Dean&Francis

ISSN 2959-6157

The Analysis and Applications of Deployable Structure

Haoze Wang[1, *]

[1]School of soil and water conservation, Beijing Forestry University, Beijing, China

*Corresponding author: wanghaoze@bifu.edu.cn

Abstract:

As a matter of fact, because of its unique portability and flexibility, the deployable structure can meet the needs of many fields of work, and has been widely used in various industries especially in recent years. With this in mind, this research will introduce the background of deployable structure, systematically introduce the basic principle as well as practical application of deployable structure. Based on the evaluations, the working principle of deployable structure represented by scissor structure, origami structure and scissor origami composite and how to work in practical applications are analyzed. According to the existing deployable structure, the limitations of deployable structure and the future development direction of deployable structure are pointed out and demonstrated. In this paper, the basic working principle and practical application of deployable structures are described by classifying deployable structures, and the types of existing deployable structures are summarized. Overall, these results pave a path for further exploration of deployable structure developments.

Keywords: Deployable structure; scissor structure; origami structure; scissor origami composite.

1. Introduction

With the increase of human demand for space, deployable structure as a basic structure widely exists in the lives. A standard deployable structure should have two stable states, when the structure is folded, the structure is small, more convenient for transportation, and after the structure is unfolded, the structure enters the working state to play its working performance [1]. So far, deployable structures have had a history of development for many years, which can be roughly divided into four stages. The deployable structure at this stage is reflected in the invention of the ancient traditional craftsmen, which is well confirmed by the appearance of the umbrella. As a representative of the rod deployable structure, the opening and closing of the umbrella bones show the most basic form of the deployable structure, laying the foundation for the birth of more deployable structures in the future. In addition, the screen is also a form of deployable structure, as a representative of the plate deployable structure, it will develop the deployable structure to no longer only rod composition, greatly enriching the form of deployable structure. In the middle of the 20th century, important progress

ISSN 2959-6157

was made in the theoretical study of deployable structures. On the one hand, mathematicians and engineers began to delve into the geometric properties of deployable structures. They explore the change law of deployable structures with different shapes during the process of unfolding and folding, and analyze the relationship of geometric parameters e.g., angle and side length. This provides a theoretical basis for designing more complex and efficient deployable structures. On the other hand, the development of materials science has also had an impact on the theoretical study of deployable structures. The researchers began to consider the effects of mechanical properties of different materials on the deployable structure, such as strength, stiffness, elasticity. Through the study of material characteristics, suitable materials can be selected to make deployable structures to meet different application needs. In addition, the study of deployable structure theory in the mid-20th century also involves the analysis of structural stability. The stability of deployable structures in different states is very important for their practical applications. Through mathematical models and experimental methods, the researchers studied the stability conditions of the deployable structure to ensure that it does not accidentally deform or collapse during use.

In the late 1960s, with the rapid development of aerospace science and technology, deployable structures ushered in important development opportunities. Due to the high space utilization and volume requirements of the spacecraft at launch, the deployable structure can be folded in the state of storage at launch, and then unfolded after entering space, perfectly meeting the needs of the space field. During this period, there were many important applications of deployable structures, such as solar panels for satellites and deployable antennas. These structures fold tightly during launch and unfold after entering orbit, providing necessary functional support for the normal operation of the satellite. With the development of deployable structure for many years, its application field is no longer limited to aerospace. With the increasing human demand for space, the deployable structure has been widely used in various fields, and all kinds of new folding furniture such as folding beds and folding chairs in furniture supplies have increased the utilization rate of the house under the condition of playing its function. In the field of electronic science and technology, folding screen mobile phones and civilian drones use folding technology to better play their performance, making people more convenient in the process of use. In terms of transportation, the emergence of the convertible is influenced by the development of the folding structure, which meets the needs of people's personalized travel. After years of development, people's research on folding structure has gradually deepened, mainly reflected in the following four aspects. The first is kinematic and geometric analysis of mechanism. The research of kinematic characteristics and geometric change law of deployable structures is continuing. Multi-DOF and single-DOF control research: With the improvement of application requirements, the control of the freedom of deployable structures has become a research focus. On the one hand, it is necessary to design a deployable structure with multiple degrees of freedom that can realize complex shape changes to meet diverse application scenarios. On the other hand, for some specific application scenarios, such as aerospace equipment that requires precise control of the deployment state, researchers are committed to realizing single-degree of freedom deployable structures to improve the stability and controllability of the structure. Research on mechanical properties of deployable structures under different development states, including strength, stiffness, stability, etc., has been strengthened. This involves the selection of materials, the optimal design of the structure and other aspects to ensure that the deployable structure can withstand various loads and environmental conditions during use.

