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Analysis of the Principles and Applications of Foldable Structures in Aerospace, Medical and Construction Fields

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Abstract:

In contrast to conventional structures, deployable structures do not have a fixed geometry and can be transformed between fully expanded and contracted. When folded, they are smaller than traditional fixed structures and can be easily stored and transported. Due to its changeable dimension, the deployable structure has been widely studied in many fields. This research lists the representative applications of deployable structures in three major fields, including aerospace, medical and construction, and analyses the characteristics of each. It is argued that deployable structures are used in several fields currently, however, the various types are not closely related so far, and some of them have not been studied in depth. It leads to the fact that most of the current designs for deployable structures are limited to focusing on specific types. Based on the usage requirements of different industries, the deployable structures often need to be redesigned, thus limiting the promotion of deployable structures in the future. It is believed that categorizing deployable structures according to the scope of application of each type and designing several generalized structural templates for conventional structural shapes will greatly facilitate the utility of deployable structures in various fields.

Keywords: Foldable structures; aerospace; medical; construction.

1. Introduction

Traditional structures, such as buildings and bridges, are fixed structures of a series of rigid bodies used to carry a certain load. Due to material properties, fixed structures may deform slightly due to loading, but these deformations are elastic and can be recovered. In general, there will be no internal movement and relative motion of the components for such a fixed structure [1]. Traditional structures must satisfy the Maxwell rules [2]. For a three-dimensional frame, if the number of bars is denoted as b, the number of joints is j, and the constraints are c. It is necessary to satisfy the Maxwell rules that $b \geq 3j - c$, otherwise it will not be stable and cannot be called a structure [2].

As a novel mechanism, the deployable structure exhibits significantly different characteristics from conventional structures. The geometry of the deployable structure is not fixed and can be altered to suit the demands of use. The geometry change is achieved by displacing the internal mechanisms in space, after which the components will still satisfy Maxwell's rules and form a stable system [3]. Therefore, it can still be considered as a structure. This structure can be traced back to the early 20th century when Bennett, in his report "A new mechanism", referred to a three-dimensional loop with four rods connected to four hinges, which exhibited rotational properties [4]. The Bennett linkage is also known as the 4R linkage because of the four revolute joints. Since then, deployable structures have been the subject of extensive research. Goldberg constructed the 5R and 6R linkage by connecting multiple 4R structures and replacing the overlapping rods created from the connection with rigid linkages [5]. In 1959, Buckminster proposed a structure that utilized the tensile properties of materials to achieve a folding function, known as the "Tensile-integrity structure" [6]. It was the first time that the deployable structures were considered for use in large-scale architectural design. In the 1960s, NASA launched a program called "Echo". The project used flexible polyester film and aluminum foil to create two orbiting satellites automatically deployed in space [7].

While the deployable structure has been developed in practical applications, experts have conducted numerous theoretical analyses of it. S. Pellegrino at the University of Cambridge and Kuznetsov at the University of Illinois, among others, have made great contributions to the kinematic analysis of deployable structures. Pellegrino used a matrix approach to analyze prestressed rod structures composed of pins and proposed singular value decomposition (SVD) of equilibrium matrix for analyzing static and kinematic problems of structural components [8, 9]. This matrix approach provides a useful method for calculating the physical state of deployable rod structures and can be applied to most prestressed cable network structures and tension-integrated systems [3]. Kuznetsov studied the underconstrained system and pointed out that the behavior of this system is influenced by a combination of interrelated static and kinematic properties [10].

In the development process, deployable structures have evolved into several branches, such as folding by material deformation, folding according to the origami principle, folding by joints, and so on. Based on the member characteristics of the deployable structure, the structure can be categorized into three types: rigid deployable structures, flexible deployable structures, and rigid-flexible deployable structures [11]. Since a vast array of models of deployable structures have evolved, this article will categorize deployable structures according to their deployment characteristics and introduce their application scenarios and their principles in three fields: aerospace, medical, and architecture. Besides, this article will also present the limitations of the current deployable structures and prospects for the future.

2. Concepts for Foldable Structure

Deployable structures can switch between unfolded and folded states autonomously and without structural abrasion. The process from folding to unfolding is called deployment, and the reverse process is called retraction [12]. According to their deformation characteristics, deployable structures can be broadly classified into two categories. One is called deformable structures. This structure usually requires the employment of flexible materials to achieve deformation, and the deformation process of this structure involves a change in the strain energy of the flexible material [1]. A tape measure is a common deformable structure with flexible and bendable tape. The tape is bent and stowed in the retracted state. When unfolded, a portion of the tape is straightened. This process is accompanied by a change in the strain energy of the tape that ultimately achieves the deformation of the structure. NASA's satellite, the "Echo," also belongs to the deformable structure.

