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EML webinar overview: Origami-based metamaterials

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ABSTRACT

Recently, origami (ancient arts of paper folding) is becoming a popular tool to design mechanical metamaterials. This overview summarizes an EML webinar on Nov. 4th, 2021. It covers some demonstrations of rigid origami-based foldable electronics, kirigami (i.e., paper cutting) based stretchable electronics, microscale origami, and deformable origami-based mechanical metamaterials. The author hopes that this overview and the EML webinar (https://imechanica.org/node/25538) may provide new opportunities to the mechanics community to future explore the interesting properties of origami-based mechanical metamaterials with unique functionalities. EML Webinar speakers and videos are updated at https://imechanica.org/node/24098.

Contents

1. Introduction

This overview aims to briefly summarize the EML webinar titled “Origami-based metamaterials: mechanics and devices” and provide additional information to help the readers to catch up the latest research progress in this area. Though the title of the webinar and this overview only explicitly have origami, it also covers some aspects of kirigami. The paper is organized by the rigid origami and kirigami based deformable electronics, followed by the mechanics properties of deformable origami patterns. The most intriguing part of the webinar was the last 1 hour Q&A session, which shows a great resonance with the audience and was included in this paper as well. Though the nature of this overview is simply a summary of the webinar that focuses on the work in my group and does not intend to conduct a comprehensive review of origami and kirigami related work, the expectation of this paper is to promote the general area of origami-based mechanical metamaterials to the mechanics community.

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2. Rigid origami and kirigami based deformable electronics

Origami (paper folding with “ori” for “fold” and “gami” for “paper” in Japanese) and kirigami (paper cutting with “kiri” for “cut” in Japanese) that may be originated in ancient China but were refined in Japan, have been adopted by the engineering community to design mechanical metamaterials and build deformable electronics. Particularly, rigid origami patterns (energy stored in creases only), such as the well-known Miura pattern has been extensively used to fabricate foldable solar panels [1] (Fig. 1a), foldable PCB board [2] (Fig. 1b), microneedle arrays for biomedical applications [3] (Fig. 1c), lithium-ion batteries [4] (Fig. 1d), in which the functional devices are placed on the rigid facets and the foldable interconnects are at the creases to enable cyclic folding and unfolding. Other rigid origami patterns, such as tessellations origami, have been utilized as well to make curved displays [5] (Fig. 1e). This strategy is similar to the rigid island-stretchable interconnects layout (Fig. 1f) that has been successfully utilized to enable stretchable electronics [6]. The main