New materials are constantly being applied to developable structures. For example, memory alloy materials, which have the characteristics of automatic shape recovery under certain conditions, can be used to achieve self-stretching driven deployable structures; Smart materials such as shape memory polymers can change shape in response to external stimuli (temperature, electric field, magnetic field, etc.), providing a new way to drive and control deployable structures; High-strength, lightweight composites are also widely used in deployable structures to improve structure performance and reduce weight. Composite and optimization of materials: Researchers not only focus on the performance of a single material, but also work on the composite application of multiple materials to give full play to the advantages of different materials. For example, rigid materials are combined with flexible materials to form a rigid-flexible coupled deployable structure, which can not only ensure the stiffness and stability of the structure after expansion, but also have good flexibility and receptibility in the folded state.

Digital design and simulation technology: With the development of computer technology, digital design and simulation technology have been widely used in the research of deployable structures. By establishing the mathematical model and computer simulation of deployable structures, the development process, mechanical properties and motion trajectory of structures can be accurately predicted and analyzed, and the cost of structural design can be reduced. One needs to optimize the design of deployable structures to achieve lightweight structures and optimal performance. By optimizing the topological shape of the structure, the amount of materials used can be reduced and the efficiency of the structure can be improved on the premise of meeting the requirements of structural strength and stiffness. In order to realize the accurate control and automatic deployment of deployable structures, intelligent control technology has become a research hotspot. At the same time, artificial intelligence algorithm and machine learning technology are combined to predict and optimize the motion process of the deployable structure, and improve the control accuracy and reliability of the structure.

This paper will first introduce the basic definition of deployable structure, then analyze the three representative structures of deployable structure, and analyze their structural characteristics and specific applications through practical cases, and finally summarize and reflect on the existing deployable structure, and look forward to the future development direction of deployable structure.

2. Basic Properties of the Folding Structure

A deployable structure is a structure that can change from a compact form to an expanded form, or from an expanded form to a compact form, under certain conditions [2]. Such structures usually consist of multiple movable parts that are connected to each other by hinges, flexible connections, or other special connections. In the folded state, the structure occupies a small space, easy to store, transport and carry; In the unfolded state, the structure can form a larger space or have a specific functional shape to meet different use needs.

The symmetry of the deployable structure is reflected in the whole and the unit of the structure. For most deployable structures, the overall structure is generally symmetrical, and this symmetry ensures that the structure maintains a uniform force when bearing external loads. In addition, the characteristics of the deployable structure determine the symmetry of the structure. Compared with the asymmetric structure, the symmetric structure has a uniform size parameter, which ensures the uniform wear of the deployable structure during use. The safety of the structure is ensured. The symmetry of structural units is mainly reflected in the number and type of structural units, and the type and number of structural units of a structure are usually even. The process of folding structure re-expansion can be divided into two dimensions: plane dimension and space dimension. In the plane dimension, the expansion of the structure only occurs in a plane, for example, the angulated scissor structure (seen from Fig. 1 [3]). In three-dimensional space, a folded structure can be expanded from a compact three-dimensional form to a structure with a specific spatial shape. An example of 3d deployable structure is presented in Fig 2 [4].

