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Connection Designs between Origami Arrays with Multilayer Planes

Qian ZHANG*, Jian Feng, Jianguo CAI

*Southeast University, Nanjing, China, 200096
z.qian@seu.edu.cn

Abstract

Origami arrays can form novel structures with rich mechanical properties through stacking design. However, due to the inherent design of origami arrays, the stacking operation is often realized by line connection, which brings limitations to the processing and preparation. A novel rigid origami array with multiple platforms is proposed by the addition of a tilted design in a planar square grid structure. This origami array with a single degree of freedom can form four layers of planes during motion, and the corresponding heights of the planes are inconsistent, which endows the origami arrays with a broader design space for connection assembly. The assembly method between the arrays of the origami structure is highlighted. The presence of the platforms enables the structure to have mirror, shift and sliding connections that do not change its kinematic properties. Moreover, planar plates, grid plates, and corrugated plates are also designed to connect with origami structures. Finally, the potential applications of the proposed origami structures in different fields containing honeycomb plate structures, mechanical metamaterials, and acoustic structures are analyzed.

Keywords: origami array, platform, connection design, motion process.

1. Introduction

Origami is a traditional East Asian art that uses paper to design shapes, switching forms between two-dimensional planar and three-dimensional spatial structures [1-2]. The morphing characteristics of origami structures enable the reconfiguration of material distribution, which has outstanding advantages when oriented to complex task requirements. An origami-type honeycomb structure can be achieved by stacking units in a structured manner [3]. Among various origami configurations, the Miura-ori stands out as a prototypical example, forming a rigid folded structure through periodic repetition of arrays. Building upon this concept, Schenk and Guest [4] introduced an origami metamaterial comprised of stacked Miura-ori units, capable of synchronous folding and unfolding in three dimensions, primarily facilitated by interconnecting the crease between layers. By leveraging differentiated geometric designs in stacking directions, the origami-type stack structure exhibits self-locking properties, a negative Poisson's ratio, and multi-stage capabilities [5, 6]. Subsequently, researchers have explored diverse origami-type stacking structures by employing various origami unit forms and assembly strategies [7, 8].

Existing origami-inspired stacking structures often feature non-planar unfoldable units, which pose preparation challenges for multi-layer planar plate bending and stacking assembly. Consequently, these structures typically rely on 3D printing technology for fabrication or employ point or line connections without planar connecting elements, resulting in intricate fabrication processes and weak connection strengths [9-14]. In response, this paper introduces an origami structure featuring multiple platforms to facilitate inter-layer plane connections. Subsequently, it systematically examines the kinematic characteristics and connection designs of the origami structure, before delving into its potential applications.

2. Platform origami

Existing origami structures often change the inclination of the panels all the time during the folding motion and no plane can remain planar. This section designs novel origami patterns derived from planar square grid arrays. The origami structures always have platforms during the motion process. Figure 1 depicts the pattern design concept of the proposed platform origami (PO). As shown in Figures 1a and b, the square grids of the odd-numbered columns are spaced apart in a tilted design into diamond shapes, and the tilts are symmetrical to each other. Correspondingly, the square grids of even-numbered columns partly turn into trapezoids and partly evolve into rectangles. The obtained pattern can be uniquely determined based on the grid length l and tilt angle θ. It can be found that all vertices correspond to four creases. Referring to the design principles of Miura origami, the mountain and valley creases are assigned in Figure 1c. Three mountain creases and one valley crease intersect at a vertex, and vice versa. All vertexes have the same motion relationship between the corresponding four creases. This origami structure can achieve rigid folding without panel deformation during motion. One folding angle α can represent its motion configuration, determining the other three folding angles ρ_1, ρ_2 and ρ_3. It can be found that the pattern can be assembled by the extracted basic origami module, consisting of nine grids corresponding to four vertices. There will be four platforms during the folding process, two squares, and two rectangles.

