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On-demand Stiffness Selectivity for Morphing Systems

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14. ABSTRACT
The main accomplishment of this effort were: i) the establishment of an analytical model allowing the efficient design of bistable elements to control the stiffness of selective compliance structures; ii) establishing optimization criteria to leverage the stiffness selectivity provided by embeddable bistable elements for morphing applications; iii) to establish a design tool based on optimization for generating morphing wing topologies with inherent stiffness selectivity; iv) Demonstrating with wind tunnel tests that validity of the approach and the stability of selective stiffness morphing structures under aerodynamic loads; v) establishing two new bioinspired methodologies for morphing structures; the spring origami theory inspired by the Earwig wing and the reversible shape memory effect based on misfit pre-stress seen in the Venus fly trap; and vi) training five different graduate students aiding in translating state of the art morphing methods into industry.
During this effort's performance period, we have published 7 journal papers and 12 peerreviewed conference papers (please see details in section 4 Publications). Our published work received several awards as detailed in section 3 Honors and Awards. In additions, one of the supported students, David M. Boston, spent a summer working at Wright-Patterson Base at the RT directorate under the supervision of Drs. Jeff Bauer and Richard Beblo.

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1. Executive Summary

The main accomplishment of this effort were: i) the establishment of an analytical model allowing the efficient design of bistable elements to control the stiffness of selective compliance structures; ii) establishing optimization criteria to leverage the stiffness selectivity provided by embeddable bistable elements for morphing applications; iii) to establish a design tool based on optimization for generating morphing wing topologies with inherent stiffness selectivity; iv) Demonstrating with wind tunnel tests that validity of the approach and the stability of selective stiffness morphing structures under aerodynamic loads; v) establishing two new bioinspired methodologies for morphing structures; the spring origami theory inspired by the Earwig wing and the reversible shape memory effect based on misfit pre-stress seen in the Venus fly trap; and vi) training five different graduate students aiding in translating state of the art morphing methods into industry.

During this effort's performance period, we have published 7 journal papers and 12 peer-reviewed conference papers (please see details in section **4 Publications**). Our published work received several awards as detailed in section **3 Honors and Awards**. In additions, one of the supported students, David M. Boston, spent a summer working at Wright-Patterson Base at the RT directorate under the supervision of Drs. Jeff Bauer and Richard Beblo.

2. Main Achievements

2.1. Modelling of embeddable multistable elements for selective stiffness

We developed an analytical model for embeddable bistable elements allowing for the fast design and optimization of morphing structures with selective compliance from multistability (see Fig 1.a and **[2.J]**). This allows for the rapid design of thermally prestressed bistable elements embeddable into larger compliant structures. We generated a second route to obtained embeddable bistable elements by employing geometry. Specifically, we developed geometrically bistable embeddable elements leveraging shell structures which enable similar capabilities as the prestressed counterparts for switching the stiffness of larger compliant structures (see Fig. 1.b and **[3.C][5.C]**). We leverage the simplicity and ease of manufacture via 3D printing of the geometrically bistable elements to manufacture monolithic ribs, thus avoiding previously needed bonding steps. This is detailed in sections

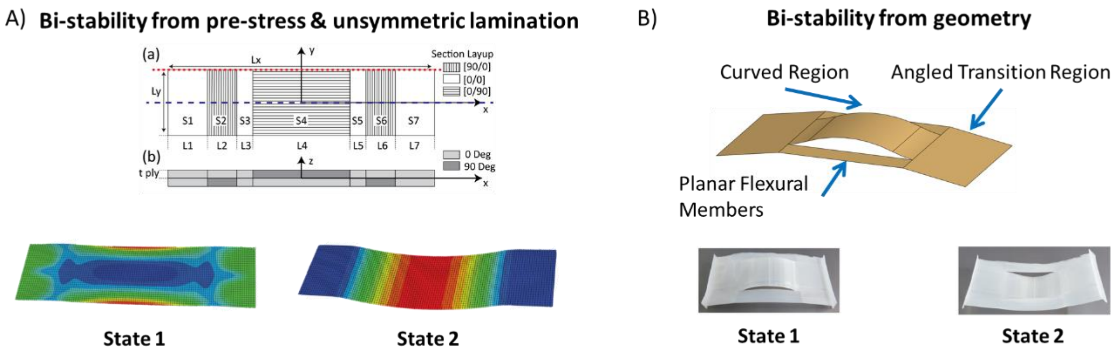

Figure 1: A) Prestressed bistable element. Bistability stems from misfit strains from different stacking sequences. B) Geometrically bistable element from shell geometries. The inversion of the central curved region causes misfit strains that stabilized the second stable state.

We extended this concept to generate a totally new class of multistable metastructures that allow for encoding a vast number of programmed mechanical behaviors into morphing systems (see Fig. 2 and **[1.J][1.A]**). This multistable metastructures are based on dome-patterned metamaterials described in **[5.J]**. In particular, our multistable metastructures from locally bistable units allow for programming bending, in-plane, and torsional effective moduli as a function of the number of inverted units. This offers an enlarged design space for obtaining selective stiffness adaption in morphing systems.

