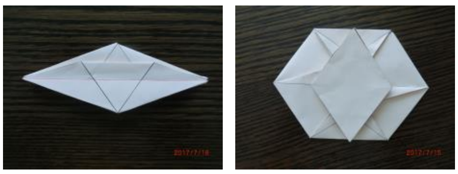
Continuous Flattening and Shapeshifting of Parallelohedra

連続的平坦折り畳みと形状シフト　－平行多面体の場合－

Chie Nara（奈良知惠）
Meiji University，MIMS（明治大学先端数理科学インスティチュート）
cnara@jeans@ocn.ne.jp

Can a polyhedron constructed from paper or similar flexible material be flattened without stretching or cutting? This problem was proposed by E. Demaine et al. in 2001 ([1]). I. Sabitov proved that a polyhedron does not change its volume under flexing, if shapes of the faces are fixed; so, we need an infinite number of line segments to move creases for changing shapes of some faces, leading to a flattened polyhedron. Three methods for continuous flattening of convex (and some non-convex) polyhedra have been shown by the author et al. (see [2] for example). We define a continuous flattening process of a polyhedron as a family of polyhedra each of which is intrinsically isometric to the original polyhedron and converges to a flat folded state where a polyhedron is permitted to touch itself without self-intersection. Fig. 1 shows a flat folded state of a rhombic dodecahedron.

Recently, Obervelde et al. presented interesting papers [3, 4] which were related to "Snapology" (see [5]). For a convex polyhedron, remove all faces and attach an excluded prismatic tube to fit the boundary of each face. The resulting figure may be flexible. If we choose, some faces remained as rigid faces instead of attaching extruded tubes, and if the resulting figure is transformable to a shape such that the part of the original polyhedron is flat folded, we say that the model has the shape-shifting property. They showed models with such property for 28 space-filling shapes. We investigated parallelohedra (whose typical representatives are the cube, the hexagonal prism, the truncated octahedron, the rhombic dodecahedron, and the elongated rhombic dodecahedron) for the property. In this talk, we show our results, and models in Fig. 2 are examples of shape-shifting ones of a rhombic dodecahedron.

Fig. 1.


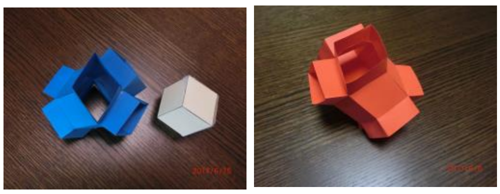


Fig. 2.

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Three dimensional measuring of thin plate and membrane

Naoko Kishimoto
Department of Mechanical Engineering, Setsunan University
kishimoto@mec.setsunan.ac.jp

Keyword : surface shape measurement, image measuring method

As a satellite is launched into orbit by a rocket, large space structures such as solar power panels and antennas must be deployable and modular assembled structures. According to increase in observation frequency and sensitivity, not only larger but also more precision space structures are required. Therefore, we have worked to develop new optical surface shape measuring methods enable to grasp surface shape of large space structures with high precision and high speed on orbit for future space antenna and telescope These methods are applicable to testing such structures on ground. In these methods, we analyse phase values of projected or painted grating patterns on the structures and perform calibration using a reference plane.

The advantages of our methods are as follows. 1) They realize high density measurement by analysing the phase of the projected or imparted grating pattern. 2) They realize high speed ant high precision measurement by calibration using reference plane. 3) They realize wide range measurement without degrading measurement precision by integrated results of multiple measurement systems.

In order to construct ultra-light weight large space structures, they must be composed of thin plate, membrane and mesh. In these flexible structures, shapes changed depending on application of tension, dynamics including vibration is complicated, and phenomenon such as wrinkling and buckling are caused. Therefore simultaneous measurement over entire surface with high precision and high speed is required. Furthermore it is important that measuring devices and systems must be simple and robust as possible considering measurement on orbit. Our measurement method meets these requirements. In this presentation, we will show some measuring results for thin plate and membrane surface.

Deformation mechanism on gripper bending process of origami forming

Kousuke Terada[1],

[1]National Institute of Technology Fukushima College, Japan

1. Introduction

Origami forming has big merits on its application to improve the flexibility of structure designs. In order to get the high quality of products by origami forming, deformation mechanism on bending process using gripper is investigated in this paper based on measurements and FEM calculations [1].

2. Measurements and FEM calculations

Fig.1 represents FEM model as an example of grooved steel sheets, which consists of 6 types (=2×3, grooving in bending inner/outer side, long/standard/short grooving length size). The depth of grooving is half of sheet thickness. The standard grooving length is the same size as thickness. Mises stress distribution in Fig.3, which is big spring back case, has stress concentration area at all bending arc due to long grooving length. On the other hand, that of Fig.4, which is small spring back case, has stress concentration area at limited bending arc. Because grooving length in Fig. 4 is much shorter than that of Fig.3. FEM results show clearly deformation mechanism on gripper bending.

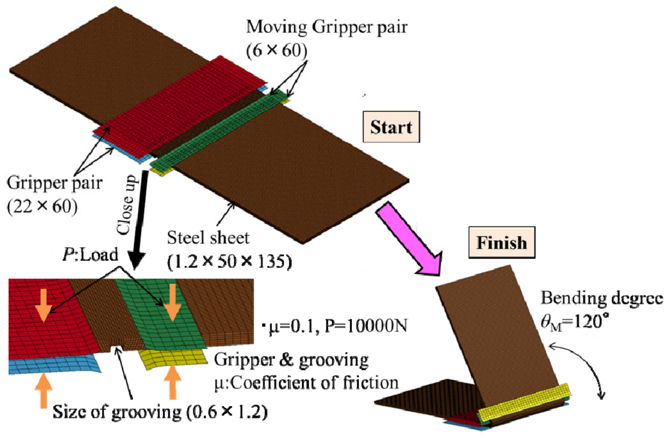

Fig.1 FEM model for gripper bending.