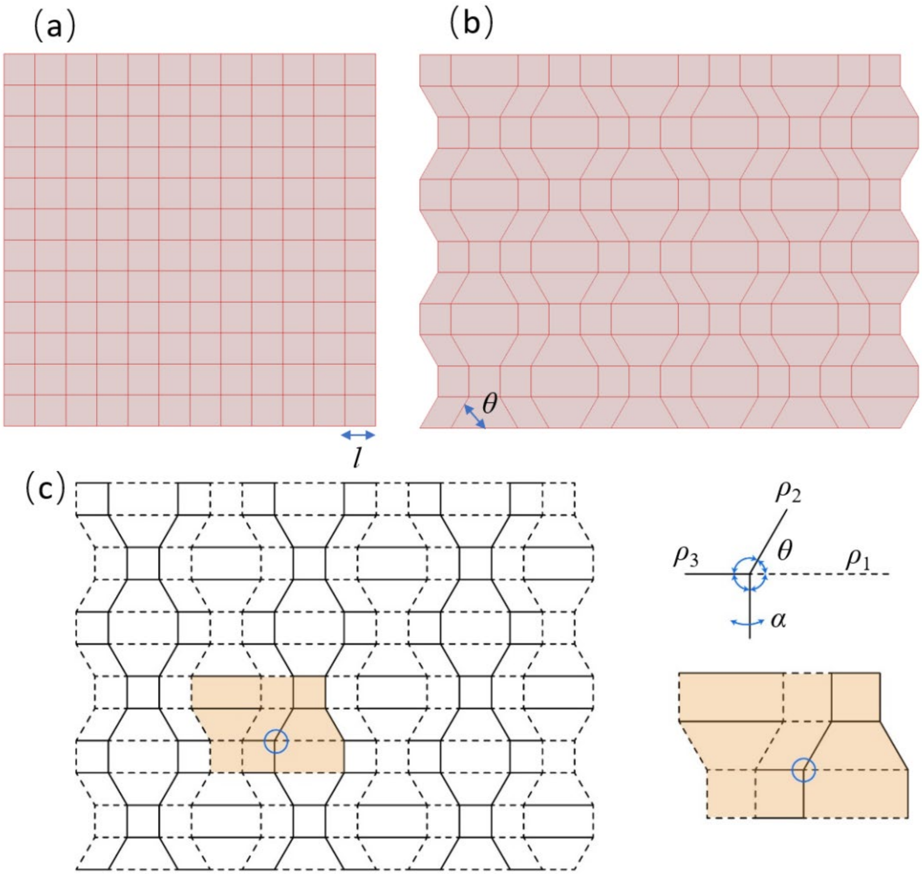

Figure 1: Pattern design of the platform origami (PO). (a) Initial square array with grid length l, (b) Introduction of the tilt angle θ, (c) Mountain and valley crease assignments with the folding angle α.

Figures 2 and 3 represent the motion process and the corresponding geometry relationship of the proposed platform origami. From the initial plane, all squares and rectangles are always kept flat during the folding process, as shown in Figure 2a. The folding behavior in two directions within the plane indicates that the origami structure has negative Poisson's ratio mechanical characteristics. For the origami pattern with the tilt angle θ of $\pi/3$, the platform origami will come into contact with itself when the folding angle α reaches $2\pi/3$. Moreover, the folding angles relationship for one vertex can be expressed as

$$\rho_1 = -\rho_3 = \pi/2\text{-arcos}((\cos\alpha\text{-}1)/\sin\alpha\tan\theta)$$

$$\rho_2 = \text{-arcos}(1\text{-}(1\text{-}\cos\alpha)/\sin^2\theta)$$

In conjunction with Figure 3a, it can be seen that as the folding angle α increases, the remaining folding angles first increase essentially linearly and then increase rapidly as they approach the fully unfolding state. At that time, the folding angle ρ_2 and ρ_3 reach π and π/2, respectively. The panels are either coplanar or perpendicular to each other.