Another type of deformable structure is called a structural mechanism. In contrast to the deformable structure, the deployment and retraction of this type of mechanism will not involve a strain change in the material. The mechanism consists of rigid bodies connected with movable joints having a certain degree of freedom (DOF), through which the whole mechanism can be deployed [1]. However, not all constructions of rigid bodies and joints are deployable, and the total DOF of the mechanism needs to be at least one. The Kutzbach criterion is used to calculate the DOF of a mechanism. Denote the number of rods in the mechanism as a, the number of joints as b, and the degree of freedom of each joint as fi. For a mechanism that deploys in the two-dimensional plane:

$$DOF = 3(a-b-1)+\sum_{i=1}^{b} f_i \quad (1)$$

If the deployment of the mechanism occurs in three dimensions, the formula will be adjusted as:

$$DOF = 6(a-b-1)+\sum_{i=1}^{b} f_i \quad (2)$$

In general, when the DOF of a mechanism is less than or equal to 0, it will be a fixed structure. There are exceptions, for example, for a parallelogram, adding a link

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to the mechanism parallel to one of the sides, using the Kutzbach criterion, the DOF can be calculated to be 0. However, due to the geometrical property, the mechanism will then have the same planar mobility as a normal parallelogram. Rigid origami is a special structural mechanism in which no deformation occurs in any part of the origami material other than the crease. A crease that protrudes upwards after folding is called a mountain, and one that depresses downwards is called a valley [13]. A single crease can only be rotated in one direction; thus, it can be replaced by a revolute joint with 1 DOF. In engineering, materials often have a certain thickness. Therefore, when using origami structures, it is important to consider the effect of the material thickness on the overall structure. The two types of deployable structures do not exist mutually exclusive and some deployable structures combine both types. Ma analyzed a spherical origami structure shown in Fig. 1 and found that the deployment of this structure is a combination of deformable structure and mechanism [14].

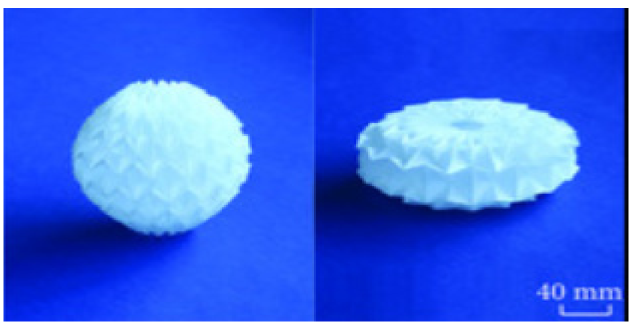

Fig. 1 Spherical Origami Structure [14].

3. Application in Aerospace

In aerospace, rockets are used to send satellites and other equipment into space for exploration. However, due to the fixed volume of the rocket as a delivery device, it is impossible to load large equipment directly into it. The deployable structure, which can be transformed between employment and retraction, provides a new way of constructing large-scale devices, such as solar panels. To increase the space utilization of transport rockets, aerospace departments in several countries have developed deployable designs for space equipment using deployable structures. This structure has numerous applications in the aerospace sector, including solar panels, deployable satellite antennas, and even entire satellites.

To maintain satellite operations, the area of satellite solar panels is always designed to be large enough to generate sufficient electricity. Researchers have made several types of foldable designs for this large-area device to allow it to fit into the transport rocket properly. At the end of the 20th century, the US company Able developed a foldable solar panel that uses rigid hinges to connect four charging panels with a unit size of 1.92m^2 [15]. The four units are in retraction during transport and the deployment is completed in space by synchronized motors. This kind of solar panel uses all rigid components, with high structural strength, but possesses a large mass, and does not meet the lightweight requirements of the aerospace field, so new foldable solar panels are being designed [15]. The Hoberman sphere is a sphere that can be expanded in three dimensions and consists of multiple closed planar loops consisting of scissor-like elements [16]. Each planar loop consists of at least three identical scissor pairs that relate to hinges, intersecting the end lines of the two sides of a pair of scissor pairs at a single point, and the angle of the circle formed by the intersection will remain constant (seen from Fig. 2) [1].