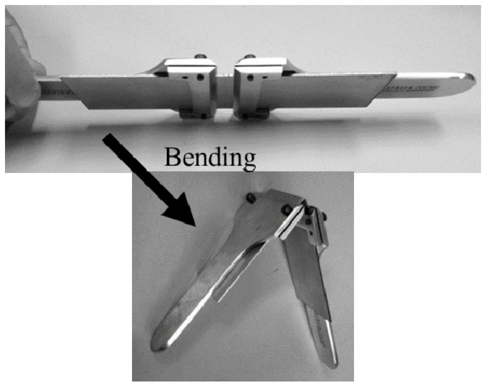

Fig.2 An example of bending tests.

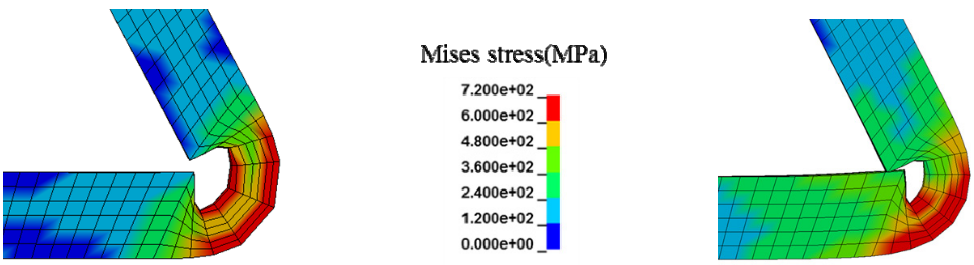

Fig.3 Mises stress distribution of big spring back case.

Fig.4 Mises stress distribution of small spring back case.

3. Conclusions

Deformation mechanism on gripper bending as many typical phenomena (big spring back, spring back less, cracks and wrinkles) can be explained clearly based on measured data and FEM results.

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Rep-cubes: Dissection of Cube to Nets*

Ryuhei Uehara

School of Information Science, Japan Advanced Institute of Science and Technology, Japan. uehara@jaist.ac.jp

A *polyomino* is a "simply connected" set of unit squares introduced by Solomon W. Golomb in 1954 [7]. Since then, polyominoes have been playing an important role in recreational mathematics (see, e.g., [5]). In 1962, Golomb also proposed an interesting notion called "*rep-tile*": a polygon is a rep-tile of order k if it can be divided into k replicas congruent to one another and similar to the original (see [6, Chap 19]).

From these notions, Abel et al. proposed a new notion [1]; a polyomino is said to be a *rep-cube* of order k if it is a net of a cube (or, it can fold to a cube), and it can be divided into k polyominoes such that each of them can fold to a cube. If all k polyominoes have the same size, we call the original polyomino a *regular* rep-cube of order k. We note that crease lines are not necessarily along the edges of the polyomino. For example, a regular rep-cube of order 2 folds to a cube by folding along the diagonals of unit squares. In Figure 1, each `T` shape can fold to a cube, and this shape itself can fold to a cube of size $\sqrt{2} \times \sqrt{2} \times \sqrt{2}$ by folding along the dotted lines.

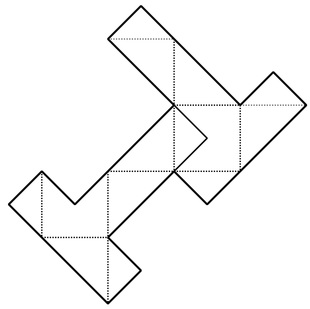

Figure 1: A regular rep-cube of order 2 [1].

In [1], Abel et al. propose regular rep-cubes of order k for each $k = 2, 4, 5, 8, 9, 36, 50, 64$, and also $k = 36gk'^2$ for any positive integer k' and an integer g in $\{2, 4, 5, 8, 9, 36, 50, 64\}$. In other words, there are infinitely many k that allow regular rep-cube of order k. On the other hand, they left an open problem that asks if there is a rep-cube of order 3. We solved this question negatively. There are no regular rep-cube of order 3. From this result, we imply a weak dichotomy of positive integers k that may allow or not to have regular rep-cubes of order k.

We enumerated all possible regular rep-cubes of order k for small k. We mention that the following problem is not so easy to solve efficiently; for a given polygon P, determine if P can fold to a cube or not. Recently, Horiyama and Mizunashi developed an efficient algorithm that solves this problem for a given orthogonal polygon, which runs in $O((n + m) \log n)$ time, where n is the number of vertices in P, and m is the maximum number of line segments that appears on a crease line [8]. We remark that the parameter m is hidden and can be huge comparing to n. In our case, P is a polyomino, and this hidden parameter is linear to the number of unit squares in P, and hence our algorithm is simpler.

Finally, we investigated non-regular rep-cube. In [1], Abel et al. also asked if there exists a rep-cube of area 150 that is a net of a cube of size $5 \times 5 \times 5$ and it can be divided into two nets of cubes of size $3 \times 3 \times 3$ and $4 \times 4 \times 4$. This idea comes from a pythagorean triple $(3, 4, 5)$ with $3^2 + 4^2 = 5^2$. We gave a partial answer to this question by dividing into more pieces than 2. Precisely, we proposed a general method for any pythagorean triple (a, b, c) with $a < b < c$ to obtain a five piece solution. That is, for any given pythagorean triple (a, b, c) with $a < b < c$, we construct a polyomino that is a net of a cube of $c \times c \times c$, and it can be divided into 5 pieces such that one of 5 pieces can fold to a cube of $a \times a \times a$, and gluing the remaining 4 pieces, we can obtain a net of a cube of $b \times b \times b$. An example for the pythagorean triple $(3, 4, 5)$ is given in Figure 2, and another one for the pythagorean triple $(5, 12, 13)$ is given in Figure 3.