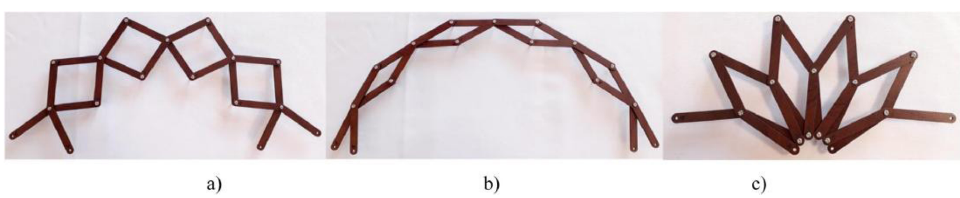

Fig. 1 Angulated scissor structure [3].

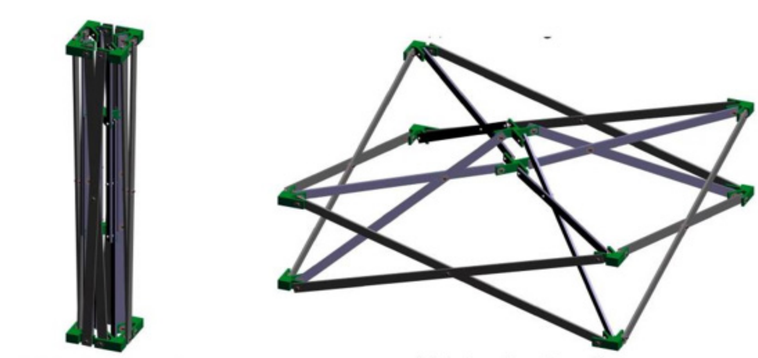

Fig. 2 The 3D deployable structure [4].

ISSN 2959-6157

3. Working Principle and Practical Application of Folding Structure

Deployable structure can be divided into rod structure and plate structure according to the structural unit, in which rod structure is mainly represented by scissor structure, and plate structure is represented by origami structure. There is also a combination of bar and plate structures: Scissor origami composite [5]. The following is an analysis of the characteristics and applications of these structures.

3.1 Scissor Structure

The scissor structure is composed of a basic unit, a basic unit mainly consists of two rods and a central hinge point, similar to the shape of scissors [6]. There are many types of scissor structure, which can be divided into general scissor structure and its variants according to the difference of the basic units of the structure. General scissor structure refers to the unit forming the overall structure as two straight rods connected at the central point, while the variants are manifested in the connection position of the nodes and the shape of the rods.

Fig. 3 shows the three scissor structures, including the general scissor structure, the structural variant that changes the connection position and the structural variant that changes the rod shape [3]. The hypothetical lines connecting the upper and lower nodes of the element are called the element lines, and Fig. 3(a) are generally scissor structural elements if the element lines are flat, while Fig. 3(b) are variants that change the position of the connection if the element lines intersect, and (c) are variants that change the shape of the member if the individual member is twisted. Fig. 4 is a unit of the scissor exoskeleton, a structural variant of a three-dimensional form that appears as a spatial curvature of the rods, arching or spherical when the structure is unfolded [7].

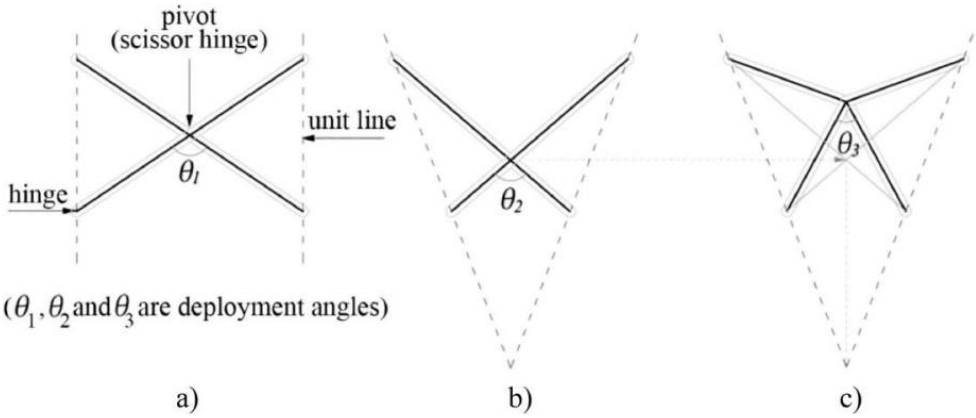

Fig. 3 The scissor structure and its variants [3].

