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Programmable Origami Metamaterials with Adaptive Stiffness

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14. ABSTRACT
The focus of this research program was origami inspired structures and metamaterials which are programmable by selection of geometrical parameters and tuneable by graded stiffness. The team created a large number of novel origami structures that exhibit distinctive mechanical properties, some of which were not achieved previously without the newly developed techniques. Through detailed analysis, a well-understood approach has been established, that enables future development of origami structures that meet real engineering requirements. The team published a significant number of research articles, some in prestigious peer-reviewed journals. The grant was successful overall, and future collaborations with the PI and the University of Oxford could be beneficial to the DAF.

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PROGRAMMABLE ORIGAMI METAMATERIALS WITH ADAPTIVE STIFFNESS

11 May 2020

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Summary

The focus of this research program is origami inspired structures and metamaterials which are programmable by selection of geometrical parameters and tuneable by graded stiffness. We have created a large number of novel origami structures that exhibit distinctive mechanical properties, some of which were not achieved previously. Through detailed analysis, a well-understood approach have been established, that enable future development of origami structures that meet the real engineering requirements. We have published a significant number of research articles, some in prestigious peer-reviewed journals. We have also engaged in various academic activities to communicate our finding to scientific communities as well as general public. It is hoped that our work can serve as a catalyst for the uptake of origami structures for engineering applications in material, aeronautics, and aerospace industries.

1. Introduction

Origami metamaterials are man-made materials whose constituents and backbone structures allow them to have unusual emergent properties, such as negative Poisson's ratio, or graded stiffness that can be altered according to external loads. These unique features are obtained by utilizing a particular set of geometrical designs known as origami folding patterns. Commonly, origami-based metamaterials adopt rigid origami folding patterns, a subset of origami that permits continuous motion between folded states along predetermined folding creases without the need for twisting or stretching facets. Prior to this project, most mechanical metamaterials based on origami used an origami structure known as the Miura-ori and its variants. The pattern has one degree of freedom so that the motion of a single folded sheet, or those of a stack of sheets, are highly synchronised. The specific properties of the structure, such as stiffness variation or locking, are activated by varying angles among the creases of the origami pattern, or superficially creating imperfections.

In this project, we examine various other origami patterns and their combinations. We consider both rigid origami and structural deformation while physical interference or geometrical incompatibility terminates rigid body motions. In some particular cases we take the thickness of the sheet into consideration which makes our approach closer to engineering reality. Moreover, we also investigate kirigami structures, i.e., origami with slits, and 2D and 3D structures inspired by modular origami, a variant of traditional origami involving folding multiple numbers of units and then assembling them together. In particular, we focus on the following four themes of origami research.

A. Kinematics of transformations of origami patterns amongst various targeted configurations;
B. Behaviour of origami structures when they undergo structural deformation;
C. Creation of novel origami structures with graded stiffness;
D. Creation of 3D novel programmable and tuneable metamaterials.

Our findings have not only led to the creation of a large number of distinct origami structures that exhibit desirable mechanical properties, but also established well-understood approaches that enable future development of origami structures that meet the real engineering requirements. We have published a significant number of research articles, some in prestigious peer-reviewed journals. We hope that our work can serve as a catalyst for the uptake of origami structures for engineering applications in material, aeronautics, and aerospace industries.

2. Theory, Analysis and Experiment

A. Kinematics of transformations of origami patterns amongst various targeted configurations

Conventional origami structures are obtained by folding a sheet according to a given origami pattern. In general, they can transform from one configuration to another. However, it is much more challenging to design an origami that enables the transformation between two predetermined configurations. Our research targets such a problem. Our work on this topic, guided by thorough kinematic analysis, is represented by a family of single degree of freedom transformable paired polyhedrons and a method for folding thick flat panels to compact bundles using kirigami.

A polyhedron is a three-dimensional shape with flat polygonal faces, straight edges and sharp corners or vertices. They can be made by cutting and joining flat sheets. In geometry, two important classes of convex polyhedrons consisting of regular polygonal faces with highly symmetrical geometry are the Platonic solids and Archimedean solids. It was known that hollow polyhedrons of the two families can transform from one to the other if two paired polyhedrons comprise the same number of identical type polygonal faces. However, all practical solutions to achieve such transformations involved a multi-degree of freedom system, making it impossible to control. Using kinematic theory, we have arrived at a design that makes the transformation a single degree of freedom system. The theory was validated by experimental models (Fig. 1). The work is one of the very few that deal with 3D origami structures (origami objects that start and end in 3D shapes). Not only are transformable polyhedrons mathematically interesting, but they also have many potential applications, e.g., they form perfect habitats for space travel which have growth capability.