[0]This paper is a survey of recent results in [1, 11].

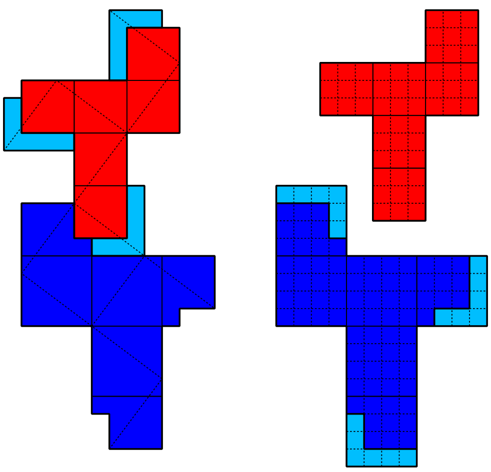

Figure 2: The set $S(3,4,5)$ of five polyominoes that folds to (a,b) two cubes of size $3 \times 3 \times 3$ and $4 \times 4 \times 4$, and (c) one cube of size $5 \times 5 \times 5$.

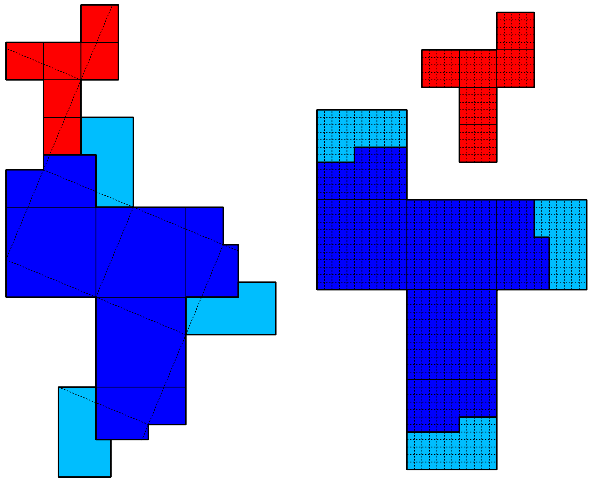

Figure 3: The set $S(5,12,13)$ of five polyominoes that folds to (a,b) two cubes of size $5 \times 5 \times 5$ and $12 \times 12 \times 12$, and (c) one cube of size $13 \times 13 \times 13$.

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An Algebraic Representation of Flat Origamis
平坦に折り畳まれる折り紙の代数表現

Kosuke Nosaka
野坂 康祐
Department of Mathematics, Kyoto University of Education
京都教育大学　大学院数学教育専修

1 Introduction

Imaginary flat origamis, which are suggested in this paper, are algebraic representations of flat origamis which represent the relation of folding steps configured a pair of operations and partial orders. Flat origamis are not always represented by composite mappings because there exists methods of folding such that developing some parts of a paper (see Figure 1 right). However, operations can represent developing a folded paper. Moreover we can verify that the Maekawa's theorem and Kawasaki's theorem hold as properties of imaginary flat origamis. Therefore, we can prove them as algebraic theorems.

2 Imaginary flat origamis

An imaginary flat origami is a partially ordered set defined as follows:

$$((f_{m1} \cdots f_{mn_m}) \cdots (f_{11} \cdots f_{1n_1})A, \preceq_m) \tag{1}$$

A is a compact set in $\mathbb{R}^2$ and $f_{11}, \ldots, f_{1n_1}$ are folding lines passed the interior of A. They separate some parts $A_1, A_2, \ldots, A_{k_1}$ from the set A. We define an operator $(f_{11} \cdots f_{1n_1})$ as a reflection by one of $f_{11}, \ldots, f_{1n_1}$ (or the composite function or the identity function) in each $A_1, A_2, \ldots, A_{k_1}$, that is, the image $(f_{11} \cdots f_{1n_1})A$ represents the state of A folded by $f_{11}, \ldots, f_{1n_1}$. Moreover, We define $A_i \prec_1 A_j$ or $A_i \succ_1 A_j$ for any parts A_i, A_j such that the intersection of the interior of $(f_{11} \cdots f_{1n_1})A_i$ and $(f_{11} \cdots f_{1n_1})A_j$ is empty. Then the partially ordered set $((f_{11} \cdots f_{1n_1})A, \preceq_1)$ is a imaginary flat origami.
Next, we consider that the image $(f_{11} \cdots f_{1n_1})A$ is folded by the lines $f_{21}, \ldots, f_{2n_2}$. Then $f_{11}, \ldots, f_{1n_1}$ and the developed fonding lines $((f_{11} \cdots f_{1n_1}))^{-1} f_{21}, \ldots, ((f_{11} \cdots f_{1n_1}))^{-1} f_{2n_2}$ separate smaller parts $B_1, B_2, \ldots, B_{k_2}$ from the set A than $A_1, A_2, \ldots, A_{k_1}$. We define an operator $(f_{21} \cdots f_{2n_2})(f_{11} \cdots f_{1n_1})$ as a reflection by one of $f_{21}, \ldots, f_{2n_2}$ (or the composite function) in each $(f_{11} \cdots f_{1n_1})B_1, (f_{11} \cdots f_{1n_1})B_2, \ldots, (f_{11} \cdots f_{1n_1})B_{k_2}$. Moreover, We define $B_i \prec_2 B_j$ or $B_i \succ_2 B_j$ for any parts B_i, B_j such that the intersection of the interior of $(f_{21} \cdots f_{2n_2})(f_{11} \cdots f_{1n_1})B_i$ and $(f_{21} \cdots f_{2n_2})(f_{11} \cdots f_{1n_1})B_j$ is empty. Then the partially ordered set $((f_{21} \cdots f_{2n_2})(f_{11} \cdots f_{1n_1})A, \preceq_2)$ is a imaginary flat origami.
By induction, we can define (1) as a generalized imaginary flat origami. It can make a paper crane and its 10 folding steps for example.