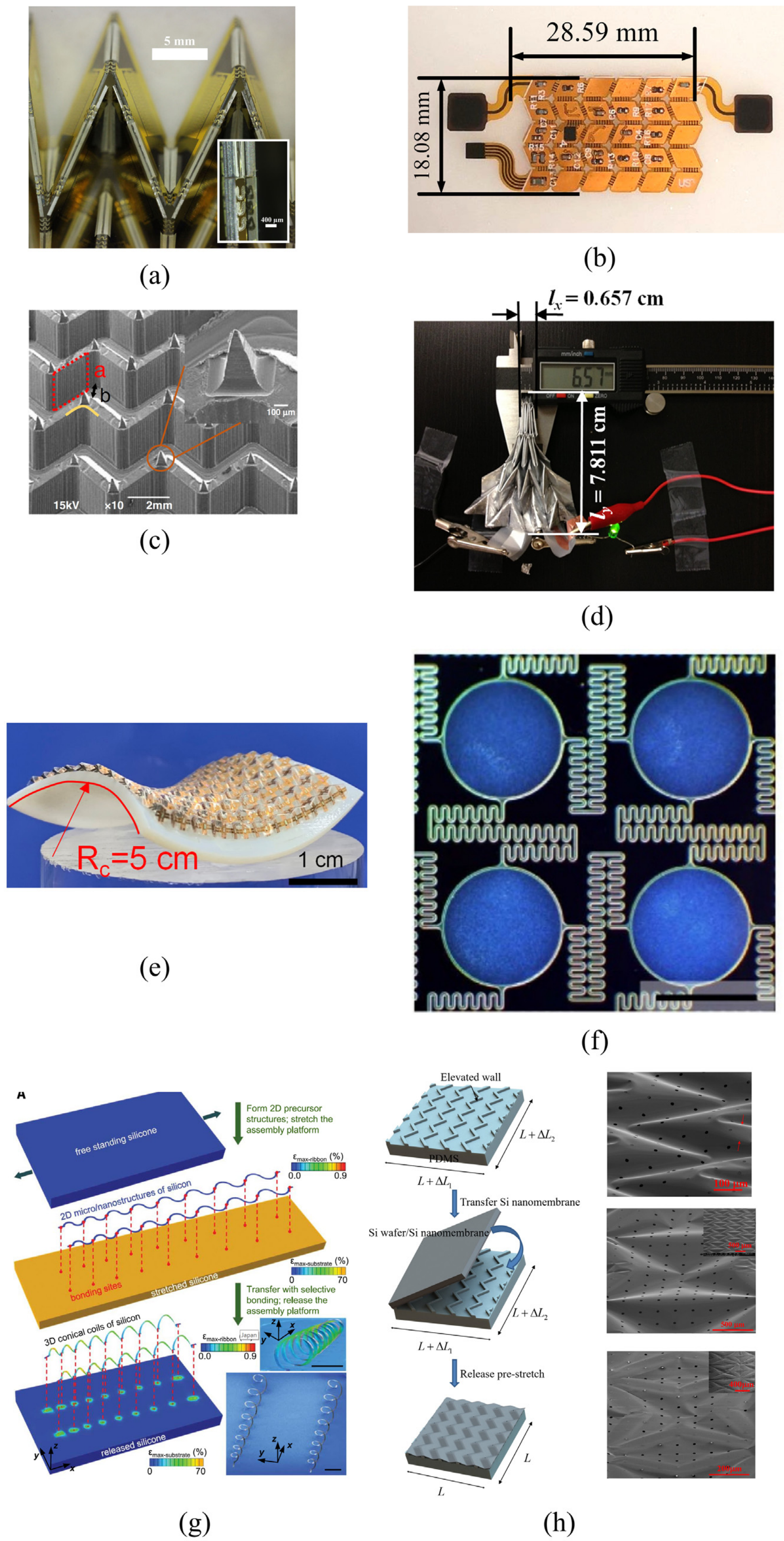

Fig. 1. Selective publications on rigid origami and kirigami based deformable electronics. (a) Miura solar cell. (b) Miura printed circuit board (PCB). (c) Miura microneedle array. (d) Miura lithium-ion battery. (e) Tessellation display. (f) A typical island-interconnect structure. (g) Microscale kirigami. (h) Microscale origami.

difference is that the rigid-origami based foldable electronics can be implemented using the mainstream manufacturing process (e.g., CMOS processes for electronics, and slurry-coating process for lithium-ion batteries).

To resolve the out-of-plane deformation during folding and unfolding, kirigami patterns was used to make stretchable lithium-ion batteries [7]. In fact, kirigami patterns have been adopted to design stretchable interconnects, though it was not specifically categorized as kirigami patterns, such as serpentine [8], semi-similar serpentine [9], and spiral patterns [10]. In addition to the macroscopic origami and kirigami patterns, their microscale counterparts can be fabricated using surface patterning [11] (Fig. 1g) or elevated walls [12] (Fig. 1h), for applications ranging from stretchable electronics to tunable electromagnetic performance. It would be expected that more applications can be explored by using rigid origami and kirigami structures.