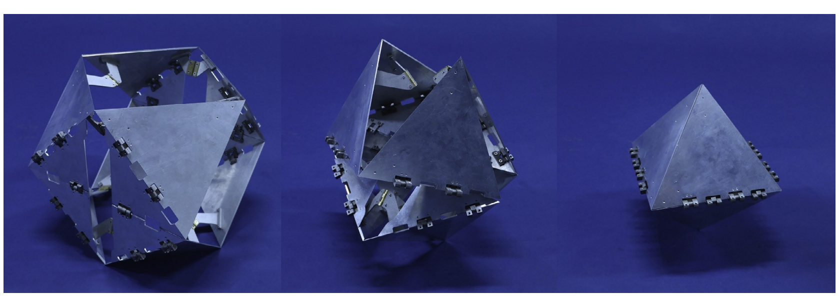


Fig. 1 Transformation sequence of a prototype from a cuboctahedron (left) to an octahedron (right).

The second strand in this theme is folding a flat surface made of identical rectangular pieces (like a chess board) to a compact bundle. The problem originated from the requirements of folding flat solar panels and antennas for space applications. By dissection of each folding step, we manage to model such problem theoretically using a mathematical approach known as the Hamptonian cycles. We then use the cycles to find a way to come up with folding patterns. An example is shown in Fig. 2.

Fig. 2 The Hamptonian cycle (blue lines) for a flat surface made form hexagons and its folding into two compact stacks. Thick black edges of hexagons are slits.

B. Behaviour of origami structures when they undergo structural deformation

In this theme, our focus is the design of origami structures that exhibit superior energy absorption capability. We have investigated origami tubes, beams and plates and assessed their performances under both static and dynamic impacts. A number of ways have been identified that lead to increase of the energy absorption capability, including adaption of cross-sections with multi-cornered or corrugated shapes, pre-fold the surface to particular shapes, or change the geometric parameters of particular origami patterns (e.g., the Miura-ori). Two examples are shown in Fig. 3. We have also identified the difference in design against static and dynamic impacts and understood which design parameters govern the structural performance.

We also examined the structural behaviour when forming the origami structure with curved creases.

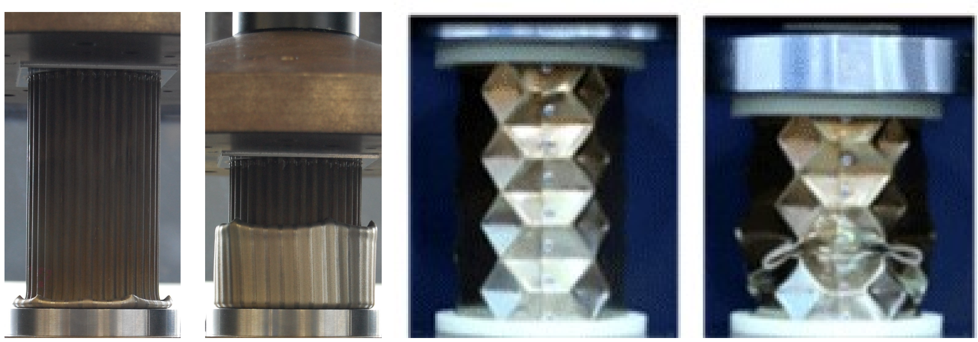


Fig. 3 Inversion of a corrugated circular tube and progressive buckling of a prefolded tube.

C. Creation of novel origami structures with graded stiffness

Materials or structures with graded stiffness can be initially “soft” under small loads; when loading increases, it becomes stiffer. The applications of this new class of material ranges from outer shells of automotive, aerospace, marine structures and body armours, which are soft when in contact with a human or bird and but can be very rigid to protect occupants when subjected to high blast or impact loads, to non-lethal projectiles (rubber bullets) for crowd control or peace support operations. The theme includes development of such structures.

The highlight of this theme is represented by our work on origami tubes based on the six-crease waterbomb origami pattern. This particular tube is well known to artists who have demonstrated that it could change from a tube to a sphere when compressed. However, little was known on its mechanical behaviour. By a thorough kinematic analysis, we have, for the first time, uncovered that the tube, in general, undergo two deformation phases: a mechanism transformation with small stiffness contributed by rotation around creases, followed by a structural deformation of facets after the mechanism motion when physical interference occurs, see Fig. 4. The structure also experiences a twist motion in the end. The change of deformation phases leads to significant variation in structural stiffness. The range of each phase can be tuned by altering geometrical parameters of the pattern. In other words, by careful selection of geometrical parameters, we can create an origami structure with graded stiffness.

