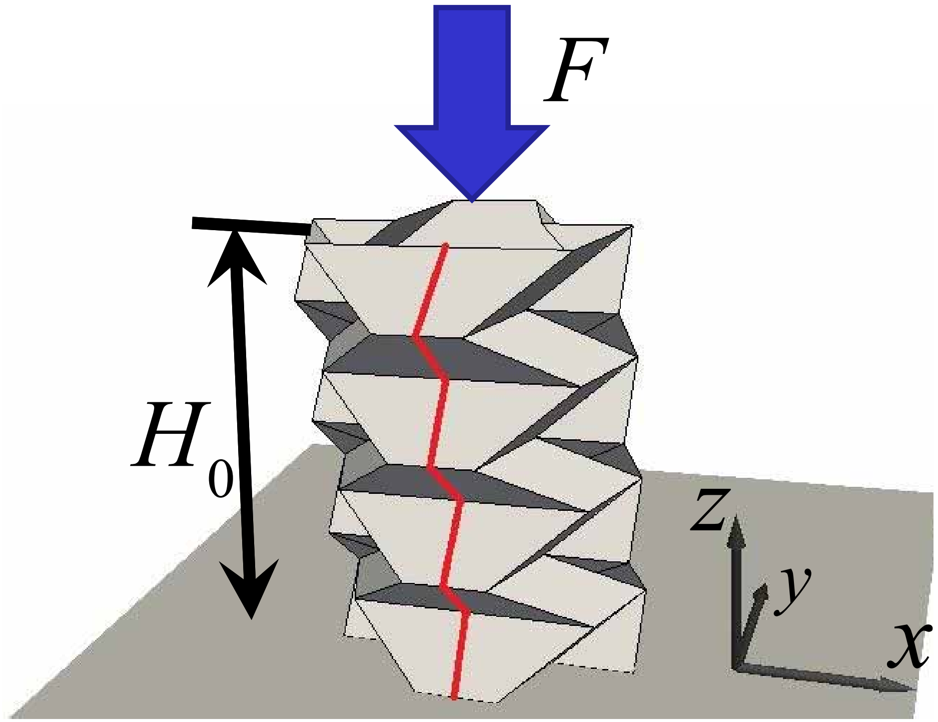
Rigid-foldable structures

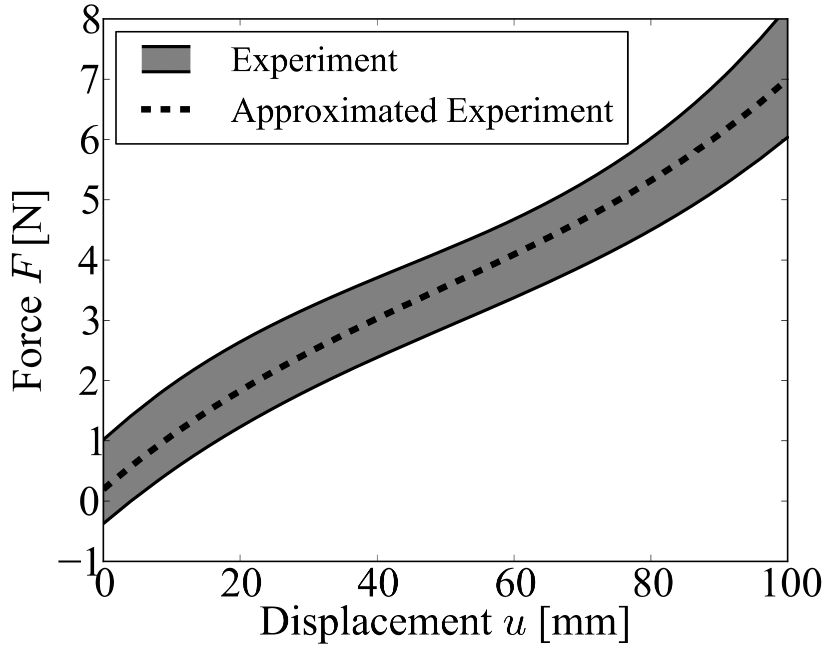
– Deformation takes place only along the crease lines



Tachi-Miura Polyhedron

Folding Behavior of TMP (Proc. Roy. Lond. 2013, A469,20130351)





Conditions for compression test of TMP bellow

Initial height H_0 [mm]	Total displacement [mm]	Displacement rate [mm/sec]
150	100	2.0

3. Folding Behavior of TMP

Comparison between experiment and prediction

Extended Hamilton Principle (Taya and Mura, 1974)

$$\delta J = \delta \int_{t_0}^{t_1} (T - U)\, dt = \int_{t_0}^{t_1} \delta D dt$$

Compression Test of TMP

$$\delta J = \int_0^{t_f} \left\{ \delta \int_V \frac{1}{2} v^2 \rho_d dV - \left(\int_{l_i} 2M \delta\theta dl_i - \int_S F \delta u dS \right) \right\} dt = \int_0^{t_f} \int_{l_i} \delta D dl_i dt$$

Kinetic Energy — Bending Work — Mechanical Work — Energy Dissipation

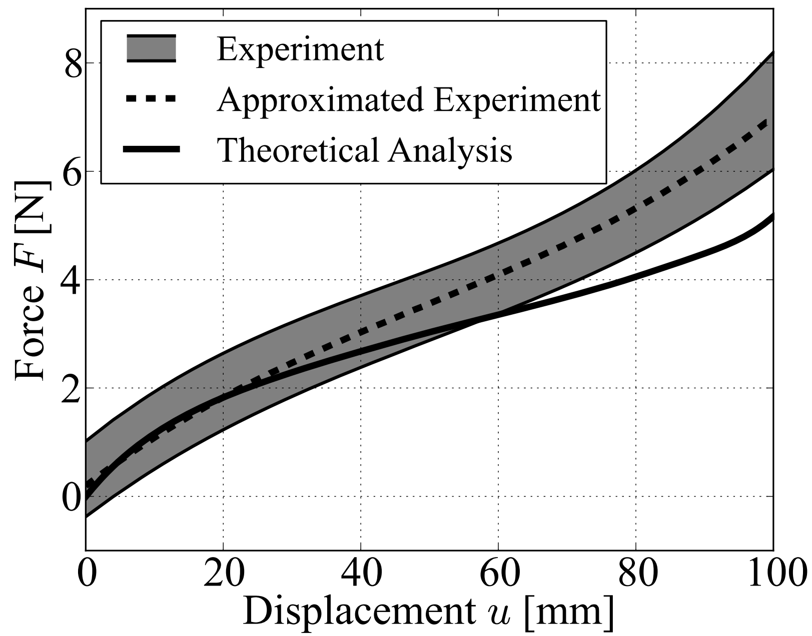
Kinetic Energy: Negligible due to compression speed