- *These results fulfil* ***<u>objective 1</u>*** *of the proposal, which aim to derive modelling tools for bistable elements that can be embedded in larger compliant structures.*

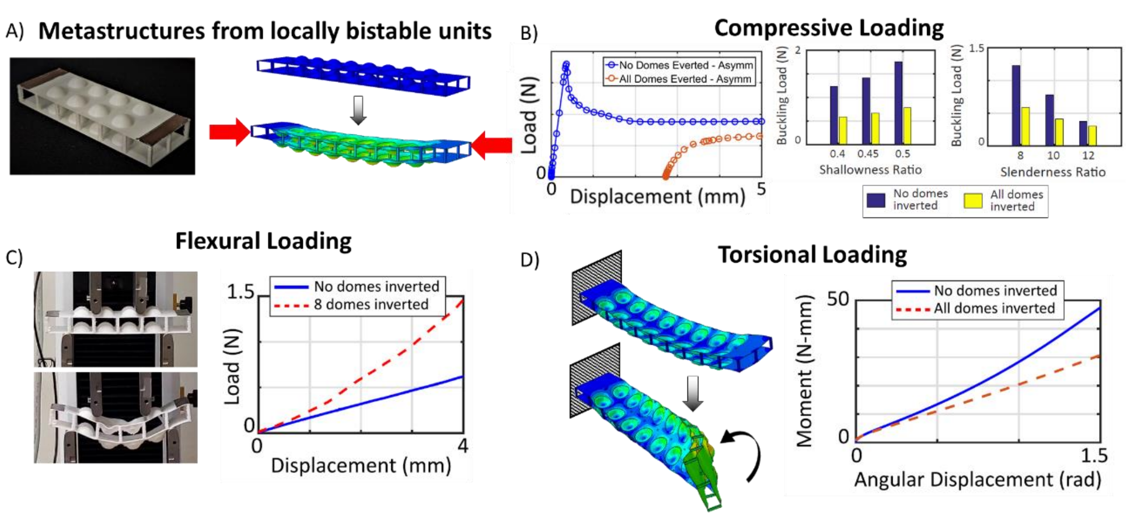

Figure 2: A) Multistable metastructure from locally bistable units, in this case domes. Each dome can be individually addressed. B) Load–displacement plots for the metastructures subjected to compressive loading when switching from no to all domes inverted. (Inset) Programmability trends in the global buckling load for the symmetric metastructure as the microscale geometric parameters are varied. C) Experimental images corresponding to A) the base state and 8 domes inverted state of a 16 dome metastructure mounted in a 4-point bend test configuration on an Intron load testing machine and experimental data for bending stiffness programmability in the 3D metastructure. The metastructure features unit cells with dimensions R = 8 mm, SH = 0.75, SL = 7.5 and PK = 3. The connecting members are 16 mm in length with a 1.5 mm side square cross-section and 0.6 mm thickness.

2.2. Selective stiffness maximization with multistable embeddable elements

Extending the aeroelastic design and optimization tool developed in the project to account for the added stiffness and actuation capability of piezoelectric laminates in morphing structures (see **[3.J] [1.C]**). This analysis showed that there exists a compromise between the amount of