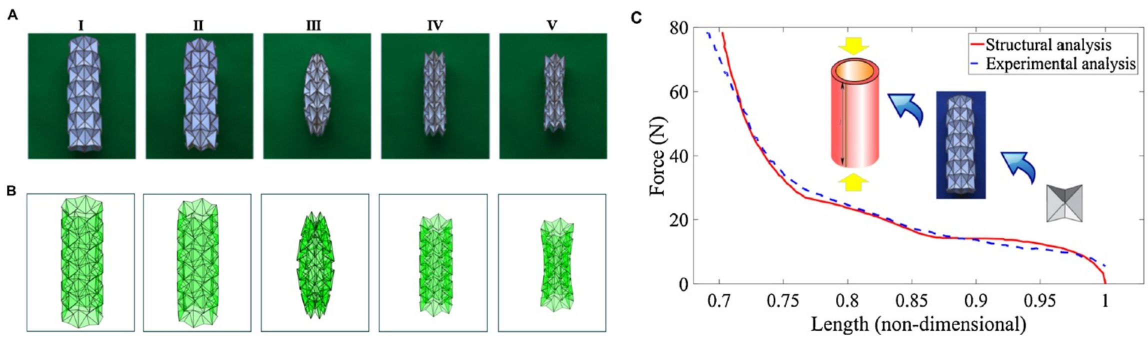


Fig. 4 Experimental and numerical simulation results of the shape change of a tube based on the waterbomb origami pattern (experimental results) and its force vs. length variation relation.

We also investigated a well-known square twist origami pattern. It is known that four square twist patterns exist which enable transformation between identical fully folded and fully expended configurations. However, some of the patterns are not rigidly foldable. Using both experiments and numerical simulation, we analysed a non-rigid foldable pattern and discovered the extent of structural deformation required to move from fully expanded to fully folded configurations, see Fig. 5. We then arrived at a theoretical model for predicting and designing mechanical properties of the non-rigid pattern. The stiffness variation can be achieved solely by geometrical means.

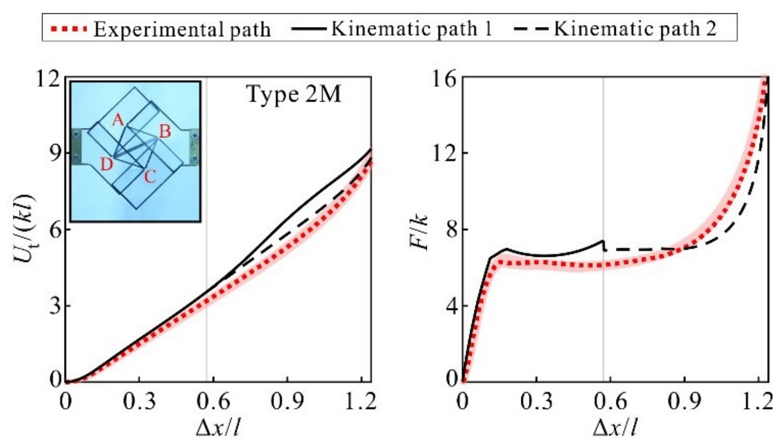


Fig. 5 Energy and force vs displacement of the non-rigid foldable square twist origami structure. The stiffness (gradient of the force vs. displacement curve) can be tuned.

Moreover, we created an origami honeycomb core structure with graded stiffness. The structure can be produced from layered sheets, just like conventional honeycombs, except that these sheets are pre-folded according to a particular origami pattern. Again the geometrical parameters in the origami pattern determine the overall stiffness of the core structure.

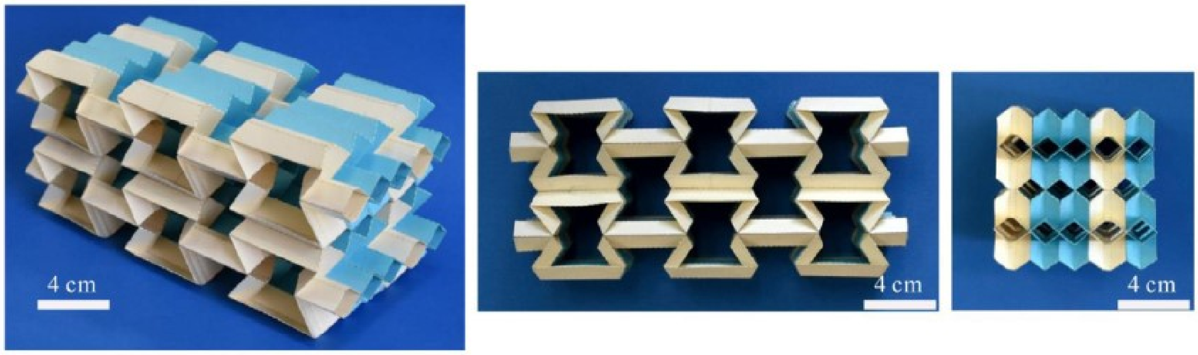


Fig. 6 Representative 3D origami honeycomb metamaterial with graded structure obtained by bonding identical sheets together.

D. Creation of 3D novel programmable and tuneable metamaterials

In this theme, we propose a kinematics based strategy to design tuneable and programmable metamaterials. In our approach, spatial kinematic mechanisms with single degree of freedom, e.g., the Sarrus and Bricard linkages, are entrenched within the construction unit cells of the metamaterial, and the one degree-of-freedom tessellations of such cells lead to a number of kinematic backbone structures for metamaterials that deform along a clearly defined deformation path, making their behaviour predictable and reliable without external synchronisation. The properties of the metamaterials can be programmed through adjusting the dimensions of the building blocks. Moreover, in some cases, the carefully chosen topology and geometry of the unit cells have inherent kinematic bifurcations of the unit cells, enabling the metamaterial to switch among different deformation paths. By utilising these underlining deformation features, we have obtained metamaterials with tuneable multi-channel permeability, programmable constant negative Poisson's ratio, or tuneable porosity, which are shown in Figs. 7, 8 and 9, respectively.

