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Study on Mechanism and Motion Analysis of Folded Deployable Structure for Space Habitation

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Abstract— **In the space habitation program for lunar exploration, it is quite difficult to design and manufacture materials locally. Therefore, the basic approach is to fabricate the materials on Earth, store them in rockets, and deploy and install them on the Moon. The habitation facility must be as compact as possible and have a mechanism with excellent deplorability and storability. The authors have focused on the Ishimatsu fold structure, which features the 3-dimensional folding of thick, rigid columnar structure. When unfolded, the cross section of this structure becomes hexagonal, and 6 surfaces composed by the same mechanism unfold simultaneously to form a prismatic columnar shape with complex shape changes. In this study, we investigated the usefulness of the Ishimatsu fold structure by dividing and expanding each module of the structure. Since each module and actuator can be stored small, they can be reconfigured to create various shapes. In this paper, we analyze the motion and dynamics of the expanded deployable structure, and investigate the power and effective placement of the actuators to enable deployment.**

I. INTRODUCTION

In space development aiming at migration to the Moon, it is expected that the settlers will live on the Moon for a long period of time and carry out various missions while carrying out planned development. As the amount of work to be performed on the lunar surface increases, a living space for the settlers and a warehouse to store their work equipment will also be necessary. In addition, the Moon's surface, which has no atmosphere, may be directly exposed to radiation and micrometeorites, and the introduction of simple space facilities that can avoid such exposure is considered essential for space development.

In the lunar habitation facility project, it is quite difficult to design and manufacture the facility by procuring materials locally, so the facility should be manufactured on the Earth, stored in a rocket, and deployed and installed on the Moon. The habitation facilities must be as compact as possible and have a mechanism with excellent deplorability and storability

Research on such deployable structures has been conducted mainly in the space field and has also been applied to building structures on Earth [1-4] and the origami type unfolding structures [5,6]. However, in space, there is a problem that membrane-type deployable structures do not provide sufficient safety because of the possibility of cosmic rays and debris scattering.

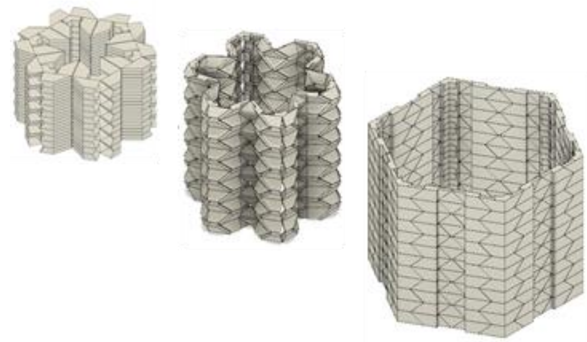

Fig 1. Deployment process of Origami-House

The authors have focused on the Ishimatsu fold structure [7], which can fold thick and rigid prismatic structures in three dimensions, and have studied deployment structures that apply this mechanism and deployment performance. As shown in Fig. 1, the structure has a hexagonal cross-section when deployed, and the six faces of the same mechanism can be simultaneously deployed and retracted with complex shape changes. We called this type of deployable structure "Origami-House" and studied the basic mechanism for its feasibility [8].

Based on a mechanism analysis of the Origami-House, this study will clarify the relationship between the forces and movements acting on each component and the forces required for deployment through actuator placement. Furthermore, we will study the expandability and usefulness of Origami-House by dividing and reconfiguring each module. Preparatory work for the dynamic analysis was conducted through modeling and basic motion analysis using mechanism analysis software (Adams). Adams is effective for dynamics analysis of structures with complex deployment mechanisms (multi-body dynamics), and the effectiveness of Adams is verified through comparison with a general simplified model.

II. KINEMATICS ANALYSIS BASED ON THE FRAME MODEL OF ORIGAMI-HOUSE

A. Basic configuration frame model

The Origami-House is a mechanism that folds into a small horizontal plane when stored, and vertically unfolds into a hexagonal cylindrical shape with complex shape changes of

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the six faces of the same mechanism simultaneously when deployed. To investigate the shape change of the deployed structure, a model consisting of each node of the face members and a frame connecting the nodes was created, and a kinematic analysis of the deployed structure was conducted. Each unit (10 members), which is a component of the deployed structure, is overlapped and joined in four stages to form a single exterior surface.