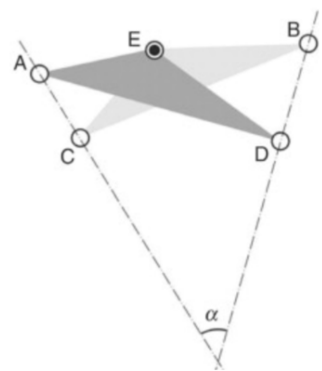

Fig. 2 Constant central angle α of a scissor pair [1].

Chen designed an autonomously rotatable deployable solar panel based on a planar closed loop of a Hoberman sphere and origami structure [17]. Chen designed an origami structure called "flasher" as a solar panel using an elastic thermotropic material [17]. This origami involves multiple parallel sets of valleys and mountains, which can be folded and unfolded by unidirectional rotation. The transformation is accomplished between a cylinder and a two-dimensional plane, and the deployment and retraction process will generate strain at the crease as illustrated in Fig. 3 [17].

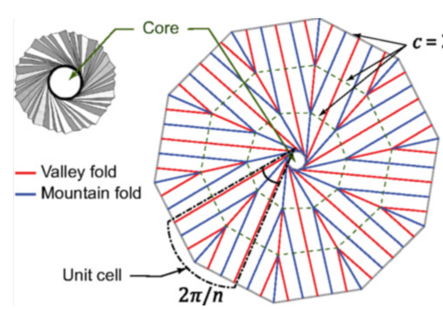

Fig. 3 Valleys and mountains of Chen's origami [17].

However, the structural strength of the solar panel would be too weak for use if only elastic materials were used to design the solar panel through origami. For this reason, Chen added Hoberman loops to supplement the strength. Similar to origami materials, the scissor pairs of the closed loop are made of a shape-memory polymer that can deform autonomously in response to changes in ambient temperature [17]. Chen defines this closed loop as an active deployment mechanism that drives the deployment and retraction of solar panels through the deformation of the loop as depicted in Fig. 4 [17]. Compared to Able‘s design, Chen‘s deployable structure is lighter and more suitable for aeronautical use, as it does not require synchronous motors to assist in its deployment while maintaining structural strength for normal use.

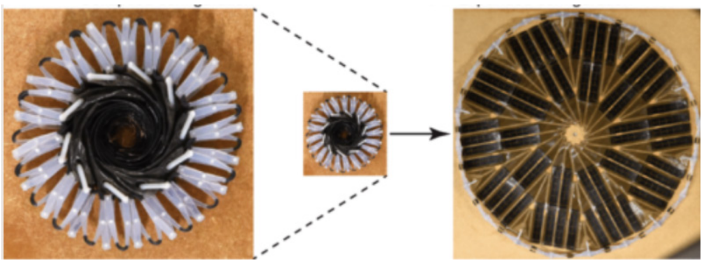

Fig. 4 Chen‘s deployable solar panel [17].

4. Application in Medical

In addition to being used for large devices, deployable structures can also be used for small precision devices. A cardiovascular disease called atherosclerosis causes the walls of the arteries to thicken, making them susceptible to clogging [18]. Previously, doctors have used bypass surgery to deal with this type of disease, where an additional blood vessel is constructed at either end of the hardened blood vessel to ensure the normal flow of blood. This type of surgery is difficult and technically demanding. The deployable structure offers a new way of treating this disease. A cylindrical deployable metal stent has been designed to address this problem by reaching the diseased area through the blood vessel and deploying it to support and widen the narrowed vessel. There are two types of these stents, one of which does not deploy on its own and requires an inflatable balloon to be passed inside the cylindrical tube, which expands the volume of the balloon to deploy the stent. The other type of stent does not require external intervention and can be deployed autonomously [18].

A research team has designed a flexible tubular stent based on an origami structure. The stent is constructed using a memory metal that will change shape as it approaches the body‘s temperature, allowing the stent to deploy autonomously once it enters the diseased area of the blood vessel [19]. The team used an etching process on the planar memory metal material to form the origami mountains and valleys, which were later rolled into a cylindrical shape to realize the cylindrical deployment and retraction of the stent [19]. Regular materials or common cylindrical structures usually have a positive Poisson‘s ratio, i.e., the diameter decreases as the length stretches, which may result in the stent not being able to fully cover the lesion when deployed, thus compromising the therapeutic efficacy of the treatment. However, by designing the crease, this origami stent realizes the inward contraction and outward expansion of the memory metal and synchronizes the expansion of the diameter and length when deploying (seen from Fig. 5) [19].