3. Origami-based mechanical metamaterials

Origami patterns are in nature mechanical metamaterials, since the mechanical properties of origami patterns mainly depend on how the patterns are folded and just slightly rely on the materials of the origami patterns. There are many existing work to utilize origami patterns to develop mechanical metamaterials, such as tunable Poisson's ratio [13], tunable stiffness [14], and multi-stability [15]. In addition to tunable Poisson's ratio that is indeed a geometric property, stiffness is more related to the energy landscape of the origami pattern. More interestingly, deformable origami patterns (energy stored in both creases and panels) (e.g., Kresling pattern) and curved origami patterns that exhibit more complex energy landscape, were discussed for on-demand deployability/selective collapsibility and in-situ stiffness manipulation. A recent review article has in-depth review of the deformable origami patterns [16].

3.1. Kresling pattern

Kresling pattern (Fig. 2a) is one of the most studied deformable origami patterns, where its planar state can be completely described by three parameters (length a, angles α and β), and its folded cylindrical state can also be characterized by three parameters (height h, radius r, and angle ϕ). Depending on the specific geometries (i.e., angles α and β), Kresling pattern can become either stiff (Fig. 2b) or flexible (Fig. 2c), and their corresponding energy landscape and strain distribution based on a truss model are also provided. By analyzing the energy landscape and strains, an origami-inspired metamaterial can be designed by assigning an asymmetrical tension/compression behavior to one of the truss members. This origami-inspired metamaterial possesses an autonomous deployability and selective collapsibility, i.e., direct compressing for high stiffness and twisting-compression for low stiffness. Under the high stiffness collapsing path, the prototyped metamaterial can bear 1600 times their own weight. This design strategy may suggest a potential route to design mechanical metamaterials based on their energy landscape. The review article has in-depth discussion of Kresling patterns with various actuation mechanisms and applications [16].

3.2. Curved origami pattern

Compared with the corresponding straight-crease origami patterns, curved origami patterns provide an elegant geometrical design. Moreover, compared with straight-crease origami, the bending energy offered by the curved panel leads to a means to manipulate the stiffness of a curved origami pattern. As shown in Fig. 2d, the stiffness of a curved origami can be positive, zero, or negative, depending on the competition between the positive stiffness provided by the panel bending and the negative stiffness provided by the snap-through of the curved crease, when the loading direction is fairly along the tangential direction of the curved crease. The transition from straight-crease origami to curved origami is not just the change of kinked lines to a curvy line; it also resolves the plastic deformation in straight-crease origami. The comparison between the straight-crease origami and the curved origami and the design methodology may open ways to design various hybrid curved/straight-crease origami patterns.

4. Questions from the panelists/audiences

The most intriguing part of the webinar was a very enjoyable Q&A session that lasted about 1 h. The panelists realized the excitement of the combination between origami (particularly deformable origami) and mechanics. Many great questions/comments were asked and some of them may shed light to the future research directions in mechanics of origami-based metamaterials:

- It may significantly broaden the design parameter space by bringing in various materials properties (e.g., anisotropic materials and gradient materials) into the origami structures (e.g., panels and creases with non-uniform thickness).
- Given that the crease plays a critical role on the properties of origami patterns, it would be the next challenge for the mechanics community to formulate a mechanics theory to describe the creases. Some factors should be considered, such as plasticity of the materials, stress concentration at the creases, and possible fatigue and fractures around the creases. Delicate experiments would need to be conducted to characterize the key properties of the creases.
- Since the curved and straight-crease origami patterns have good correlations in terms of their energy landscape, it would be useful to revise some straight-crease origami to curved crease patterns.

5. Opportunities for the mechanics community

The great discussion with the panelists, the inspiring Q&A session, and the resonance between the audience and myself makes me believe that the mechanics of origami-based metamaterials would offer some opportunities to the mechanics communities. Some topics can be considered in the future: (1) An analytical model to describe an origami structure with explicit constitutive relationship for the creases. Delicate experiments would be necessary to characterize different types of creases with distinct materials properties and crease hardness (e.g., hard crease vs. soft crease). (2) Machine learning method to design hybrid straight-crease and curved origami patterns. The input space would include material properties, geometrical constraints, crease compatibility, and loading direction; while the output can be a designated mechanical property, such as a snap-through behavior, a bistable state, or a load bearing capability. (3) Demonstration for practical applications. To make a long-term viable field, origami-based metamaterials need to demonstrate its unique functionalities through practical applications. It would require intimate collaboration between several fields, including mechanics, mechanical engineering, material science, and biomedical engineering.

