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Analysis of the Principle, Applications and Improvements of Foldable Structure for Bridge Design

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Abstract:

As a matter of fact, the foldable structures have been widely adopted in these years. With this in mind, collapsible structures in Bridges are mainly studied and investigated in this research. The development history of foldable structure is discussed. And how folding structures have been gradually used in construction projects such as the famous London Bridge throughout history. Several common foldable structures and their principles include their advantages and disadvantages and the difficulty of implementation. It is also briefly stated in the article. The foldable structure of several representative bridge projects from 2022 to 2024 has also been demonstrated. The paper then describes the development direction of foldable structure in the future, the defects of foldable structure and the possible impact of environmental protection on the material selection of foldable structure. The purpose of this paper is to summarize the existing collapsible structures of Bridges with famous engineering projects in the past four years as examples. Combined with the social background, the future development direction of the structure is analyzed and predicted.

Keywords: Foldable structure; bridge design; material selection.

1. Introduction

The history of deployable structure can retrospect to ancient years, a classic case is umbrella. Wooden foldable umbrella with cloth soaked in oil used as umbrella cloth and foldable chair is the evidence that human have already use foldable structures in basic tool in ancient times recorded by history. Then the usage of foldable structures in building field be implemented in 1960s. Piñero, who is a Spanish engineer did the first try to design a theater that can fold to reduce space [1]. When it comes to later 20 centuries, with the developing of astronautical technology, techniques for folding structures were developed because of the space-saving require of space instruments [2-4]. These techniques were mainly used for putting solar panels and antennas in limited spaces and make them can automatically deploy. In the middle of 20 centuries tensegrity system was developed and mainly used in urban sculpture, the characteristic of tensegrity system is the zero moment of force environment in these system [2], the system is It consists of a pressure rod and a rope. The combination of lazy tong system which is very famous tensegrity system [3] and tensegrity system become a Amechanical structure that locks itself. Nevertheless, knots between ropes which usually happened in these kinds of systems prevents the system from deploying [3]. The mainly usage for deployable structure in the solar power board on satellite, can divided into flexible system and rigid system, The former has a reflective surface such as a flexible material, while the latter is composed of rigid body parts. An example of this is the shifted and separated double pantograph ring on satellite as seen from Fig. 1 [4]. Application of folding structure in bridge have much more examples than in space explore areas. The foldable bridge is not only talented in the field of disaster relief but also insure the passage of ships. The disaster relief bridge which is foldable can dates back to World War II in England. Called scissor-bridges, the bridge is mounted on the tank to cross the ditch [5]. This kind of bridge developed to DSB system (Dry Support Bridge) in 2003. It is a system based on vehicle, the bridge span reached 40 meters, the width reached 40 meters and this system can be transported by rail and helicopter (depicted in Fig. 2) [5]. Another time-tested example is the London tower's bridge, it was built to face both the passage of people, carriages and the passage of ships. In the middle of 19 centuries, 120,000 people and 20,000 cars cross the bridge each day. [6] To make it possible for high-mast ships to pass traditional bridges will have steep slope that the wagon is difficult to climb. To solve this problem, Horace Jones and John Wolfe Barry design a foldable structure they called bascule bridge which means the bridge can be opened like a seesaw to allow ships to pass in 1878s [6].

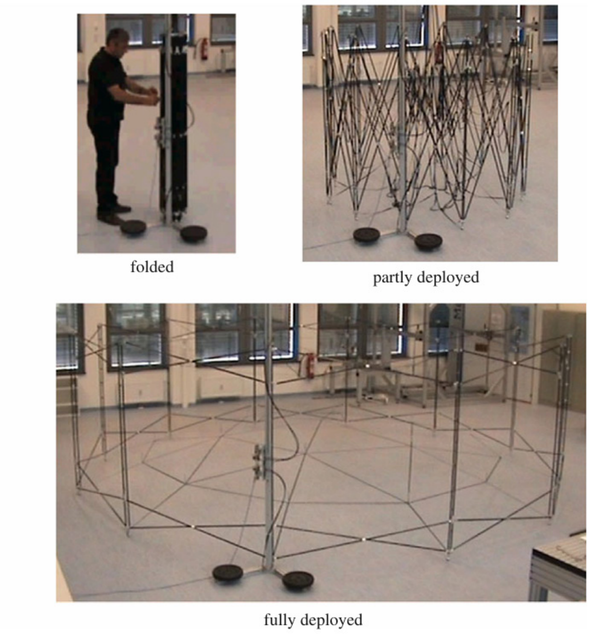

Fig. 1 Double pantograph ring breadboard [4].

