An Overview on the Applications of Mechanisms in Architecture. Part II: Foldable Plate Structures

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Abstract. Transformable structures in architecture can adapt their shape or function offering
dynamic answers to modern problems, such as deployment for creating temporary spaces,
responsiveness to climatic influences and change of use, in a society which embraces the
concept of sustainable design. Depending on how the transformation is carried out,
transformable structures can be deployable or demountable, as a kit-parts system. According
to their structural system, deployable structures can also be classified in four main groups: spatial
bar structures; foldable plate structures; tensegrity structures; and membrane structures. In this
paper, a review on the deployable structures based on foldable plate structures will be done.

1. Introduction
Transformable structures in architecture have the ability to change morphology and readjust in
response to varying conditions and needs that can include changing environment and climatic
conditions, different functional requirements and emergency situations. Depending on how the
transformation is carried out, transformable structures can be deployable (include mechanisms that
enables the structure to deploy from a compact configuration to a larger, expanded state) or
demountable, as a kit-parts system (with dry, reversible connections between the constitutive
components, enabling the structure for disassembly) [1], [2].

According to their structural system, deployable structures can be classified in four main groups:
spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates;
tensegrity structures; and membrane structures. Because of their wide applicability in the field of
mobile architecture, their high degree of deployability and a reliable deployment, two sub-categories
are studied in greater detail: bar structures, generally, and pantograph (scissor-like) structures,
especially, and foldable plate structures, respectively [2].

The interest in deployable structures and their multiple applications has significantly increased
since the second half of the last century. In the discipline of architecture, the future of design is based
on the creation of dynamic and flexible spaces, temporary and lightweight structures for a sustainable
form of engineering [3-6].

In this paper, an overview on the deployable structures based on foldable plate structures will be performed.

2. Foldable plate structures
Foldable plate elements (FPEs), also called rigid-foldable origami elements or hinged plate elements
form the basis of kinetic surfaces, which are traditionally continuous. But they can also
discontinuously connected [7]. The rigid plate elements are connected by rotational joints along their outer edges and the value of the relative angle between these edges will determine the boundary conditions of the resulting kinetic surface. As result, their kinematic behaviour will be affected by simply changing the relative inclination of the edges.

Since the basic element is a surface (not quasi-linear, like a SLE) and since these surface elements oftentimes need to be continuously connected, the maximum compactness achieved in foldable plate structures is much lower. But they have other qualities connected to the advantages of adaptive structures versus those of typically deployable ones.

These structures have considerable shape flexibility (multiple degrees of freedom), but once erected they possess significant stiffness. Almost all of them are based on the ancient Japanese art of origami. Their designing process often starts with a single sheet that is folded (without any cutting) into a threedimensional shape [8]. Sometimes developability and continuity of the obtained surface are unnecessary constraints when thinking of architectural applications.

2.1 Patterns and tessellations

For foldable plate surfaces both modularity and homogenous mechanical behaviour are important. Therefore, an efficient method for designing them is to start with the basic repeated patterns made up of copied or similar elements. These are named tiling patterns or tessellations. All of the patterns are made up of Mountain (shown in orange lines) and Valley (shown in blue dotted lines) folds (figure 1). The FPE’s rotate clock- and counterclockwise around these folds, relative to the orientation of the surface.

2.1.1 Miura-ori pattern

This pattern (figure 1) was invented by Japanese astrophysicist Miura K [9], who devised the compactly foldable surface (figure 2) to use it as a deployable solar sail for a space unit (figure 3). A big advantage of the mechanism is the fact that it has only one degree of freedom, making it easy to actuate. For these reasons, the Miura-ori pattern is one of the most widely studied patterns in contemporary engineering [7].

Figure 1. Miura-ori fold pattern [7].