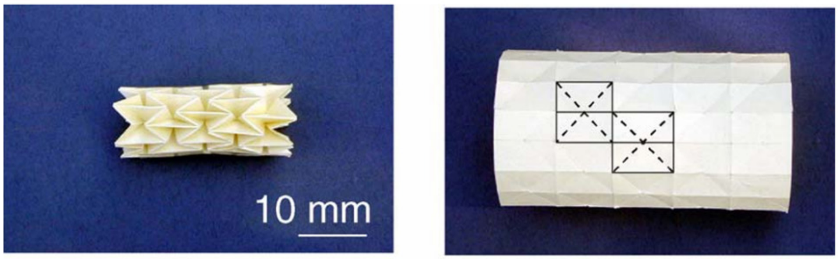

Fig. 5 Deployment and retraction of the stent [19].

Origami stents isolate the blood from the diseased area of the blood vessel when deployed, while another type of stent has a skeletonized design where the blood will remain connected to the vessel wall. Auxetic stents are representative of this type of stent, which is characterized by using materials or structures with negative Poisson‘s

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ratios to expand both the length and the diameter of the stent, as in the case of origami stents [20]. The researchers designed a topological unit as shown in Fig. 6 and arranged this unit in an orderly manner according to the transverse and longitudinal directions, respectively, and combined them to form a two-dimensional expansion plane of the stent structure as shown in Fig. 7 [20]. Using finite unit software for Poisson's ratio calculation, the measured values of these two arrangements are around -1 [20]. Deployment of this type of structure relies on a change in the size of the pores in the skeletonized portion; however, this change is not autonomous and depends on the volume expansion of the balloon that enters the vessel with the stent to achieve intravascular deployment.

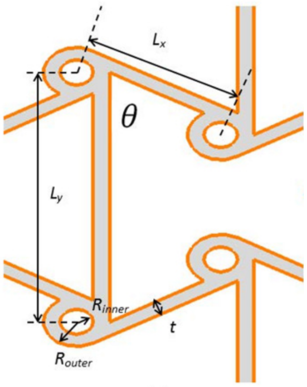

Fig. 6 The topological unit [20].

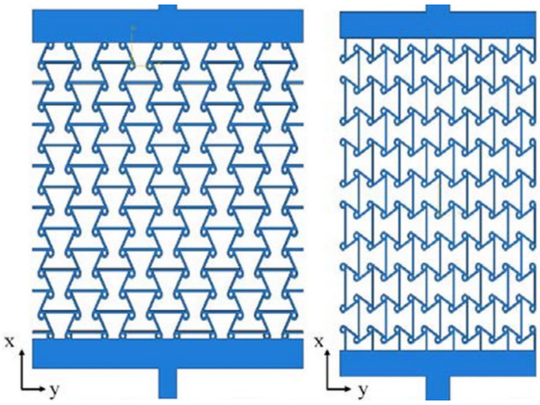

Fig. 7 Two-dimensional structures arranged horizontally and vertically respectively [20].

5. Application in Construction

Besides, aerospace and medical applications, as a special structure, deployable structures also have a wide range of applications in the construction field. Offices and residential buildings are constructed with reinforced concrete or similar materials to ensure the safety of the occupants and to reduce the potential safety hazards arising from structural problems. For this construction, the stability of the structure is the primary factor in the design. Moreover, the footprint of this sort of building is fixed when planning, and once it is put into use, its functional purpose will not change. Therefore, the scenarios for the application of deployable structures in this sort of building are not numerous.

In contrast to this fixed type of building, some buildings need to be transported between different regions as needed, and emergency buildings are one of them. The purpose of this type of building is to build temporary shelters in a short time in the event of an accidental disaster such as an earthquake or a tsunami that destroys people's homes and makes them uninhabitable. Due to the unpredictable nature of disaster locations, these structures need to be transported to the disaster area and constructed in a short period. The emergence of deployable structures provides an ideal option for this type of construction. A team designed a new deployable emergency building based on reciprocal structures, which allows for greater strength through mutual support between the bars [21]. Fig. 8 shows a basic reciprocal structure where each of the four rods is hinged to a central rod with one degree of freedom. After a certain angle of rotation, the individual rods will be constrained by the bar to stop rotating.