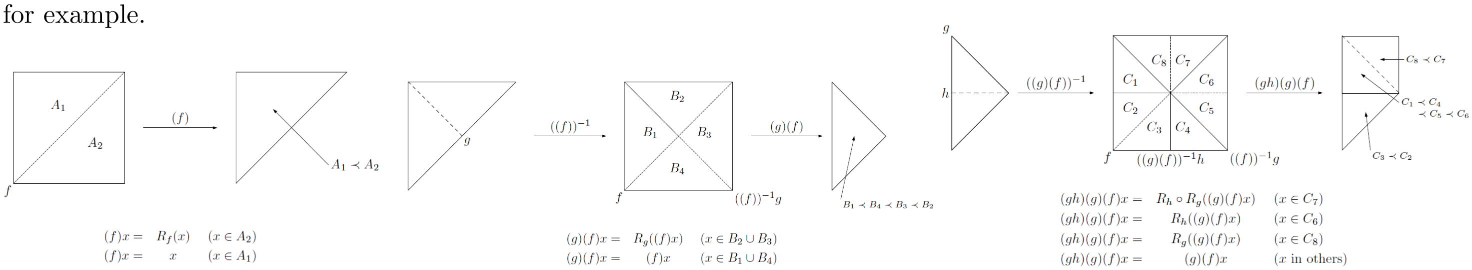

Figure 1: Some folding steps of a paper crane

3 Properties of Imaginary Flat Origamis

1-vertex foldable flat origamis are imaginary flat origamis which are not broken and have only one point where creases meet in the interior of the set A. The following statements hold.

Theorem 1 (Maekawa [1]). *the difference in the numbers of mountain creases and valley creases is 2*

Theorem 2 (Kawasaki [1]). *the sum of the alternate angles of each adjacent creases is* π

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Special Talk

The Central Role of Combinatorics in Origami

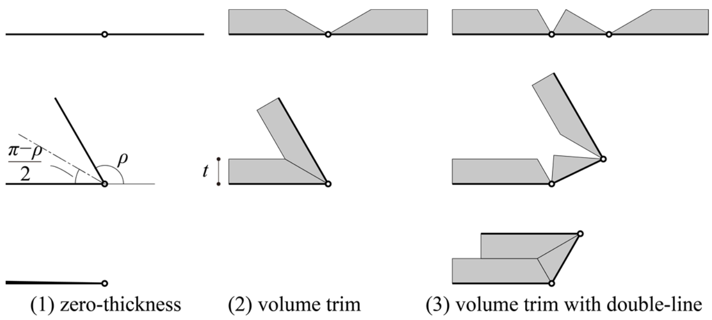
Dr. Thomas C. Hull
(Western New England University)

The art of origami is inherently geometrical, and a lot of the mathematical research done on origami centers around geometry. However, combinatorics (the mathematics of counting things) plays a very important role in understanding how paper, or any material, can fold. Maekawa's Theorem is a well-known example. This talk will describe some of the mathematical results known (and not known) for counting the number of ways an origami crease pattern can fold flat, that is, counting the number of valid ways to assign mountain and valley creases to a crease pattern. We will highlight the importance of such enumeration research in recent applications of origami in physics and engineering.

厚みのある剛体折紙　　Thick Rigid Origami

舘 知宏　　Tomohiro Tachi

剛体折紙はパネルとヒンジによる折紙の機構モデルであり、繰り返し折りたためる展開構造物や機構のデザインに用いられる。通常折紙は厚み 0 のモデルで考えるが、物理的な実装の際には、パネルの厚みを考慮しその干渉を解消する必要がある。パネル厚を解決するため、多くの手法が提案されてきている。(a)折り線を厚み方向にオフセットする手法[1,2]では、折り線が一点で交わる頂点を、対称性を用いた一点で交わらない過拘束メカニズムに置き換える。そのため 180° の完全な折り畳み状態を実現できるが、対象となるパターンは特定の一自由度パターンに限られる。またパネルの厚みがパターンに依存すること、ヒンジの位置が同一平面上にないことから製造は多くのパーツの組み立てによらざるを得ない。(b)折り線の位置を移動せずにパネルにテーパーやオフセットを施す方法[3,4]は、厚み 0 の折紙のメカニズムを保持して、干渉しない部分にのみ厚みを加える仕組みである。最も汎用性が高く、またヒンジ層を挟み込んだパネル層を平面状態で加工するだけで良いため、製造行程において折紙の可展性のメリットが生かせる。ただし、折り畳み角と厚みとの間にトレードオフがあり、特に 180 度に折り畳むことはできない。(c)(b)の改良として、折り線パターン自体を、あらかじめ変更し、折り線を二重線とすることで、折り畳み角の制限から逃れる方法[5,6]が提案されている。著者らが提案した[6]の手法では適用可能なパターンはまだ限られるものの、面に穴を作らずに折り線を二重線とできるため、家具・建築などの厚みのある折紙構造の実現方法として有力であると考える。