Bending Work: Apply the prediction force

$$B = \int_{l_i} 2M \delta\theta dl_i = \int_s F' du$$

3. Folding Behavior of TMP

Comparison between experiment and prediction



Result of compression test

Mechanical Work ***W*** **[J]**	**Bending Work** ***B*** **[J]**	**δJ** **[J]**	**$\delta J/W$** **[%]**
0.338	0.292	0.046	13.6

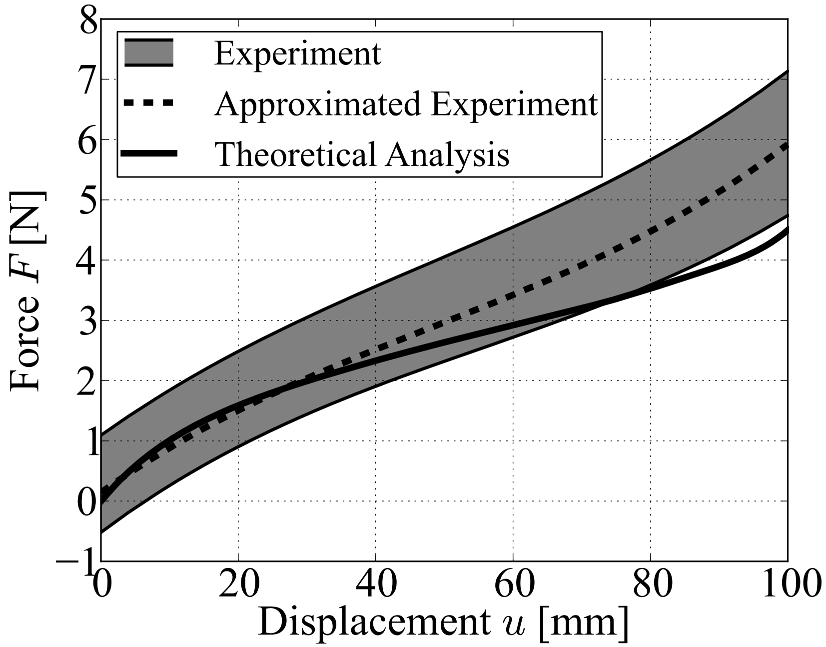
Where are the energy dissipations ?

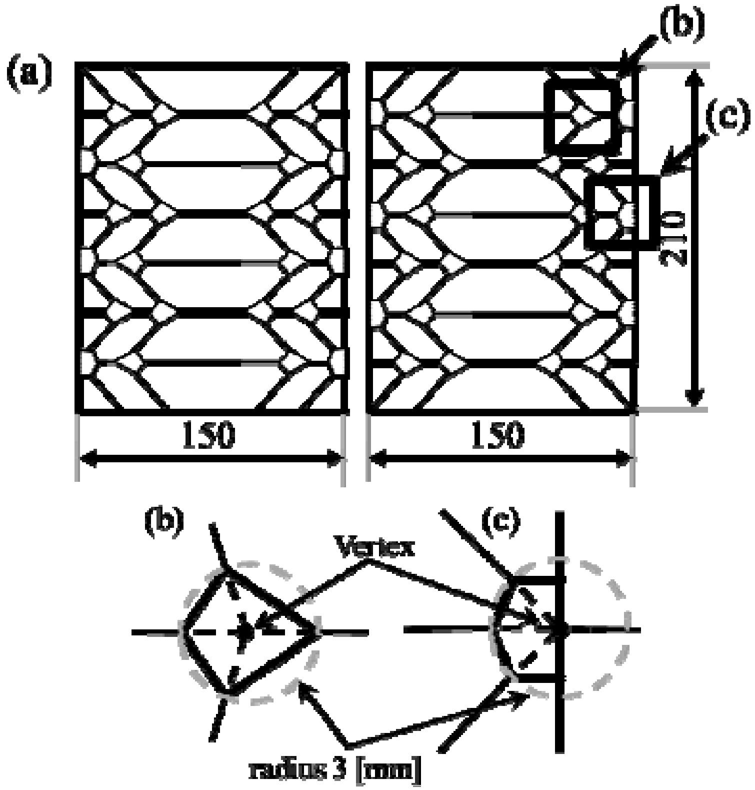
- 1. plastic work at the high stress concentration points; vertices and crease lines
- 2. friction work of the top and bottom surfaces over the fixed boundary