Fig. 4 Scissor exoskeleton [7].

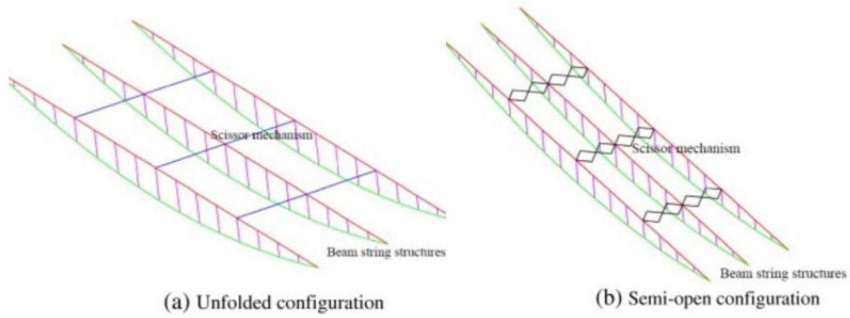

Fig. 5 Parallel linear beam string structures: a) fully deployed state; b) deployed state [9].

Scissor structure is widely used in life. Here, the function of the scissor structure is analyzed by taking the retractable roof as the object. The first is a parallel retractable roof, which is a rectangular structure, similar to Parallel linear beam string structures [8], where the main beam is connected by the scissor structure as the roof. It can be shrunk and expanded as needed. The second type is Iris dome [9]. This structure is a retractable roof designed by Hoberman in 2000. The structure as a whole is circular and composed of structural units angulated scissor-like element, then the elements form an overall linkage structure. The third is angulated scissor structure [3]. As shown in the Fig. 5, Fig. 6 and Fig. 7, the scissor structural units composed of curved rods are connected to each other. Similar to the second structure, this structure is also widely used in the basic form of telescopic roof [9].

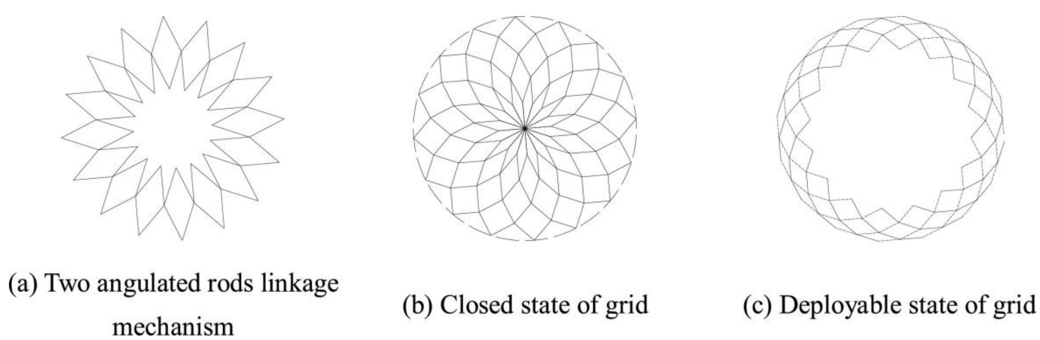

Fig. 6 Angulated scissor-like-element: b) fully deployed state; c) deployed state [9].

Fig. 7 The unfolding process of angulated scissor structure: a) deployed state; b) fully deployed state [9].

3.2 Origami Structure

Origami structure originated from origami art, which is a deployable structure composed of many plates directly connected at the edge, and belongs to a kind of plate structure. The following is a basic structure of origami structure, including mountain fold, valley fold and panel. In the process of folding, mountain fold bulges outward and valley fold depressions inward to achieve the folding effect. Fig. 8 illustrates a kind of origami structure [10]. The common crease patterns mainly include Miura-ori pattern, Waterbomb pattern, Yoshimura pattern and Kresling pattern [10]. These creases enrich the way origami structures unfold and promote the development of origami structures to more areas.