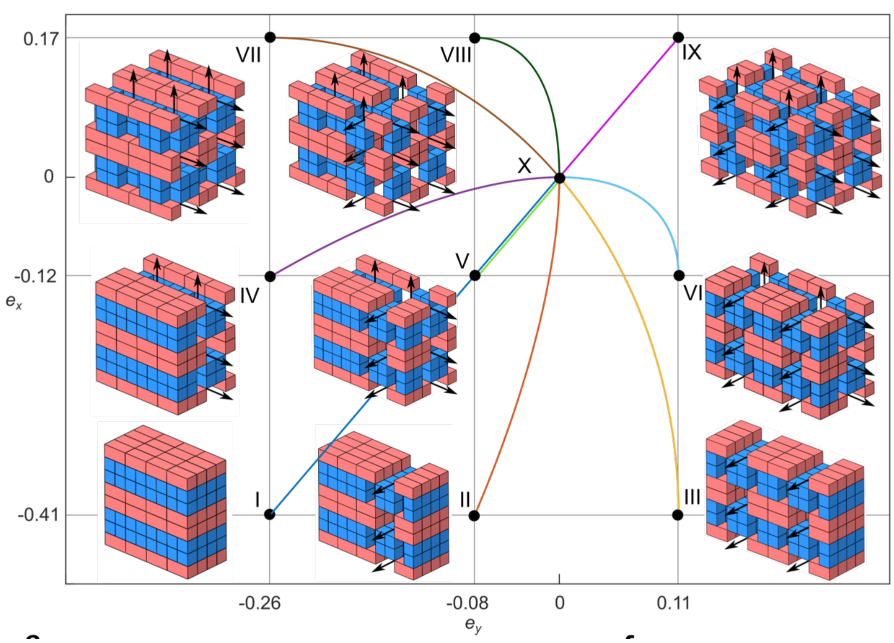


Fig. 7 The metamaterial with tuneable multi-channel permeability (shown by arrows). It has nine terminal configurations, and they can be switched from one to another via a kinematic bifurcated state X.

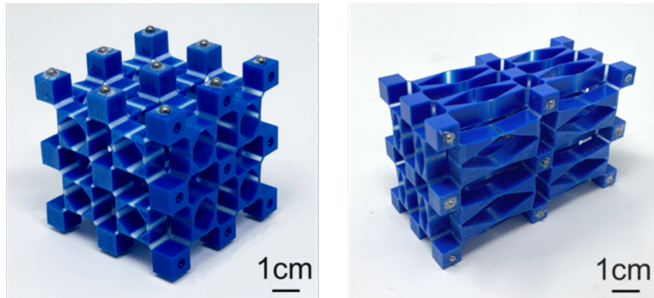


Fig. 8 Two metamaterials. One has constant Poisson's ratios -1 (therefore an isotropic material) and the other has -0.7, -1.273 and -1.818 in three orthogonal directions.

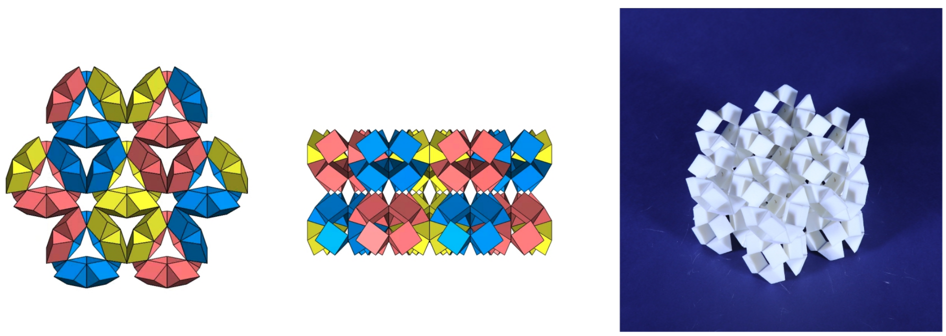


Fig. 9 Another 3D programmable metamaterials with tuneable porosity (top, side views and 3D printed model) in which connections amongst modules form the Bricard linkages. The modules can be packed together without any voids, whilst they can expand to a very porose structure.