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Application of pairing origami structure to aluminum cans

—Comparison of TMP and NP from the viewpoint of rigid folding and crushing force

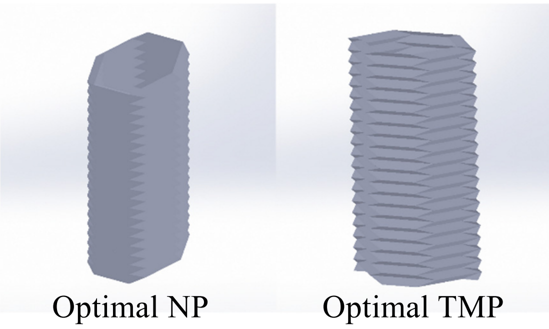
２枚貼り折りによるアルミ缶適用に関する検討

—TMP と NP の圧潰力と剛体折りの観点からの比較

阿部　綾 Aya ABE (Meiji University)

Abstract.　Polyhedrons by Nojima and by Tachi-Miura, which both are two symmetrical origami structures, can be folded in the axial or radial direction, and it is convenient if they can be applied to aluminum cans. We studied the crushing characteristics of both structures from the viewpoint of rigid folding, and explore their possibility.

概要. 野島ポリヘドロンと舘-三浦ポリヘドロンは両方とも2枚貼りの対称な折紙構造であり, 軸方向にも半径方向にも折り畳むことができる．それらをアルミニウム缶に適用することができれば便利である. 我々は, 両構造の圧潰特性および剛体折りの観点からの比較を通して, その可能性を探る.



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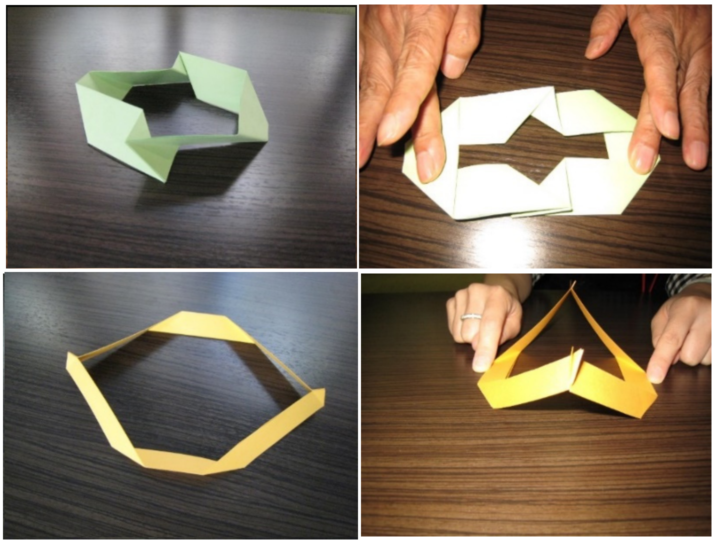
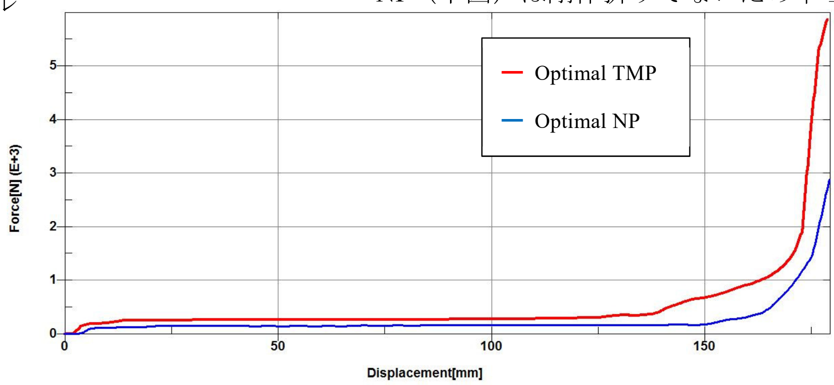
高さ 200mm，底面完全固定，上面から構造体を圧縮する条件で有限要素法によるシミュレーション結果から圧潰力を小さくするための最適化で得られた２枚貼り折り解析モデル



TMP（上図）は剛体折りのため折り畳むと平坦化するが NP（下図）は剛体折りでないため平坦に折り畳めない



TMP はヒンジ部分の折り線の多さや剛体折りであるために底面固定部分で圧潰に無理が生じる現象が顕著となることから，剛体折りでない NP よりも圧潰荷重値が大きく,また底つきが早いと考察される

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Origami in Architecture: Concept | Configuration | Construction