ISSN 2959-6157

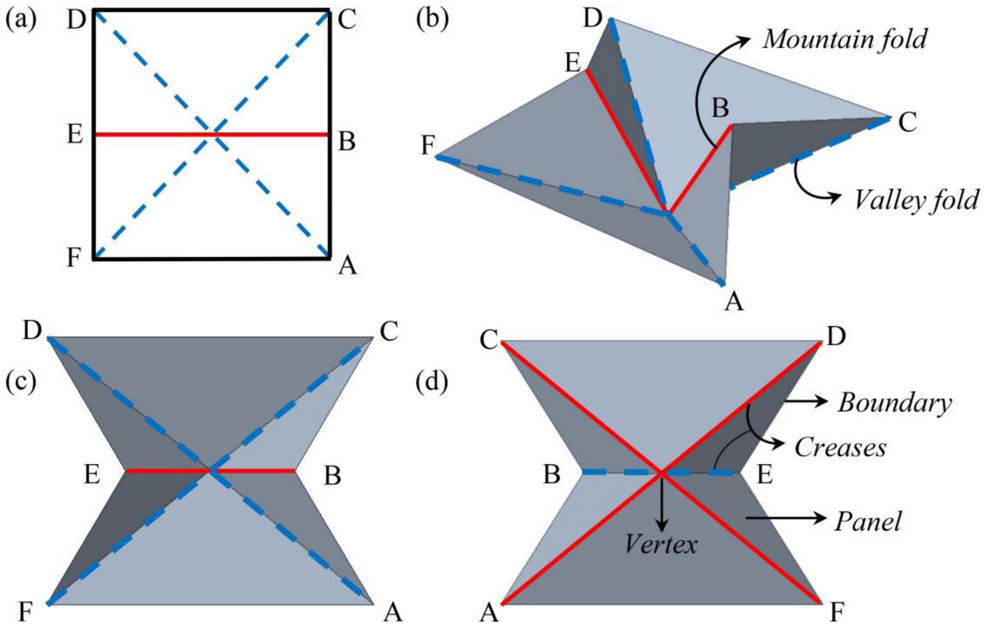

Fig. 8 A kind of origami structure [10].