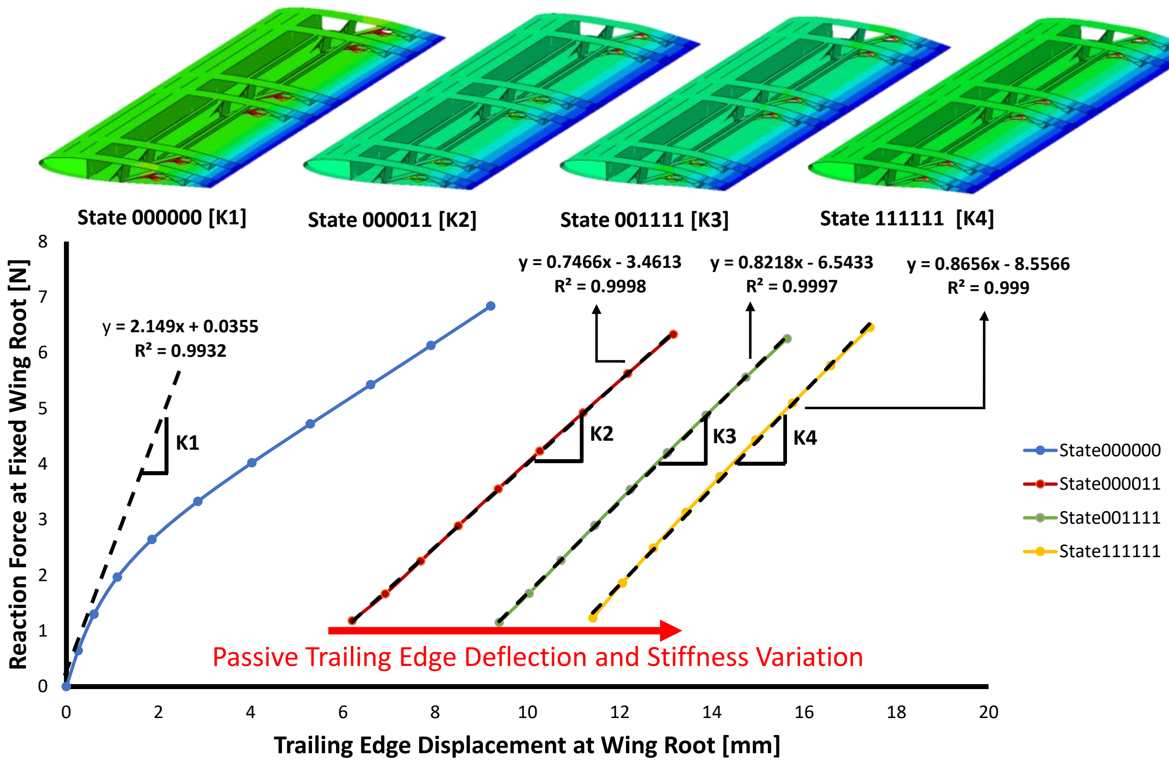

Figure 3: Structural response of a multistable wing around each structurally stable state. This morphing wing is composed of 6 morphing ribs grouped in pairs and can hold up to 64 structurally stable configurations. The switching of each rib is presented as a binary 0 (stiff state) or 1 (flexible state), with each statically stable global configuration represented by a 6-digit combination. We show 4 states to highlight the passive trailing edge deflection (camber morphing) and global stiffness variation achieved.

actuation material and added stiffness of piezoelectric layers to obtain maximum deflection, while minimizing the weight penalty. *This study highlights the multifunctionality of piezoelectric laminates, providing stiffness in addition to actuation, in compliance-based morphing structures*. See paper: **[3.J].**

Geometrically bistable elements offer the interesting possibility to lock-in deflected structurally stable configurations, thus eliminating the need for constant actuation when actuating a compliant structure. This can be achieved by programming into the morphing structure several statically stable states to operate optimally at multiple design conditions. Fig. 3 presents a multi-stable wing design composed of 6 bistable morphing rib topologies that demonstrates this concept. This ability to hold on two multiple deflected configurations is a result that was not anticipated in the original proposal and is one of the most impactful contributions of this project.

We have conducted analyses and experimental validation investigating the effect of positioning these geometrically bistable elements within a single compliant morphing rib structure. Our work revealed that significant stiffness adaptation could be obtained from positioning the element close to the trailing edge and in parallel to a compliant skin, for example built following a corrugated architecture. We established an optimization tool capturing the main mechanical response of the bistable element and establish the following design objectives:

Minimize:

$$\Phi = \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 + P_\Phi$$

Subject to:

$$g_1 = 1 - C_{l,flex}/0.800$$

$$g_2 = 1 - C_{l,stiff}/0.147$$

where,

$$f_1 = -C_{l,flex}/C_{d,flex}$$

$$f_2 = -C_{l,flex}/C_{l,stiff}$$

$$f_3 = V_{flex} + V_{stiff}$$

$$P_\Phi = \sum_{i=1}^{2} \begin{cases} 100 * g_i & g_i > 0 \\ 0 & g_i \leq 0 \end{cases}$$

The optimization scheme of an individual bistable morphing rib topology was formulated around the notion that the aircraft must operate optimally around two distinct flight conditions. The selected design flight conditions were a cruise maneuver at flight velocities of M=0.04 and M=0.10 (15m/s and 35m/s respectively). These are relatively low-speed flight conditions that were selected based on current UAV design trends. The constraint functions were designed to satisfy the lift requirements at each flight condition. Since the lift increases with the square of the velocity, a lower lift coefficient is required at faster flight speeds while a higher lift coefficient is necessary to achieve an equivalent lift per unit area at a slower flight condition. Therefore, a target $C_{l,flex} = 0.800$ was selected for the flight speed of $\mathrm{V} = 15m/s$ (g_1), while a lower $C_{l,stiff} = 0.147$ is necessary to achieve the same target lift force per unit area at the higher flight speed of $V = 35m/s$ (g_2). The second constraint ensures that the aircraft is still maneuverable at the higher speed flight condition.

The objectives were formulated from the observation that the bistable morphing rib concept features two distinct effects when switched to the second stable state: passive trailing edge deflection (camber morphing) and a reduction in the global stiffness of the structure. The first objective (f_1) is to use the stored strain energy from switching the bistable element to increase the camber of the airfoil, thus maximizing the lift-to-drag ratio (CL/CD) at the lower speed flight condition. The second objective (f_2) maximizes the lift coefficient ratio between the stiff and the deflected flexible configurations when morphed by the piezoelectric actuators. Finally, the third objective (f_3) was formulated to minimize the MFC actuation voltage requirements about each stable configuration. Notice that the actuation about each stable state (V_{flex} and V_{stiff}) are not the same and must be considered separately to optimize the combined effects of passive camber morphing and global stiffness reduction of the morphing rib around each state. These 3 objectives along with the two constraints discussed were formulated using a weighted fitness function with an exterior step-linear penalty function to account for the constraints. The weight values (α) of each objective were heuristically chosen such that all objectives would have magnitudes between 0 and 1.

- *These results fulfil **objective 2** of the proposal, which aim to establish optimization criteria to maximize the efficacy of morphing structures. We will extend this result to account and understand the actuation compromises in morphing structures with selective stiffness provided by bistable elements.*

2.3. Concurrent optimization and analysis tool for designing morphing wings with selective stiffness

We utilized our aeroelastic design tool to introduce a method for passive load alleviation for rotary wings and blades exploiting selective compliance from multistable elements. In particular, we demonstrated the capability of a selective stiffness morphing flap designed using a bistable element for reducing potentially dangerous gust loads at desired flow conditions. Although developed for rotary wings, this result can be extended to fixed wing aircraft for reducing the impact of gusts without the need for active control and actuators. See papers: **[6.J][6.C].**

The optimization objectives proposed in section **2.2** are implemented to design a single morphing rib topology. The rib profile selected was a NACA0014 airfoil with a chord of 400mm. This profile and dimensions were selected to have sufficient space for the internal structural elements. The internal topology is parametrized using 10 nodes: 3 nodes that will be constrained to the upper surface of the profile, 3 nodes constrained to the lower surface, 2 internal nodes constrained to the line of symmetry of the airfoil, and 2 nodes constrained to the lower surface that will determine the location of the corrugation. The 8 structural nodes will be connected using a Delaunay Triangulation to generate the internal truss elements of the morphing rib topology. Additionally, a discrete variable will determine which of the generated trusses must be substituted by a geometrically bistable element.