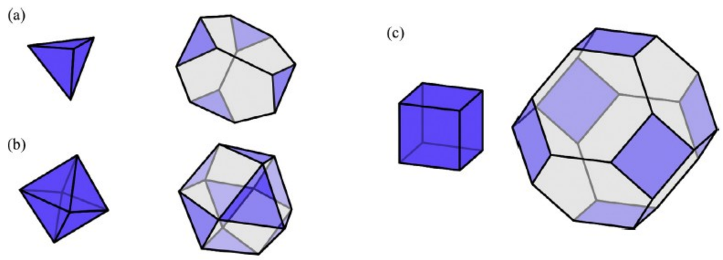
3. List of Publications

Twenty-five publications which have already appeared in peer reviewed journals, and two in peer reviewed conference proceedings are listed. A couple of papers under review are also mentioned. They are grouped according to the themes, with a brief introduction on key papers.

A. Kinematics of transformations of origami patterns amongst various targeted configurations

- Chen Y, Yang F and You Z, Transformation of polyhedrons, International Journal of Solids and Structures, 138, 193-204, 2018, doi.org/10.1016/j.ijsolstr.2018.01.012

  Polyhedral transformation amongst Platonic and Archimedean solids enables large volumetric change. It has great potential in applications where transportability and protection of payload are critical design features, e.g., small or micro satellites, space habitats or planetary rovers. However, existing designs initiated by Buckminster-Fuller introduce many degrees of freedoms, making the control of transformation process extremely difficult and cumbersome. This paper develops a kinematic method to enable polyhedral transformation with a single degree of freedom. We envisage that our method could be suitable for extension to other paired polyhedron sets.



Shape transformation between three paired Platonic and Archimedean polyhedrons.

- Yang F, You Z and Chen Y, Mobile assembly of two Bennett linkages and its application to transformation between cuboctahedron and octahedron, Mechanism and Machine Theory, 145, 103698, 2020, doi.org/10.1016/j.mechmachtheory.2019.103698

  In the conference paper, we used the Bennett linkage to create one degree of freedom transforming polyhedrons. Here we investigate the mobility of a combination of two Bennett linkages and apply it obtain transformation between a cuboctahedron and octahedron.

- Yang J and You Z, Compactly folding rigid panels with uniform thickness through origami and kirigami, IDETC2019–97946, Proceedings of the ASME 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE, August 18 – 21, 2019, Anaheim, USA

<u>B. Behaviour of origami structures when they undergo structural deformation</u>

- Zhang J, Karagiozova D, You Z, Chen Y and Lu G, Quasi-static large deformation compressive behaviour of origami-based metamaterials, International Journal of Mechanical Sciences, 153-154, 194-207, 2019, doi.org/10.1016/j.ijmecsci.2019.01.044

  This paper deals with the energy absorption capability of origami structures. An analytical model of the quasi-static response of Miura-ori based metamaterial to in-plane compression has been developed to describe the major mechanical characteristics related to the strength and energy absorption capacity of this material in the analysed loading direction. It is demonstrated that, for certain geometrical designs, the origami-based materials can outperform the honeycombs with the same relative density.

- Karagiozova D, Zhang J, Lu G, You Z, Dynamic in-plane compression of Miura-ori patterned metamaterials, International Journal of Impact Engineering, 129, 80-100, 2019, doi.org/10.1016/j.ijimpeng.2019.02.012

  This paper studies the responses of Miura-ori metamaterials to in-plane dynamic compression, namely: compression of uniform density metamaterials at a constant velocity and impulsive loading modelled as an impact with initial velocity, and a mass impact of a metamaterial with graded density. We have found that similar to other cellular materials, the Miura-ori patterned metamaterials exhibit increased energy absorption capacity when increasing the loading rate, but their dynamic energy absorption capacity is not uniquely defined by their relative density, and is strongly dependent on their topology.

- Shang Z, Ma J, You Z and Wang S, Lateral indentation of a reinforced braided tube with tunable stiffness, Thin-Walled Structures, 149, 106608, 2020, doi.org/10.1016/j.tws.2020.106608

- Ye H, Ma J, Zhou X, Wang H and You Z, Energy absorption behaviors of pre-folded composite tubes with the full-diamond origami patterns, Composite Structures, 221, 110904, 2019, doi.org/10.1016/j.compstruct.2019.110904

  The paper studies the introduction of pre-folded origami patterns to thin-walled tubes to increase energy absorption capability when subject to impact. Thin-walled CFRP tubes with a full-diamond origami pattern have been examined. The effect of the origami patterns on the energy absorption properties and collapse modes of these tubes subjected to quasi-static axial loads has been investigated both experimentally and numerically. While compared with their metal counterparts, the CFRP origami tubes can effectively reduce the initial peak forces while increasing the overall energy absorption capacity.