Fig. 8 Basic reciprocal structure, figure reprinted from [21]

This deployable structure simplifies the design of the connection between the bars and provides stability after deployment without adding extra constraints [21]. The team used this structure as a basic unit to design the emergency building as shown in Fig. 9. This structure eliminates the need for additional support rods and can be autonomously stabilized after deployment [21]. In addition, the reciprocal structure reduces the deformation of rods due to bending moments and improves structural strength without the use of excessive materials, providing an economical and reliable solution for the design of emergency structures

[21].

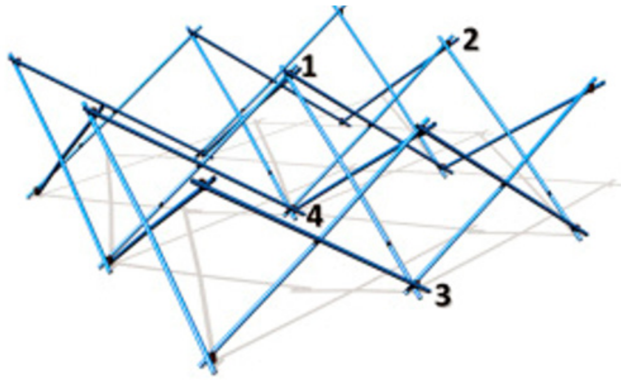

Fig. 9 Emergency building designed with reciprocal structure, figure reprinted from [21].

There is also a deployable modular building that uses an origami-like design, consisting of columns and deployable roof and floor. Considering the insufficient strength of single-layer origami, the team designed a sandwich-shaped rigid origami structure that can be deployable and retracted according to a rotating hinge [22]. Fig. 10 shows a floor/ceiling sandwich structure with one DOF that can be folded along a single direction [22]. When this modular structure is deployed, the column lengths do not change, i.e. the longitudinal length of the structure remains fixed while the lateral length changes [22]. This modular building allows for the production of several components in the factory and their rapid deployment on-site.

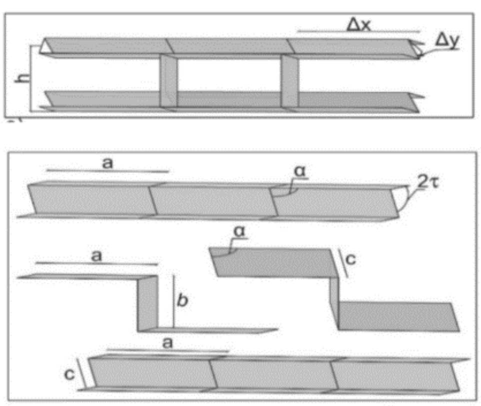

Fig. 10 The sandwich structure of the ceiling/roof [22].

6. Limitations and Prospects

Depending on the usage scenario and requirements, the deployable structure requires adjustments. For the application mentioned above, the expanded structure is designed as a flat, cylindrical, or rectangular body with different dimensions, depending on the occasion. Currently, there is no template for a deployable structure that can be used across the board, and even when designing the same structure, such as a sphere, there are many different designs, such as the Hoberman ball with scissor-like elements, the origami-based waterbomb, or the inflatable expansion with flexible materials. Besides the uncertainty of the structural shapes when designed, the current discussion on deployable structures also suffers from insufficient research on some of the structures. Reciprocal structure, for example, is a relatively neglected research topic, while origami and scissor-like originals have received much attention. If a multitude of deployable structures can be studied and classified according to the applicable fields for each type of structure. In that case, some template-like structural designs can be proposed for some conventional application scenarios. In that case, the deployable structures will potentially gain wider use across the board.

7. Conclusion

To sum up, the deployable structure can be switched between the deployed and retracted states. When deployed it can fulfill the same functions as the fixed structure, while in the retracted state it has a smaller volume than the traditional structure, making it easier to store and transport. This article explains the definition of a deployable structure, describes the evolution of the development of this structure, and classifies it according to its deployment characteristics. This study lists representative applications of deployable structures in aerospace, medical, and architectural fields that have been designed as planar, cylindrical, and rectangular shapes with different usage requirements. As an emerging structure, some types of this structure have not been widely researched and do not currently have a design that is common to most industries and needs to be customized for the application. Designing different structure templates for regular scenarios based on the characteristics of the deployment will greatly ease the design and increase the popularity of this structure.

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