MATLAB's genetic algorithm (GA) was used to find the optimal topology. The optimization algorithm combined Abaqus CAE to generate the topology along with a weakly coupled aeroelastic tool that uses the Xfoil (XFLR5) aerodynamics analysis tool to evaluate the aeroelastic response of each individual. The genetic algorithm evaluated a population of 150 individuals over a maximum of 80 generations to identify the optimal topology. The resulting optimal topology

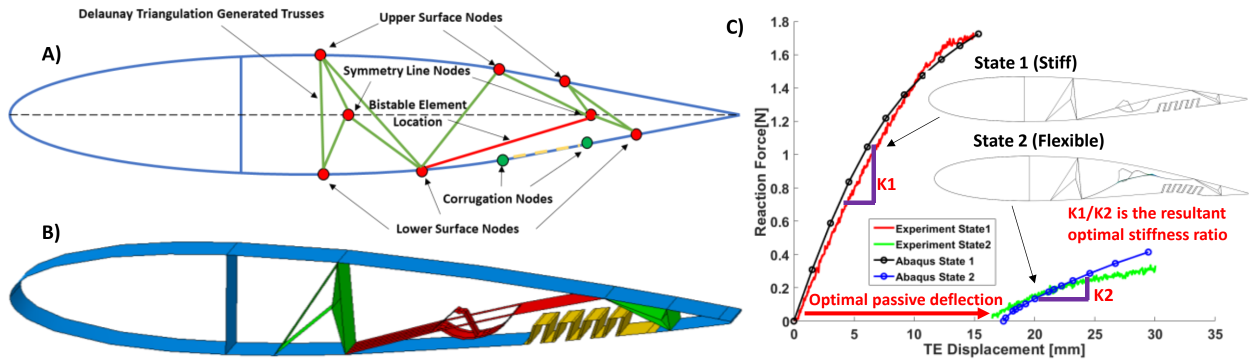

Figure 4: Morphing topology parametrization and final optimal geometry structural response. A) Shows the relative location of the internal structural nodes (red dots), the corrugation nodes (green dots), the location of the corrugation (yellow dashed line); and provides an example topology with internal trusses (green lines) and bistable element location (red line) generated by the Delaunay Triangulation. B) Optimal topology with double-walled corrugation (yellow) and geometrically bistable element modified with an actuation horn (red). C) Experimental structural response shows good agreement of the experimental passive camber morphing response and the selective stiffness behavior with the numerical FE model.

shown in Fig. 4 was manufactured, and its structural response was experimentally characterized. This optimal morphing rib was used to design a morphing wing section (2 morphing ribs) to show the feasibility of testing an experimental demonstrator in a low-speed wind tunnel.

A wing section demonstrator was manufactured out of 2 optimized compliant rib topologies which were 3D printed using a FDM Markforged X7 printer and a carbon reinforced nylon filament. The double-walled corrugation geometry features a high bending stiffness in the chordwise and spanwise direction, but low in-plane stiffness to allow for expansion and contraction of the bottom skin surface when deflecting the trailing edge. The corrugation was manufactured from thermoplastic polyurethane (TPU) in an Ultimaker 5S 3D printer. The top and bottom skins are manufactured of a 3-ply laminate layup [0,0/90-pw,0] using a woven composite laminate and unidirectionally reinforced plys. Additionally, 4 MFC 8557-S1 actuators are placed on the top skin of the rib. These MFCs were loaded to deflect the trailing edge of the rib and study its aeroelastic response and control around the two statically stable states and distinct aerodynamic loading conditions. The morphing wing section was fitted with two servos with nylon fishing wires attached at the servo arms. The bistable element features an actuation horn where the nylon wire is attached to pull and apply the necessary actuation force to switch the bistable element from one stable state to the other.

The Wind Tunnel tests were performed in the Boeing Wind Tunnel at Purdue University. This wind tunnel was fitted with a load balance with 4 strain gauges to measure lift, drag and rolling moments. A LabVIEW data acquisition system was used to log lift, drag, rolling moment, and wind tunnel velocity data. A secondary LabVIEW VI was used for the actuation controls of the bistable element and to supply the necessary voltage to the MFC actuators. The experiments were performed at a free stream velocity of 15m/s and 30m/s, and the aerodynamic performance data was logged as the wing section model angle of attack was swept from -10 degrees up to +10 degrees. A digital image correlation system was used to track a speckle pattern applied to the top surface of the morphing wing section. This allowed for the structural response imaging of the wing section at various operating conditions.

