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Geometric assembly of rigid-foldable morphing sandwich structures

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ABSTRACT

Morphing plate-based sandwich mechanisms consist of three layers: an inner core designed to achieve a particular deployed geometric envelope and two outer faces designed to preserve core rigid-foldability from flat-folded to a deployed sandwich form. This paper examines rigid-foldable morphing sandwich mechanisms based on the Miura rigid origami pattern. An alternative mechanism is developed that has improved stability and locking capability compared with the existing mechanism reported previously. These improvements are demonstrated with steel prototypes. The alternative mechanism is then extended to form a family of new morphing sandwich structures, including a fan-shaped mechanism, and single-curved cylindrical and conical mechanisms. Each are derived by substituting the base Miura core pattern with a Miura-derivative pattern, and attaching faces that have compatible rigid-foldability and avoid self-intersection during deployment. Morphing mechanisms and geometric derivations are validated with physical prototypes.

1. Introduction

1.1. Miura-ori and rigid origami

The Miura-ori is a fundamental origami pattern that is developable, flat-foldable with a single degree-of-freedom (DOF) kinematic mechanism [1], and formed from a tessellated arrangement of a single repeated parallelogram plate [2]. It is also rigid-foldable, which means it can fold by rotation of rigid panels about hinged creases without twisting or stretching of panels. The properties of rigid-foldable origami are useful for numerous engineering applications, including space [3], sub-sea [4,5], military [6–8], and sandwich structures [9,10]; and biomedical [11], automobile [12], robotic, and self-folding devices [13,14].

There are numerous methods to parametrise a Miura-ori pattern, but this paper shall adopt a method described by the authors in [15]. Five parameters are required to specify the unfolded pattern geometry: side lengths a and b, sector angle ϕ, and straight and zigzag crease numbers m and n, shown in Fig. 1. An additional variable parameter is used to simulate the single DOF of the pattern, for example longitudinal or lateral edge angle η_A or η_Z, and once specified it uniquely defines a Miura-ori. The folding pattern depicted in Fig. 1 is generated with $a = 40$ mm, $b = 50$ mm, $\phi = \pi/3$, $m = 5$, $n = 5$, and varying η_A from π (unfolded) to $\pi/3$ (flat-folded). Relationships between variable and constant parameters are given in [15], along with a series of Miura-derivative core geometries that are formed by altering a single characteristic of the Miura-ori base pattern to generate a range of global curvatures. Miura-derivative patterns have previously been used directly for numerous single-layered folded plate structures [16–19].

1.2. Multi-layered rigid-foldable assemblies

Symmetric reflection of Miura-ori about the ground plane creates a polyhedral tube pattern with preserved single DOF rigid foldability [20], known commonly as the Tachi-Miura polyhedron (TMP) bellows. It can be tessellated to create 3D cellular structures, extruded into zonogon tubes [21], or stacked bidirectionally to form woven arrangements [22]. The general condition for rigid-foldability in multi-layer deployable prismatic structures is given in [23] by treating them as a closed chain of N spherical $4R$ linkages.

The rate of in-plane expansion of Miura-ori has been shown to be only a function of edge angle η_Z [24]. Different layers in Miura-ori polyhedral tubes could therefore have different heights. An immediate development of this was a single DOF multi-layered Miura-ori stack in which a *face* layer, $A'B'C'I'H'G'$ in Fig. 2(a), is set with a height of zero, i.e. in a flat state, and used to constrain a *core* layer $ABCIHG$ at a partially folded configuration. These can be stacked infinitely to create a space-filling multi-layer metamaterial or a single additional face layer can be attached to create

