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Designing of three-dimensional structures based on earwig wing folding

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Abstract

Origami embodies a traditional aspect of Japanese culture. This technique facilitates the compact folding of deployable structures and improves construction and transportation performance. While these advantages are attractive, designing deployable structures for optimal folding presents challenges. Hence, this study applies a biomimetic engineering approach inspired by the folding mechanism observed in earwig wings. Insect wings exhibit significant potential and have been implemented in a roofing structure. Our earlier work revealed the underlying simple geometrical rule within the complex crease patterns of earwig wings and developed a fan-shaped design tool using Rhinoceros + Grasshopper. However, in the initial design tool, the unfolded state was limited to planar structures. Here, we extend the crease pattern design tool by introducing non-deployable vertices, demonstrating how to construct three-dimensional shapes such as domes. While maintaining foldability, cutting around the crease forms non-deployable vertices, creating pyramid shapes. This enables the design of structures that can unfold into not only completely flat structures but also three-dimensional shapes like domes. Furthermore, we propose a folding method with mountain and valley assignments different from the original folding mode to facilitate thickness accommodation. Consequently, this study enables the three-dimensional structure to be designed based on the crease patterns of earwig wings through folding simulations.

Keywords: Origami, Biomimetics, Insect Wing, Deployable Structure, Form Finding

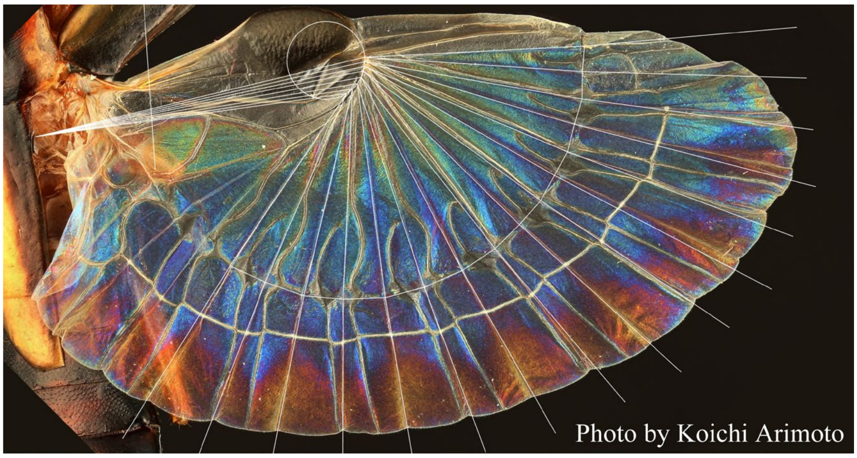

Figure 1: Earwig (*Proreus simulans (Stål)*) wing, Photo by Koichi Arimoto.

1. Introduction

Origami is a commonly known traditional art of paper folding in Japanese culture. In recent years, there has been extensive research on various fields, including engineering, such as aerospace and architecture, because this technique enables large structures to be folded into a compact form (e.g. Meloni et al. [1], or Zhai et al. [2]). The structures, also called deployable structures, have the advantage of improving construction and transportation performance in architecture (Rivas-Adrover [3]). In particular, rigid origami, which is continuously deployable without the deformation of each facet, can be folded even with rigid materials and has the potential for application to architecture (Tachi [4]). This designing approach is complex and remains challenging because sophisticated knowledge is needed to design it without interference due to the thickness of the material. Biomimetic investigations help identify functional principles of kinematic architecture for such problems (Körner [5]). Attempts to explain the optimality of artifacts through morphological analogies between organisms and artifacts have been made for a long time (Otto [6]). For example, the unfolding of hornbeam leaves has been modeled to the Miura-ori using numerical methods (Kobayashi et al. [7]). The folding of insect wings varies from species to species (e.g. Saito et al. [8], or [9]), and the relationship between insect wings and the folding of the Four-crease vertex origami (Haas and Wootton [10]) has been studied.

In this study, we focus on the deployment mechanism of earwig wings (Haas and Kukalová-Peck [11], or Saito et al. [12]), as shown in Figure 1. The aim was to develop a design method for three-dimensional deployable structures.