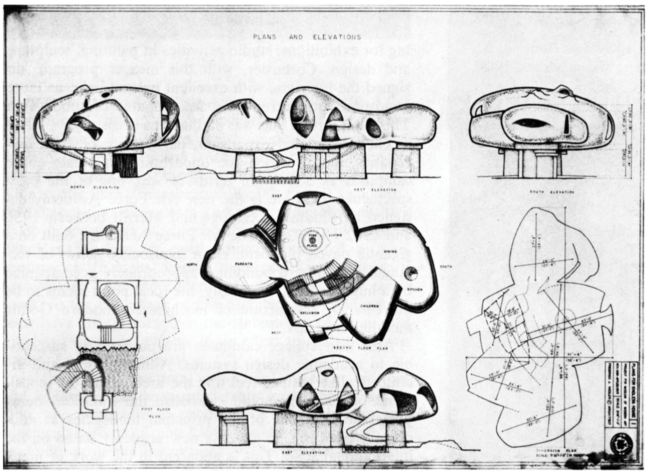
折紙的建築術：構想・構法・構成

Yoshinobu Miyamoto, Aichi Institute of Technology

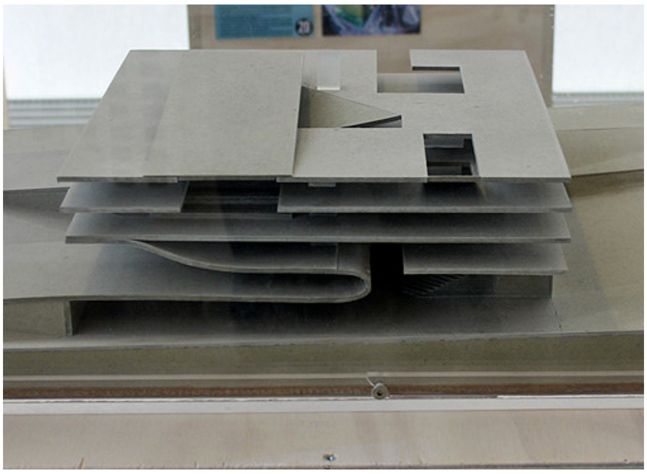
愛知工業大学　宮本好信

We will show how origami technique or folding has been used for architecture both in design concepts and their realization. Folding is a method for manipulation of form, form finding and composition of spaces. It is useful for adjusting functional spaces to the programming requirements and enhancing visual effects for facades and interior spaces. Folding is useful also in tectonic aspects in architecture and building construction. Corrugated metal sheet, folded metal roof, folded plate structure and foldable building elements are ubiquitous. We look into the future possibility of strategic integration of folding from the concept to the realization.

建築における折り紙の応用は、構想/企画/意匠の分野と構造/構法/材料の両分野で行われている。前者では「折り」は形態操作、形態生成、空間構成の手法として、建築企画と機能空間構成の整合、外観や内部空間の視覚的演出のために利用される。後者では機能性・安全性・経済性の具現化手法として利用され、金属波板、金属折板屋根、折板鉄筋コンクリート構造、展開構造などが普及している。構想から建設まで折り紙を総合的に活用する可能性を展望する。



Endless House (1924,1950,1960)
Frederick Kiesler (1890–1965)
The un-built project demonstrated the continuous connectivity of spaces or folded spaces.
link



Villa VPRO model (1993–1997)
MVRDV (1993–)
The public broadcasting center's folded floor was realization of the integration of the program requirements and the functional space.

link

3D-Modeling for the Developments of Polyhedra

Takashi Horiyama

Graduate School of Science and Engineering, Saitama University, Japan

A development of a polyhedron is a simple polygon obtained by cutting edges or faces of the polyhedron and unfolding it into a plane. While we can realize a development by a paper (i.e., we can draw it on a paper), we may have troubles when we fold it into a polyhedron. Since it has no thickness, the folded polyhedron is fragile. More precisely, the hinge is flexible enough to be bend with at most 180 degrees, and thus we cannot fix the dihedral angles between adjacent faces.

To avoid such trouble, we use the technique of rigid-foldable thick origami [1]. By this technique, zero-thickness ideal facets (denoted by red lines) are realized by thick panels: First offset the ideal facets by constant distance in two directions, and then trim facets by the bisecting planes of dihedral angles between adjacent facets.

If we trim the facets in the same side, all facets are folded in that side. If two polyhedra have a common development of the same shape (see e.g., [2], [3]), we can realize it so that it can be folded into the two polyhedra: We prepare hinges on the place where at least one polyhedron has a folding line. One side of the hinges is trimmed if they correspond to a polyhedron, and the other side is trimmed if they correspond to another polyhedron.

Reference

[1] T. Tachi, Rigid-Foldable Thick Origami, Origami 5 (Fifth International Meeting of Origami Science, Mathematics, and Education), pp. 253-263, 2011.