3. Folding Behavior of TMP

Comparison between experiment and prediction

TMP without vertices





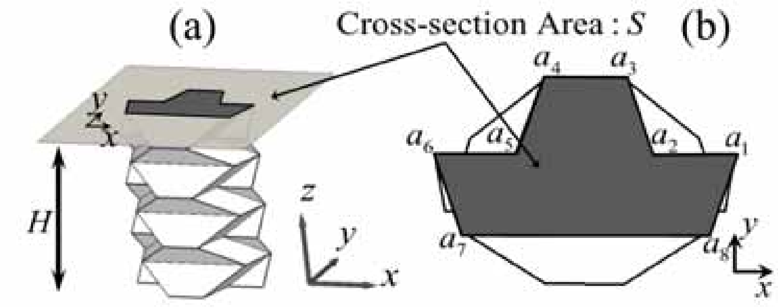
Result of compression test

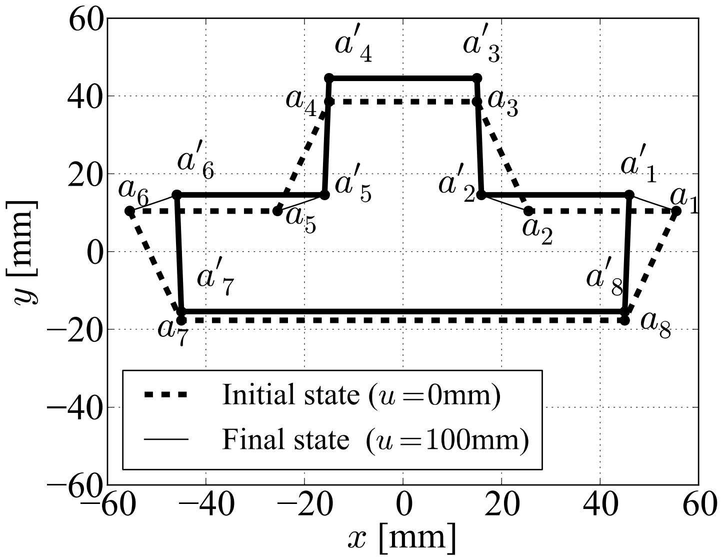
Mechanical Work W [J]	Bending Work B [J]	δJ [J]	$\delta J/W$ [%]
0.285	0.254	0.031	10.9