- Yuan L, Ma J and You Z, Energy absorption capability of origami automobile bumper system, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2019, doi.org/10.1177/0954406219862307

- Shang Z, Ma J, You Z and Wang S, A foldable manipulator with tunable stiffness based on braided structure, 2019, doi.org/10.1002/jbm.b.34390

- Ma J, Dai H, Shi M, Yuan L, Chen Y and You Z, Quasi-static axial crushing of hexagonal origami crash boxes as energy absorption devices, Mechanical Sciences, 10, 133-143, 2019, doi.org/10.5194/ms-10-133-2019

  This paper examines the energy absorption characteristics of the origami crash box under quasi-static axial crushing. Both experimental and numerical results show that the origami pattern develops a diamond-shaped mode, bringing a reduction in initial peak force and a significant increase in energy absorption compared to the conventional hexagonal tube. The sensitivity of its energy absorption performance to various parameters is studied, and it is shown to achieve 68.29 % increase in the specific energy absorption and 13.91 % reduction in the initial peak force in the optimal case.

- Li Y and You Z, Origami concave tubes for energy absorption. International Journal of Solids and Structures, 169, 21-40, 2019, doi.org/10.1016/j.ijsolstr.2019.03.026.

  Here we try to increase the energy absorption performance of thin-walled tubes by having cross-sections of concave polygons. Through the introduction of origami initiators, a reliable and progressive buckling failure mode can be successfully triggered, which is an uncommon feature for tubes with concave cross-sections. These origami concave tubes can achieve ultra-high energy absorption capability accompanied with relatively low peak forces.

- Li Y and You Z, Open-section origami beams for energy absorption, International Journal of Mechanical Sciences, 157–158, 741-757, 2019, doi.org/10.1016/j.ijmecsci.2019.05.006

  Origami tubular structures subjected to axial compression have been well studied in the past, but not the beams under bending. This paper is one of the few on open-section origami beams created to increase the energy absorption capability under impact. It has been found that the origami beams can achieve 23.0−40.0% higher energy absorption with 12.7−20.7% lower load uniformity than those of a conventional beam.

- Li Y and You Z, External inversion of thin-walled corrugated tubes. International Journal of Mechanical Sciences, 2018, 144, 54-66, doi.org/10.1016/j.ijmecsci.2018.05.044.

  External inversion of thin-walled circular tubes is a well-understood problem. However, little has been done in the past to increase its energy absorption capability. Here by the introduction of corrugation to the thin-walled tubes, we manage to make the inversion of such tubes insensitive to the surface imperfections. In consequence, the thin-walled corrugated tube can be inverted reliably. Our findings have greatly extended the utilisation of the inversion mechanism in practical applications.

- Xiang XM, Lu G and You Z, Energy absorption of origami inspired structures and materials, Thin-Walled Structures, 157, 107130, 2020, doi.org/10.1016/j.tws.2020.107130

  This paper reviews comprehensively the performance of origami structures under impact loadings. It focuses on the deformation and energy absorption capability of origami structures subjected to static and dynamic loading.

- Xiang X M, You Z and Lu G, Rectangular sandwich plates with Miura-ori folded core under quasi-static loadings, Composite Structures, 195, 359-374, 2018, doi.org/10.1016/j.compstruct. 2018.04.084

  This research presents a parametric study on rectangular sandwich plates with Miura-ori folded core using numerical simulation and analytical analysis. Two loading conditions are studied: three-point bending and uniformly distributed pressure loading. It has been found that the maximum bending strength is governed by the incipience or fully plastic yielding of the core material for relatively thick cores, or elastic buckling of the core compression for thin cores. Furthermore, the yielding moment, fully plastic bending moment and elastic buckling moment of the incipience of core buckling have been evaluated.

- Wang H, Zhao Z, Jin Y, Wang M and You Z, Unified parametric modelling of origami-based tube, Thin-walled Structures, 133, 226-234, 2018, doi.org/10.1016/j.tws.2018.09.043

- Xiang X, Lu G, Ruan D, You Z, Zolghadr M, Large deformation of an arc-Miura structure under quasi-static loads, Composite Structures, 182, 2017, 209-222.

- Song K, Zhou X, Zang S, Wang H and You Z, Design of rigid-foldable doubly curved origami tessellations based on trapezoidal crease patterns, Proceedings of the Royal Society A 473 (2200), 2017, doi: 10.1098/rspa.2017.0016

- Ma J, Hou D, Chen Y and You Z, Peak stress relief of cross folding origami, Thin-Walled Structures, 123, 2018, 155-161. doi.org/10.1016/j.tws.2017.11.025

  When using origami to fold a membrane reflector surface for aerospace applications, the vertices where folds meet often experience high stress concentration. The paper investigates ways to reduce such stress concentration. The findings can be used to real aerospace deployable antenna reflectors made from flexible membrane surface.

