Design of a New Type of Deployable Bridge

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Abstract. In order to ensure that the rescue workers can quickly cross the natural obstacles such as ditches and valleys to enter the disaster area when the traffic facilities are destroyed seriously by natural disasters, a new type of developable bridge is designed. The design of the bridge is based on the theory of shear hinge and the one-dimensional shear hinge element is used as the basic element. Under the function of dead-weight, the bridge can be unfolded by rope traction. It can be locked into service state after being unfolded to the design position. In this paper, through kinematic simulation and finite element static analysis, the developability and bearing capacity of the developable bridge are verified. The results show that the deployable bridge can meet the design requirements.

1. Introduction

The key characteristic of a deployable structure is that is has two different stable state: the fully folded state and the fully unfolded state. When the deployable structure is in the fully folded state, it is small in size and easy to transport and store. When it is fully deployed, the structure is stable and can bear loads.

Because of its advantages of being easy to transport and store in the fully folded state and being able to bear loads in the fully unfolded state, the deployable structure has been applied to the common articles of daily use, such as telescopic doors and umbrellas. In civil engineering, aerospace engineering and other fields the deployable structure also has a good application prospect.

In the field of bridge engineering, the deployable bridge has a good application prospect because of its advantages of convenient transportation and fast erection speed. In 1926, a inventor in the Netherlands, L. Deth had invented a kind of emergency deployable bridge which is the prototype of the large deployable bridge[1]. In 2007, the University of Wisconsin designed a deployable bridge system of fiber reinforced concrete[2]. There is a “deployable roller bridge” in London, England[3]. The whole bridge can be folded into octagonal structure by hydraulic system, which is convenient for ships to pass through the river smoothly. In 2013, Hiroshima University[4] in Japan designed a movable bridge with a scissor-hinged structure for deployment.

In the 1960s, the Planning and Design Institute of the Ministry of communications of China designed a detachable “321” portable steel bridge on the basis of the original British Bailey bridge, and further developed the “200” portable highway steel bridge[5]. In 2010, Sun Guangxu[6] of National Defense Science and Technology University designed a new type of deployable bridge section based on the task requirements of detachable beam bridge. In 2011, Guan Fuling of Zhejiang
University and her team[7] designed a kind of light military deployable bridge using scissor hinge and sleeve deployable mechanism. In 2016, Xiong Haibei et al.[8] of Tongji University designed a kind of deployable arch bridge with the triangle shear type element as the basic deployable component.

When natural disasters such as earthquakes and floods occur, a large number of conventional bridges will be destroyed, there is an urgent need for a convenient transportation, rapid emergency bridge to cross the obstacles, and the developable bridge can achieve such a goal.

In this paper, a new type of deployable bridge structure is proposed with the shear hinge element as the basic element. In this paper, the author used SolidWorks mechanical design software to design the components of the developable bridge. After that, the author uses SolidWorks to carry on the simulation assembly and the interference inspection to the developable bridge. The mechanical system simulation software ADAMS is used to simulate the deploying process of the deployable bridge. Using SolidWorks simulation finite element analysis module to analyze the stress and deformation of deployable bridge structure.

2. Bridge structure design

2.1. The design goals of the deployable bridge
Depending on the scenario, the deployable bridge designed in this paper should meet the following requirements: first of all, when the bridge is fully extended, the span should more than 22m and the bridge height should less than 3m. Secondly, in terms of bearing capacity, it can be used for large vehicles with a weight of 30 tons to pass through, and the material will not yield when passing through the bridge. Thirdly, as an emergency bridge with span less than 50, the mid span deflection under the design load shall be less than \( \frac{L}{120} \), where \( L \) is the bridge span. At last, the deployable bridge should be flexible to be closed and unfolded, and the time of closing and unfolding should be less than 10min.

2.2. Conception of the project of the developable bridge
The main structure of the developable bridge designed in this paper adopts the shear hinge structure because that the deployable principle of the shear hinge structure is simple, and it is convenient to store and transport. Another reason for the design to chose the shear hinge structure is that the shear hinge structure can achieve different configurations easily by adding different constraints which is easy for designers to choose the type of bridge.

When the construction member only bears the axial force, the material bears the most uniform force and can give full play to the performance of the material, while the reasonable arch structure has the characteristics of only compression and not bending, so the developable bridge type of this paper is arch bridge. In consideration of the convenience of production and assembly, the arc-shape is selected for the arch axis. At the same time, the arc-shaped arch axis is selected, and the span of the developable arch bridge can be realized by increasing or decreasing the number of shear hinge structures.

In order to improve the stability of the structure on both sides of the developable arch bridge, diagonal supporting bars and tie bars along the driving direction of the developable arch bridge are proposed. The main structure, supporting bar and tie bar of the developable arch bridge form a triangle so as to improve the stability of the structure. The horizontal thrust of the arch end is borne by the tie bar, which reduces the requirements of the geological conditions of the arch bridge. The concept of the developable arch bridge is shown in the Figure 1.