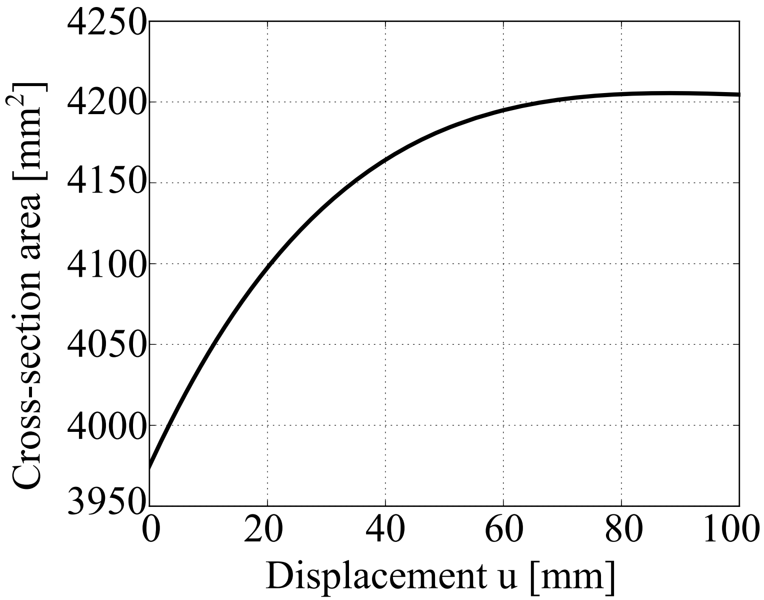
3. Folding Behavior of TMP

Energy Dissipation

1) Friction at the top and bottom

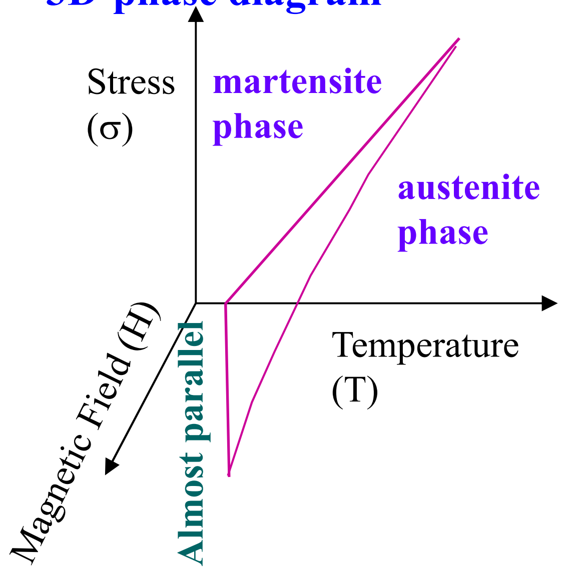






Concept A: Hybrid Mechanism of FSMA and FSMA composites

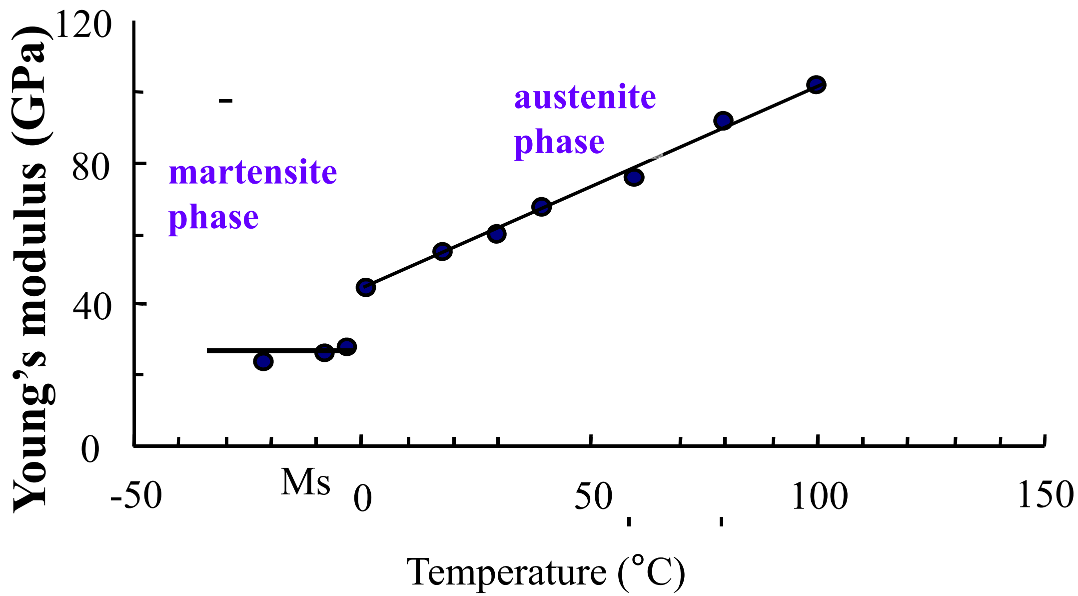
3D-phase diagram



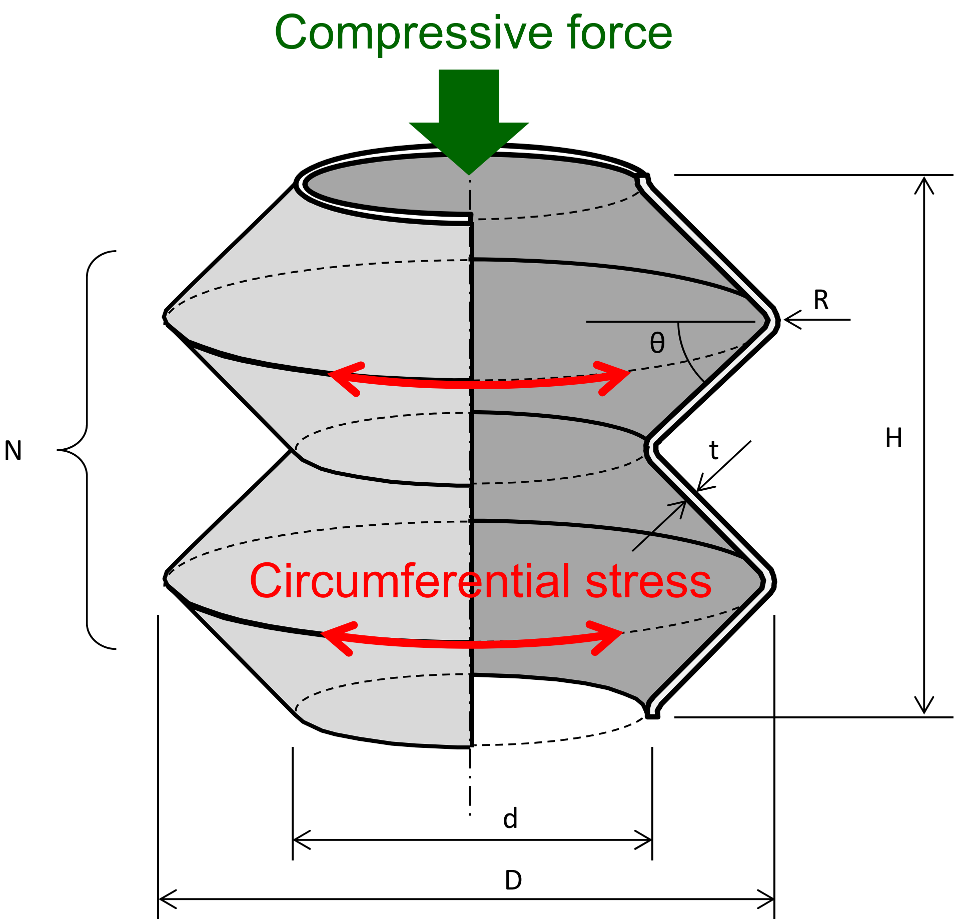
The effect of uniform (constant) magnetic field is very small

$$\sigma^{t}_{ij,j} + f^{m}_{i} = \rho \dot{v}_{i}$$
$$f^{m}_{i} = \mu_0 M^{p}_{j} H_{j,i}$$

Chain-reaction:
Applied magnetic field gradient
→ magnetic force
→ Stress-induced martensite transformation
→ low stiffness of FePd
→ large deformation



