Development of Newly Designed Ultra-Light Core Structures*

Taketoshi NOJIMA** and Kazuya SAITO***

By folding a thin flat sheet with periodically set slits or punched out portions into the third dimension, ultra-lightweight strong and functional core models are newly devised. The basic idea of this modeling arises from the application of origami technique to engineering. Based on the space filling models, fundamental flat cores and skew type sponge cores have been newly developed. By applying these models, such modified core models as curved cores and 3D honeycomb core are newly devised.

Key Words: Origami Technique, 3D Honeycomb, Sponge Core, Plane Tiling, Space Filling

1. Introduction

Origami structures consisting of zigzagged faces have solidification character as well as foldable/deployable functions. One of the present authors proposed 'Origami Kougaku (engineering)' and envisages the formation of a new origami technology discipline (1) and proposed several new types of foldable/deployable structures (2)–(4). In this report, some strong and functional ultra-lightweight cores are proposed by origami technique; a thin flat sheet with periodically introduced slits or rectangular punched out portions is bent in a zigzag way into three dimensional structures. Core structures have often been used not only for the strong members but impact-resistant structures. In addition, these structures are able to act as good acoustic absorbers, noise insulators and heat retainers. They are aesthetically pleasing both architecturally and geometrically, displaying changeable shadow patterns created by the interplay of light with the tongued and grooved surfaces. In the future such ultra-light cores having these functional properties are expected to be developed. To meet the demand, simple but efficient core models have to be devised taking engineering processing into account.

The main purpose of the present paper is to present designing method of new core structures. During the course of this research, fundamental core models based on space-filling models known in classical geometries were developed first, followed by sponge type cores using the concept of skew polyhedra. Afterwards some modified models such as cylindrical cores or 3D honeycomb cores were developed based on these fundamental ones.

2. Space-Filling Models Based on Classical Geometries

It is well known that only cubes within platonic polyhedra stack to completely fill space (Fig. 1 (a)). Combination of two tetrahedra and one octahedron (parallelepiped) can fill space (Fig. 1 (b)). Only truncated octahedron within semiregular polyhedra fills space by itself (Fig. 1 (c)). The rhombic dodecahedron, the dual of the cuboctahedron, can also fill space by itself (Fig. 1 (d)), being known to be constructed in body centered cubic lattice system (5). When we can use 2 kinds of regular polyhedra, four other kinds of model have been known. They are shown in Fig. 1 (e)–(g) except for the model consisting of great rhombicuboctahedron and regular octahedral prisms. Figure 1 (a), (d) and (e) are representative regular skew polyhedra (6), and these figures show such a situation. By adapting one planar array (i.e., one column) in these models, fundamental flat cores are designed using a sheet with punchings or slits; the main objective is to devise plane tiling patterns deployable to 3D structures. Taking engineering applications into account, punched portions or slits are chosen to be as minimal as possible.

3. Design of Modeling by Using Plane Tiling

3.1 Space-filling cubic core and sponge

Figure 2 (a) shows a fundamental development chart to make cubic cores of skew type; squared black portions are punched out. The punched sheet can be folded in two ways as in Fig. 2 (b) and (c) (named Type A and B, respectively) and both become skew type cubic polyhedra (Fig. 2 (d) and (e)). Such a sheet can also be bent to a...
shape of an array consisting of 3 faces of cubes (Fig. 2 (f) and (g)). When the sheet is bent, punched portion deforms into rhombic shape; one diagonal extends and the other shrinks. Therefore, the punched portions can be replaced by the squares with a diagonal slit and a valley fold line (Fig. 2 (h)). Even when the punched portions in Fig. 2 (a) are arranged as in Fig. 2 (i), three kinds of folds are possible as in Fig. 2 (a). Skew type core model produced by Type A folding is shown in Fig. 2 (j).

### 3.2 Other space filling core models

A skew type parallelopipedal core model of Fig. 1 (b) is produced by the lattice patterned chart as in Fig. 3 (a) consisting of rhomb of apical angle 60° and 120° (its origami sample is Fig. 3 (b)). The model made by 3 faces of parallelopiped is produced by the chart shown in Fig. 3 (c) consisting of plane tiling of the same shaped rhomb with slits thick solid lines along the lines between the vertically long rhombs. Space filling core is made by gluing these two pieces symmetrically (Fig. 3 (d)). A core model consisting of half truncated octahedron is produced by the plane tiling pattern combining regular hexagon and rhomb of apical angle 60° shown in Fig. 3 (e) where every other rhomb is punched out and the remaining rhombic portions are folded into the inside of a half octahedron using horizontal slits and vertical valley folds when produced (Fig. 3 (f)). Produced core consisting of a half octahedron is shown in Fig. 3 (g). Because this core is bidirectionally symmetrical, it is very stable against verti-
Fig. 3 Development charts to produce fundamental cores and sponges (black portion; punched out), (a), (b); skew type core consisting of parallelopipided, (c), (d); half parallelopipided, (solid line; mountain fold, dotted line; valley fold), (e), (f); chart to make half truncated octahedra, (g), (h); produced octahedral core and sponge, (i), (j); development chart for dodecahedral core and its sample, (k); development chart to make truncated tetrahedral core, (l), (m); truncated tetrahedral core and its sponge, (n), (p); development chart for cuboctahedral core and its sample, (q), (r); development chart for great rhombicuboctahedral core and its sample.