The overall structure of the study tasks is divided into six chapters. Chapter 2 provides an overview of earwig wings and designing crease patterns. Chapter 3 describes flat foldability and the differences between the new folding mode and the previous study. Chapter 4 describes the three-dimensional folding simulation of the crease patterns using the Physics engine. Chapter 5 describes the results by producing a physical prototype. Chapter 6 summarizes the results of this study, its possibility of engineering application, and future work.

2. Earwig wings and designing of crease pattern

2.1. The details of Earwig

Earwigs belong to the insect order Dermaptera. Some species of Dermaptera, such as the bearded Anisolabella marginalis, live on flat land in leaf litter or decaying wood and do not have wings, while others, such as Eparchus yezoensis, live on the forest floor and do. The hindwings are thin, large, and folded to store under tegmina. Previous research has documented the wings modeled in origami (Rojas et al. [13]). As shown in Figure 2, the earwig wing's deployment and flap are then stabilized in shape using an elastic hinge mechanism (Faber et al. [14]). This unique crease pattern of the Dermaptera wing achieves the highest storage efficiency of all insects, and some species can fold their wings to less than approximately 1/15th of their unfolding state (Haas et al. [15]). The crease pattern of the earwig hindwings can be folded from the center after closing like a fan from both sides, as shown in Figure 3. This study's main aim is to design an architectural deployable structure using the crease pattern of the earwig hindwings. The following section briefly describes the process for designing the crease pattern of the planar structure.

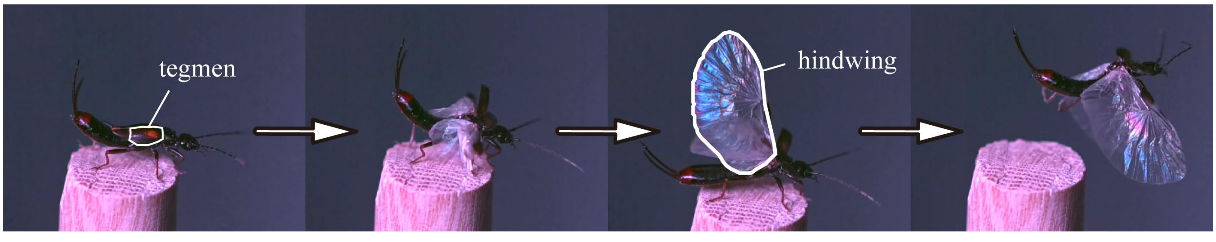

Figure 2: Deployment and flap of the earwig wing.

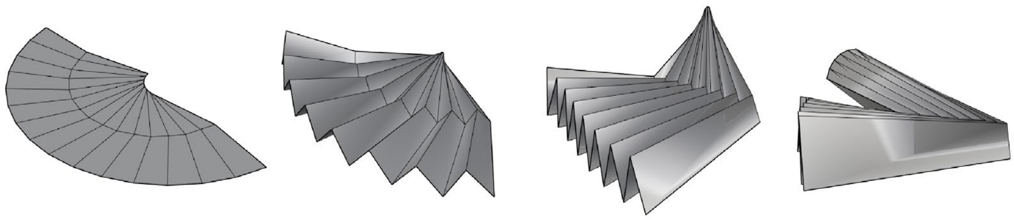

Figure 3: Folding and unfolding simulation of the earwig wing.

2.2. Design process of crease pattern

Previous research has shown the design method from the complex crease patterns of the earwig hindwings. The design software has been implemented to customize the crease pattern of the unfolding fan (Saito et al. [12]) using Rhinoceros7 (McNeel & Assoc., USA) and its extension Grasshopper (McNeel [16]). Figure 4 shows the parameters modified in this design tool as follows:

1. **Basic elements:**

   The positions of 3 elements (circle O, point A, and line MN) can be modified to create a crease pattern (Figure 4 (a)).

2. **Hub radius:**

   Changes the radius of the center circle O corresponding to the pivot of the fan (Figure 4 (b)).

3. **Rib angle:**

   Changes the angle of each rib radiating from the circle O (Figure 4 (c)).

4. **Modify angles:**

   Modify the angles between the top and end sides (Figure 4 (d)).

5. **Outer Radius:**

   The positions of 3 elements (circle O, point A, and line MN) can be modified to create a crease pattern (Figure 4 (a))..

6. **Rib Number:**

   Changes the number of ribs radiating from the circle O (Figure 4 (f)).