Fig. 2 DSB system (2003) [5].

Because of the increasing needs of foldable structures and adaptive organization such as seismic field for civil engineering, aerospace, architectural engineering projects. Deployable structure is showing more potential because of it's ability of undergo huge geometric transformations, which means It can save space or have many different functions. This kind of structures provides solutions with unique advantages for engineering and design challenges. However, because there are limits on theoretical research and material strength, the potential of deployable structures is not fully realized in these areas. Under this environment, textual study is going to summarize the principle and the application of developable structure and show the future prospects of these structures, especially on the applications on bridge design field.

The purpose of this paper is to discuss the deployable structures in Bridges in a certain span of time, from the origin of deployable structures to their principles and corresponding examples, as well as to predict their future

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development direction. In the following sections of this article, the definition of a developable structure will be described along with formulas and pictures. Three bridge projects with foldable structures from 2020 onwards will then be cited as examples. Finally, according to the current environmental and social trends, the future development direction of the developable structure in the bridge is predicted and some suggestions are given.

2. Concepts for Foldable Structure

A collapsible structure is defined as follows. Foldable structures are a kind of transform structures. Transform structures means structures that have the ability to change shape and readjust itself to fix the different function, like the environment or weathers. These are all demands which have constantly changing possibilities [7, 8]. Deployable structure can be divided into four different parts and there are significant differences between them. These four kinds are spatial bar structures consisting of hinged bars; foldable plate structures consisting of hinged plates; tensegrity structures; and membrane structures [9]. Another way to classify deployable structures is to divide them into one-dimensional, and two-dimensional deployable structures [10]. One-dimensional deployable structures can be used for moving heavy stuff away from the satellite or used for giant mechanism as actuator. Therefore one- dimensional deployable structures seems potential in folding Bridges. The two projects of folding Bridges mentioned above are also examples of its potential. Two-dimensional deployable structures are mainly used for solar panel arrays and the antenna on the spaceship [10]. This application also shows two-dimensional deployable structures has ability on save space.

Compared to permanent structures foldable structure has advantages in three dimensions. The first advantage of foldable structures is its reusability, and the folding structure is easier to transport because the smaller space it occupied when it is folded. The second advantage is foldable structures can reduce unnecessary capital investment because it can easily be transported between places need them. The third advantages of this kind of structures is that foldable structures also cause less both time and economy In the construction process. To meet these advantages, foldable structures always have well designed joints which make sure the bar is easy to store in the storage state and smooth and reliable during expansion. Therefore, two popular materials for nodes are metal and plastic. However, materials like plastic and metal composites are also popular. However, for bridge engineering, one-dimensional foldable structures are more commonly used than two-dimensional foldable structures. The reason is that the two-dimensional foldable structure is more complex, with relatively high flexibility, and it brings more complex mechanical structures. This means higher failure rates and maintenance costs, and two-dimensional foldable structures are not outstanding in their ability to carry loads. Because of the above reasons, one-dimensional structures account for the vast majority in the field of folding Bridges.

3. Principle and Applications in Bridge

Foldable tubular bridges are one kind of the bridge folding scheme was proposed in 2023 [11]. This bridge is based on foldable polyhedral tubes (T-hedral type) which forms the main part of the bridge as depicted in Fig. 3 [11]. These structures above are formed by planar quads [11] and it can easily be controlled by a single drive swivel because it only has one degree of freedom (as given in Fig. 4). The blue part of the triangle on the above pictures for both sides of the added plate structure can effectively increase the load that the bridge can bear. It plays the role of bending beam. The addition of these two structures does not affect the folding characteristics of the bridge, allowing the tubular bridge to withstand greater traffic load while folding normally. T-hedral tubes as a collapsible structure, it has obvious advantages in terms of Bridges because its basic structure can be made in advance, easily transported and finally quickly developed on the construction site (seen from Fig. 5) [11].