Our testing results show that switching between stable states while under aerodynamic loads is possible and does not induce aeroelastic instability, such as flutter. Additionally, the lift variation achieved from switching to the secondary state and passively morphing the camber does not decay considerably as the wind tunnel velocity was increased. This result shows that the compliant structure has a good balance between controllability and load carrying capacity as it can sustain its passive morphed configuration even at higher aerodynamic loads. The full data set of these results, including MFC actuation and validation of numerical predictions, are currently being analyzed and assembled in a conference papers (to be presented in the AIAA SciTech Forum 2022, see **[12.C]**) and in an upcoming journal publication currently under preparation (see **[1.P][2.P]**).

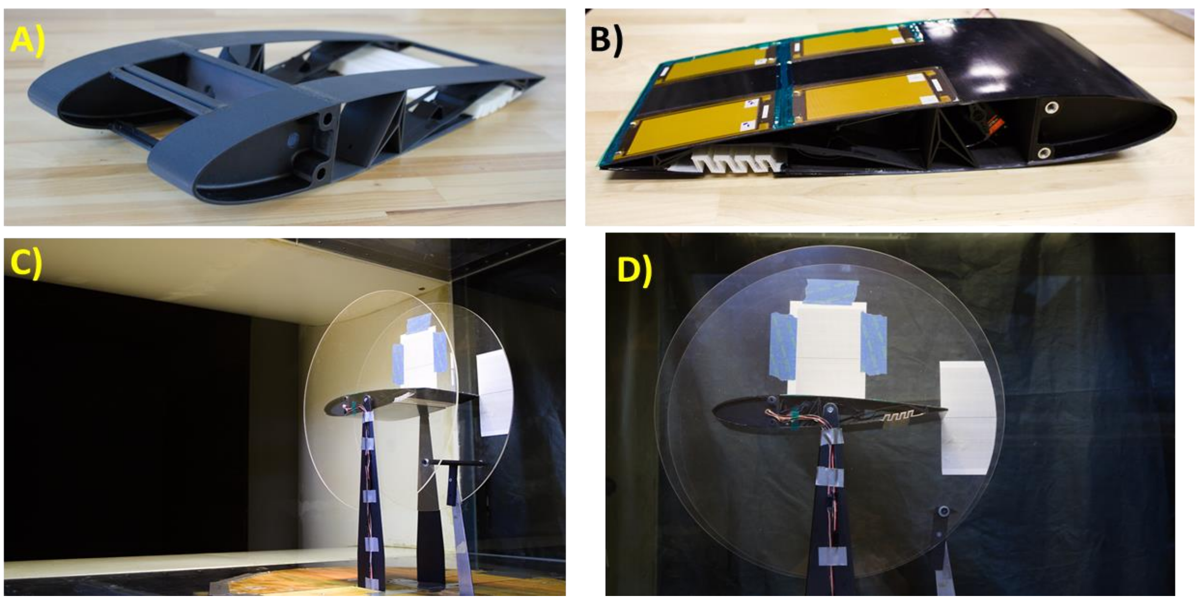

Figure 5: Experimental demonstrator and wind tunnel tests. A) Isometric view of multistable wing section skeleton with two optimized morphing rib topologies (black) and corrugation (white). B) Side view of fully assembled demonstrator with composite skin and MFC actuators. C) Isometric view of the wing section mounted on two pylons with endcaps and guide vane mechanism looking upstream of the low-speed Boeing Wind Tunnel. D) Side view of the mounted demonstrator.

- *In combination, these results fulfil **objective 3** of the proposal, which aimed to establish a design tool based on aeroelastic optimization considering the compliance of morphing structures and showing applications.*

2.4. Interaction with BRI on Avian Inspired Morphing

This project was associated to the BRI on Avian Morphing, a collaboration that significantly increased the results of this effort. We had strong collaboration with Prof. André Studart from ETH Zurich, an interaction that resulted in several publications (see **[1.J][4.J][5.J][4.C]**). Our main contribution from were:

1. ***Spring origami theory***: we establish a new origami theory enabling crease stretching inspired from the Earwig's wing (see **[1.J]**). This allowed to explain the complex folding and bistability of the Earwig. We leverage this bioinspired principle to design a compliant, bistable gripper capable of conforming to and holding onto objects of unknown shape without the need from continuous provision of external actuation. This is achieved by using the strain energy stored in the pre-stressed creases (the spring effect) of our origami gripper, thus requiring energy only for initiating the actuation (see **[8.C]).** Our spring origami theory opened up a new avenue to attain reconfiguration in origami structures by enabling multistability from prestress on the creases. This avoids the prior need of facet flexibility to achieve multistability in origami, thereby allowing the use of rigid or brittle materials in reconfigurable origami systems using this spring principle. Our theory has received significant attention from academia a popular media, as detailed in the sections **3** and **4.4**.
2. ***Reversible shape memory effect with thermoplastics:*** We establish a method for realizing reversible shape memory effect by leveraging prestressing of polymer chains during 3D printing. The conventional shape memory effect in thermoplastics feature a permanent as manufactured shape and a temporary shape programmed by inducing deformation above T_g and subsequent fast freezing. Upon re-heating, the polymer molecules regain their mobility thus taking the thermoplastic from the temporary (energetically unfavorable) shape to its permanent (energetically favorable) shape. Thus, this effect is a one-way, one-time shape adaptation mechanism. We introduced a reversible shape memory effect by inducing misfit pre-stress in thermoplastic manufactured with directional deformation. We achieve this by leveraging the characteristics of fused deposition molding (FDM) 3D printing as detailed in **[4.J][4.C]**. Our approach results in thermoplastics that are multistable above T_g enabling shape reconfiguration between multiple permanent shapes encoded by the misfit pre-stress, while providing a stiff state when frozen to room temperature. This approach allows for creating thermoplastics with multiple permanent shapes that can be accessed many times, yielding a multiple-ways, multiple-times shape memory effect. We envision this approach to be useful for morphing structures, smart building applications, specialty packaging, and smart camouflage (see [9.C]).