These combined parameters output the crease pattern and folding state; however, the software has been limited to designing two-dimensional structures such as a roof, as shown in Figure 5.

The next chapter describes a method to modify the crease patterns for designing three-dimensional structures.

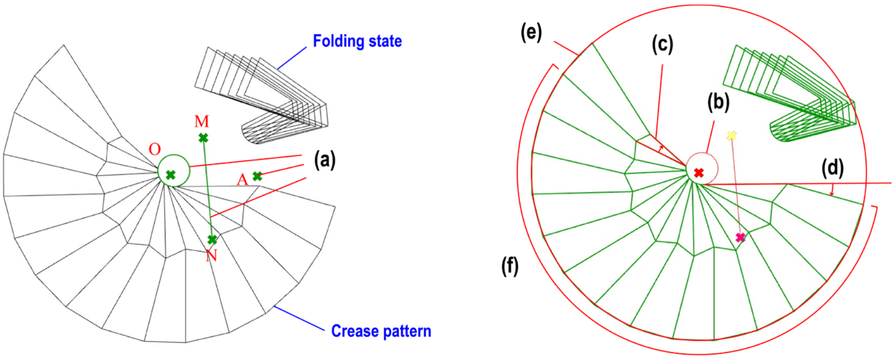

Figure 4: Parameters of the crease pattern, (a) Basic elements, (b) Hub radius, (c) Rib angle, (d) Modify angles, (e) Outer Radius, (f) Rib Number.

Figure 5: Deployable roof for a food truck (osake-mushi).
(S. Shibata, S. Nakamoto, K. Saito, Suzusan Zaimoku, VUILD, 2022)

3. Difference of the original folding mode

3.1. Flat foldability

Using the designing method shown in Chapter 2, the crease pattern is modified to satisfy the flat foldability, as shown in Figure 6. If the internal angles are α, β, γ, and δ, the flat foldability around vertices of four folding lines is the sum of the diagonals is equal, as in the equation below:

$$\alpha + \gamma = \beta + \delta \tag{1}$$

Here, a certain angle θ each is defined to remove from adjacent interior angles γ and δ: $\gamma'=\gamma-\theta$ and $\delta'=\delta-\theta$. When the removed angle edges are coincident with each other, a crease pattern is deployable into a three-dimensional shape while keeping the flat foldability (O'Rourke [17]), as in the equation below:

$$\alpha + \gamma' + \beta + \delta' < 2\pi \tag{2}$$

While maintaining foldability, cutting around the crease forms non-deployable vertices, creating pyramid shapes. This enables the design of structures that can fold into three-dimensional shapes like domes instead of flat structures, as shown in Figure 7.

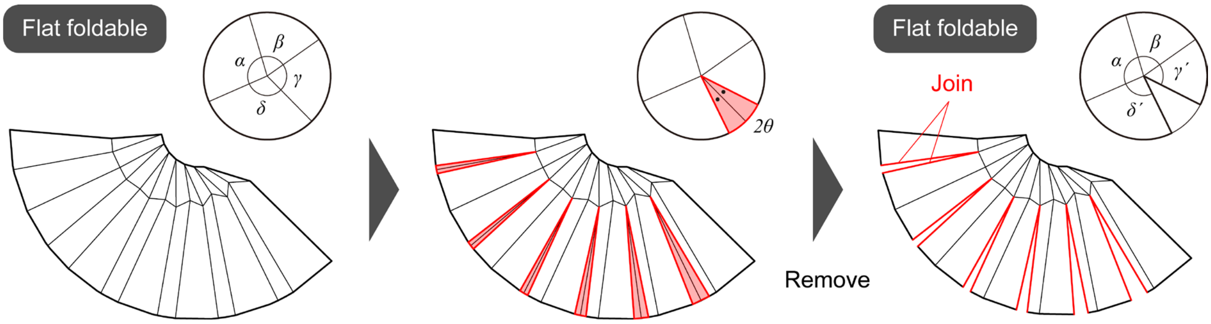

Figure 6: Modifying the crease pattern with keeping the flat foldability.