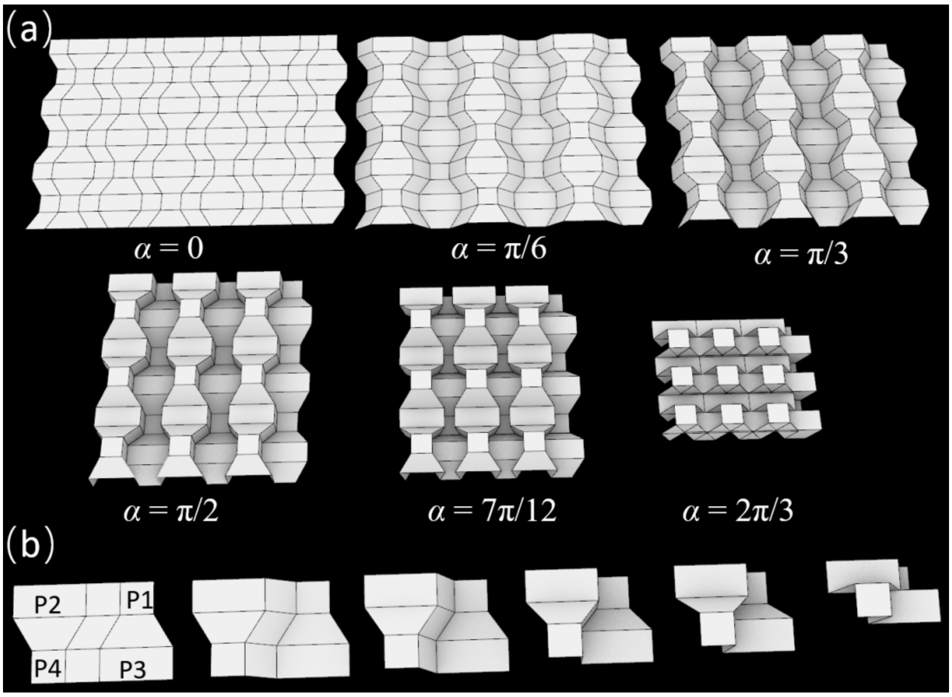

Figure 2: Folding processes of the platform origami (PO). (a) Five states during the folding process with different folding angles, (b) Folding process of the basic units with four platforms P1, P2, P3 and P4.

Four platforms P1, P2, P3 and P4 of the basic unit in Figure 2b exhibit different heights during folding. Using platform P1 as a reference, the relative height differences of the other platforms are analyzed in Figure 3b. The relative height dH_{21} of platform P2 shows a trend of first increasing and then decreasing, while the relative height dH_{31} of platform P3 always increases. This is consistent with the folding angle ρ_2 exceeding π/2 while the folding angle ρ_3 is always below π/2. The relative height dH_{41} of platform P4 is the sum of the relative heights of platforms P2 and P3. For this geometric design, there exists a state S1, where the heights of platforms P2 and P3 are the same. The corresponding folding angle α is equal to 0.639π, as shown in Figure 3d, which is very close to the limit folding state of 2π/3. Moreover, the height characteristics of the platform origami can be customized in conjunction with geometric relationships, e.g., it is possible to achieve an overall platform height that has a maxima point, which allows for a pattern design with self-locking characteristics.