![Figure 1. Conception of the developable arch bridge.](image)
2.3. Scheme design of main structure of deployable arch bridge

2.3.1. The developable condition of shear hinge structure. The developable arch bridge designed in this paper is based on shear hinge structure and the smallest element is shear hinge element. Figure 2 is the schematic diagram of shear hinge unit. When the two points of the shear hinge element (point A and C) move in opposite direction, the shear hinge structure can be folded. It can be imagined that when the shear hinge structure is folded to the final state, point A, B, D and point C, B, D will be almost in a straight line. At this time, the distance between two points B and D is the maximum. Therefore, it is easy to obtain the developable condition of shear hinge structure:

\[ AB + AD = BC + CD \]  

(1)

![Figure 2. Shear hinge element.](image)

As shown in Table 1, by adjusting the length of the member, the shear hinge structure with different shapes can be formed.

| Member length relationship | The shape of shear hinge structure |
|----------------------------|-----------------------------------|
| AB=AD=BC=CD               | Rectangle                         |
| AB=BC,AD=CD, AB≠AD        | Arch                              |

2.3.2 The main structure design of arc arch. Figure 3 is for the structural diagram of circular arc arch shear hinge. Now it is known that the radii of the three arcs are \( R_1 \), \( R_0 \), \( R_2 \) and the degree of the central angles \( \delta \) corresponding to each scissor hinge element. According to the cosine theorem, we can know the length of each of bar:

\[ l = (R_1^2 + R_2^2 - 2R_1R_2\cos\delta)^{1/2} \]  

(2)

![Figure 3. The shear hinge structure of circular arc arch](image)

In order to meet the design span requirements, the arch axis of the extendable arch bridge designed in this paper is an arc with a radius of 45.5m and a center angle of 30°. According to the developable principle of shear hinge and the design of arch axis, the dimensions of the final designed main component is shown in Figure 4.
2.4. The overall scheme design of the developable arch bridge
The whole structure of the developable arch bridge designed in this paper is rut structure, which consists of two single span bridges. Single span bridge is composed of bridge deck, bridge foot deck, bridge foot, pin shaft, support bar, tie bar and locking hook. The bridge deck, bridge foot panel and bridge foot are made of aluminum alloy materials, and the rest of the components are made of stainless steel. The main structure of the arch bridge is composed of four groups of deck, two groups of deck and bridge foot. The supporting bar and tie bar are used to assist the bearing of the bridge body. There are six groups of supporting bars, which are respectively installed at the bridge deck interval on both sides of the bridge body. There are two kinds of tie bars, sixteen in all, which are arranged on both sides of the bridge body, and the two ends are hinged. The pin shafts are used to connect the various components. The function of the locking hooks is to keep the deployable arch bridge structure stable and working normally. In the SolidWorks software, the simulation assembly is carried out, and interference inspection is carried out for the inspection of the developable arch bridge. The result shows that there is no interference.

As the deployable arch bridge to fully deployed state, the span of the developable arch bridge is 24m, the width of the bridge deck is 1.4m, and the rise height is 1.6m. The Fully expanded graph of the developable arch bridge is shown in Figure 5.

3. Simulation of the unfolding process of the developable arch bridge
In order to check the unfolding feasibility of the developable arch bridge, this section carries out kinematic simulation of the developable arch bridge through ADAMS, the mechanical system simulation software.

3.1. Principle of developable arch bridge
As shown in Figure 6, it is necessary to hoist the solid line arrows B and C in the drawing with steel cable, then use the moment M(Figure 7) in formed by the staggered distribution of tension and gravity to expand the developable arch bridge. Similarly, the deployable arch bridge can be folded when the dotted arrows A and D are hoisted.
3.2 ADAMS simulation
The kinematics simulation of deployable arch bridge is carried out by using Adams software, which is divided into three steps:

Firstly, the geometric model of developable arch bridge should be established, but because the modeling ability of ADAMS is not well, this paper adopts building model in SolidWorks and then import into ADAMS. In the process of importing the model from SolidWorks, the geometric model of the deployable arch bridge is reasonably simplified that the hinge shafts with small mass and independent of the developability are removed.

Secondly, the physical model is established by adding kinematic pairs, boundary conditions and material properties. After the physical model is established, the author check the model and find that the model includes 50 parts, 74 revolutes, and 2 sliding pair. The system freedom of the deployable arch bridge is zero, which shows that under the driving action, the model can make certain movement.

Finally, the author verified the expansibility of the designed deployable arch bridge by simulation. The process of model folding can be observed as Figure 8 and 9.

4. Analysis of bearing capacity of deployable arch bridge
In this section, the author mainly uses the simulation module of SolidWorks mechanical design software to analyze the deformation and internal force of the developable arch bridge under the action of gravity and design load when it is fully expanded.

4.1 The establishment of the finite element model of the developable arch bridge
This section establishes the finite element model by using the model designed in SolidWorks software in the section 1.

