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Deployable Solid: A New Folding Structure

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Abstract. The idea from Japanese traditional Origami is applied to folding of three dimensional structures. A series of foldable structures called deployable solids are presented. Combinations of these assembled structures are investigated and some models are shown. Practical aspects of deployable solids are also discussed.

1. Introduction

Since the ancient Greeks, the geometrical characteristics of polyhedra have been investigated and applied to many fields such as art and architecture. Recently the rigidity or flexibility of polyhedra were discussed and Wunderlich's jumping octahedron was proposed as a movable polyhedron (CROMWELL, 1997). Many polyhedra made by tubular members (FUJIMOTO, 1995) or molecules (HOSOYA, 1983) are well known. This kind of structures has been often demonstrated as performances by instructors of special structures (SCHWABE, 1999). But, as far as the authors know, it has not been discussed in scientific papers that focus on the deployable connection of structures.

The flexibility and expandability of connections and frames are required for the configuration. The authors found that the idea from Japanese traditional Origami can be applied to this system and the importance of it has been recognized. The connections and the attached frames consisted of thin walled materials are thought to be one mechanical structure and called "deployable solid".

In the following, the main three kinds of deployable solids are briefly introduced. Then combinations and variations of these connections and frames are described. Finally, some network structures and practical problems about them are discussed.

2. Basic Connection Types

There are many connections for space frames based on regular polyhedra. Most of them can be made foldable by replacing their edges with hinge lines. We found some of these connections with deployable solids are useful. They are based on regular tetrahedra, hexahedra and octahedra (EBARA and KAWAGUCHI, 1998, 2001).

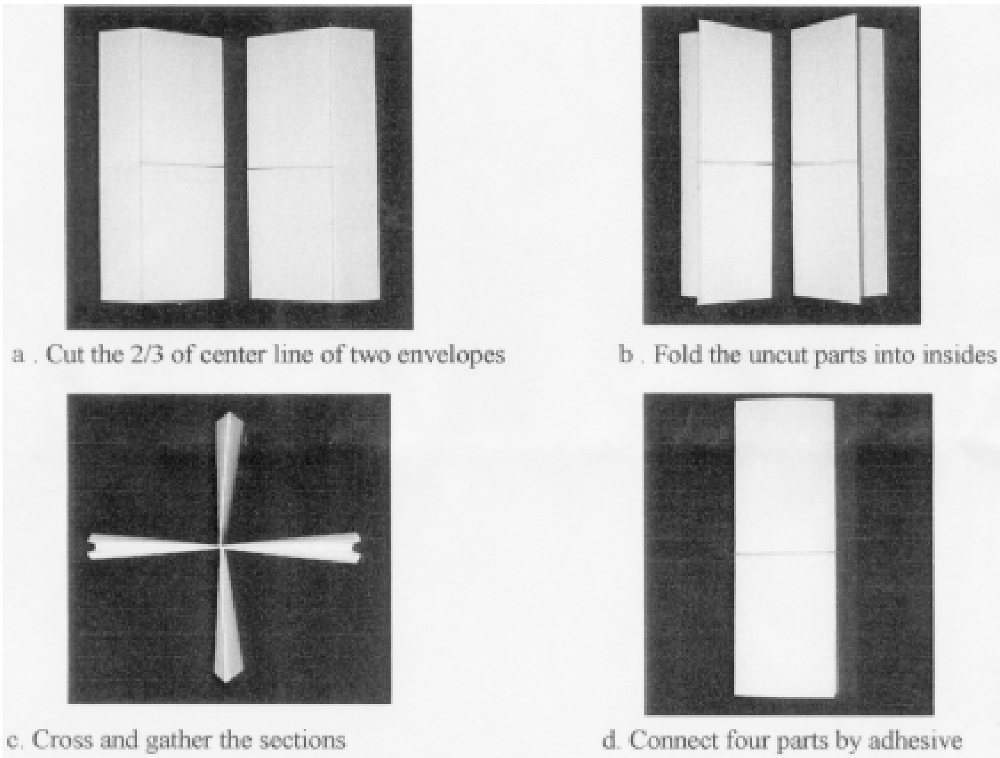


Fig. 1. How to make envelope TET.