Fig. 2 shows the deployment status of one unit that was manufactured as a model, and Fig. 3 shows the deployment, diagram used for analysis, the configuration of each unit contact number, and deployment angle. The exterior surfaces are joined on six sides to form a hexagonal prism when the deployment rate is 100%. Each unit has 16 nodes, and the exterior face has 49 nodes, for a total of 283 nodes. Thus, each module is joined by its own hinge, and their arrangement creates a complex Ishimatsu fold.

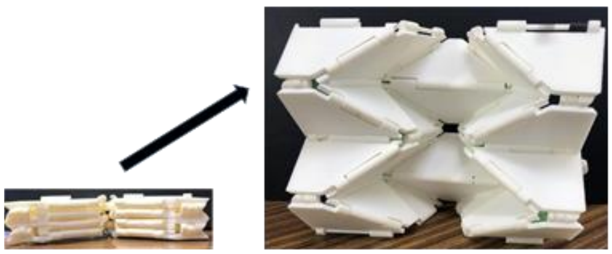


Fig 2. Two units' model that makes up the Origami-House and its deployment status

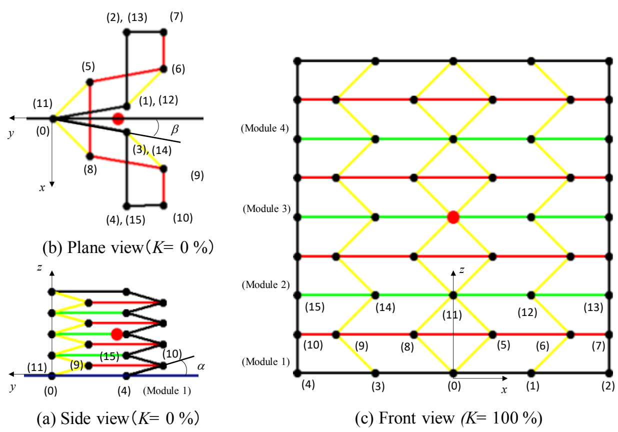


Fig 3. Deployment diagram used for analysis, the configuration of each unit, contact number, and deployment angle.

B Kinematics Analysis

The unfolding of the origami house depends on the angles of unfolding α in the y-z direction and β in the x-y direction. When the thickness of the member is taken into account, α varies from 12 to 90 [deg] and β varies from 0 to 90 [deg]. However, α and β do not change independently, but depend on the gap between each hinge, etc. In this analysis, these values are assumed to change at almost constant intervals. The shape change of the origami house is shown in Fig.4 with the expansion rate *K* as a parameter. It can be seen that at a deployment rate *K* = 0 %, the structure is folded small and concentrated in the center, but as the deployment rate increases, it expands outward significantly with complex shape changes, becoming a vertical hexagonal pillar at a deployment rate *K* = 100 %. The rate *K* increases 4.7, 2.0, and 2.6 times in the height, horizontal, and diagonal directions, and the volume is 18.8 times larger than the initial shape.

III. STATICS ANALYSIS OF DEPLOYED STRUCTURE AND DEPLOYING DRIVING FORCE

A. Relation between the center of gravity of the structure and the point of action

To fully deploy the Origami-House structure from the contracted state (deployment rate K = 0%) (deployment rate K = 100%), a force is required to pull up the entire structure from the outside. If the structure's deployment speed is slow, assume that the entire weight of the structure is at its center of gravity, and calculate the force vector in the direction of the point of action (point of pull) that pulls up the weight at the top of the surrounding outer wall. The static force required to