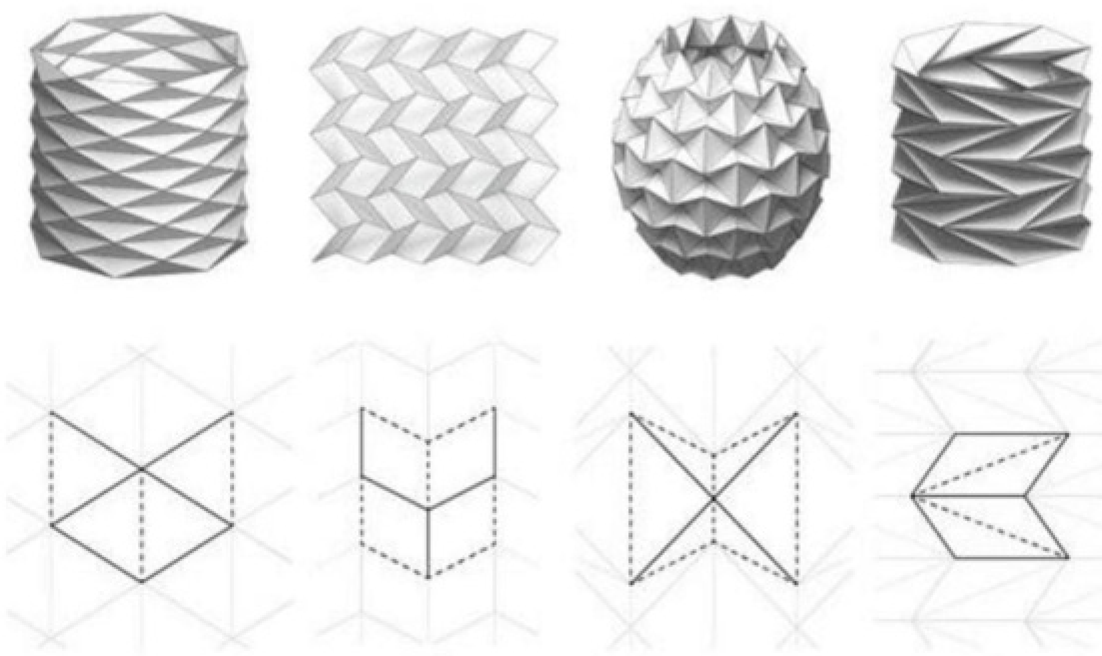

Fig. 9 Yoshimura, Miura-Ori, Waterbomb and Kresling origami (from left to right) [10].

Origami structure is widely used in various fields. In architecture, origami structure has the characteristics of light weight and easy control, so this kind of structure can be applied to the curtain wall of the building to respond to the intensity of sunlight, change the degree of expansion of the deployable structure, and control the entry of natural light. Al Bahr Towers‘ solar facade uses this structure to control the amount of incoming light while using shape memory alloys to reduce energy consumption (seen from Fig. 10) [11]. In addition, in aerospace, origami structure is applied to the solar panel of the spacecraft, DFH-4 solar cell array adopts the origami structure, when the satellite reaches the transfer orbit, the main compression device is unlocked, the outer plate is expanded 90°, when the satellite reaches the quasi-synchronous orbit, the secondary lock device is unlocked, the connection frame and the solar panel are expanded and locked, and enter the working state as depicted in Fig. 11 [12].

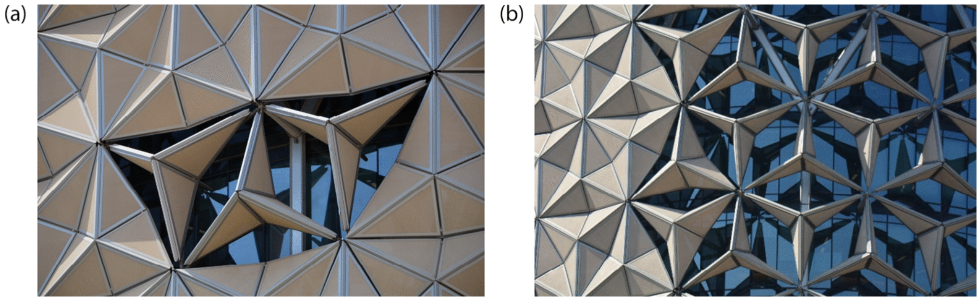

Fig. 10 The curtain wall of Al Bahr Towers [11].

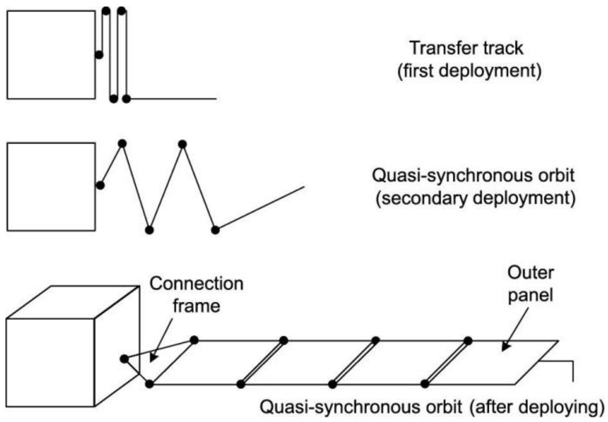

Fig. 11 The deployment process of solar arrays [12]

3.3 Scissor Origami Composite

This kind of structure is a combination of the first two structures, and has the characteristics of scissor structure and origami structure, and coordinates the folding methods of the two. Generally, the plate surface of the origami structure bears the load, and the scissor structure strengthens the load by connecting each plate. The component units of this type of structure are also relatively simple, usually consisting of a general scissor unit and a basic plate deployable structure. As a composite structure, this kind of structure is generally used in Bridges. The first application example is applied in emergency rescue. Due to the poor stability of the plate structure itself, the scissor structure is added on both sides of the bridge deck to strengthen the bearing capacity of the bridge deck, and the railings can ensure the safety of the rescued (depicted in Fig. 12) [13]. A second example is the rolling bridge in the United Kingdom, which rotates and contracts when boats pass and expands when pedestrians need to cross (seen from Fig. 13) [5].