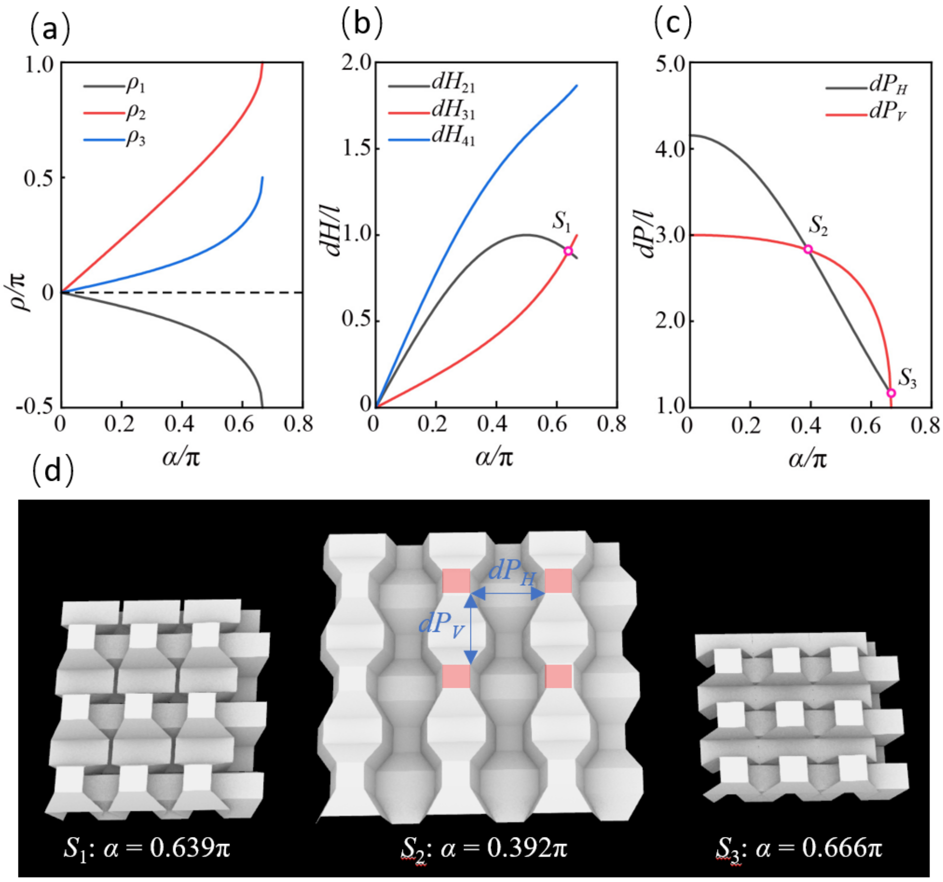

Figure 3: Geometry relationship of the platform origami (PO). (a) Folding angles of the creases, (b) Relative height difference of the platforms, dH_{21} (platform P2 to P1), dH_{31} (platform P3 to P1) and dH_{41} (platform P4 to P1), (c) Horizontal and vertical net spacing between the highest platforms in the array dP_{H} and dP_{V}, (d) Three states with specific geometric characteristics.

The in-plane motion characteristics of the platform origami are further analyzed as shown in **Figure 3c**. Both the horizontal and vertical net spacing of platform P4, dP_H and dP_V, gradually decrease with the folding process to 1.15l and l, respectively, but the process of horizontal net spacing reduction is more uniform, while the rate of vertical net spacing reduction is very slow at the initial stage. During the motion process, there are two states S2 and S3, the horizontal net spacing can be the same as the vertical net spacing. The consistency of the net spacing in both directions provides the possibility that the platform origami structure can be arrayed in a rotational connection, and the two states indicate that there may be a bistability behavior.

3. Inter-array connection analysis

The designed origami arrays have uniformly distributed platforms that can be used for inter-array connection assembly while avoiding the limitation of inter-array line connection. The simplest way for out-plane assembly is through a mirror connection, where the platform P4 of a single-layer array A can be connected to the platform P4 of its mirror array A, as shown in Figure 4a. Figures 4b and c show the assembled structures with a six-layer array and a paper model with two-layer arrays, respectively. Due to symmetry, the assembled array can still be rigidly folded. In addition, the assembled structure has channels in two directions, and the channels are connected, i.e., the channels can be formed in a checkerboard grid format. In addition, the assembly structure has channels in two directions, which are connected. There will be a chessboard channel and the volume can be regulated as the folding motion.