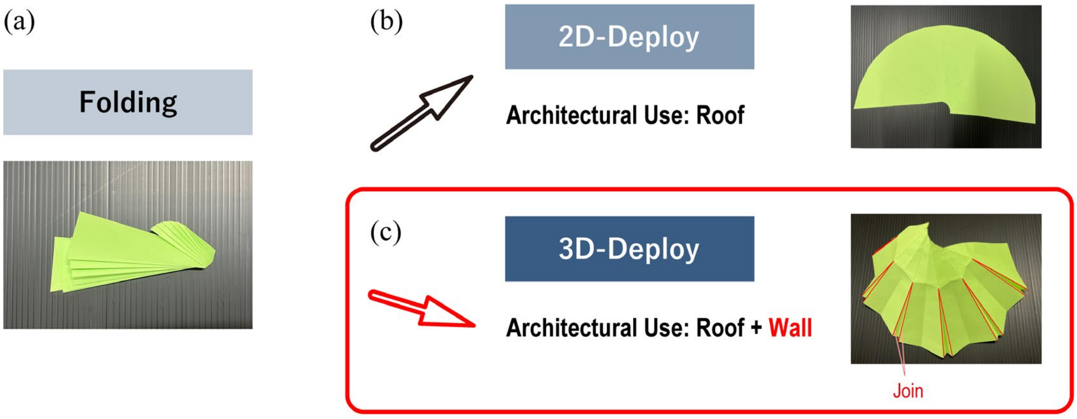

Figure 7: The differences of deployment, a) Folding state of the crease pattern,
b) Two-dimensional deployed shape, c) Proposed three-dimensional shape by joining edges.

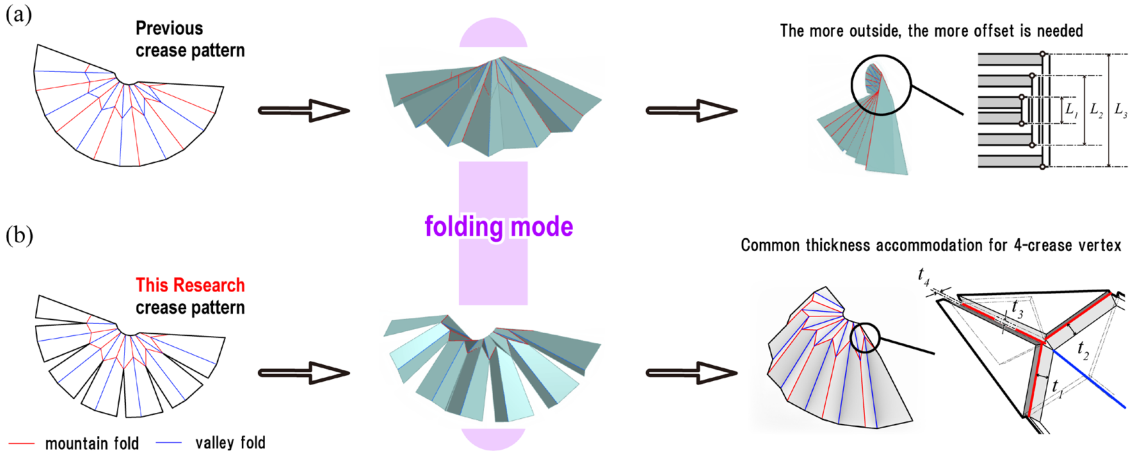

Figure 8: The differences of mountain-valley fold line assignments, folding mode, and thickness accommodation, a) The original folding mode, (b) The proposed folding mode.

3.2. The difference of folding mode

We propose a folding method with mountain and valley assignments different from the original folding mode to facilitate thickness accommodation, as shown in Figure 8. In the original folding mode, the fan shape must be stacked and then folded at once from the middle. The thickness-accommodation becomes more complicated as the number of ribs increases and more folds (Figure 8 (a)). It is necessary to offset the mountain line more significantly for the outer side in consideration of thickness. In the proposed folding mode, the top side is folded inward. It enables all facets to be folded with the same thickness (Figure 8 (b)).

Figure 9: The deployment of the thick-panel model made of MDF.

3.3. The model of thick panels

We made the deployable thick-panel model of the designed mechanism, as shown in Figure 9. The model of thick panels can remain rigid foldable if the symmetry of the rotation axis is considered around a four-crease (Chen et al. [18]). We used a medium-density fiberboard (MDF) with a thickness of 1.0 mm. The facet hinges are cloth tapes. The mountain folds are colored black, and the valley folds are colored white. We validated that the model can be deployed smoothly despite its thick panels.