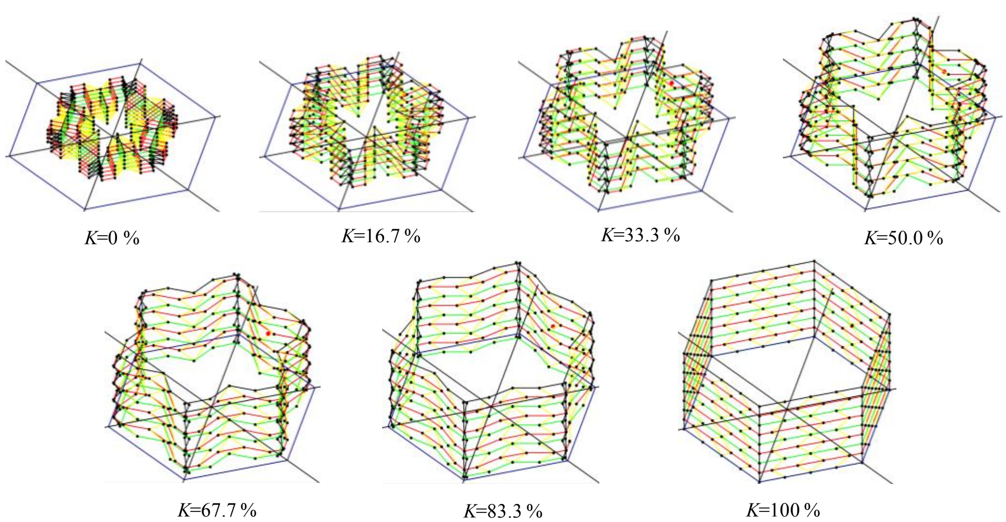


Fig 4 . Shape changes of the three-dimensional exterior surface of the deployable structure deploy the entire hexahedral structure was analyzed [9].

Fig.5 shows the geometric relationship between the center of gravity of the expanded structure and the force acting on the top of the exterior wall. Since the center of gravity G of the hexahedron is at the center of the structure and varies up and down according to the rate of expansion, the force F that pulls up the top of the exterior wall surface is determined by the geometric relationship between the center of gravity position and the point of force action A.

From Fig. 5, the magnitude and direction of the pulling force varies depending on the position of the point of action, and the pulling force at point A (top of the outer wall) is $Mg/\sin\theta_2$. When deploying an origami house structure, this tensile force requires a different driving force depending on the placement of the actuators.

The required force vectors and driving forces for the three types of actuators placed from the outside of the structure are shown in Fig.6 and its content are explained below;

(1) Case 1 (Horizontal deployment mechanism) ：The actuator is placed at the upper or lower horizontal part of the structure to enable a horizontal deployment mechanism. In this case, the force to pull the structure upward is performed only by horizontal force, which requires a very large force in the range where the angle in the z-direction is small. Especially in the initial position, other driving mechanisms to raise the jack may be necessary. The driving force F_1 required for the actuator in case 1 is shown by Eq. (1)

$$F_1 = \frac{Mg}{sin\theta_2 \cdot cos\theta_2} \tag{1}$$

(2) Case 2 (Diagonal deployment mechanism): The actuators are placed diagonally at the top and bottom ends of the structure to enable a diagonal deployment mechanism. In this case, the mechanism is capable of producing sufficient force within a small range of angles in the z-direction to pull the structure upward and horizontally. The angle θ_K of the actuator changes depending on the deployment rate, and the telescopic length of the actuator becomes long, so it is necessary to devise a way to extend and retract the actuator. The driving force F_2 required for the actuator in case 2 is shown by Eq. (2)

$$F_2 = \frac{Mg \cdot cos(\theta_K)}{sin\theta_2 \cdot cos\theta_2} \tag{2}$$

(3) Case 3 (Vertical deployment mechanism): The actuators are placed in vertical positions at the top and bottom edges of the structure, allowing for a vertical deployment mechanism. In this case, a force is required to pull the structure upward and horizontally, so a very large force is required in a range where the angle β in the z-y direction is small. The actuator driving force F3 in case 3 is expressed by Eq. (3)