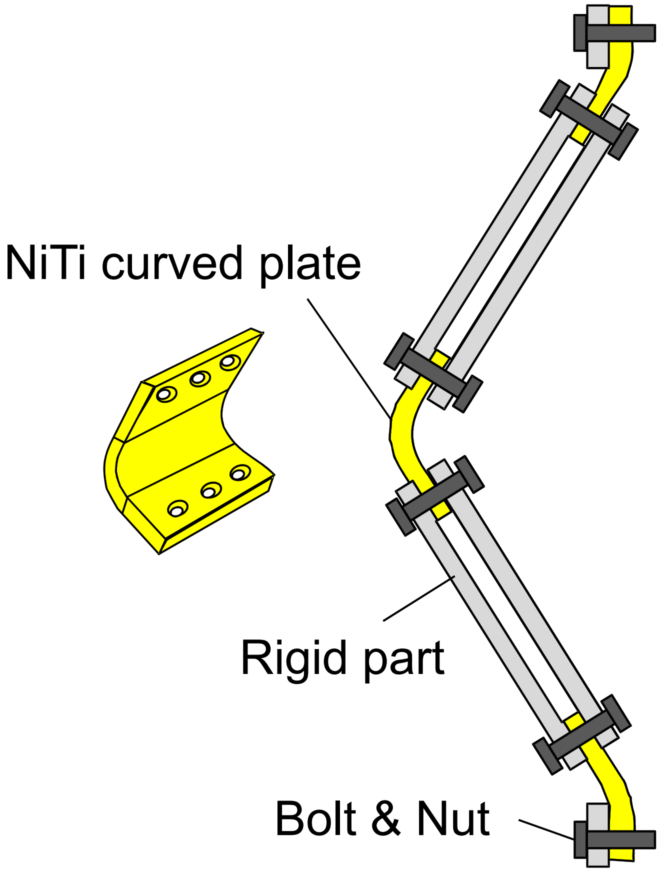
Early bellow design

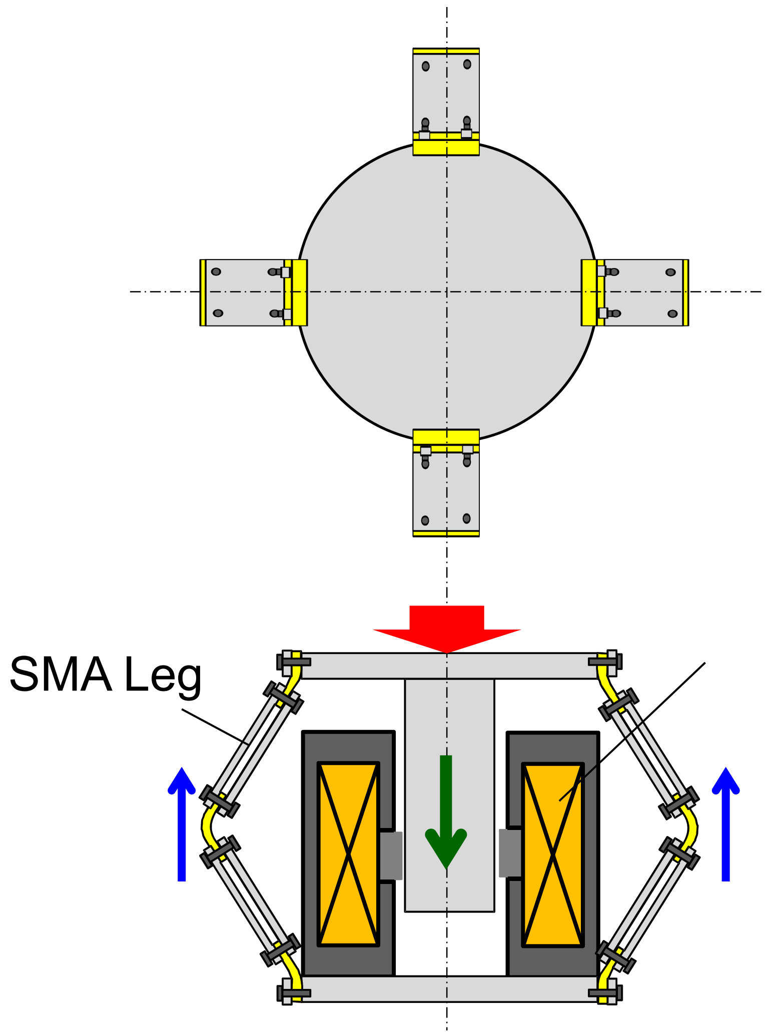


- Parametric study on this bellow using FEA has been done to optimize the design to reduce the reaction force.
- However, it was found that this shape is not suitable to reduce the reaction force because of its circumferential stress.
- Moreover, this shape is not easy to manufacture.