Figure 2. Miura-ori mechanism in closed and semi-deployed configurations [7].
A mention on the geometrical characteristics of the Miura-ori pattern is the existence of a barshaped counterpart of the basic 4-facets tile in the form of a spherical linkage, as demonstrated in figure 4 [10]. Similarly, any origami pattern can be replaced by an array of spherical linkages by replacing the foldlines by the rotational axes of compact revolute joints. This method is not only interesting for the analysis of origami mechanisms, but also gives the possibility to develop more compact, simple, mechanisms based on plate elements [7].

**Figure 3.** Solar sail application of Miura-ori mechanism [9].

**Figure 4.** Corresponding bar linkage of single Miura-ori vertex [10].

### 2.1.2 Yoshimura pattern

This pattern (figure 5) is formed by triangular facets, and typically folds into a singly curved corrugated surface. However, also doubly-curved surfaces can be reached when the pattern is not flat-foldable.

The Yoshimura pattern has multiple degrees of freedom, but it can be stabilized fairly well and shows a high rigidity when done so. Because of that it is suitable for engineering and architectural purposes [7].

The barrel vault is the basic shape of interest that can be developed, as shown in figure 6 [2], which results from the regular pattern shown in figure 5.

Irregular tessellations can also be generated easily from the Yoshimura pattern. Their only necessary condition for rigid-foldability is that the sum of two adjoining deformation angles stays constant (see figures 7 and 8).
Figure 5. Yoshimura fold pattern [7].

Figure 6. Barrel vault from Yoshimura pattern [2].

Figure 7. Yoshimura variations retain rigid-foldability when the sum of two adjacent deformation angles is constant [2].

Figure 8. Rigid-foldable Yoshimura structures [11]
Polar, doubly curved geometries can be made by taking away the semi-facets at the top of the pattern and connecting the remaining full facets with each other (see figure 9). Different combinations of regular singly- and doubly-curved patterns are shown in [2] for a maximum of five facets in the curved direction (figure 10). It has to be noted that these geometries can only exist in the erected state shown. They cannot form a fully closed loop and at the same time stay rigid-foldable.

**Figure 9.** Doubly-curved Yoshimura variation in compacted and fully deployed state [7]

**Figure 10.** Combination of single- and doubly curved mechanism into static structures [2]
2.1.3 Waterbomb pattern
This pattern (figure 11) is formed by triangular facets with straight-angled apexes and it typically introduces a double curvature in its surface (figure 12). Waterbomb pattern has also multiple degrees of freedom, and because of this reason it is less suitable for large-scale applications, but may be used in smaller design applications.

![Figure 11. Waterbomb fold pattern [7].](image)

![Figure 12. Folded waterbomb pattern [12].](image)

2.1.4 Resch pattern
Resch pattern (figure 13) was invented by the geometrist and artist Ronald D. Resch during the 1960’s [12]. Many variations on the basic pattern have been proposed by Resch and other researchers, but all of them typically have two degrees of freedom, one ‘twisting’ and a folding one [7].

In figure 14 the partially folded pattern is shown. The same pattern, at a large-scale, was tested by Resh and his students (see figure 15).

Some other regular variations of this pattern with square, triangular and hexagonal facets in the top layer are shown in figure 16. Because of their multi-degrees of freedom, the Resch patterns are able to be made irregular more easily than the Miura-ori and the Yoshimura patterns, for example, without affecting the foldability [13].
Figure 13. Resch fold pattern [7].

Figure 14. Hexagonal Resh pattern in a partially-folded configuration [7].

Figure 15. Large-scale folded Resh pattern [14].
2.2 Architectural applications

Architectural application of foldable plate mechanisms is limited till now, due the lack of knowhow and tradition in materialization. It may be different when the problems of hinges, plate thickness, waterproofing and compactability will be researched on a larger scale [7]. Still, in this paragraph, some examples from the limited current applications are given, starting with the large scale theoretical projects and moving towards local design elements.

Tachi T. [15] proposed some more theoretical origami structures, based on the waterbomb pattern (see an example in figure 17). This structure has multiple degrees of freedom, making it deformable to the user’s needs or follies. Due to its high mobility, it is also structurally...
highly unstable, and a strong connection to the ground plane would be needed here to stabilize it. Another application proposed by the same author is the Miura-ori pattern used to make a temporary and deployable connection between two buildings (figure 18).