2.1. Four-member connection (TET)

This connection is based on a regular tetrahedron and named a deployable solid TET. It consists of four tubular members with regular triangular sections intersecting each other at an equal angle of 109°28′. How to make the envelope model of TET is illustrated in Fig. 1. The unfolding sequence of this connection is illustrated in Fig. 2.

a. In the folding configuration, each triangular section is folded into a plane with one side bent in and two pairs of tubular members are flattened against each other and aligned straight. In this state no distortion is imposed on the members.

b. In the intermediate state, a slight distortion of the thin walls of tubular members due to geometrical incompatibility is induced at certain locations near the intersection between the members. Therefore a certain amount of load should be applied to start and to carry out the unfolding sequence.

c. When the unfolding is completed, the configuration is geometrically compatible and again no distortion is induced. Three-dimensional folded plate action provides high bending rigidity to the connection. The number of degrees of freedom of the connection during the unfolding process is one.

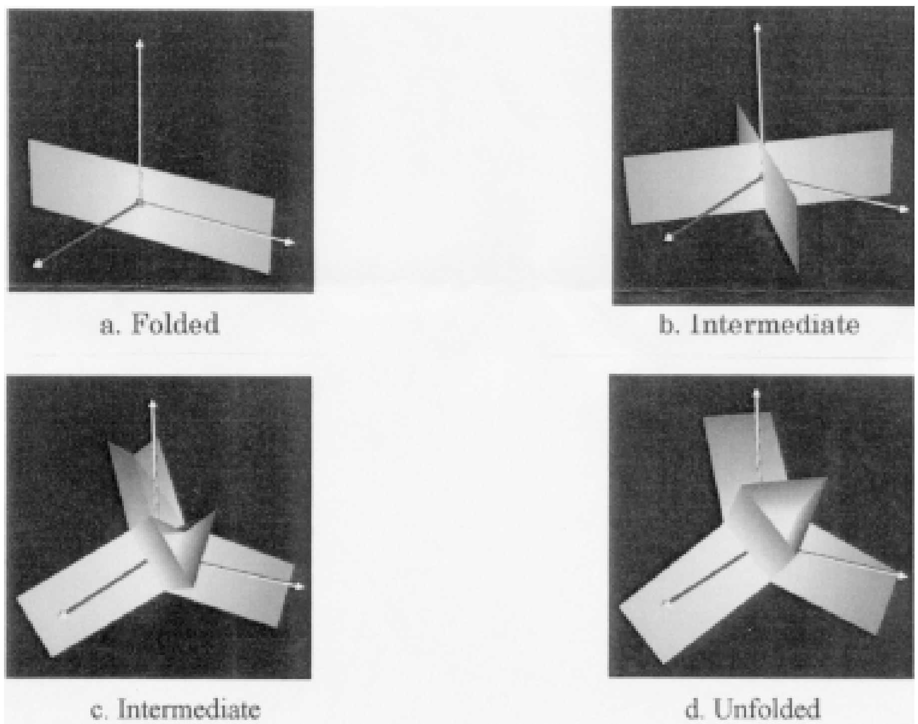


Fig. 2. Unfolding sequence of TET.

One of the remarkable features of this model is the existence of a small potential energy hill between the folded and the unfolded states, so that the model is so-called *bi-stable* state (THOMPSON and HUNT, 1984)

Both folded and unfolded configurations are stable. If the distortion of the member is undesired, one can remove it by making slits or holes in the appropriate parts of the thin wall of the tube members.

2.2. Six-member connection (HEX)

This connection is based on a regular hexahedron and named HEX. The unfolding sequence of the connection model for six tubular members with square cross-section intersecting at right angles is illustrated in Fig. 3.

a. The square sections are flattened by being transformed into lozenge sections, so that the connection model is folded flat.

b. The connection model is unfolded by opening out the flattened lozenge sections. No distortion is imposed on any of the members during the sequence.

c. The sequence is completed when all of the lozenge sections are opened into squares.