$$F_3 = \frac{Mg \cdot \cos\theta_2}{sin\theta_2} \tag{3}$$

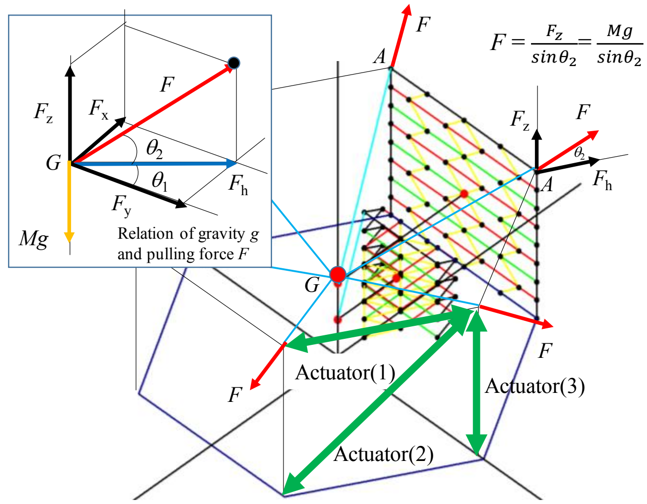
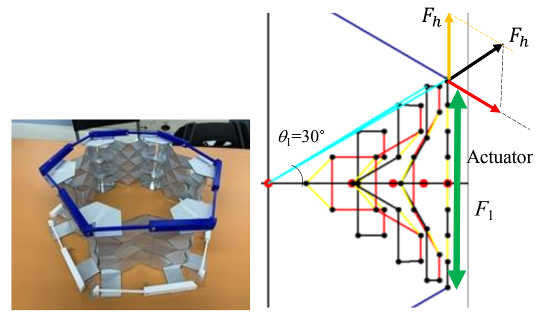
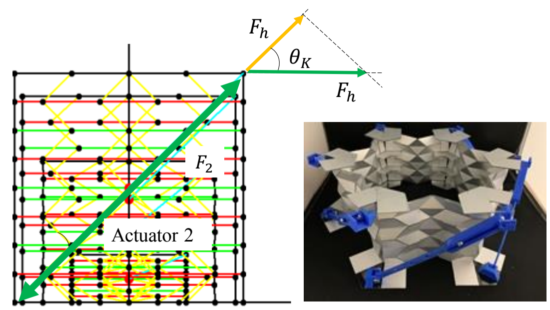


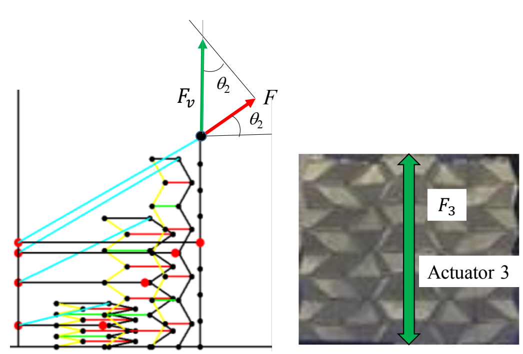
Fig 5. One unit model that makes up the Origami-House and its deployment status



(Case 1) Horizontal deployment mechanism



(Case 2) Diagonal deployment mechanism



(Case 3) Vertical deployment mechanism

Fig 6. One unit model that makes up the Origami-House and its deployment status

B. Comparison of driving force to deploy the structure

The relationship between the required driving force and the deployment rate K for the actuator placement shown in section *A* was calculated. Here, the required driving force is expressed as the ratio of the driving force to the overall dead weight, and the relationship is shown in Fig.7. In the range where the deployment ratio is small, each actuator requires a driving force five times greater than its own weight, and the driving force gradually decreases as the deployment ratio increases. The values are almost equal when the deployment ratio exceeds 60%. It can be seen that the horizontal arrangement of actuators requires the most driving force, and that the method in which actuators are arranged diagonally to provide driving force in the horizontal and vertical directions is more efficient.

The deployment rate of the structure is about four times in the vertical direction, and the vertical and diagonal placement of the actuators requires considerable ingenuity in actual placement because the actuators have a large expansion and contraction rate in the vertical and diagonal placement. On the other hand, the horizontal deployment rate is about 2 times, which could be handled by modifying existing actuators, but the driving force would be rather large, which is an issue. In terms of operation, if the deployment rate can be used in the range of 20-100%, it will be easier to select the driving force of the actuator, and a horizontal arrangement with about twice the expansion/contraction rate is effective.

C. Features and application examples of expanded Origami -House

The origami-house has each unit connected to form a hexagonal shape when unfolded, and is characterized by its compactness when stored and airtightness when unfolded. On the other hand, we investigated the expansion of various deployable structures by separating each unit and actuator part. The characteristics of the expansion mechanism are shown below.