3. Honors & Awards Associated to Grant

The following honors and awards recognize the PI or/and the students supported by this effort.

1. 2020, NSF CAREER Award, MoMs program. Project Title: ***The Mechanics of Hierarchical Multistable Metastructures*.**
   Award recognizing the PI
2. Fronstispiece in Advanced Science: ***Mechanical Metamaterials: Dome-Patterned Metamaterial Sheets***. https://doi.org/10.1002/advs.202070125

3. Symposium on Robotic Materials Keynote Talk. Delivered by *A. F. Arrieta*. ***Programmable robotic structures from multistable metastructures.*** 56th Annual Technical Meeting of the Society of Engineering Science (SES2019) October 13 – 15, 2019, St. Louis, MO, USA.
   Award recognizing the PI
4. 2019, ASME Best Paper Award in Bioinspired Materials and Systems for paper entitled: ***Bioinspired Spring Origami.*** Science, 359(6382), 1386-1391, 2018
5. 2019, Finalist in Best Student Hardware Paper Competition, ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2019), Louisville, KY, USA, September 9–11, for the paper entitled: ***Design and manufacture of a multistable selectively stiff morphing section demonstrator.***
6. 2018, ASME Gary Anderson Early Achievement for: "*notable contributions of a young researcher in his or her ascendancy whose work has already had an impact on the fields of Adaptive Structures and Material Systems.*" ***Award recognizes domestic or international researchers***
   Award recognizing the PI
7. 2018, Best student paper, ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018), for the paper entitled: ***Switchable Bistability in 3D Printed Shells with Bio-inspired Architectures and Spatially Distributed Pre-stress***
8. 2018, Third place best poster award for poster entitled: ***Bio-inspired distributed pre-stress from magnetically aligned microstructures for fast morphing***. 4th Midwest Mechanics of Materials and Structures workshop, Illinois Institute of Technology, Chicago, August 4.

4. Publications

This project resulted in 7 journal papers, 12 peer-reviewed conference papers, and 16 conference abstracts (including an invited symposium Keynote, **[11.A]**). Two of our papers were published in the high-impact journals **[1.J]** in Science (Journal Ranking in Google Scholar: #2) and **[5.J]** in Advanced Science (Journal Ranking in Google Scholar: #2). Furthermore, these publications have attracted unusually high attention as measured by AltMetric; paper **[1.J]** has a 289 score implying this manuscript is in the 99th percentile of all tracked articles of the same age and 88th percentile compared to all papers in Science of the same age; and paper **[5.J]** has a 90 score implying this manuscript is in the 96th percentile of all tracked articles of the same age and 93rd percentile compared to all papers in Advanced Science of the same age. This high AltMetric score reflects popular media articles about our work including in National Geographic and Nature's News and Views. Please see a selection of popular media articles about these two papers in section 4.4**.**

Students and postdocs under the supervision of Prof. Arrieta are underlined.

4.1. Journal Publications

[1.J] J. Faber, *A. F. Arrieta*, A. R. Studart. ***Bioinspired spring origami***. Science, 359(6382), 1386-1391, 2018. https://doi.org/10.1126/science.aap7753
****Consult AltMetric score here: https://www.altmetric.com/details/34725985***
****ASME Best Paper Award in Bioinspired Materials and Systems***

[2.J] J. P. Udani, *A. F. Arrieta*. ***Analytical modeling of multi-sectioned bi-stable composites: stiffness variability and embeddability,*** Composite Structures, 216, 228-239, 2019. https://doi.org/10.1016/j.compstruct.2019.02.015

[3.J] A. C. Henry, G. Molinari, J. R. Rivas-Padilla, *A. F. Arrieta.* ***Smart morphing wing: optimization of distributed piezoelectric actuation***. AIAA Journal, 57(6), 2384-2393, 2019. https://arc.aiaa.org/doi/full/10.2514/1.J057254

[4.J] K. S. Riley G, K. J. Ang, K. A. Martin, W. K. Chan, J. A. Faber, *A. F. Arrieta*. Encoding multiple permanent shapes in 3D printed structures materials and design. Materials & Design, 194, 108888, 2020. https://doi.org/10.1016/j.matdes.2020.108888

[5.J] J. A. Faber, J. P. Udani, K. S. Riley, A. R. Studart, *A. F. Arrieta*. ***Dome-patterned metamaterial sheets***. Advanced Science, 7(22), 2001955, 2020. https://doi.org/10.1002/advs.202001955
****Consult AltMetric score here: https://wiley.altmetric.com/details/92963767***

[6.J] W. D. K. Cavens, A. Chopra, *A. F. Arrieta*. ***Passive load alleviation on wind turbine blades from aeroelastically driven selectively compliant morphing***. Wind Energy, 24(1), 24-38, 2020. https://doi.org/10.1002/we.2555

[7.J] J. P. Udani, *A. F. Arrieta*. ***Programmable mechanical metastructures from locally bistable domes***. Extreme Mechanics Letters, 42, 101081, 2021. https://doi.org/10.1016/j.eml.2020.101081

4.2. Conference Publications

[1.C] A. C. Henry, G. Molinari, *A. F. Arrieta*. ***Smart morphing wing: optimization of distributed piezoelectric actuation***. 2017 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, Gaylord, Texas, January 8 – 13, 2017.