![Figure 18. Deployable passageway between buildings, from Miura-ori pattern [7].](image)

A deployable shelter based on the Yoshimura fold pattern was proposed in [2] (figure 19), to which the plate elements have been substituted by bars lying on the perimeter of the facets. Then, half of the bars are removed in locations where they were doubled. The joints used for this shelter are based directly on the vertices of origami folds. To give structural height to the resulting barrel vault a fabric screen is added as a tensile layer.

![Figure 19. Shelter based on the Yoshimura fold pattern: a) corresponding bar structure; b) joint detail [2].](image)

A really materialized large-scale project, based on a regular Miura-ori pattern with trapezoidal facets, is the retractable roof system developed by the Venezuelan architect Hernandez C. H. [16], which was firstly used in the expo of 1992 in Sevilla and later in projects such as a pool cover in Venezuela (figure 20). The roof is not self-supporting, but carried by light-weight trusses.

![Figure 20. Real project based on Miura-ori pattern: a) pool deployable roof; b) joint detail [16].](image)
The architect Tang M proposed a mobile bamboo pavilion based on a variable pattern (figure 21). The basic pattern is fairly simple, but it needed to be triangulated in order to be even mobile. The circular origami-fold mechanism can be locked and made static by simply fixing the opposing ends to each other.

![Figure 21. Radial shelter from variable pattern [15].](image)

Foldable plate structures have been successfully applied to kinematic facades of modern buildings. For these facades, the elements can be programmed to respond to climatic factors, to improve energy efficiency, to reduce solar heat again, or for aesthetic reasons as an art installation or to act as a live signage, etc. These applications are easier to be materialized, since the active folding angles are not big. Thanks to that, the designs taking into account the plate thickness are more easily achieved. A simple example is the shading device proposed by Ernst Giselbrecht + Partner (figure 22) [17]. Here, each single-fold and sliding mechanism is separately actuated.

![Figure 22. Hinged shading façade [17].](image)
Another example is the iconic façade designed by Aedas Architects (figure 23). In this project, the one degree of freedom modules of six elements each can closely regulate the solar gains. It is a computer-controlled facade made of umbrella like panels which open and close as per suns movement through the day, to achieve optimal shading and light entering the building.

Figure 23. Triangulated folding façade: a) The Al Bahr Towers [18]; b) detail of the façade modules [19].
The individual triangular screens appear to work like umbrellas, using a linear actuator to open and collapse them.

The next example is a kinetic façade applied to the university building in Kolding, Denmark [18]. Sensors monitor surrounding heat and light levels, and facade panels open partially or fully accordingly (figure 24).

![Figure 24](image_url)

**Figure 24.** Triangulated folding façade: a) Kolding – University of Southern Denmark; b) detail of the façade modules [18].
On a smaller scale, foldable plate structures are applied to build acoustic panels. An interesting project was done by RVTR, where a simple Resch pattern has been applied. The front layer of bamboo facets function as reflectors, while the tucked in facets work as absorbers (figure 25). Different acoustic atmospheres can be created by increasing and decreasing the operating angle. A central electronic panel with sensors can adapt the different actuators in real-time. The actuators themselves are simple prismatic joints between the facets (three actuators per module) [20].

3. Conclusion
Transformable structures in architecture have the ability to change morphology and readjust in response to varying conditions and needs that can include changing environment and climatic conditions, different functional requirements and emergency situations. Depending on how the transformation is carried out, transformable structures can be deployable or demountable, as a kit-parts system. According to their structural system, deployable structures can also be classified in four main groups: spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates; tensegrity structures; and membrane structures. Because of their wide applicability in the field of mobile architecture, their high degree of deployability and a reliable deployment, two sub-categories are studied in greater detail: bar structures, and foldable plate structures, respectively. In this paper, a review on the deployable structures based on foldable plate structures has been performed.

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