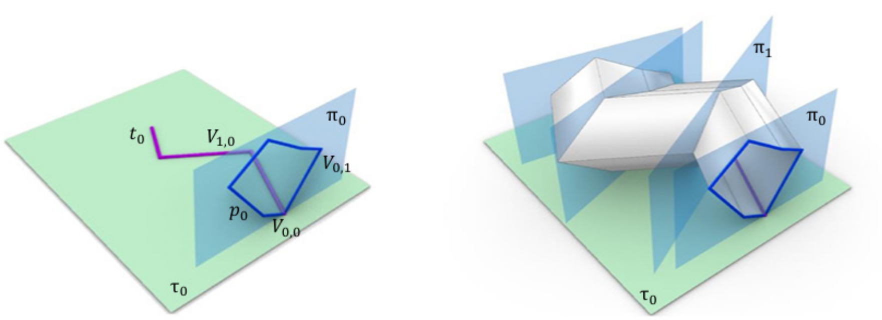

Fig. 3 Foldable tubular bridges [11].

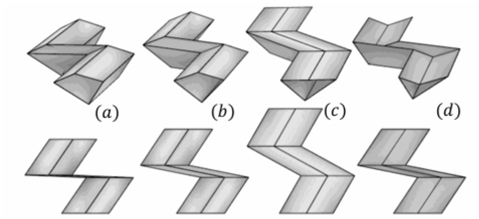

Fig. 4 The way that polyhedral tubes (T-hedral type) folds [11].

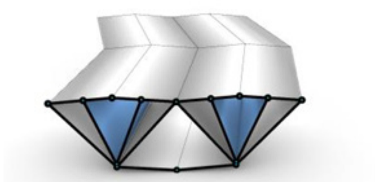

Fig. 5 Design structure of bridge [11].

In order to quickly solve the damage caused by natural disasters, folding Bridges are widely used for their advantages of rapid deployment and convenient transportation. Scissors mechanism is used as main structure in the emergency bridge published in 2017, which called Mobilebridgeversion4.0 (MB4.0) [12]. Seen from Fig. 6, scissors mechanism is combined by two linear elements have a joint at the center of two bars. This kind of mechanism have the same shape as scissors and their length can vary greatly before and after folding. In order to match the function of disaster first aid, the bridge system is easy to transport. It can use track or lorry [12], these two modes of transportation unlike train transport, which requires a landing environment based on rail and helicopter transport, trucks and trailers are extremely common and relatively reliable modes of transport after natural disasters.

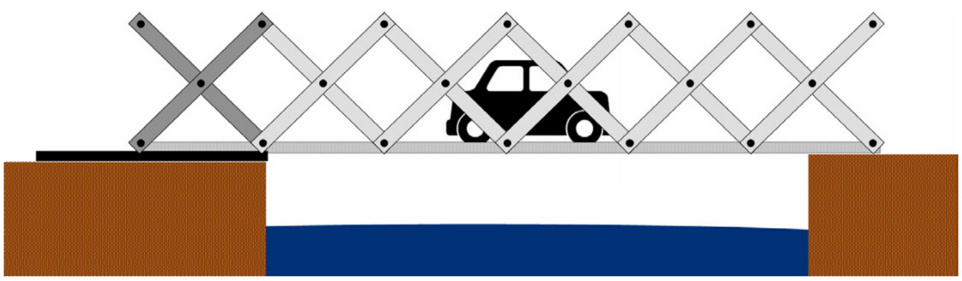

Fig. 6 New concept of a scissor bridge based on Origami-folding idea [12].

Fig. 7 The bridge was testing [12].