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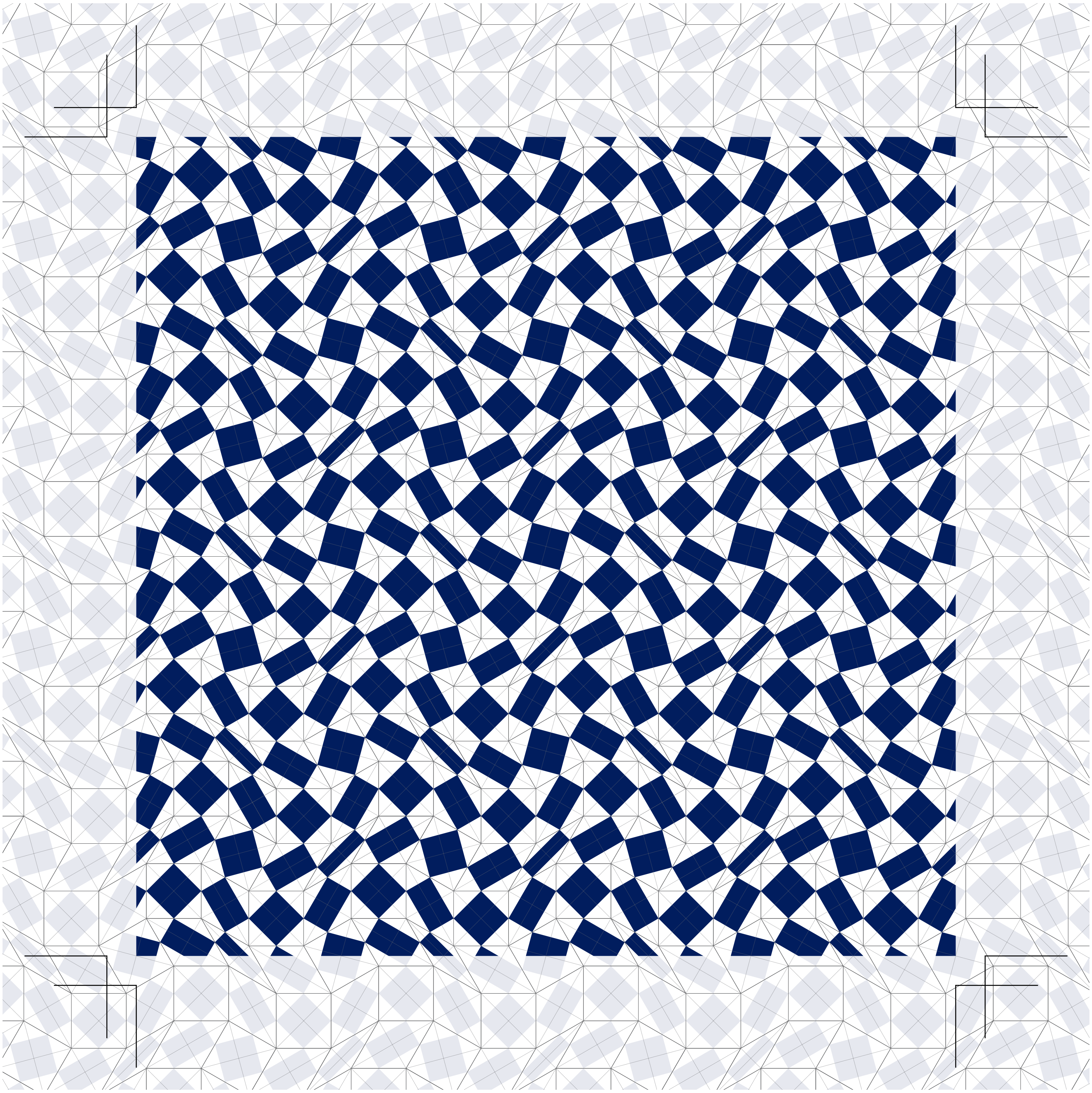
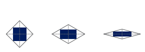
[3] T. Biedl, T. Chan, E. Demaine, M. Demaine, A. Lubiw, J. I. Munro, and J. Shallit, Notes from the University of Waterloo Algorithmic Problem Session, September 8, 1999.

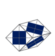


1.



PIECES

2.



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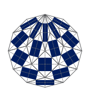

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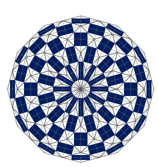

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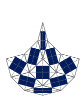

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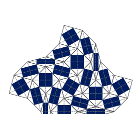

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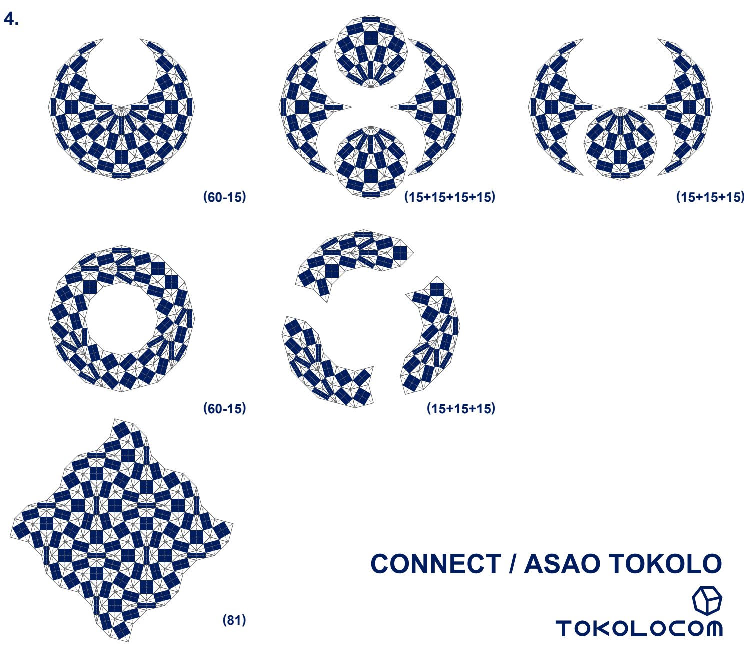

CONNECT / ASAO TOKOLO

TOKOLOCOM

スリット付き正多面体の裏返し

(Reversing of regular polyhedra with slits)

Jin-ichi Itoh (Kumamoto University)
(Joint work with Naofumi Horio)

Recently H. Maehara defined an origami-deformation of a polyhedral surface with boundary in Euclidean space, and he showed that every rectangular tube can be subdivided so that it becomes reversible (it is called s-reversible).

In this talk we discuss on the reversibility of regular polyhedra with several slits around vertices. In the case of cube and icosahedron, if we cut them along all edges around antipodal vertices, we get tubes, then they become s-reversible.

Theorem. Octahedron with slits as Figure 1 is s-reversible. Tetrahedron with slits as Figure 2 is s-reversible. Cube with slits as Figure 3 is s-reversible.