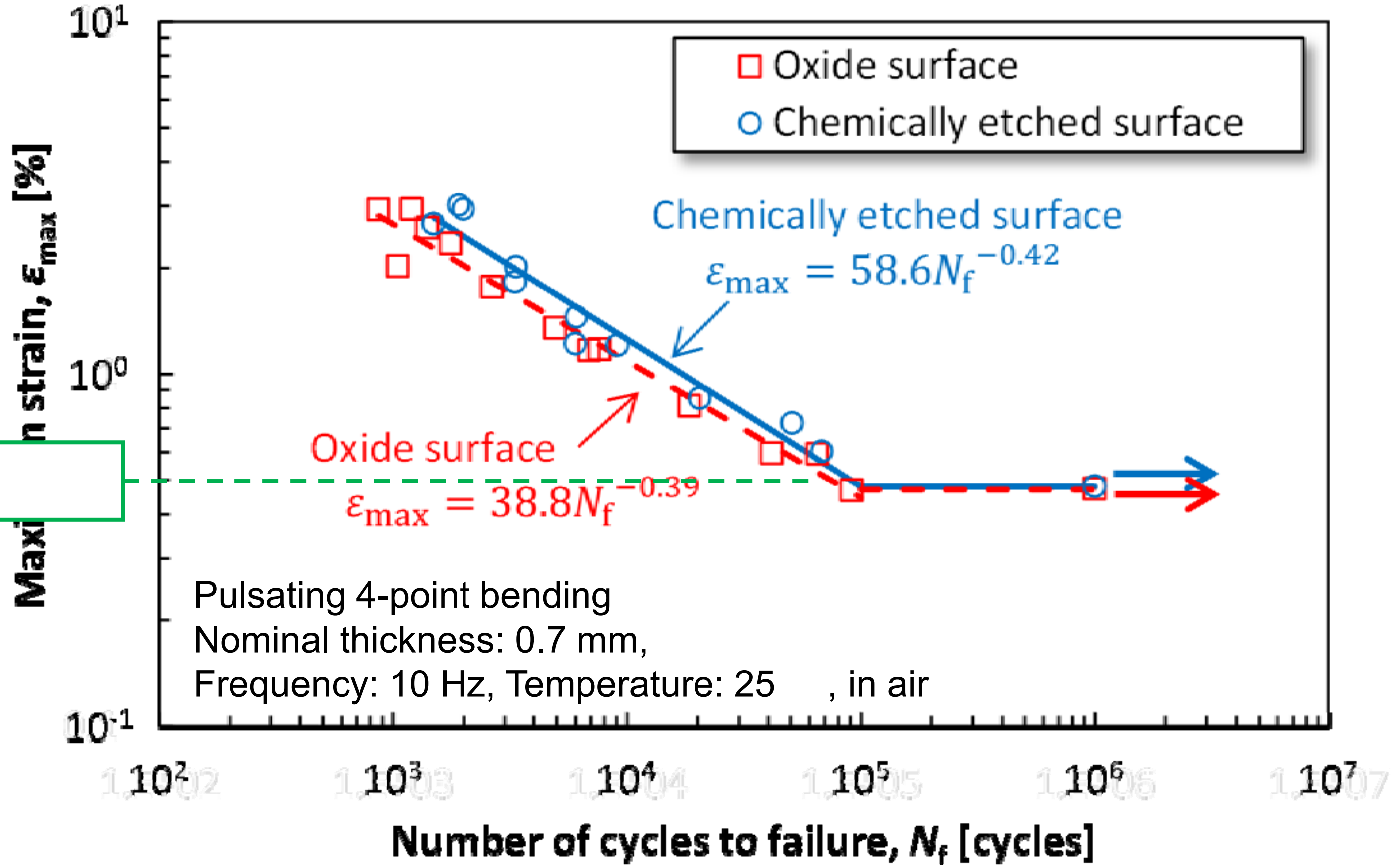
Switched to new design

Segmented type bellow actuator





Bending fatigue curve



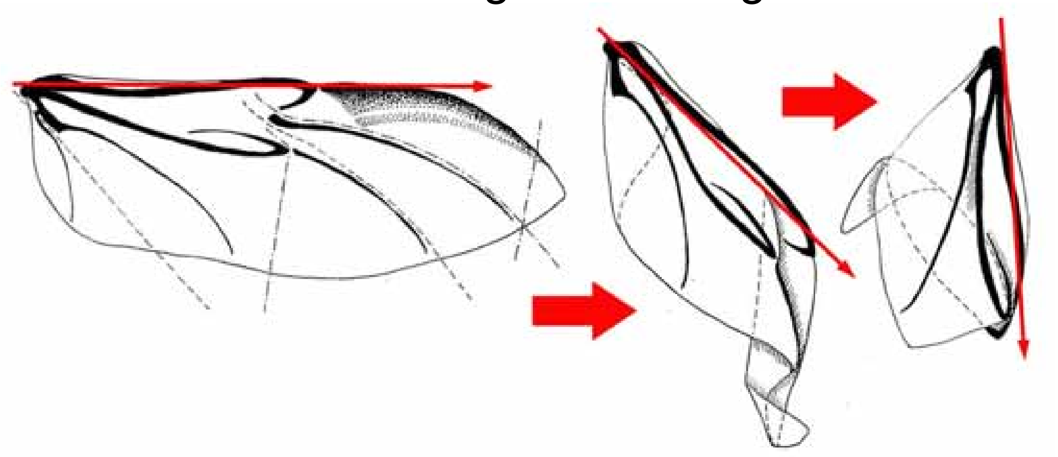
- Fatigue life of chemically etched specimen is slightly longer.
- Fatigue limit is around proportional limit strain (ε_{pr}).

Wing folding and unfolding of a beetle (*Allomyrina Dichotoma)*

During the time on the ground the beetles store their hind wings under a thick forewing (Elytron) from damages.

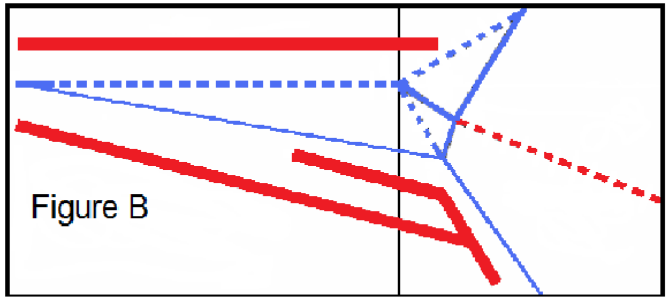
When the beetle is about to fly, it open's the thick fore wing and forcefully opens the hind wing to straighten the wing.

Unfolding of hindwing

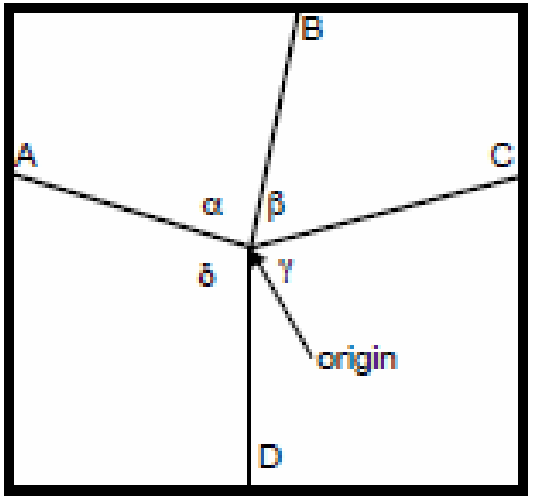


(Nomura, 2010)

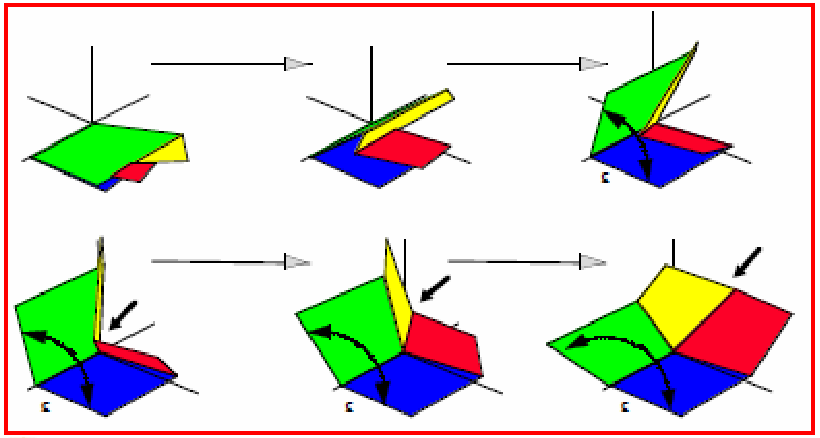
Past Study-1 on origami folding(Haas, 1996)



(Haas, 1996)



The complex wing of the beetle is a combination of several basic vertex mechanism.



At every vertex where 4 lines converge 3 mountain folds to 1 valley fold or 3 valley fold to 1 mountain fold is formed.

Conclusion

Folding Ratio = $\frac{\text{Surface Area of Unfolded Wing}}{\text{Surface Area of Folded Wing}}$