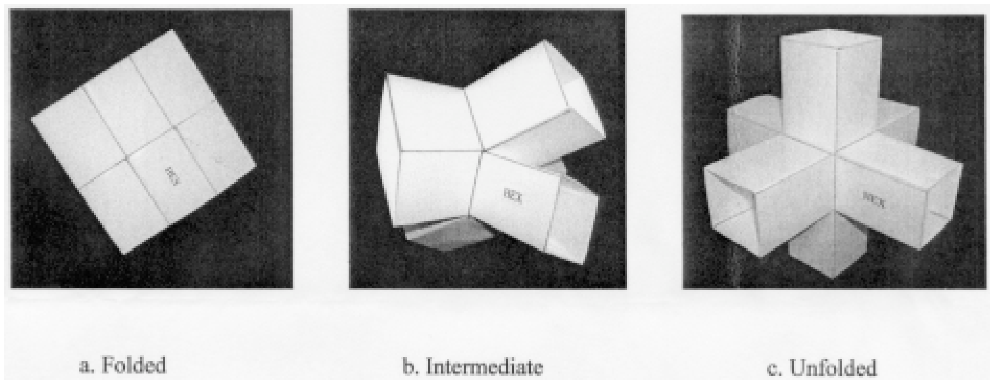


Fig. 3. Unfolding sequence of HEX.

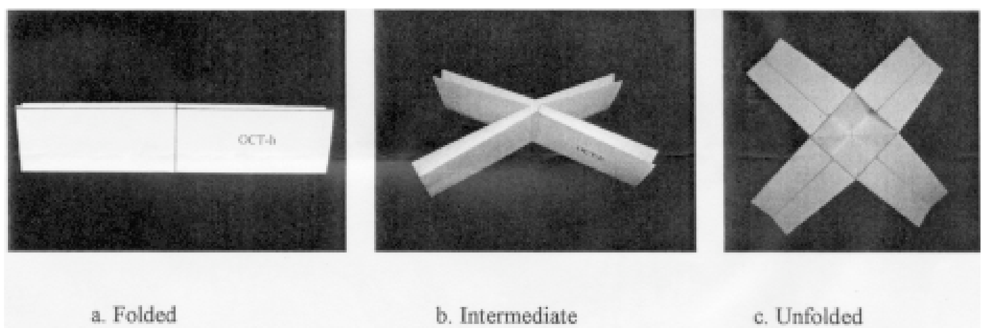


Fig. 4. Unfolding sequence of OCT-h.

Since the model has stress-free mechanisms, no distortion is induced at any stage of the unfolding. The completion of the sequence is when the lozenge sections become square. But, the model has mechanisms in all configurations, final state is not as stable as in the case of the four member connection TET. This connection has three degrees of folding freedom.

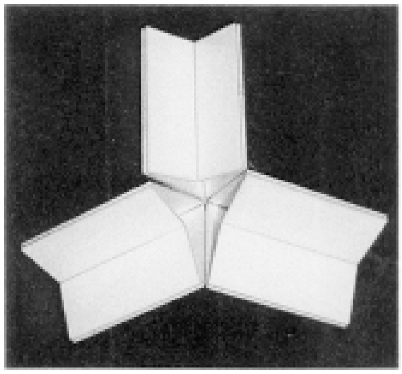
2.3. Eight-member connection (OCT) and a half of an eight-member connection (OCT-h)

This connection is based on a octahedron and named OCT. This doployable solid connection model has eight tubular members with regular triangular cross section intersecting at 70°32′. The unfolding sequence of this connection is illustrated below.

a. In the folded configuration, each cross-section is flattened by forming central fold line along one face. Thus, the pairs of tubular members can be flattened onto each other. In this state no distortion is imposed on the members.

b. In the intermediate state, distortion of the thin walled tubular member is imposed due to geometrical incompatibility, at certain locations near the points of intersection.