The bridge was tested shows when it is opened it allow cars to pass (seen from Fig. 7). In the test in 2015, Mobilebridgeversion4.0 It took one hour for the transport bridge to reach the site and be ready for normal use while crossing a 17-meter-wide river, the bridge was deployed in only five minutes and the bridge used very few technicians. No cranes were even used to get the bridge to the other side of the river. During this test, more than one car passed the bridge to test its ability to withstand the load, and the bridge did not suffer any damage during the experiment. The typical structure is a simple collapsible structure, so the bridge has a high reliability because of its simple structure. The reliability of bridge is very important in disaster relief. Therefore, this kind of bridge is not only simple in structure, easy to produce, but also has high reliability. Applicable to disaster relief. Another form of collapsible bridge is inflatable collapsible bridge. There are three main types of pontoons: belt pontoons,

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self-propelled pontoons and split pontoons.[13] The deck of the split-type pontoon bridge is separate from the part of the hull that provides buoyancy. In the process of building the bridge, the hull needs to be erected first, and then the bridge deck needs to be installed. Compared with the previous bridge, the installation step of the belt pontoon bridge is simpler, and it is only necessary to expand the bridge body and dip it into the water surface, and the installation step is over. Self-propelled pontoon bridge is a combination of vehicle chassis, folding bridge and buoyancy structure. They are faster and more adaptable, and some of them can even be transported amphibious [13]. Rigid-flexible combination foldable bridge is a new type of pontoon bridge that combines the advantages of two materials above as given in Fig. 8 [13].

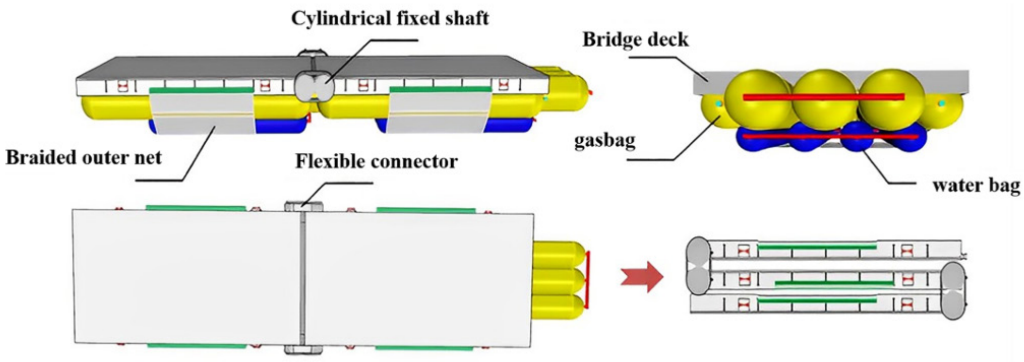

Fig. 8 Rigid-flexible combination foldable bridge [13].

The bridge consists of three parts, the deck is made of aluminum to reduce the weight of the bridge, the link between the decks is made of flexible materials, the bottom of the air bags are water bags and they are all wrapped in a mesh to connect them together. The air bag and water bag are composed of seven layers of composite material, which has the ability to resist rupture at higher atmospheric pressure [13]. The function of the water bag can not only prevent the air bag from being scratched by sharp objects under the water, but also play a role in lowering the center of gravity, so that the pontoon bridge is more stable in the current.

Of the above three kinds of Bridges, one is the rapid construction of daily Bridges. One is a simple scissors folding bridge for disaster relief. The last is a composite buoyancy bridge, which is also used in disaster relief. These three kinds of Bridges have different structural designs, but they have common characteristics in application field and function. Tube folding bridge and TV folding bridge. All three types of Bridges have the ability to deploy quickly. The rapid expansion of the first type of tubular folding bridge is reflected in the reduction of the time spent on construction. The rapid deployment capability of the second scissor-like folding bridge is reflected in the reduction of the time spent on rescue. The last type of composite pontoon bridge reduces the time required to cross the river. The composite pontoon bridge can be used for both daily traffic and emergency disaster relief. The composite pontoon bridge is the only one of the above three types of collapsible bridge that uses flexible materials, uses air as buoyancy, and adds water bags as counterweight to prevent the bridge body from tumbling. Compared with the previous two Bridges, the structure is more complex, but the multi-layer structure of the air bag can effectively reduce the probability of rupture and improve the reliability of the bridge.