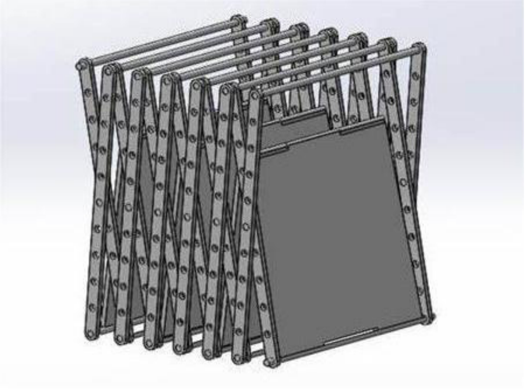

Fig. 12 The retracted deployable bridge [13].

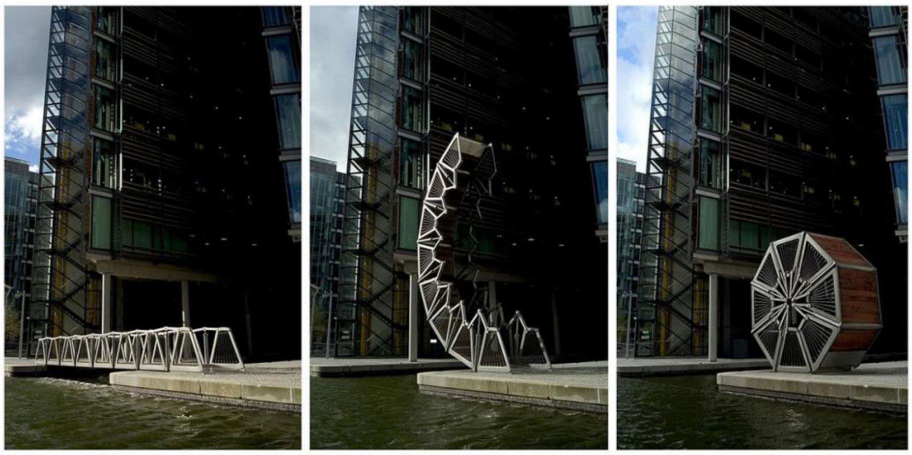

Fig. 13 The rolling bridge [5].

ISSN 2959-6157

4. Application Limitation and Improvement of Folding Structure

Due to the structural characteristics of the deployable structure itself, there are usually some limitations. Deployable structure is usually composed of many units, involving various parts and hinges, so it requires fine design and calculation to ensure the dimensional accuracy of the parts at the folding, in this process will produce a lot of calculation and experiment, resulting in the increase of time and manpower and material costs. In practical applications, the deployable structure needs to be opened and closed frequently to meet the working requirements, and needs to bear a certain load, so in the process of use, structural units such as hinge points will occur wear and fatigue. In some areas, the deployable structure of the development of a variety of ways, the need for specialized tools or skills, improve the use of this structure threshold, in some large structures, folding structure development needs to rely on specialized power equipment, which also increases the cost of power.

With the aid of computer software, the stress of the structure and the characteristics of the working environment are accurately simulated in the software to improve the design accuracy of the structure and reduce the cost of manpower and material resources. The introduction of more ductile fatigue resistant materials, reduce the wear and fatigue caused by the structure in the process of long-term work, and strengthen the strength of the structure in the easy to wear area, extend the service life of the structure. The folding mode is optimized, the dynamic system is used instead of manual operation, and the working efficiency of the structure is improved. In addition, the intelligent control system is added, and the sensor is used to identify changes in the environment and directly control the working state of the deployable structure.