(a)



(b)

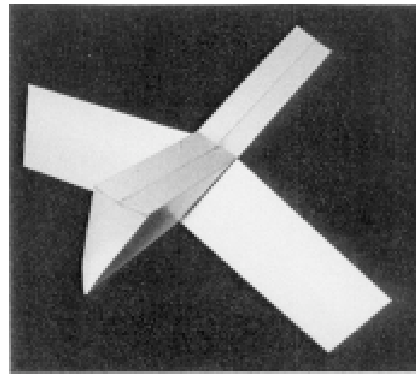


Fig. 5. (a) M3. (b) TET-v with Isosceles triangle section.

Therefore, a certain amount of force must be applied to start and continue the unfolding sequence.

c. When the unfolding is completed, the final configuration is geometrically compatible and again no distortion is induced. Three-dimensional folded plate action provides high bending rigidity to the connection.

The most important characteristic of this connection is that one hinge line is folded into another hinge line. Therefore, a rather complicated distortion pattern is induced near the points of intersection. By making slits, or cutting off at some locations of the thin wall, this distortion can be removed.

If we cut this connection into two portions of four members each, either portion can be used as a connection for four members and named OCT-h. It can be folded through a stress-free sequence. Since the angles of intersection of the members of this connection can be varied, it provides a joint that can be used for a variety of curved surfaces. The schematic view of this connection is shown in Fig. 4.

3. Variations

Many variations and combinations can be generated from the deployable solid connections described above. This enables us to design a variety of deployable thin-walled moment frames. In the following some of the possible variations are illustrated.

Variation of OCT-h with three intersecting tubular members is named M3. Variation of TET with isosceles triangle cross-section member is called TET-v. They are shown in Figs. 5(a) and (b) respectively.

4. Assemblage of Doployable Solid

The assemblage of deployable solids form many kinds of structures. They are illustrated in the following session.

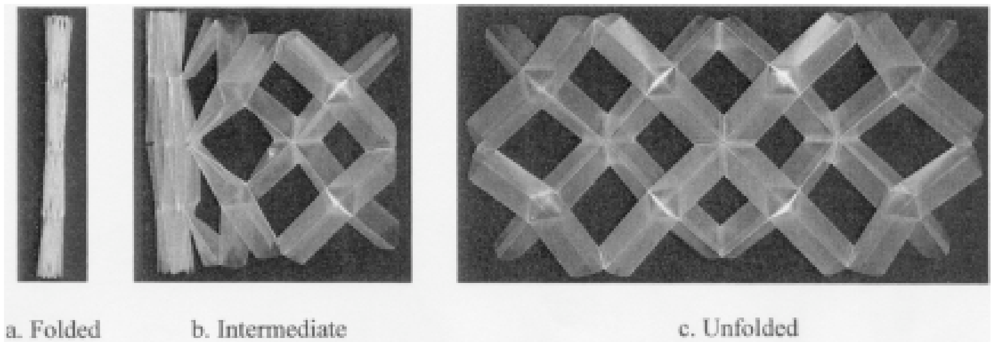


Fig. 6. Three-dimensional continuous frame by TET.