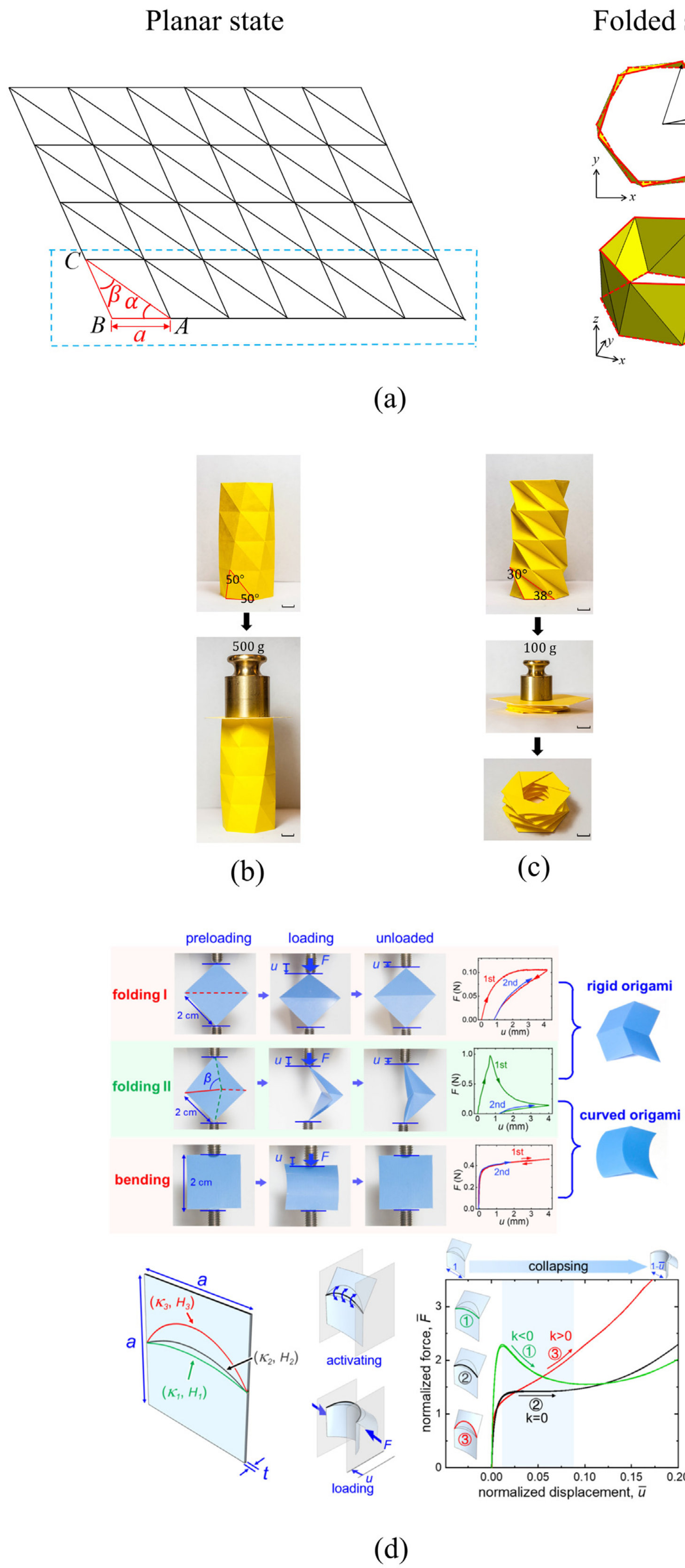

Fig. 2. Deformable origami based mechanical metamaterials. (a) A Kresling pattern at its planar and folded states. (b) A stiff Kresling pattern that can carry load. (c) A flexible Kresling pattern that can be easily collapsed. (d) A curved origami pattern that can cover positive, zero, and negative stiffness.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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