4. Simulation

4.1. Simulation from a planer state to a dome-shape

A folding simulation from the crease pattern was employed for the three-dimensional shape model using Grasshopper and Kangaroo2 plug-in (Piker [19]). The diagonal length of each facet was fixed to set the cable (Goals name: Length), and the internal angles of each adjacent edge were fixed to set the spring hinges (Goals name: Angle), as shown in Figure 10 (a). To join each of the removed cutting boundaries, constraint conditions were added so that the points at each end coincide (Goals name: Length), as shown in Figure 10 (b). The displacement of a vertex on the apex side was restrained (Goals name: Anchor), and a vertical load (Goals name: Load) was subjected at each point to specify the folding mode. Figure 11 shows the result of the folding simulation of how each boundary section cut from the crease pattern is joined together to form a three-dimensional shape.

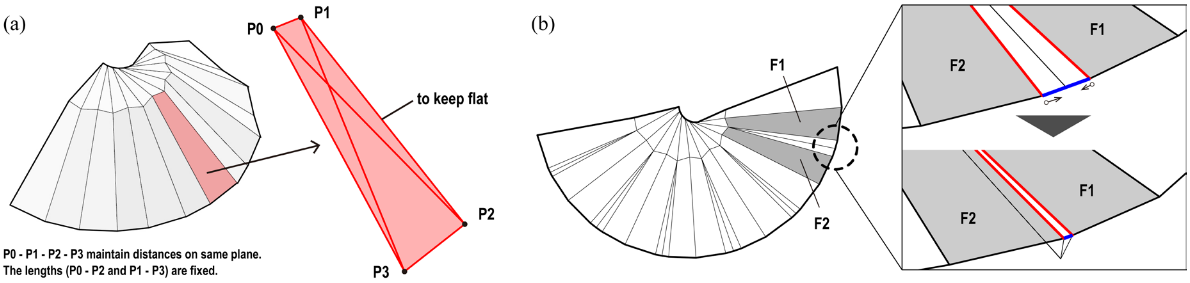

Figure 10: The constraint conditions in the folding simulation,
a) to keep each facet shape, b) to join each of the removed cutting boundaries.

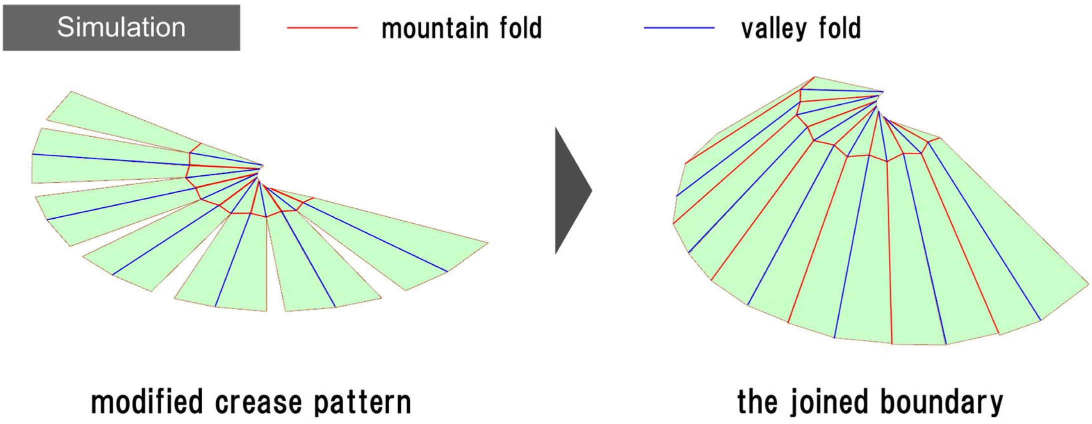

Figure 11: The simulation from a modified crease pattern to a dome-shape.