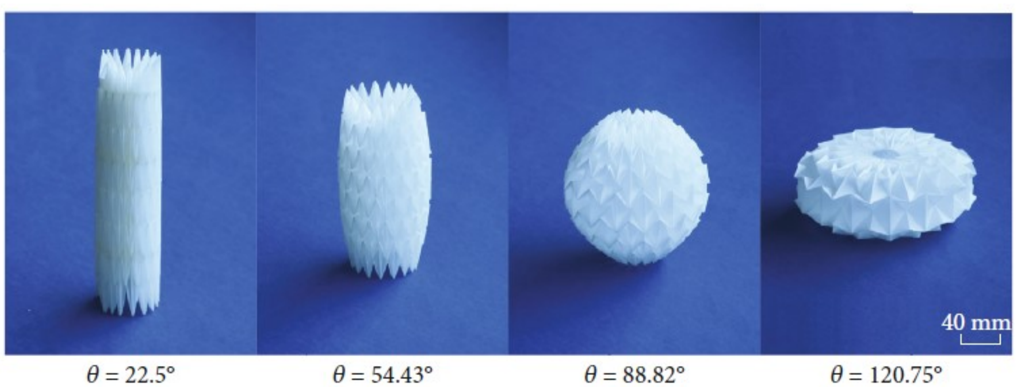
- Lee T, You Z and Gattas J M, Elastica surface generation of curved-crease origami, International Journal of Solids and Structures, 136-137, 13-27, 2018, doi.org/10.1016/j.ijsolstr.2017.11.029

  Commonly curved creases in origami are created using a piece-wise straight creases. This paper presents an analytical geometric construction method for curved-crease origami that avoids the need for surface discretisation.

C. Creation of novel origami structures with graded stiffness

- Ma J, Feng H, Chen Y, Hou D and Zhong You, Folding of tubular waterbomb, Research, 2020, 1735081, 2020, doi.org/10.34133/2020/1735081

  It has been suspected that some origami structures could have capability of motion involving both rigid folding (only facet rotation about crease lines) and structural deformation. Using a combination of kinematic and structural analysis, we confirm this is the case for a tubular origami structure based on the waterbomb pattern. For the first time we have uncovered that a waterbomb tube can undergo a mixed motion involving both rigid origami motion and nonrigid structural deformation, and the transition between them can lead to a substantial change in the stiffness. This property makes it possible to be used to create metamaterials of variable stiffness. We have derived theoretically the range of geometric parameters for the transition to occur, paving the road to program the mechanical properties of the waterbomb origami.



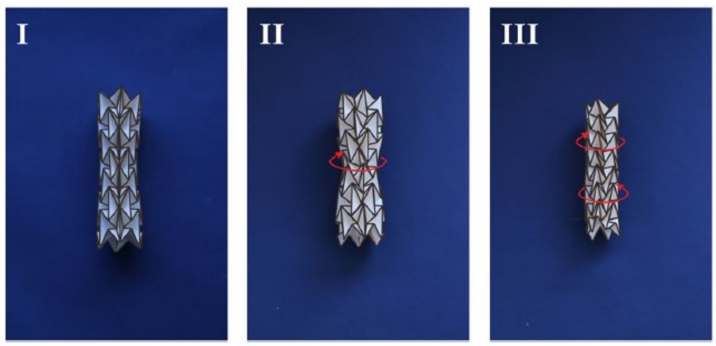
A physical model showing the start and end of rigid folding regime.

- Mukhopadhyay T, Ma J, Feng H, Hou D, Gattas J M, Chen Y, You Z, Programmable stiffness and shape modulation in origami materials: Emergence of a distant actuation feature, Applied materials Today, 19, 100537, 2020, doi.org/10.1016/j.apmt.2019.100537

  This is the second paper on the tubular waterbomb structure. Through computational and experimental analyses, we uncovered that a waterbomb based tubular metamaterial have the capability of achieving a near-zero stiffness, followed by a contact phase that initiates a substantial increase in the stiffness with programmable features during deformation of the metamaterial. Initiation of the contact phase as a function of the applied global load can be designed based on the microstructural geometry of the waterbomb bases and their assembly. This creates a new possibility of developing a distant actuation feature in the metamaterial enabling us to achieve controlled local actuation through the application of a single far-field force. The distant actuation feature eliminates the need of installing embedded complex network of sensors, actuators and controllers in the material.

- Feng H, Ma J, Chen Y and You Z, Twist of tubular mechanical metamaterials based on waterbomb origami, Scientific Reports, 8, Article no. 9522, 2018, doi.org/10.1038/s41598-018-27877-1

  In this paper, we report a twist motion of tubular mechanical metamaterials based on waterbomb origami that is previously undiscovered. We demonstrate through a detailed kinematic analysis that the initial twist can be a rigid-origami motion, whereas all the subsequent twist motion requires material deformation. Experimental results show the enhancement in stiffness of the tube with the occurrence of the continuous twist motion. We envisage that this finding could greatly expand the application of the waterbomb tube in the design of origami metamaterials with programmable and tuneable mechanical properties.