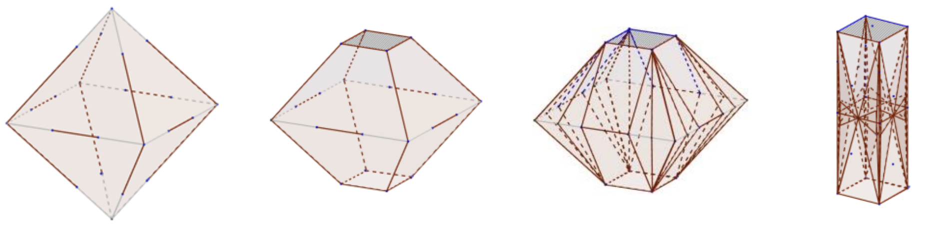

Figure 1

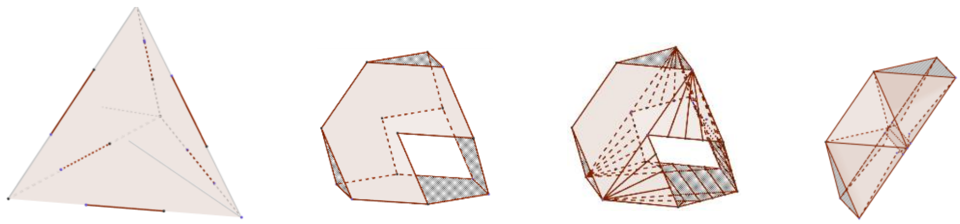

Figure 2

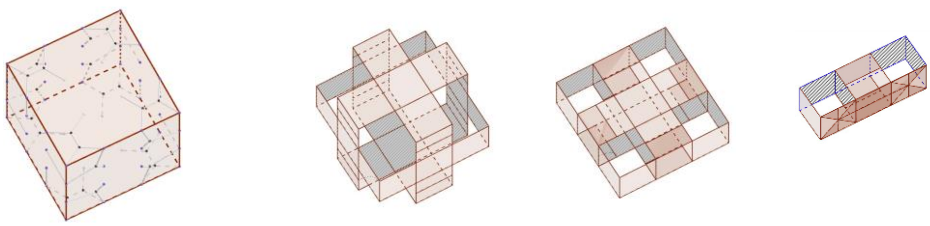

Figure 3

[1] H.Maehara: Reversing a polyhedral surface by origami-deformation, European Journal of Combinatorics 31 (2010), 1171-1180

Development of Origami structure superior to present energy-absorbing vehicle structure by ultra-cheap forming method

自動車の現行エネルギー吸収材特性を凌ぐ折紙構造体及びその超安価な製造法の開発

Ichiro Hagiwara 萩原一郎（Meiji University）

Abstract. Current vehicle energy absorbers have two defects during collision, only 70 % collapsed in its length and high initial peak load. We have found so called Reversed Spiral Origami Structure (RSO) can solve these defects. However, the manufacturing cost is too high to be applied in real vehicle structure. To address the problems, a new structure, named Reversed Torsion Origami Structure (RTO), has been developed, which can be manufactured at a low cost by using simple torsion of Origami engineering. This structure is possible to replace conventional energy absorbers and expected to be widely used such as in building structures.

概要. 現行の自動車のエネルギー吸収材[1]には、１）初期ピーク荷重が高い、２）自長の70%しか潰れない、の二つの欠点がある。折紙構造でこれらの欠点を解消できることは先に見出していた[2]が製造費が高いという課題があった。ここに、廉価な製造で同様に上の特性を有す構造が得られた[3]。

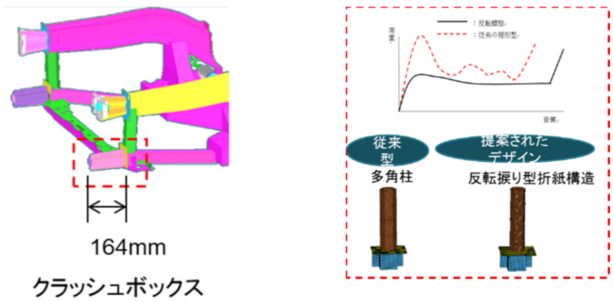

Fig.1 Load-displacement characteristics of RSC and conventional one.

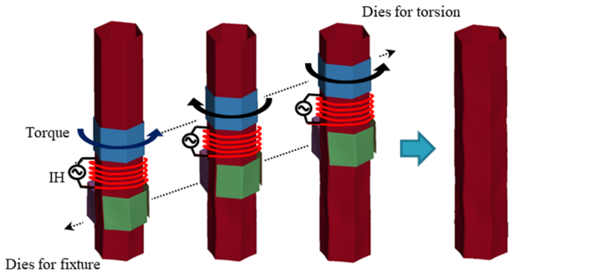

Fig.2 Schematic drawing of the three steps in the torsion forming process: (1) fix the first segment and twist the third segment through a certain angle, thus deforming the second segment; (2) move the dies one segment along the axial direction; (3) repeat step (1), twisting in the opposite direction.

●自動車用衝撃吸収バンパー（クラッシュボックス）：衝突の際に求められる，高エネルギーを吸収し，かつ衝撃荷重を抑えることが可能.

●現行の中空ハット型断面構造より安価に製造可能

なお本研究は、埼玉工業大学の趙希禄教授および同教授研究室員との共同研究の成果である。

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[1] 萩原一郎，津田政明，北川裕一，ビードの配置決定方法，第 2727680 号(1991).

[2] 萩原一郎， 山本千尋， 陶金， 野島武敏， 反転らせん型モデルを用いた円筒形折り紙構造の圧潰変形特性の最適化検討，日本機械学会論文集 A 編，Vol.70，No.689（2004），pp.36-42.

[3] 萩原一郎、趙希禄、衝撃吸収体の製造装置および衝撃吸収体の製造方法、特願2017-089216（平成29年4月28日）