Best ratio degrees		
Alpha degree	**Beta degree**	**Ratio**
14°	85°	3.14

Ratio Comparison	
Real Beetle Wing	bio-inspired Wing
2.32	3.141

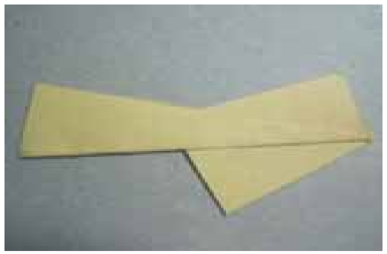
Folded

Unfolded

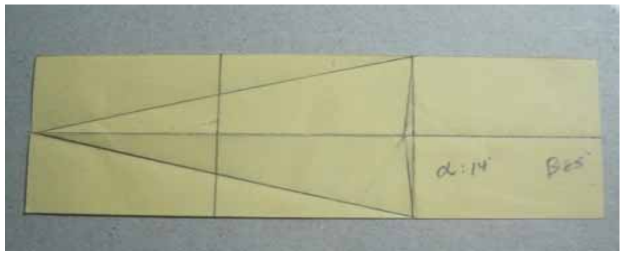
Beetle Wing

→

Bio-inspired Wing

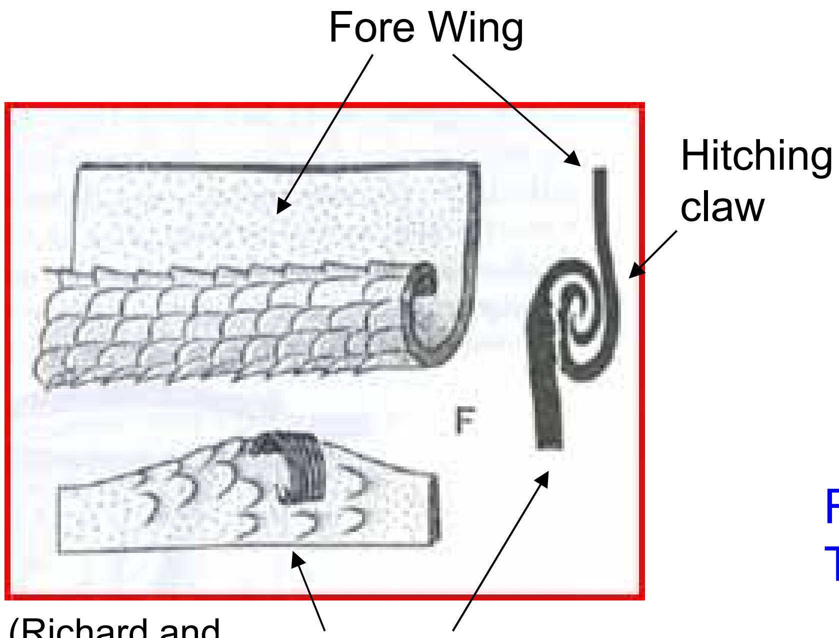


→



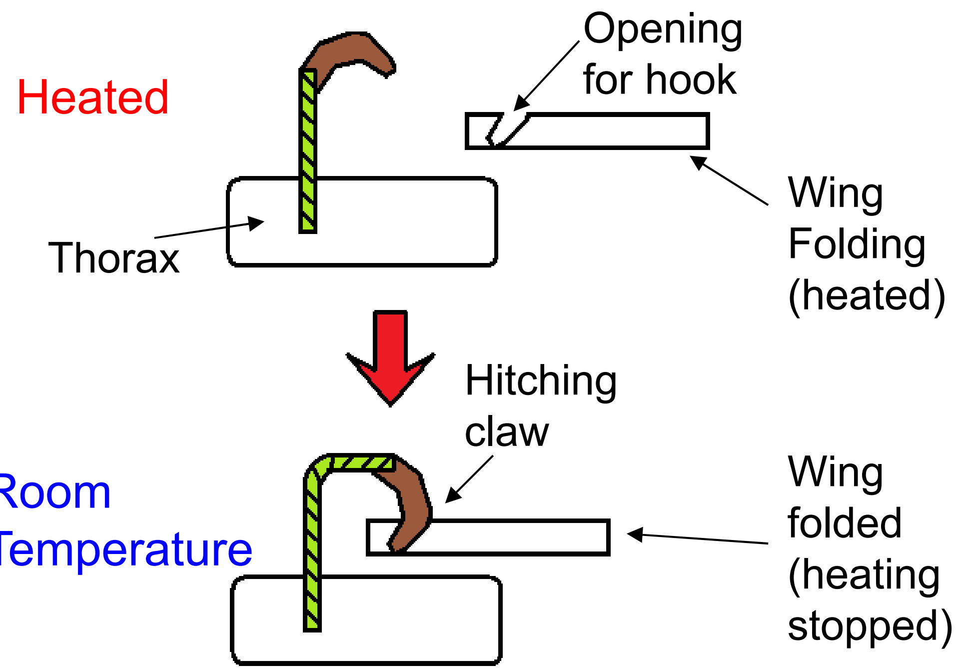
Hitching methods

Nature Design: Insect wing hitching method

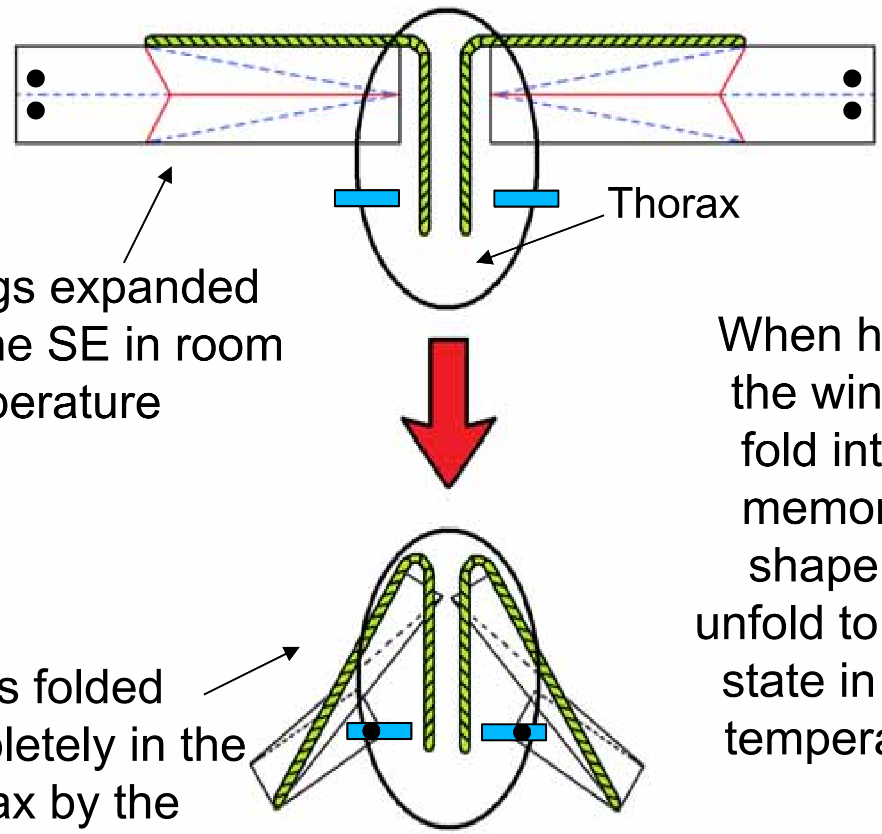


(Richard and Davies, 1977)