- 4 units (or 2 units) and an actuator are arranged, and the structure is such that the entire structure is closed when deployed.
- When stored, each unit and actuator can be separated, making the entire structure even more compact.
- By combining each unit and actuator, shapes can be created according to the application.
- The actuator is basically a scissor structure, but other structures are also possible. Since there is space between each unit, it can be easily expanded and stored.

An application example of the expanded origami house is shown below, and an outline of the expanded origami house is shown in Fig.8.

(1) Application example 1:

A slightly elongated origami house can be constructed by combining 2 sets of 4 units of the deployable structure with an actuator. It can be applied to residential facilities such as on the lunar surface, such as warehouses for storing materials and work vehicles

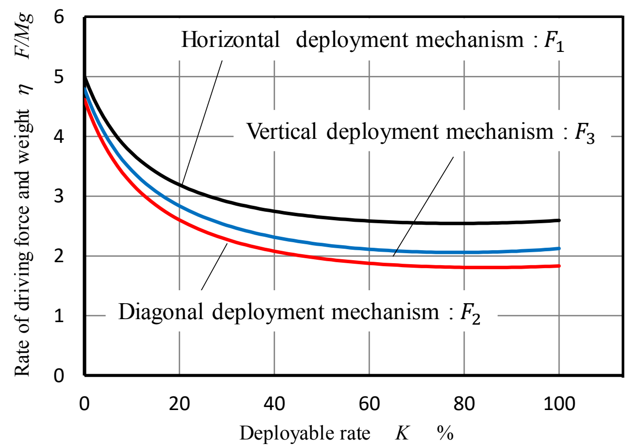
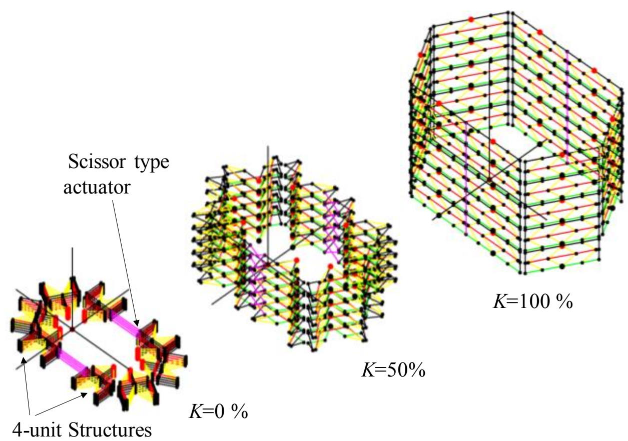
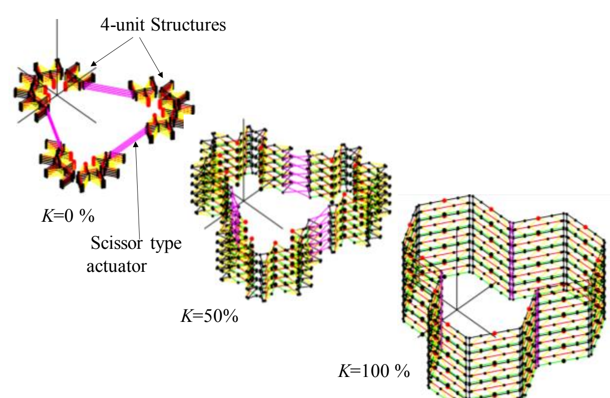


Fig 7. Relationship between actuator driving force and deployment rate (K)



(1) Application example 1



(2) Application example 2

Fig 8. Application examples of expanded Origami House used in space habitation

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(2) Application example 2:

Three origami houses can be built inside by connecting 4 units of the deployable structure in a triangular shape via three sets and actuators. By separating the living facility into three rooms, you can easily create a private space.

By further expanding this development method, it is possible to construct simple large-scale residential facilities.