[2.C] K. S. Riley, H. Le Ferrand, *A. F. Arrieta*. ***Modeling of bio-inspired, snapping composite shells with magnetically aligned reinforcements.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2017), Snowbird, Utah, USA, September 18 – 20, 2017.

[3.C] D. M. Boston, *A. F. Arrieta*. ***Design of monolithic selectively compliant morphing structures with locally bi-stable elements.*** 2018 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, Kissimmee, Florida, January 7 – 12, 2018.

[4.C] K. J. Ang, K. S. Riley, J. Faber, *A. F. Arrieta* ***Switchable bistability in 3D printed shells with bio-inspired architectures and spatially distributed pre-stress.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018), San Antonio, Texas, USA, September 10 – 12, 2018.
****Best student paper, ASME SMASIS 2018***

[5.C] D. M. Boston, J. Rivas-Padilla, *A. F. Arrieta* ***Monolithic morphing rib with selective stiffness from embeddable bi-stable elements.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2018), San Antonio, Texas, USA, September 10 – 12, 2018.

[6.C] W. Cavens, A. Chopra, *A. F. Arrieta*. ***Passive load alleviation in wind turbine blades from selectively compliant bi-stable morphing flaps.*** 2019 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, San Diego, California, January 6 – 11, 2019.

[7.C] J. Rivas-Padilla, D. M. Boston, *A. F. Arrieta*. ***Design of selectively compliant morphing structures with shape-induced bi-stable elements.*** 2019 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, San Diego, California, January 6 – 11, 2019.

****Finalist in Best Student Hardware Paper Competition, ASME SMASIS2019***

[8.C] S. Rojas, D. M. Boston, *A. F. Arrieta*. ***Actuation simplification for grippers based on bioinspired spring origami.*** SPIE Smart Structures/NDE: Bioinspiration, Biomimetics, and Bioreplication IX, Denver, Colorado, March 3 – 7, 2019. https://doi.org/10.1117/12.2514389

[9.C] W. K. Chan, K. S. Riley, *A. F. Arrieta*. ***Perceived value change via 3D printed bistable structures.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2019), Louisville, KY, USA, September 9 – 11, 2019.

[10.C] D. M. Boston, J. R. Rivas-Padilla *A. F. Arrieta*. ***Design and manufacture of a multistable selectively stiff morphing section demonstrator.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2019), Louisville, KY, USA, September 9 – 11, 2019.

[11.C] J. R. Rivas-Padilla, D. M. Boston, *A. F. Arrieta.* ***On-demand stiffness selectivity of deflected morphing wing via internal bi-stable elements.*** 2020 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, Orlando, Florida, January 5 – 10, 2020.

[12.C] J. R. Rivas-Padilla, D. M. Boston, *A. F. Arrieta.* ***Topology optimization and experimental validation of a selectively stiff multistable morphing wing section.*** 2022 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, San Diego, California, January 3 – 7, 2022.

4.3. Posters and Abstracts

[1.A] J. Faber, *A. F. Arrieta*, A. R. Studart. ***Learning from the earwig wing: a bioinspired approach towards fast morphing structures using multistability***. 21st International Conference on Composite Materials (ICCM), Xi'an, China, August 20 – 25, 2017.

[2.A] K. S. Riley, H. Le Ferrand, *A. F. Arrieta.* ***Use of bio-inspired programmable materials to achieve fast morphing shells with desired deformations.*** 28th International Conference on Adaptive Structures and Technologies (ICAST), Cracow, Poland, October 8 – 11, 2017.

[3.A] K. S. Riley, *A. F. Arrieta*. ***Bio-inspired distributed pre-stress from magnetically aligned microstructures for fast morphing.*** Gordon Research Conference on Multifunctional Materials & Structures. Ventura, CA, USA, January 14 – 18, 2018.

[4.A] K. S. Riley, K. J. Ang, J. Faber, *A. F. Arrieta.* ***Multi-stable shape programmable shells from 3D printed induced pre-stress.*** Gordon Research Conference on Multifunctional Materials & Structures. Ventura, CA, USA, January 14 – 18, 2018.

[5.A] K. S. Riley, *A. F. Arrieta*. ***Bio-inspired distributed pre-stress from magnetically aligned microstructures for fast morphing.*** 4th Midwest Mechanics of Materials and Structures workshop, Illinois Institute of Technology, Chicago, August 4, 2018.
****Third-place award in poster presentation***

[6.A] *A. F. Arrieta*, J. Faber, K. S. Riley, A. R. Studart. ***Extending origami: crease pre-stressing for functional adaptation.*** IUTAM Symposium Architectured Materials Mechanics, September 17-19, 2018, Chicago, IL.

[7.A] J. Rivas, D. M. Boston, *A. F. Arrieta*. ***Structural response of morphing ribs with selective compliance from multistability.*** 29th International Conference on Adaptive Structures and Technologies (ICAST), Seoul, Republic of Korea, October 1 – 4, 2018.

[8.A] K. S. Riley, *A. F. Arrieta*. ***Multifunctional designs with switchable bistability.*** ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2019), Louisville, KY, USA, September 9 – 11, 2019.