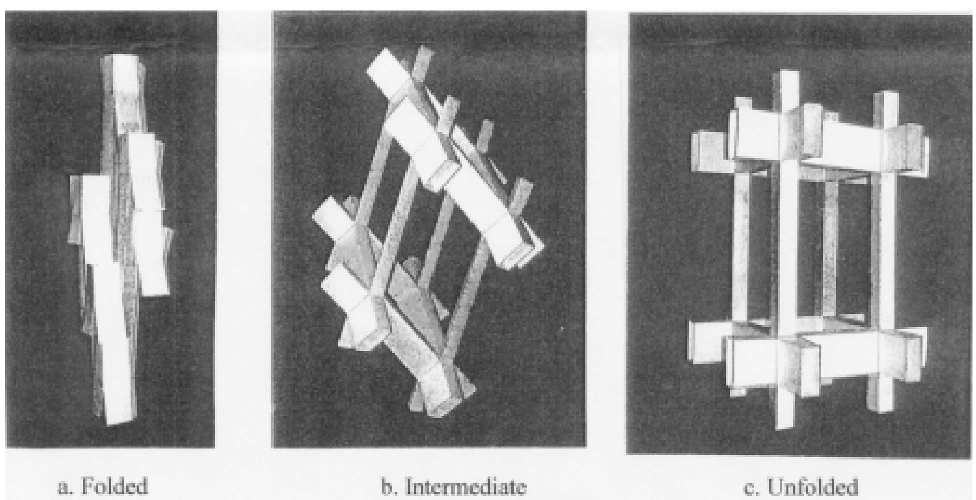


Fig. 7. Combination of different sections of HEX.

4.1. Assemblage with TET and HEX

A three-dimensionally continuous frame by TET and the combination of tubular members with different rectangular cross sections by HEX are shown in Figs. 6 and 7.

4.2. Assemblage of OCT-h and M3

Many assemblage can be generated from the combination of OCT-h and M3. Varying the length of the members or the width of the folded plates, we can generate curved surfaces such as a bowl tipe frame, a palabola anntena, a sphere dome, a honeycomb type frame and an ocean fishery (RYTHER, 1969). They are illustrated in Fig. 8.