4. Improvements and Suggestions

For shear Bridges, the axial pressure received is small and the bending moment is relatively large (seen from Fig. 9) [14]. Maximum strain on the hinge occurs when the vehicle is stationary at point d in the picture above. Therefore, in order to improve the performance of the folding bridge, you can upgrade it from the following two aspects. The first is to reduce the time taken to transport and deploy the bridge. As mentioned above, the two main applications of bridgeable Bridges are to ensure the passage of ships and rescue after disasters. In order to increase the number of ships that can pass each day, it is necessary to reduce the time the bridge spends on the switch. When it comes to rebuilding after a disaster, less time to start means less damage to people and government and personal property. Reducing the development time can also be divided into different solutions. The first method is to increase the power of the expanded parts, such as increasing the voltage of the motor responsible for the expanded part of the bridge, so that the motor reaches a higher speed. However, this method has obvious disadvantages. First, in the process of bridge expansion, the stress on various components such as hinges will increase, which is reflected as the shear stress of the center hinge in shear bridges. In the current environment, the widely accepted method to improve the expansion speed of bridge is to reduce the friction between bridge components. As a movable structure, foldable bridge components will inevitably have friction during the development process, so friction has become two important forces to overcome in addition to gravity during the development process of foldable bridge. The methods of reducing friction can be divided into changing the hinge material and adding bearings and can also be achieved by adding lubricating oil. In order to reduce the transportation time of the folding bridge, an optional method is to combine the vehicle with the bridge itself and other equipment required for its deployment, so that the loading and unloading time of the bridge can be reduced. Another approach, more intuitive but more difficult to implement, is to reduce the bridge's own weight. In order to achieve this, it is necessary to find lighter materials with the same or higher strength, and to optimize the folding structure to reduce the weight of the bridge while the overall strength is unchanged. Another property of a foldable bridge that can be improved is its load carrying capacity. The improvement of carrying capacity also means the improvement of carrying efficiency. In order to achieve this effect, materials with bending resistance such as carbon fiber can be used as rods, and special alloys such as titanium can be used as hinges, which can not only improve the carrying capacity of the bridge, but also reduce the weight of the bridge. However, with the development of materials science, it is possible that the emergence of better materials will greatly increase the carrying capacity of all folding Bridges without changing the structure.

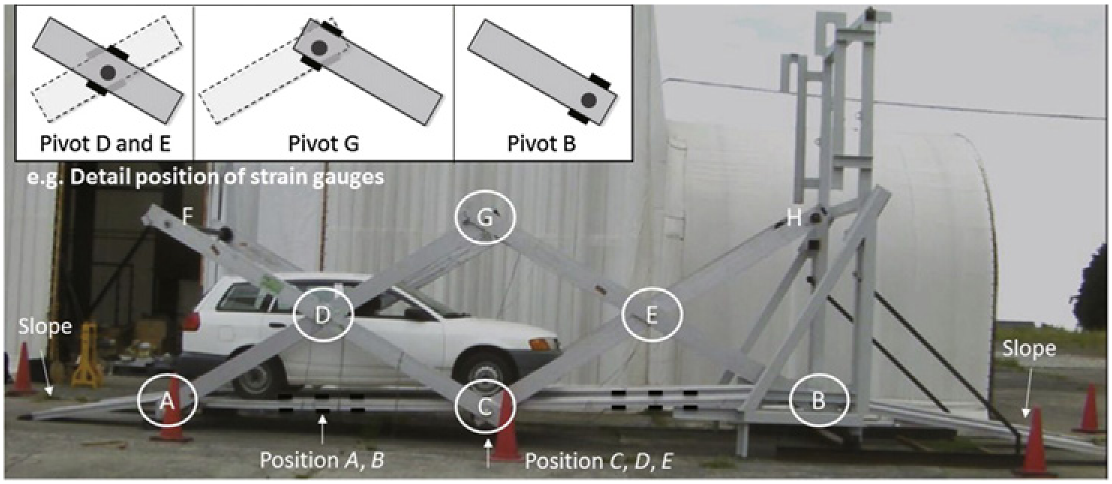

Fig. 9 Experimental setup of the MB1.0 with AD Van [14].