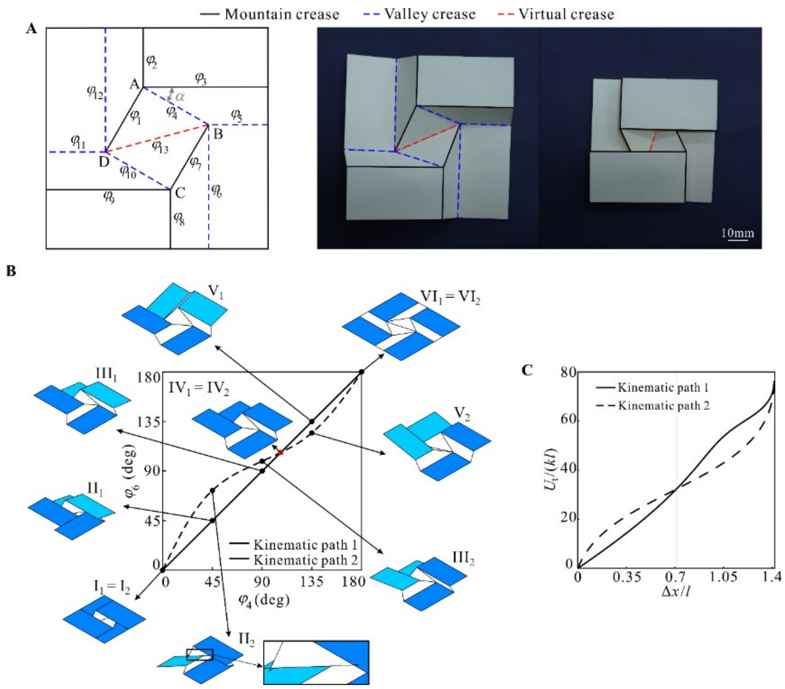
Card model of a waterbomb tube where a twist motion starts from the fully squeezed row and then spreads row to row till the ends of the tube

- Wang H, Zhao D, Jin Y, Wang M, Mukhopadhyay T and You Z, Modulation of multi-directional auxeticity in hybrid origami metamaterials, Applied Materials Today, 20, 100715, 2020, doi.org/10.1016/j.apmt.2020.100715

  In this paper, we created a novel unique origami honeycomb structure with programmable multi-directional auxeticity by hybridizing the concept of re-entrant honeycomb with the Miura pattern. The scale-independent material exhibits both in-plane and out-of-plane negative Poisson's ratios. More interestingly, we are able to program the Poisson's ratios to have mild to extreme auxeticity and map their mutual interaction as a function of the microstructural configuration. Theoretical and experimental analyses are combined in this paper to demonstrate the concepts of modulating multi-directional Poisson's ratios.

- De Waal L and You Z, graded origami honeycomb tube for energy absorption, IDETC2019-97898, Proceedings of the ASME 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE, August 18 – 21, 2019, Anaheim, USA

- Ma J, Zang S, Feng H, Chen Y and You Z, Theoretical characterization of a non-rigid-foldable square-twist origami for property programmability. International Journal of Mechanical Sciences, 105981, 2020, doi.org/10.1016/j.ijmecsci.2020.105981



Introduction of a central diagonal crease makes the square twist pattern rigidly foldable but with two folding paths.

D. Creation of 3D novel programmable and tuneable metamaterials

- Yang Y and You Z, Geometry of transformable metamaterials inspired by modular origami, Journal of Mechanisms and Robotics, 10, 2018, 021001, doi.org/10.1115/1.4038969

  In this paper, we carry out a fundamental research on two-dimensional (2D) transformable assemblies inspired by modular origami. Using mathematical tiling and patterns and mechanism analysis, we have developed various structures consisting of interconnected transformable quadrilateral modules. Moreover, by the introduction of paired modules, we are able to adjust the expansion ratio of the pattern. We find that the design flexibility among these structures makes them ideal to be used for creation of truly programmable metamaterials.

- Yang Y, Maiolino P, Chen Y and You Z, Three-dimensional kinematic metamaterials with tuneable directional permeability or programmable constant negative Poisson's ratios. (This paper is under review)

- Yang Y, Zhang X, Chen Y and You Z, Three-dimensional transformable metamaterials inspired by modular origami. (This paper is under review)

4. Other activities

The PI and his assistants have also engaged in other activities related to this program.

A. Organised and chaired the 7th International Meeting on Origami in Science, Mathematics and Education (7OSME) in Oxford, United Kingdom between 5th and 7th September 2018.

The OSME meeting, held approximately every four years, is one of the most important gatherings of the origami community around the world.

B. Organised origami sessions in every ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE)
The sessions have become most important event in origami engineering research.

C. Delivered invited talks internationally

I delivered keynote speeches at Origami and Deployable Mechanisms Workshop (Okinawa Institute of Science and Technology, Japan, 28-31 May 2019), the International Symposium on Structures and Materials Inspired by Origami (Shanghai, China, 19-23 September 2019), and the 3rd International Workshop on Origami Engineering (Melbourne, Australia, 20-22 January 2020)

5. Personnel and Finance

Two post-doctoral research associates, Drs Tanmoy Mukhopadhyay and Xiao Zhang, were hired during the program. Five graduate students were conducting research.

Financial report will be submitted by the University of Oxford, which administrated this program.