Fig. 4 Modified core models based on skew type cubic models, (a) development chart to make core of shallower bottom, (b), (c); diamond shaped core and its development chart, (d), (e); assortment box type core and its chart, (f), (g); cylindrical skew type core and its chart, (h); schematic view of half U-shaped core, (i), (j); conical type core and its chart, (k), (l); spherically curved core and its chart.

cal compressive force, though it has foldable function in the core plane direction. Regular octahedral sponge core shown in Fig. 1 (c) can be produced by folding over a single layer model of planar array repeatedly until there are several layers shown as the model in Fig. 3 (h). A plane tiling chart to make a half rhombic dodecahedral model (Fig. 1 (d)) is shown in Fig. 3 (i), where the thin rhombs are punched out. The fat rhombs, which construct side walls when 3-dimensionalized, have silver ratio in their diagonal lengths. Its origami model is shown in Fig. 3 (j). By punching out hexagonal portions around the centers.
Fig. 5 3D-honeycomb core models, representative development charts to make samples, (a), (b); basic development chart to produce equi-thick honeycomb core and its sample, (c), (d); development chart for equi-thick honeycomb core with glueable portions and its sample, (e), (f); cross-section of tapered honeycomb core and its development chart, (g), (h); development chart for aerofoil cross-sectioned honeycomb core and its sample, (i), (j); development chart for tapered honeycomb with glueable portions and its sample

(solid circles) of the slits in Fig. 3 (c), plane tiling pattern consisting of regular hexagons as in Fig. 3 (k) is obtained. By folding this like origami, truncated skew regular tetrahedral type core is produced (Fig. 3 (l)). Skew regular sponge structure like Fig. 1 (e) is produced by folding over a long sheet with this pattern (Fig. 3 (m)). Figure 3 (n) and (p) are a plane tiling pattern and its sample for the model shown in Fig. 1 (f). The pattern consists of equilateral and rectangular triangles and punched portions are rhombs with the acute angle 30°. Gray regions are folded into the inside of small rhomicuboctahedron when produced. Truncated cubic type core like Fig. 1 (g) is made by cutting the corners of Fig. 2 (a). The development chart and its origami sample are shown in Fig. 3 (q) and (r), respectively.

3.3 Applications of skew type cubic core models to design modified models

The models designed above are constructed by using the patterns consisting of regular polygons giving flat cores. In this section, by using plane tiling patterns with arbitrary shaped polygons, some useful cores having different functions as well as curved cores are designed modifying skew type cubic core models. The shapes of punched portions are set up to be rhombic. The depth of
the cubic core of Fig. 2 (a) can be altered according to the ratio of the side length of rectangle. Figure 4 (a) shows such an example with smaller size of punched squares giving a shallower core. Figure 4 (b) and (c) show plane tiling patterns consisting of equilateral triangles and squares and produced diamond-shaped core, respectively. As far as plane tiling is possible, arbitrary shaped core can be produced. As is shown in Fig. 4 (d), by doubling the horizontal columns of Fig. 4 (a) which construct side walls, assortment box type core (Fig. 4 (e)) can be designed.

By replacing square punched portions with rhombic ones as in Fig. 4 (f), very strong cylindrical skew type core shown in Fig. 4 (g) can be obtained. A half U-shaped core can be designed by combining the charts in Figs. 2 (a) and 4 (f). It's schematic model is shown in Fig. 4 (h). By the same way, using the pattern shown in Fig. 4 (i), a conical shell of equi-thick wall is produced. These curved cores are made by Type B folding in the skew type cubic polyhedra. By differing the sizes of squares and using rhombic shapes as punched portions like in Fig. 4 (k), rough spherical core is obtained (Fig. 4 (l)). Because the design of spherical core is quite complicated geometrically, exact analysis has not been performed at present.

4. Application of Fundamental Modelings to Development of New 3D Honeycomb Structure

In the same way as in Fig. 3 (c), we cut the slits (solid thick lines) alternately in vertical direction on a sheet (Fig. 5 (a)). Next set the mountain fold (M) and valley fold (V) lines in pairs perpendicularly to the slits. After folding the sheet repeatedly in M and V versions at the vertical fold lines including slits, the back of shaded area A to that of B, and the front of A’ to that of B’ are glued. By stretching the sheet, conventional uniformly thick honeycomb core shown in Fig. 5 (b) is obtained. When the slits are wide like Fig. 5 (c), a honeycomb core with glueable portions on the surface can be designed (Fig. 5 (d)).

Development chart of a tapered core with the cross-section like in Fig. 5 (e) is shown in Fig. 5 (f) noting that every other slit in vertical direction are zigzagged. The development chart for producing an aerofoil cross-section is shown in Fig. 5 (g) and the produced aerofoil model is shown in Fig. 5 (h). A tapered honeycomb core with glueable portions can be produced by using the chart in Fig. 5 (i) and the produced model is shown in Fig. 5 (j). By these designing methods, arbitrary shape of cross-sectioned honeycomb cores can be manufactured from a single flat sheet. This kind of cores are generically named 3D honeycomb core by the present authors.

5. Summary

Based on the space filling models of classical geometries, fundamental flat cores and their sponge type cores have been developed. To perform this, plane tiling patterns deployable into the third dimension were designed, and the patterned flat sheets were periodically punched and/or slit before processing. Based on these models, such modified cores as cylindrical and conical ones and arbitrary cross-sectioned 3D honeycomb cores are newly designed. Taking engineering applications into account, the numbers of slits or punched portions were chosen to be as minimal as possible when they were designed. One of the simple core models like the skew type cubic core is now at a stage of trial manufacturing by using a pressing machine.

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References