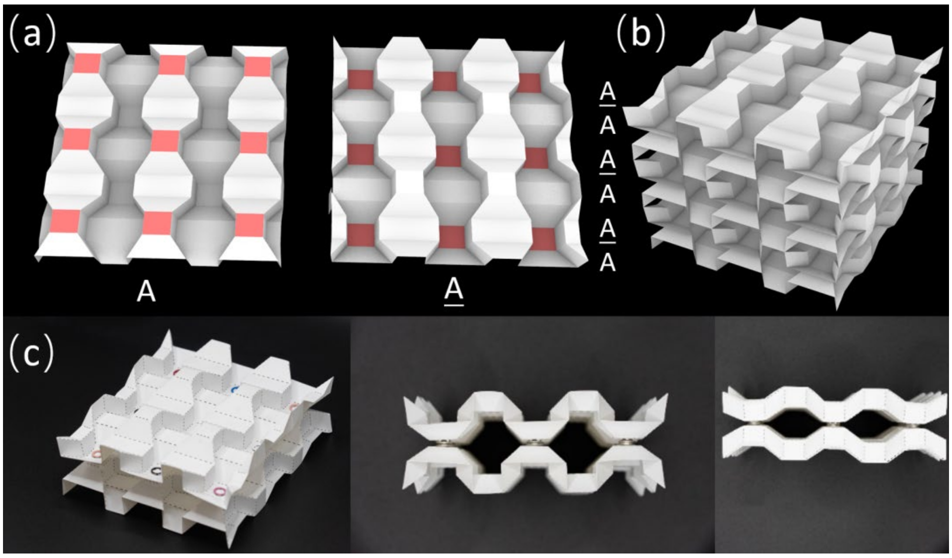

Figure 4: Mirror connection designs between platform origami arrays. (a) single layer array and its mirror array with designated connection region, (b) Assembled structures with six layers array, (c) paper model with two-layer arrays and the corresponding front and side views.

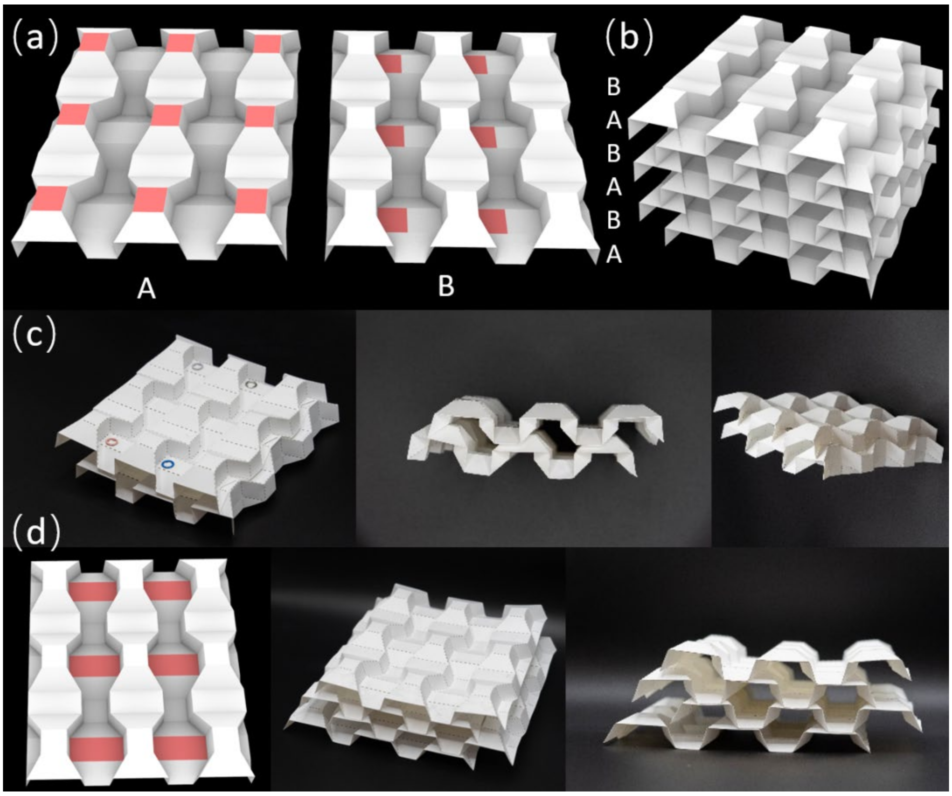

Figure 5: Shift connection designs between platform origami arrays. (a) single layer arrays with designated connection regions, (b) Assembled structures with six layers arrays, (c) paper model with two-layer arrays and the corresponding front and side views. (d) Sliding connection design and the corresponding paper models.