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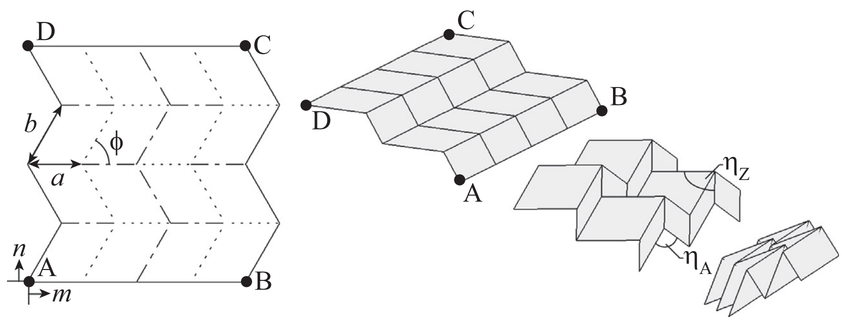
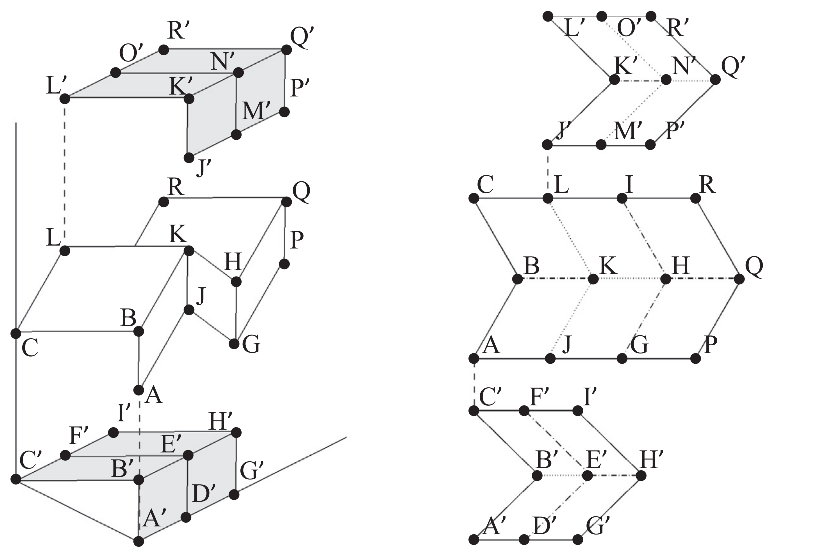
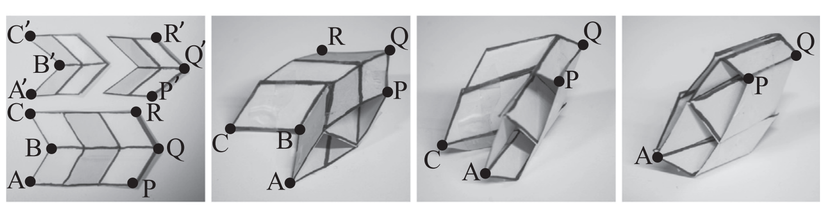


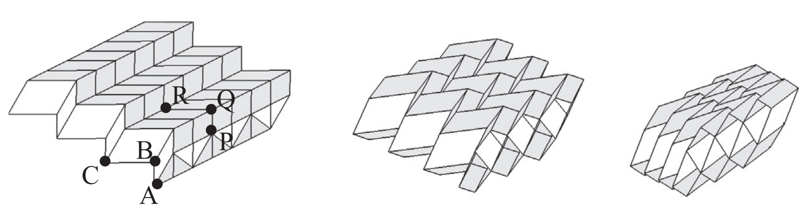
Fig. 1. Miura crease pattern parameters, on left; and single DOF rigid-foldable mechanism and variable parameters, on right.



(a) Unit face and core alignment (b) Unit face and core crease patterns



(c) Unit mechanism prototype, from left to right: crease patterns, deployed assembly, partially-folded assembly, flat-folded assembly



(d) Simulated morphing sandwich

Fig. 2. Assembly of existing mechanism.

a triple-layered *morphing sandwich structure*, shown with face $J'K'L'R'Q'P'$ connected to core $JKLRQP$ in Fig. 2(a). If six parameters as discussed above are required to define a face pattern on a known partially-folded core pattern, three face parameters are shared with the core. With reference to Fig. 2(a), these are side length $b = A'B' = J'K'$, folded angle $\eta_Z = \angle A'B'C' = \angle J'K'L'$, and a matched m. The remaining three face parameters n^F, a^F and ϕ^F, are derived from known core parameters and the following relations:

$$n^F = n - 1, \text{ for } n = 4, 6, 8, \ldots \quad (1)$$

$$a^F = A'D' = J'M' = AG/2 = a\sin(\eta_{A,set}/2) \quad (2)$$

$$\phi^F = \angle D'A'B' = \angle M'J'K' = \angle ABC/2 = \eta_{Z,set}/2 \quad (3)$$