IV. ATTEMPT ON DYNAMIC ANALYSIS OF ORIGAMI HOUSE DEPLOY STRUCTURES

A. Purpose of using analysis software

The Origami-House, which is an unfolding structure made of Ishimatsu folds, unfolds and stores while making extremely complex changes. Therefore, it is difficult to grasp the forces and rotational forces that act on the hinges and actuators of each member within the unit. Therefore, we modeled an Origami-House using mechanical analysis software (Adams) and prepared a dynamic analysis when it was unfolded and stored. Adams is software that performs multibody dynamics and motion analysis that is widely used around the world. By connecting members in a three-dimensional CAD drawing and setting constraint conditions (rotation, contact, load, force, etc.) that match the actual system, it is possible to analyze the movement and dynamics of the system. Table 1 shows the relationship between the degree of restraint and degree of freedom for the joint restraint conditions using this structure.

B. Deployable structure model and constraints

The image of a revolute joint that allows movement of two relative surfaces with a single hinge axis is a mechanism in which the hollow shaft and a2 are constrained by a fixed joint, and a cylindrical shaft fixed to a1 can rotate inside the hollow shaft. Fig.9 shows the detail of mechanism and constrains for joint axis. The actuator extends in the z-axis direction, The cylindrical joint, which rotate around the axis, was mainly constrained. Fig.10 shows one example of a mechanism model and constraint conditions created in Adams. The myriad of constraints are set for each joint on the deployment planes, and their states are displayed. The total number of degrees of freedom for the entire joint must be equal to the total number of constraints, which was a challenge in terms of creating the model.

C. Analysis result by simulation

In order to analyze unfolding situation of the structure, the maximum value obtained from Fig. 7 was applied as a pulling force *F* to the position of point A shown in Fig. 9 without placing the actuator.

Fig. 11 shows the results of Adams analysis as the shape changes with the expansion rate (k=0%, 33%, 66%, 100%). Immediately after the calculation starts, the shape changes very slowly, but as the expansion rate increases, the speed of expansion increases. This seems to be because the applied force was greater than the force required at each deployment rate, and an accelerating force was added to the deployment. Therefore, even in Adams' analysis, it seems necessary to provide control to feed back the surplus of the applied force. The shape change shown in Fig.4 reproduced the same motion as in the analysis by Adams, confirming that the results are almost valid. It is now possible to consider future actuator development.

D. Future analysis contents and predictions

Currently, we are conducting an analysis in which actuators are placed in a part of the structure. Fig.12 shows the Adams

Table 1 Relationship between the degree of restraint and freedom of the joints

	Joint Name	Translation X	Translation Y	Translation Z	Rotation X	Rotation Y	Rotation Z	Count of constraint	Degree of freedom
Joints	Revolute	×	×	×	×	×	○	5	1
	Spherical	×	×	×	○	○	○	3	3
	Fixed	×	×	×	×	×	×	6	0
	Cylindrical	×	×	○	×	×	○	4	2
	Planar	○	○	×	×	×	○	3	3
Primitives	Inline	×	×	○	○	○	○	2	4
	Parallel	○	○	○	×	×	○	2	4

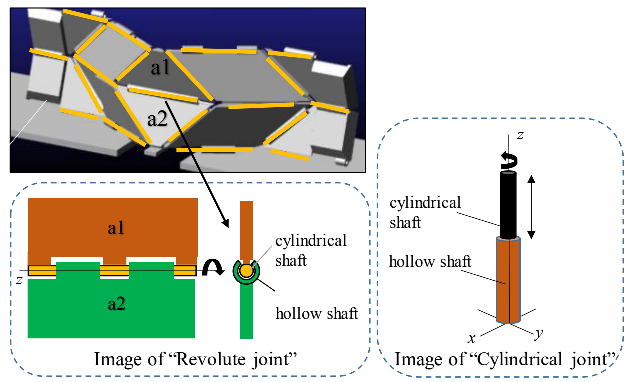


Fig.9 Detail of mechanism and constrains for joint axis.