Other platforms can be used to realize inter-array assembly as well. Figure 5 demonstrates the utilization of the relative shift of two arrays to achieve assembly. The platform P4 of the single-layer array A is connected to the P3 platform of the other single-layer array B. This geometric relationship is also compatible and the assembled array still has the rigidly foldable property. The assembled height is lower than the mirror connection method corresponding to Figure 4. It is worth noting that the assembled origami structure only has channels in a single direction. The channel in the other direction is filled in by the stacking. The entire P3 platform of array B can be used to connect with array A, as shown in Figure 5c. The height, motion, and stiffness characteristics after different connections are consistent. The configurations of the channels will be different. In addition, the layers can be loosely connected, and sliding connections can still ensure the overall integrity of the assembled origami structure. At this point, an additional degree of freedom of motion can be increased to control the position of the sliding connection, resulting in richer motion and mechanical characteristics.

Due to the presence of the platform, the origami array is very easy to combine with other parts, such as the panel, grid, and corrugated plate shown in Figure 6. For panels, origami arrays can be constrained in different folding states. The combined structure no longer maintains rigid kinematic properties, and the load-bearing capacity is dramatically improved. Meanwhile, the channel characteristics in both directions are preserved. The load-bearing part of the constrained origami array can be simplified to a grid structure by removing the redundant parts. Corrugated sheets can likewise be connected to origami structures in the folded state. The movement pattern of the origami structure in both directions can be considered similar to that of the corrugated sheet, both of which are in the undulating folding and unfolding mode, but the movement in both directions is constrained by each other. The origami structure connected to the corrugated plate also loses its movable characteristics and only a single direction of access remains. Different connection ways also result in different load-carrying capacity characteristics.

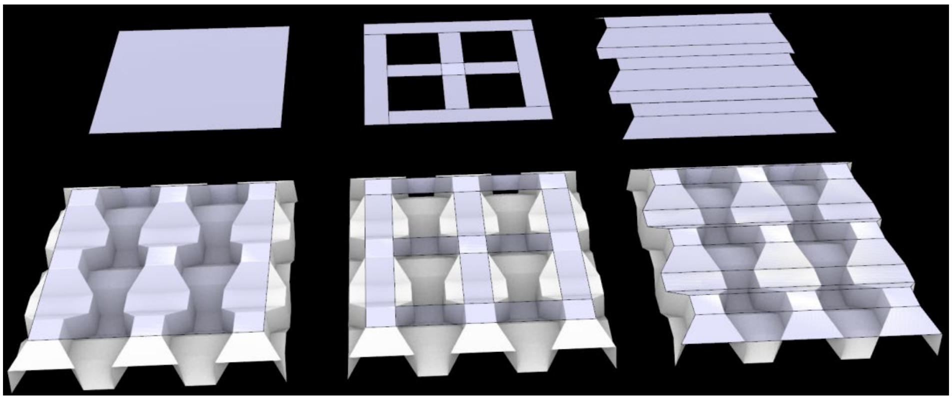

Figure 6: Nonuniform connection designs of platform origami arrays with additional connecting parts including panels, grids and corrugated sheets.

4. Application Potential Analysis

The kinematic properties and different connection designs of platform origami can lead to rich mechanical features that are used in various fields. Figure 7 illustrates several application potentials. Platform origami can be utilized to connect to flat panels to form a honeycomb plate structure in Figure 7a. Different initial states can be used to regulate the bending stiffness in both directions. The connection of the platform to the flat plate creates channels in both directions ensuring the air permeability of the honeycomb plate structures. As opposed to the traditional honeycomb structure consisting of hexagonal grids, the performance of the face-to-face connection performs better than the traditional line-face connection. Compared to the plate structures consisting of unidirectional corrugated sheets, the difference in mechanical properties between the two directions is smaller and tunable.

Figure 7b demonstrates the promising application of this origami structure in the field of mechanical metamaterials, where the multilayer origami arrays are assembled by platform connection in the manner of Figure 5c. It can be found that the mechanical metamaterials obtained from this assembly have two-stage energy consumption characteristics during compression. In the early stage of compression, the structure mainly undergoes crease deformation. When compressed to the full fold corresponding to Figure 3d, the load-bearing capacity is significantly increased and the panels will be deformed. Figure 7c shows the possibilities of this origami structure to be applied in the field of acoustic absorption. Multi-layer origami arrays are stacked directly on top of each other to obtain any desired pores characteristics for sound absorption. In addition, the sliding connection imparts a richer variation of pores features. The obtained can also be folded to change the structure morphology by folding and unfolding.