[9.A] J. Udani, *A. F. Arrieta*. ***Programmable structures from local bistability.*** 22nd International Conference on Composite Materials (ICCM), Melbourne, Australia, August 11 – 16, 2019.

[10.A] J. Udani, *A. F. Arrieta*. ***Adaptable stiffness metastructures from local bistability for reconfigurable robotics.*** 56th Annual Technical Meeting of the Society of Engineering Science (SES2019), St. Louis, MO, USA, October 13 – 15, 2019.

[11.A] J. Udani, *A. F. Arrieta*. ***Programmable robotic structures from multistable metastructures.*** 56th Annual Technical Meeting of the Society of Engineering Science (SES2019), St. Louis, MO, USA, October 13 – 15, 2019
****Symposium on Robotic Materials Keynote Talk. Delivered by A. F. Arrieta***

[12.A] J. R. Rivas-Padilla, D. M. Boston, *A. F. Arrieta*. ***On-demand stiffness selectivity of deflected morphing wing via internal bi-stable elements.*** 2020 AIAA/AHS Adaptive Structures Conference, AIAA SciTech Forum, Orlando, Florida, January 5 – 10, 2020.

[13.A] K. S. Riley, D. Wang, M. H. Jhon, *A. F. Arrieta*. ***Design optimization of pre-stressed multistable structures.*** Gordon Research Conference on Multifunctional Materials & Structures. Ventura, CA, USA, January 19 – 24, 2020.

[14.A] J. P. Udani, *A. F. Arrieta*. ***Programmable metamaterials featuring shape and stiffness adaptability based on local bistability***. ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2020), Online Event, September 15 – 16, 2020.

[15.A] J. C. Osorio, *A. F. Arrieta*. ***Effect of boundary conditions on multistability of tape springs***. ASME Conference on Smart Structures, Adaptive Structures and Intelligent Systems (SMASIS2020), Online Event, September 15 – 16, 2020.

[16.A] J. P. Udani, *A. F. Arrieta*. ***Programmable metamaterials featuring shape and stiffness adaptability based on local bistability***. 57th Annual Technical Meeting of the Society of Engineering Science (SES2020), Online Event, September 29 – October 1, 2020.

4.4. Selected popular media articles about project's papers

Bioinspired Spring Origami *(Paper* [1.J])

1. National Geographic Weird and Wild: "*An ode to earwig wings, which break standard laws of origami.*" *https://www.nationalgeographic.com/animals/2018/11/earwig-origami-wings-how-they-work-insect-flight*
2. Science News: "*Earwigs take origami to extremes to fold their wings.*" *https://www.sciencenews.org/article/earwigs-take-origami-extremes-fold-their-wings*
3. News and Views, Nature 555, 594 (2018), "*Wing origami.*" *https://www.nature.com/articles/d41586-018-03775-4*
4. Neue Zurcher Zeitung Newspaper, Zurich, Switzerland: "*Origami-Strukturen aus dem 3-D-Drucker falten sich selbst*" (*Origami-structures from 3D printing that fold themselves*).

https://www.nzz.ch/wissenschaft/origami-strukturen-aus-dem-3-d-drucker-falten-sich-selbst-ld.1368782

5. Blick Newspaper, Switzerland: *"ETH-Forscher drucken selbstfaltende Origami-Strukturen" (ETH researchers print self-folding origami structures).* https://www.blick.ch/life/wissen/materialforschung-eth-forscher-drucken-selbstfaltende-origami-strukturen-id8156112.html
6. Tech Times: "The origami-like wings of Earwigs could inform how we design foldable devices." https://www.techtimes.com/articles/223544/20180323/the-origami-like-wings-of-earwigs-could-inform-how-we-design-foldable-devices.htm
7. PhysOrg, "*Earwigs and the art of origami.*" https://phys.org/news/2018-03-earwigs-art-origami.html

Dome-patterned metamaterial sheets *(Paper* [5.J]):

8. AAAS Eureka Alert, "*Oddly satisfying metamaterials store energy in their skin*." https://www.eurekalert.org/pub_releases/2020-12/pu-osm120220.php

4.5. Manuscripts in preparation

[1.P] J. Rivas-Padilla, D. M. Boston, *A. F. Arrieta*. ***Topology optimization and experimental validation of a selectively stiff multistable morphing wing section.*** In preparation.

[2.P] J. Rivas-Padilla, D. M. Boston, *A. F. Arrieta*. ***Wind tunnel tests and aeroelastic response of a selectively multistable morphing wing sections.*** In preparation.

5. **Supported Students**

This grant supported 4 individual students pursuing 5 distinct degrees over the project duration. In total the project supported 2 PhD and 3 MSc students, with 1 PhD and 3 MSc already graduated. The following list identifies the students that were fully or partially supported by the grant:

1. Jose R. Rivas-Padilla, PhD in Mechanical Engineering, Purdue University. Graduation date: August 2023 (expected). **US Citizen**
2. Janav P. Udani, PhD in Mechanical Engineering, Purdue University. Graduation date: March 2021.
3. David M. Boston, MSc in Aeronautics and Astronautics Engineering, Purdue University. Graduation date: August 2018. **US Citizen**
4. Katherine R. Riley, MSc in Mechanical Engineering, Purdue University. Graduation date: August 2018. **US Citizen**
5. Jose R. Rivas-Padilla, MSc in Mechanical Engineering, Purdue University. Graduation date: August 2018. **US Citizen**