

Mechanical Metamaterials Inspired by Modular Origami

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Abstract

Mechanical metamaterials with complex microstructures often exhibit superior physical properties, such as high stiff over weight ratio, graded stiffness and negative Poisson's ratio. The geometric design of microstructural cell of such materials is crucial to achieve the targeted mechanical functions. Typical examples include metal microlattices with high recoverability, and ceramic composite trusses that have enhanced fracture toughness. In recent years, origami mechanisms provide a new source of inspirations as some origami folding can be readily used for the structural geometry of the metamaterials. So far most origami-inspired metamaterials have been based on the Miura-ori. By changing the crease angles of Miura-ori patterns, the packed metamaterial can have features such as graded stiffness, and locking and pop-through transformations. Other origami-inspired metamaterials include a series of 3-DOF transformable metamaterial with periodic structure consisting of extruded cubes, which is designed by combining modular origami and kirigami.

In this paper, our attention is drawn upon designing metamaterials by combining modular origami and spatial linkages network. Typically modular origami is done by creating polyhedron blocks first through paper folding, and then assembling these blocks together to complete the overall structure. In a previous study we were able to generate a family of planar transformable assemblies using mathematical tiling patterns. Here we show that the planar assemblies could be made into a spatial structure by adopting the Sarrus linkage.

The Sarrus linkage was the first published overconstrained mechanism by Pierre Frédéric Sarrus back in 1853. It is a $6R$ spatial linkage capable of rectilinear motion, Figure 1(a). The designed unit, known as the Sarrus Modular Origami (SMO) module, contains a Sarrus linkages at each of the pillars, which are then linked by a transformable planar $4R$ linkage on each side as shown in Figure 1(b-d). The SMO module has one DOF for rectilinear motion with two boundary states when the distance between plates A and B reaches the minimum and the maximum. Duplicating the SMO module in three othogonal directions results in an assembly which would be the structure of a transformable metamaterial (Figure 1(e-g)). The transformable nature means that the structure is a porous cube initially where all the pores have the same orientation. During the transformation, the volume of the structure increases in all of the three orthogonal dimensions, giving it a negative Poisson's ratio. In the final state, the material ends up with pores in all three orthogonal directions. The material based on such a structure will have different stiffness, density and porous orientation at every configurations.

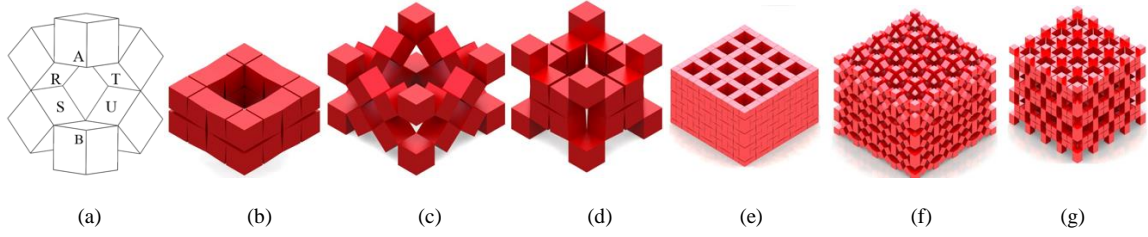


Figure 1: Geometry design of the SMO module. (a) A Sarrus mechanism by cube units. (b-d) Transformation of a SMO module. (e-g) Deformation of a SMO material

Other SMO modules can also be produced by varying the shape and connection order of the planar $4R$ linkages and the Sarrus linkages. For the $4R$ linkages, the number of the rigid blocks can be increased, leading to different geometrical shapes as shown in Figure 2(a). The shape of the rigid blocks can also be changed to, for instance, polygons with curved surfaces as shown in Figure 2(b) as long as the corners of a module where the connections are made to its neighbouring modules form a specific shape. The advantages of these customized structures is that they have bigger contact surfaces along the edges of the blocks so that the overall structure could bear larger share forces. Moreover, the corner blocks could be replaced by a triangular or hexagonal one so that structures such as those shown in Figure 2(c) could be made.

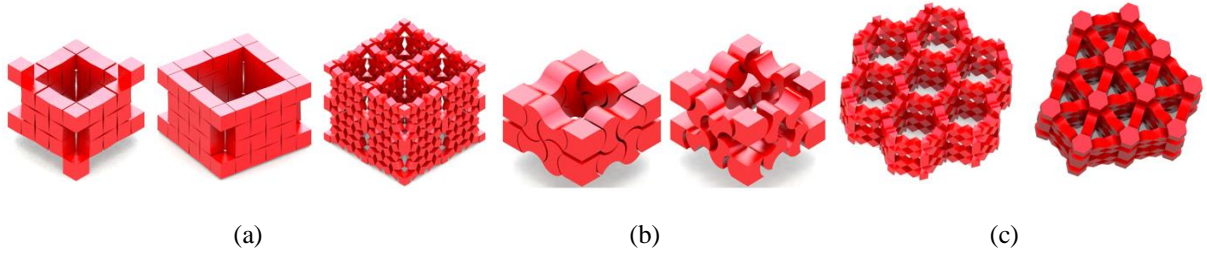


Figure 2: General SMO module. (a) SMO module with more tiles (b) SMO module with curved edges (c) SMO metamaterial in different tiling patterns.

We also produced the physical models of the SMO assemblies using 3D printing, and conducted mechanical tests on the models to evaluate their mechanical properties. The structures are extremely flexible and compliant initially during the mechanism motion, and become stiff when the cells are compressed together. Various structures can also be combined together to achieve different shapes and graded stiffness at desired locations. Therefore, the metamaterial based on such structures could be highly adaptive to the physical environment they operate in, including external loading and volume change. These features could be very useful in applications in automotive and aerospace industries.