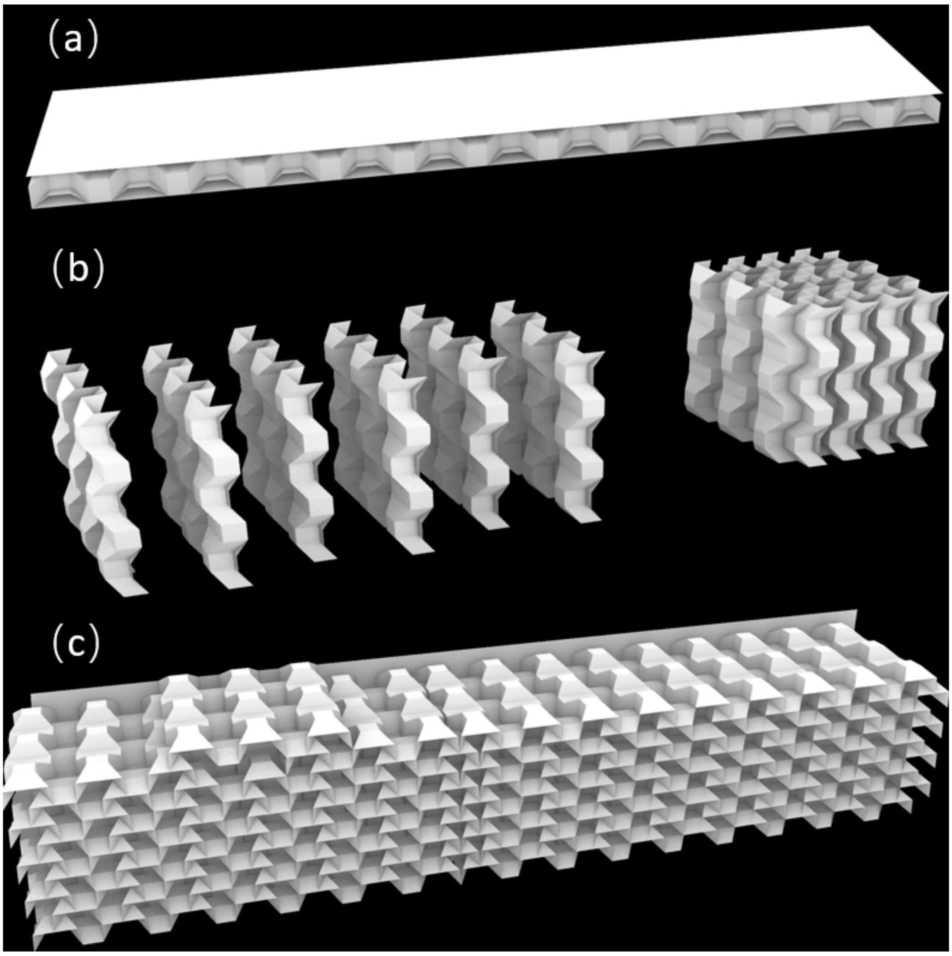

Figure 7: Application scenarios analysis. (a) Honeycomb plates with adjustable bending resistance in two directions, (b) Mechanical metamaterials with two-stage energy dissipation characteristics, (c) Sound-absorbing structure with programmable pores

5. Conclusion

Starting from a planar square grid structure, the addition of a tilted design combined with mountain-valley creases assignment yields a novel rigid origami array with multiple platforms. The geometrical kinematic relations of this origami structure are first systematically analyzed, the height of each platform and the distance between platforms during motion are computationally determined, and the geometrical kinematic relations foreshadow the potential of this origami structure for the design of mechanical properties.

The assembly method between the arrays of the origami structure is highlighted. The presence of the platforms enables the structure to have mirror, shift and sliding connections that do not change the kinematic properties of the array, and the corresponding laws of geometric and channel properties are qualitatively compared. In addition, the methods of connecting this origami array to planar plates, grid plates, and corrugated plates, which change the kinematic properties of the origami array, are also discussed. Finally, the potential applications of the proposed origami structures in different fields containing honeycomb panel structures, mechanical metamaterials and acoustic structures are analyzed.

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