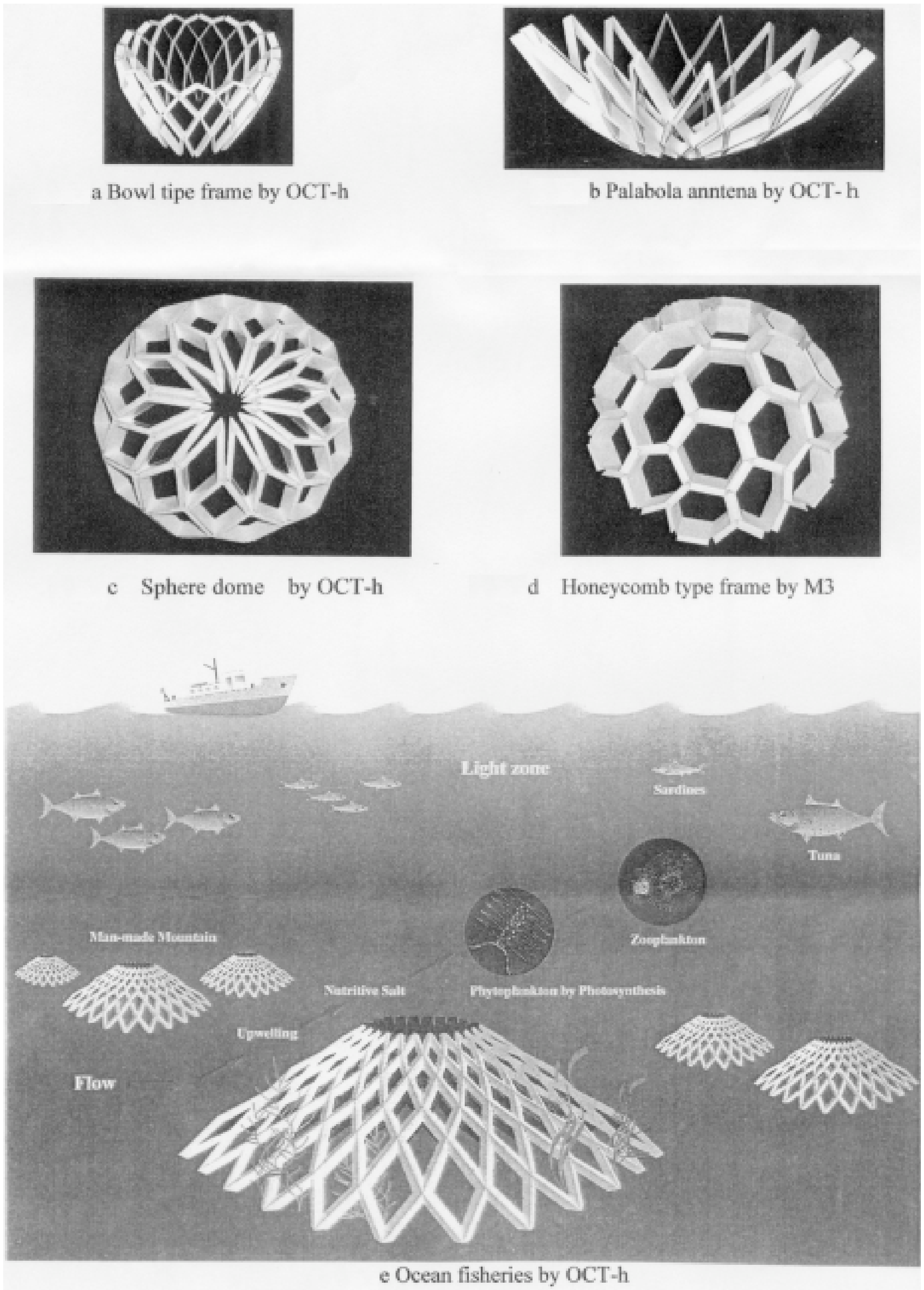


Fig. 8. Assemblage of doployable solid OCT-h and M3.

5. Practical Considerations

Lightweight moment frames such as steel frame structures, are usually composed of thin walled members. The connections jointing these thin-wall members are three dimensional thin-wall structures. Rigidity of these connections is mostly preserved after replacing their inter-connecting rigid lines with hinge lines. With this alteration, some connections are folded into a plane plate configuration.

To apply the deployable solids presented in this paper, some practical judgements are necessary.

a. According to the mechanical behavior, the proposed deployable solids can be divided into two groups. In the first group (TET, OCT) distortion is induced to tubular members during folding and unfolding. In the other group (HEX, OCT-h, M3) no distortion is induced. For the first group, before and after unfolding, the stability of the connection is maintained according to the existence of a potential energy hill. But, to avoid the excessive distortion, it is necessary to discuss in further detail behavior of the connection. For the second group, the stabilization method of the final unfolded configuration must be considered.

b. The stabilizing method for the deployable solids should be simple and effective, by using wedges or plate springs. In special cases, the connections may be filled with concrete.

c. The connections can be made separately from the beams and columns and transported to the construction site, then unfolded and assembled.

d. For precise folding, the position of the hinges must be selected carefully and it is better to form the hinges during fabrication of the tubular members.

e. An appropriate hinge system should be chosen according to the purpose and the use of the connection. The different types of hinges are compared in Table 1.

Table 1. Comparison of hinge types.

Kind of Hinge	Characteristic	Weight	Cost	For many repetitive folding	Durability	Fireproof ability
Rotating Hinge	Generally used, Mechanical	Heavy	Expensive	Good	Bad	Bad
Membrane	Thin, Not mechanical					
a. Nylon	Plastic material	Light	Cheap	Good	Bad	Bad
b. Stainless	Stainless fiber	Light	Expensive	Good	Good	Good
c. Carbon fiber	Carbon fiber and plastics	Light	Expensive	Good	Good	Bad
Shape memory Alloy	Utilization of the shape memory alloy	Heavy	Expensive	Bad	Bad	Bad

6. Conclusions

In this paper, several kinds of deployable solid named TET, HEX, OCT-h and M3 with foldable tubular members were investigated. After then, their applications to the deployable structures were discussed. Their features can be summarized as follows:

a. The four-member deployable solid TET has a *bi-stable* mechanism. During the unfolding sequence the connection has to "climb over" a strain energy hill.

b. The six-member deployable solid HEX can be used for general moment frames. As it has a stress-free mechanism, stabilizing devices are necessary in the final state. It can be used for the construction of three-dimensional structures, such as a fishery and wave-energy dissipation.

c. Combinations of deployable solid OCT-h and M3 can be used to construct curved surface structures such as a sphere dome, a parabola antenna and a honeycomb type frame. Combinations of different units will give us possibilities of new design and construction method for deployable network structures.

d. The materials for the hinge lines have been discussed. According to the purpose and use of the structure, the material should be chosen carefully, not only for strength, but also durability and cost.

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