5. Limitations and Prospects

Foldable Bridges have obvious advantages in the field of disaster relief and traffic protection, but they also have some disadvantages reflected in their structure and function, in order to ensure that the space occupied by folding Bridges is small, they usually use more complex mechanical structures, which represents a large number of parts and complex interactions between them. Inevitably, this structure makes the failure rate of foldable Bridges proportional to the complexity of the structure itself. Due to its complex structure, this high failure rate compared to ordinary Bridges is inevitable. High failure rates result in high maintenance costs including replacement of faulty parts and maintenance of critical structures during annual inspections. Compared with concrete Bridges, foldable Bridges have relatively small load carrying capacity, which is also due to the limitations of their materials. The bearing capacity of concrete Bridges stems from the high strength of concrete. However, the heavy weight of concrete itself and its tensile resistance make it unable to be used in folding Bridges. Compared with concrete bridge, the design time of foldable bridge is much shorter than that of concrete bridge. Its design will inevitably appear immature phenomenon. The risks and possible problems can only be solved through continuous discovery and exploration, that is, gradually with engineering practice.

Another disadvantage of folding Bridges is that their complex structure requires construction personnel and engineers to have a high level of design and implementation standards. This will result in a significant increase in construction costs. For the same reason, the repair of foldable Bridges still needs to be repaired by highly skilled engineers. At the same time, when the bridge is opened and closed, the traffic function of the bridge itself cannot

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be guaranteed, and it is easy to cause local traffic congestion, which is also a difficult shortcoming of the bridge to solve. The above shortcomings are caused by the foldability itself, so they cannot be completely solved, and can only be continuously optimized through design or updated materials.

The future development direction of collapsible Bridges can be concentrated in the following five aspects. The first aspect is that with the development of technology and the progress of materials science, more advanced folding structures and building materials with lighter unit weight and higher strength will appear. Under the action of these new structures and materials, the reliability and bearing capacity of foldable Bridges will be significantly improved. The second aspect is that the foldable bridge will undergo intelligent transformation in the future, such as intelligent adjustment according to different weather conditions and traffic flow to adapt to different environments, so as to achieve improved efficiency. Intelligence also includes real-time monitoring and early warning of Bridges to improve the safety of Bridges. The third aspect is the improvement of sustainability and environmental protection. With the continuous development of human society, the importance of environmental protection and sustainability has also been paid attention to, so the choice of foldable bridge materials may be more inclined to environmental protection materials in the future. Environmentally friendly materials that are easily degraded and pollution-free during production. It reduces the cost of disassembly and recycling of foldable Bridges at the end of their service life, and also protects the environment. The fourth aspect is foldable bridge. The application environment may become richer, and foldable Bridges may no longer just be used as a tool to cross rivers or through rough terrain. Collapsible Bridges can also be explored in space. Oceangoing scientific research has played an important role. The rapid connection between two areas and the high adaptability of folding Bridges make folding Bridges have high potential in other fields. The fifth aspect is the beautification of the urban environment. The folding bridge has a unique mechanical beauty and can be integrated with the urban landscape. It makes the urban environment more beautiful and improves the quality of life of citizens.

6. Conclusion

To sum up, this study studies foldable structures in Bridges, focusing on their development history such as the emergence of umbrellas as the origin of foldable structures. Existing excellent designs include collapsible Bridges for military use and pontoon Bridges for disaster relief. Principle analysis, such as the diagram showing that the bearing force of the hinge changes with the position of the load when the typical structure is used as the main stress structure in the collapsible bridge. The future development and limitations of foldable structures in Bridges are also discussed. It is concluded that with the development of material science and the progress of folding structure design, the attributes of folding Bridges, including bearing capacity, life, environmental protection and aesthetics, will be greatly improved. Meanwhile, the limitations of foldable structure in maintenance cost and failure probability are also found. The collapsible structure of the bridge has great potential in other fields, such as in aerospace and ocean scientific research, the structure of the collapsible bridge can be effectively used and played.

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