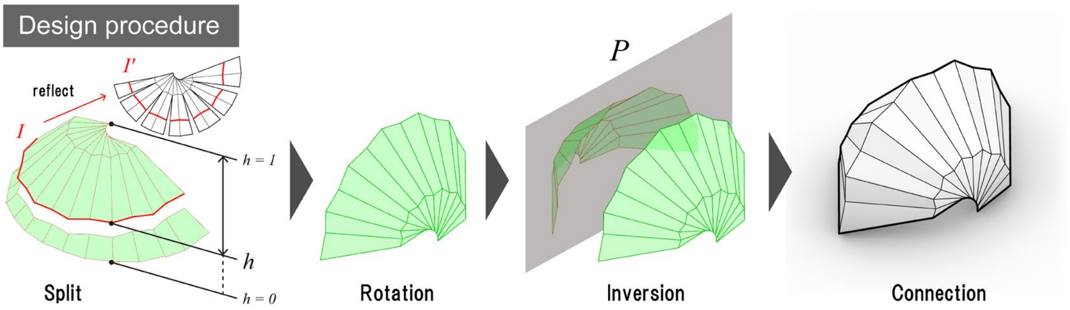

Figure 12: The design procedure of the connected three-dimensional shape.

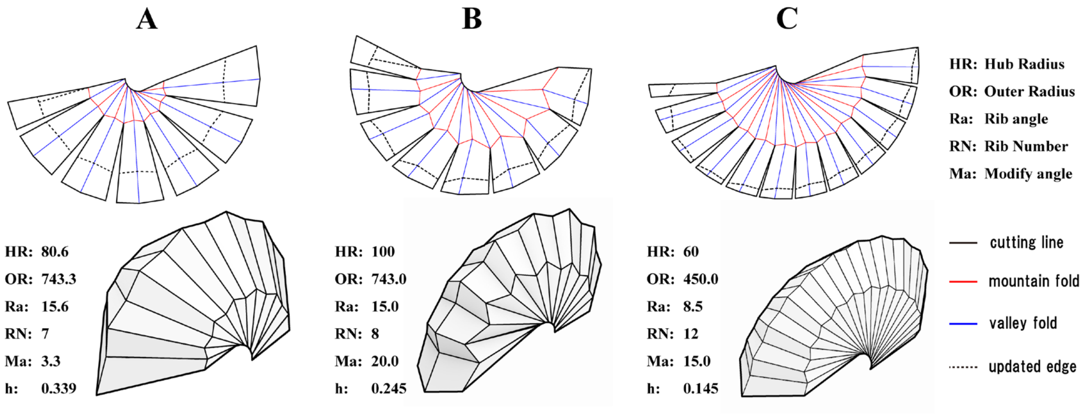

Figure 13: Differences in shape varied with parameters.

4.2. The proposal of the three-dimensional shape

We describe the process of designing the crease pattern of the dome-shape. In this process, the height h from the ground level of the simulated dome-shape is set, and the dome-shape is split at the intersection with the ground plane as shown by the red line (*I*) in Fig 12. Finally, the intersections are added as a new cutting line of the crease pattern (*I'*).

The normalized height parameter *h* is set from the lowest 0 to the highest edge 1. A line *I'* is added to the crease pattern corresponding to the three-dimensional intersection line *I*. The rotated three-dimensional shape is inverted and connected concerning the horizontal plane P, as shown in Figure 12. Finally, the intersection lines of a three-dimensional shape interfering with the ground on the edge side are calculated, and lines are added to the crease pattern. Some parameters of the crease pattern are varied, such as the three shapes A, B, and C, as shown in Figure 13.

5. Physical model

A model was created based on the crease pattern up to Chapter 4, as shown in Figure 14. The model assumes a temporary tent that can be deployed manually. Its scale is 1/25th, and thick tracing paper (112 g/m^2) is used as the material. The mountain fold connecting the top and end sides can be deployed as a serial linkage, as shown in Figure 14. The boundary of the deployed form is joined together using a zipper. The joined boundary no longer satisfies the flat foldability, and the folding angle of the three-dimensional shape can be fixed while keeping the deployment state. Other components are assumed to be anchors, membranes, rib frames, and walls. Anchors are driven to fix the facet in contact with the ground at the start of deployment. Rib frames are in the blue line section, and walls are in the green sections on the sides, as shown in Figure 15.