4.1.1 Material properties of finite element model In the global model, only elastic analysis is needed. If the stress of the structure exceeds the yield strength, the structure needs to be strengthened. Table 2 is for the material properties of each component of the developable arch bridge.
Table 2. The material properties of each component.

| Material          | Density (kg/m$^3$) | Poisson's ratio | Modulus of elasticity (Pa) |
|-------------------|--------------------|-----------------|---------------------------|
| Bridge deck       |                    |                 |                           |
| Bridge foot deck  | Aluminium alloy    | 2700            | 0.33                      | 6.9×10$^{10}$ |
| Bridge foot       |                    |                 |                           |
| Pin shaft         | Stainless steel    | 7800            | 0.28                      | 2.1×10$^{11}$ |
| Support bar       |                    |                 |                           |
| Tie bar           |                    |                 |                           |
| Locking hook      |                    |                 |                           |

4.1.2 Analysis type and boundary conditions. The static analysis method can be adopted for the model, so the static stress analysis is selected when setting the type of calculation example, which mainly focuses on the stress and deformation of each component of the structure.

People can connect the bridge foot with the ground well on both sides of the bridge, so the boundary condition is set to restrict the 6 degrees of freedom of the bridge foot module on both sides, so that the bridge foot is firmly connected with the ground. Boundary conditions are set in the fixture and fixed geometry is selected.

When using the finite element analysis module of SolidWorks, the connection between the parts defined in the previous assembly is only the position relationship, not the connection between the parts. Before the finite element analysis, it is necessary to establish the connection between the components. The basic developable element of the developable arch bridge designed in this paper is the shear hinge element, so the connection between the components is hinge. There are many kinds of joints and contact ways in SolidWorks. Because the connection between the parts is hinge joint, the pin joint is selected. Joint property is fixed ring (no translation) so that the two parts of the pin connection can rotate relative to each other, but not translate relative to each other. The author has checked the freedom of the developable arch bridge. After checking, the developable arch bridge has been completely constrained.

4.2 Deformation and internal force of deployable arch bridge under dead weight

The deformation cloud chart under the action of self weight is shown in Figure 10. It can be seen from Figure 10 that the deformation of the main body of the span module of the developable arch bridge under the action of self weight is not large, the maximum deflection in the middle of the span is 3mm, and the maximum deformation occurs at the tie bar. Figure 11 is the stress cloud chart under the self weight of the deployable arch bridge. The maximum stress in the middle part of the whole small span of the folding bridge is 20MPa, and the maximum stress appears in the bending part of the support bar is 70MPa.

![Figure 10. Cloud chart of deformation under dead weigh of deployable arch bridge.](image1)

![Figure 11. The stress cloud chart under the dead weight.](image2)
4.3 Deformation and internal force of deployable arch bridge under design load

It can be known from the overall scheme design part of section I that the design of the deployable arch bridge is jointly borne by two bridges when bearing the design load. When taking one of the bridges for analysis, the design load is halved.

Mid span loading is the most unfavorable condition for the stress of the deployable arch bridge. Therefore, two 5meters long and 0.7meters wide cuboids are placed in the mid span module, and 15 tons of pressure is applied on them to simulate the design load.

The deformation nephogram under the design load is shown in Figure 12. It can be seen from Figure 12 that the maximum deformation of the deployable arch bridge under the design load is 125mm in the middle of the span, which is less than \( L/120 \) of the bridge span. This means that the expandable arch bridge can meet the deformation requirements under the design load.

It can be seen from Figure 13 that the maximum stress of the bridge deck under the design load is 190MPa, which appears in the middle of the span. The maximum stress of the deployable arch bridge appears at the foot of the bridge, which is 240MPa.

![Figure 12. Cloud chart of deformation under design load.](image1)

![Figure 13. The stress cloud chart under design load.](image2)

From the above finite element analysis, it can be seen that the developable arch bridge designed in this paper can meet the use requirements under the design load.

5. Conclusion

Based on the requirement of high-mobility engineering support for rapid deployable emergency bridge, a new design scheme of the deployable arch bridge is presented in this paper. The folding process of the deployable arch bridge is simulated to ensure that the deployable arch bridge can be unfolded and folded according to the design. At the same time, the stress and deformation of the deployable arch bridge under the design load are analyzed, and it is found that the bearing capacity of the deployable arch bridge can meet the design requirements.

The deployable arch bridge designed in this paper has novel structure, simple configuration and can be manufactured in factory. The deployable arch bridge has a good adaptability, according to demand can be reasonable increase or decrease the number of bridge span modules to meet the requirements of crossing different obstacles. It is very convenient to transport and unfold the arch bridge designed in this paper. The problem of large deformation of deployable arch bridge under design load can be improved in the future structural design.

In conclusion, the expandable arch bridge designed in this paper can preferably meet the requirements of rapid emergency bridge for building the emergency rescue channel in non military emergency activities such as disaster relief.

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