Bio-inspired hitching method



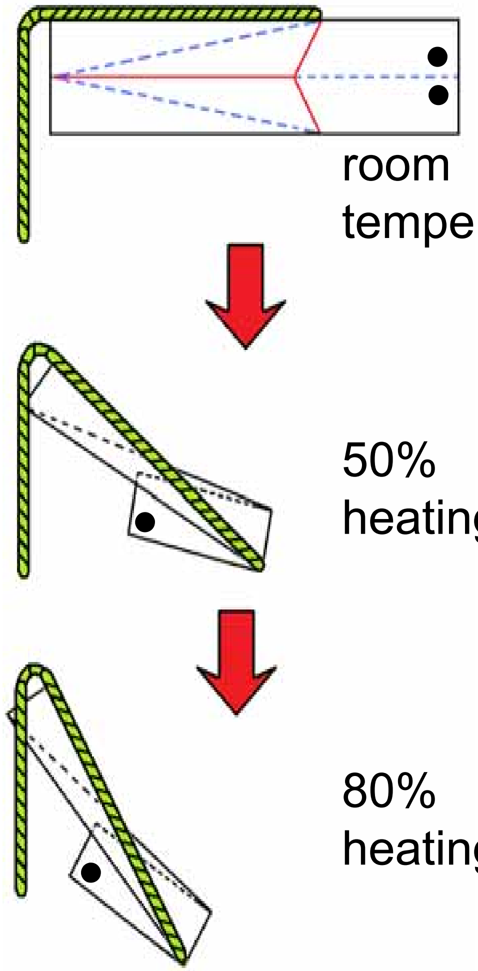
Bio-inspired Wing Storage



Wings expanded by the SE in room temperature

Wings folded completely in the Thorax by the SMP, SMA and remain folded by the hook.

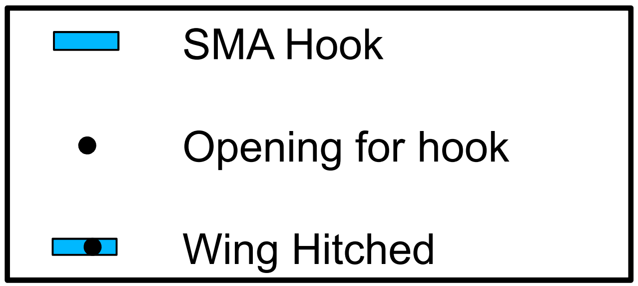
When heated the wing will fold into it's memorized shape and unfold to it's flat state in room temperature.



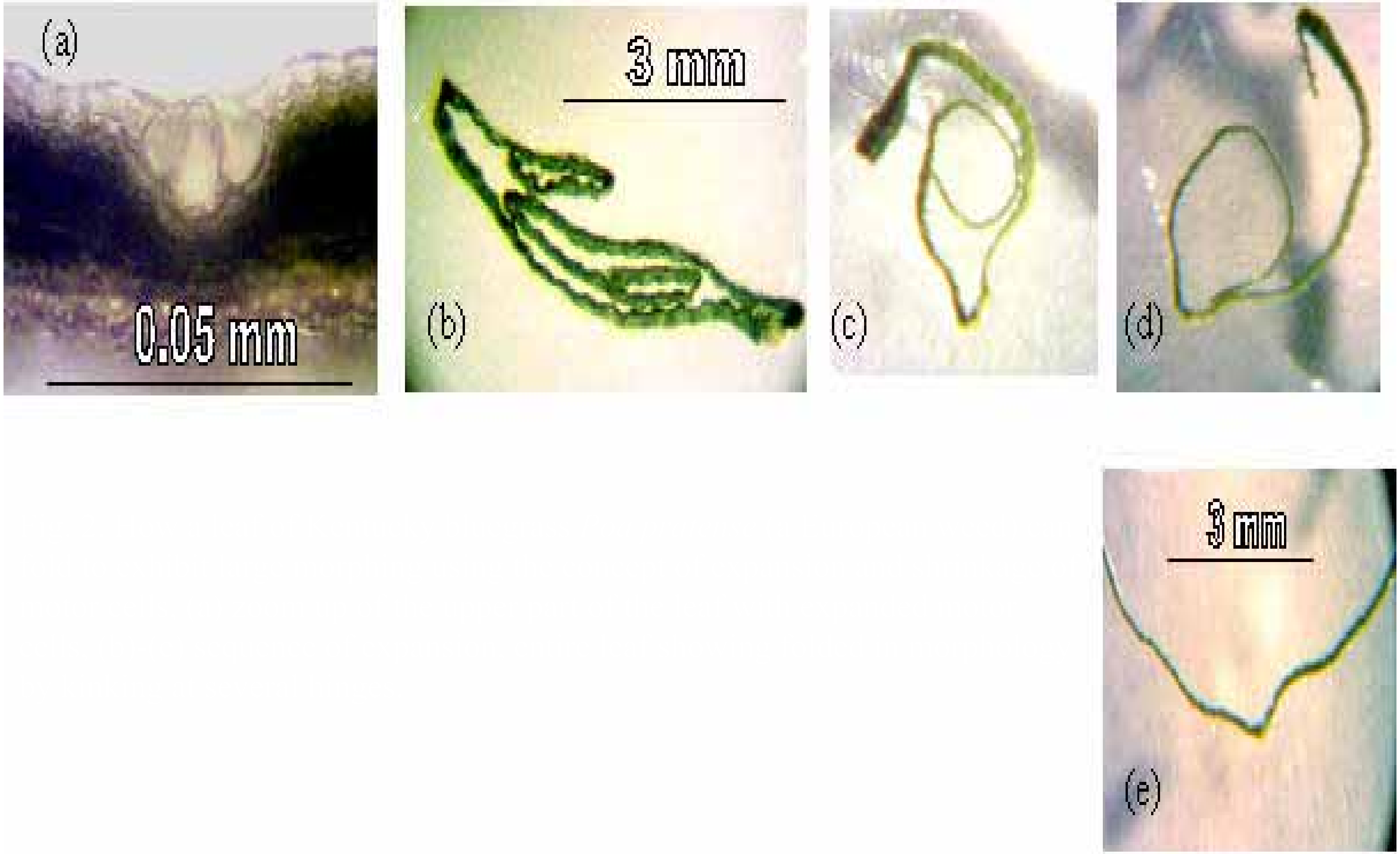
room temperature

50% heating

80% heating



Folding of leaves(Kentucky Blue Grass)



Expansion of Super-configurable MAV