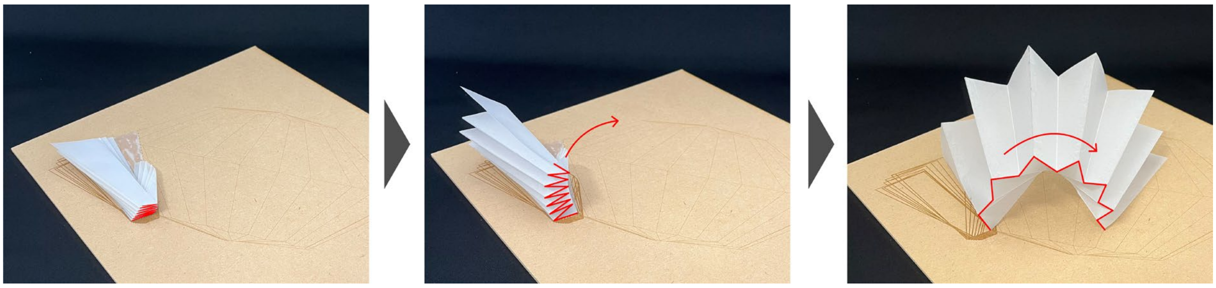

Figure 14: The deployable model as a serial linkage.

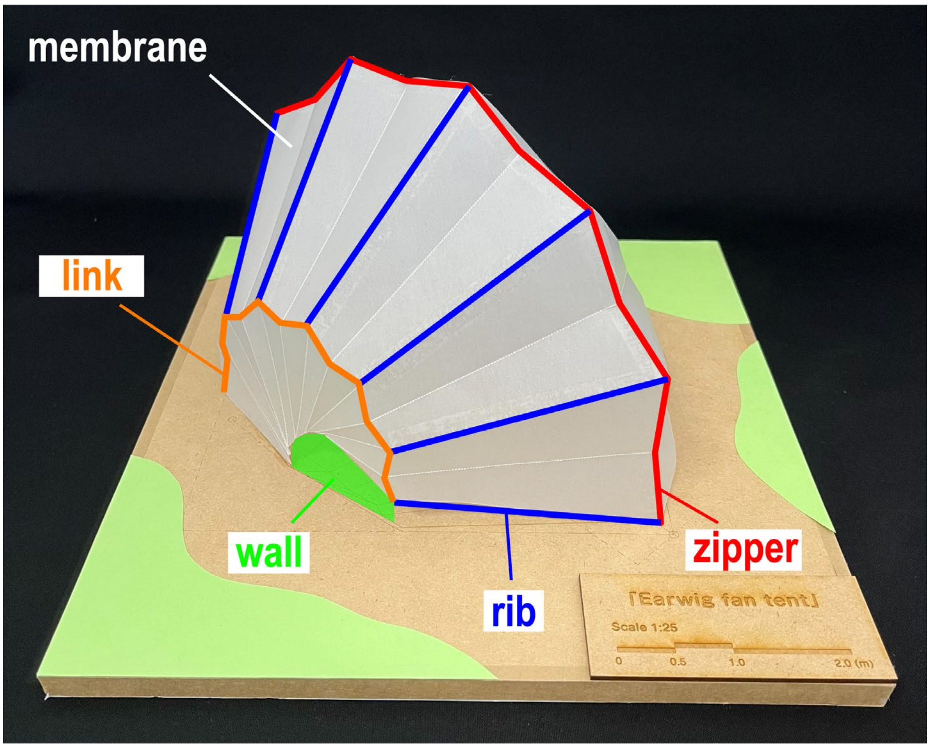

Figure 15: The proposed components and materials of the temporary structure.

6. Conclusion

In this study, we proposed a three-dimensional design method by cutting out a part of the crease pattern inspired by the earwig hindwings while maintaining flat foldability. Therefore, we simulated the three-dimensional shape from the proposed crease pattern. Several parameter combinations result in a variety of shapes emerging. The beauty of our method lies in its versatility. It allows the user to customize the three-dimensional shapes based on the crease pattern of the earwig fan using any combination of shape parameters.

We made a tracing paper model using the modified crease pattern, with a scale of 1/25th from one of the parameters. By verifying the physical model through its deployment, this adaptability opens up design possibilities in a deployable structure.

This study focused only on the geometry based on origami without the mechanical properties of full-scale structures. Hinge strength and thickness accommodation will be challenged when the method is applied to full-scale structures; however, these findings highlight the potential usefulness of the crease pattern of earwig fans in architecture.

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