5. The Future Development Direction of Folding Structure

At present, the materials used in deployable structures are mainly traditional materials such as steel and wood, although these structures are widely used in construction, machinery and other fields, but as folding materials are applied to more fields, the structure needs to determine the use of materials according to the characteristics of the working environment. The future deployable structure should not only meet the working performance, but also generate energy, such as deploying solar panels on the deployable structure, which can make greater use of solar energy resources when the structure is unfolded. This can compensate for the energy consumption of the structure during the development process. Thanks to the development of artificial intelligence, the deployable structure will be more intelligent, artificial intelligence analyzes the characteristics of the working environment, and automatically controls the structure to unfold or fold in a specific time, so that the structure can better play the work efficiency and reduce energy consumption.

6. Conclusion

To sum up, this paper introduces the discussion of the basic principle of deployable structure from the development background of it, and draws the following conclusions. Deployable structure can be classified according to different basic units. In the scissor structure, the basic unit is the bar; In origami, the basic unit is the board. Therefore, the two should be divided into two different deployable structures. In the same deployable structure, the basic units that make up the structure will become a new structure due to the difference in the shape and connection of the structural units. In the scissor structure, the basic units are the connection of two rods, but there are variations of these basic units, which results in a new structure. At present, folding construction has structural complexity, strength problems, durability and other limitations, which need to be solved by the innovation of materials and the assistance of software. In the future, with the development of artificial intelligence, deployable structures will be more intelligently applied. The literature collected in this study is limited, and the rigor of each document has not been verified, so there may be some errors. In addition, with the development of deployable structures, the classification standards in this paper may not be applicable to future structures. In short, there is still a large space for the development of deployable structures, which is of great significance for the study of it.

References

[1] Yan W, Ji F, Zhang M. Folding Structure System and Type. Journal of Architecture and Civil Engineering, 2006, 23: 17.

[2] Cai J, Wang Y. Novel developable and foldable structures. Engineering Mechanics, 2022, 39(S): 1-8.

[3] Najmeh F D, Yaser S, Feray M. Geometric and analytical design of angulated scissor structures. Mechanism and Machine Theory, 2021. 164: 11.

[4] Santana M V B, Arnouts L I W, Massart T J, Gonçalves P B, Berke P Z. Corotational 3D joint finite element tailored for the simulation of bistable deployable structures, Engineering Structures. 2021, 207: 11.

[5] Jian J M, Cher S T, Shahrin M, Ahmad RM Zainal A. State-

of-Art review on deployable scissor structure in construction. Structures, 2022, 42: 160-180.
[6] Yuan L, Sudarshan K. Deployable scissor structures: Classification of modifications and applications. Automation in Construction, 2024, 165.
[7] Miguel N C, John R, Michael S A, Bai S. A compact 3-DOF shoulder mechanism constructed with scissors linkages for exoskeleton applications. Mechanism and Machine Theory, 2019, 132: 264-278.
[8] Cai J, Feng J, Jiang C. Development and analysis of a long-span retractable roof structure. Journal of Constructional Steel Research, 2014, 92: 175-182.
[9] Wang Y, Zhang Q, Pan N, Xu Y, Lu D, Cai J, Feng J, Mechanical properties of hoberman radially retractable roof structures. Thin-Walled Structures, 2024, 203.
[10] Larissa M F, Guilherme V R, Marcelo A S. An overview of the mechanical description of origami-inspired systems and structures, International Journal of Mechanical Sciences, 2022, 223.
[11] Attia S. Evaluation of adaptive facades: the case study of Al Bahr Towers in the UAE. QScience Connect, Special Issue on Shaping Qatar's Sustainable Built Environment 2017, 2: 6.
[12] Ma X, Li T, Ma J, et al. Recent Advances in Space-Deployable Structures in China. Engineering, 2022, 17: 2.
[13] Yan C H, Tan A. Design and analysis of emergency deployable bridge. International Journal of Mechanical Engineering and Robotics Research, 2020, 9(10): 1393-1399.