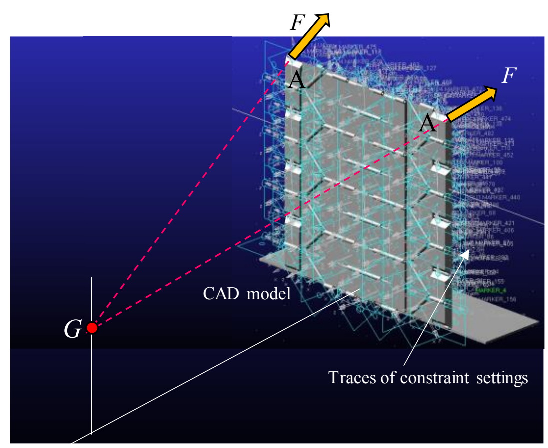


Fig10 Analysis model of the deployable structure created on Adams and the constraint

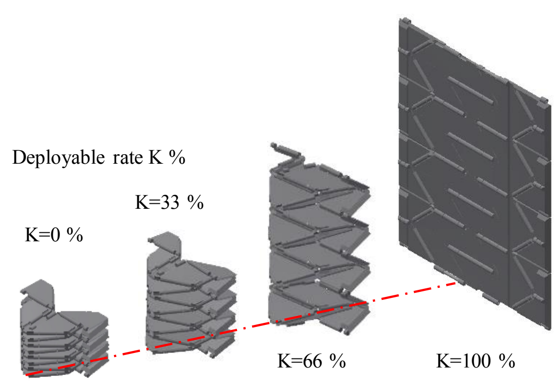
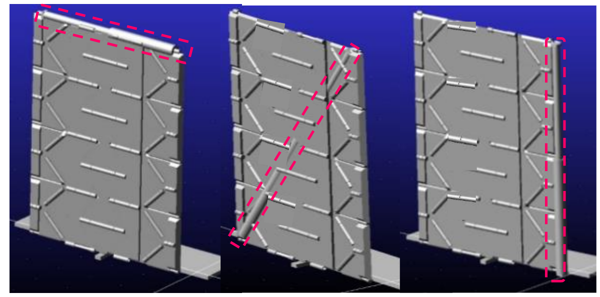


Fig 11. Results of Adams analysis as the shape changes with the expansion rate

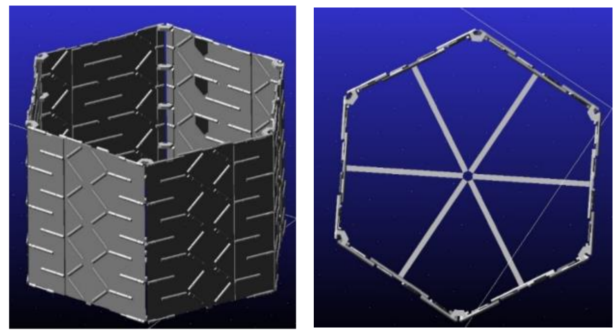
model diagram with actuators arranged. The basic layout is the same as the model shown in Fig.6, and horizontal, diagonal, and vertical layouts are planned. Additionally, as shown in Fig.13, we are currently creating a model that will have a 6-sided columnar structure when deploying, and will clarify the mechanical relationships when unfolding three-dimensionally.

When dynamics are considered, it is expected that the expansion of each unit will not change simultaneously, but will change sequentially starting from the part where the force is applied. Therefore, it is thought that a different arrangement of actuators will affect the deployment status of the structure and the required energy efficiency.



(a) Horizontal Actuator (b) Diagonal Actuator (c) Vertical Actuator

Fig 12. Analysis model diagram with 3-types of actuators arranged to investigate the shape change and power rate



(a) Front view (b)Top view

Fig 13. Analysis model diagram with 6-sided columnar structure when deploying

V. CONCLUSION

We analyzed the unfolding mechanism of an origami house using Ishimatsu-fold, from storage to unfolding. When unfolded, the origami house forms a hexagonal pillar and is a stable structure. To calculate the forces required for deployment, static vector analysis was performed with three different actuators placed at different locations outside the structure, and modeling and preparatory work for dynamic analysis was performed using the mechanical analysis software Adams.

The force required for deployment depends on the arrangement of the actuators, and the smaller the deployment rate, the greater the force required. Therefore, the minimum force required for the actuators needs to be fed back from the initial deployment state according to the deployment rate. This analysis confirms that placing the actuators horizontally is effective. Since the dynamics of the deployed structure may be easily analyzed under various conditions using Adams analysis, modeling and preparatory actions were performed for this analysis.

In the future, Adams analysis will be performed on the external arrangement of the actuator and the effects of the region including all six surfaces, and practical actuator designs will be considered.

Finally, we would like to express our gratitude to all those involved who cooperated with this research.

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