

# A New design of deployable pedestrian bridge deck based on origami theory

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**Abstract.** As one of the basic civil engineering structures, bridges greatly impact people's daily life. However, many bridge accidents are caused by boat crashes because of the driver's carelessness or other climatic and hydrological factors. Besides, some pedestrian bridges are not frequently used and thus make a waste of water space. This design will overcome the challenge and tackle the problem successfully based on the origami and kirigami theory by using a connector composed of a slider and a revolute joint. The bridge can be folded up and down via a particular folding method. The basic structure units have two degrees of freedom (DOF). The whole mechanism can be folded and unfolded by sliding and rotating the connector. According to the structural folding position analysis results shown in the diagrams, the new deployable bridge deck structure design can validly tackle the problems of clearance limitation under the bridge via the special-designed cross-section of the bridge deck. I hope the design model will be widely applied in the river-crossing bridge and bring convenience to all pedestrians and boat drivers.

**Keywords:** Pedestrian bridge, Origami theory, Degrees of freedom.

## 1. Introduction

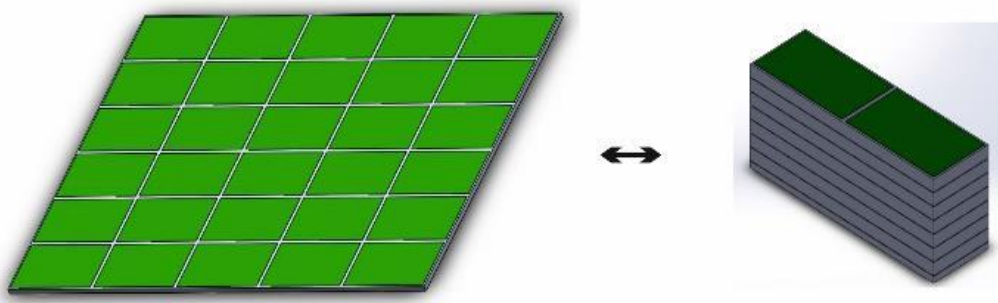
In the development of construction, it has experienced the procession from static structures to dynamic structures. The architecture at the very beginning originated from the first house built by people in ancient times, and the purpose of this kind of structure is only to protect themselves from beast attacks and bad weather. There is no internal movement or movable elements inside of it. Then with the development of aerospace engineering, civil engineering, and architectural engineering, the demands and requirements in these fields are increasing, then it comes to the deployable structure to satisfy different requirements in different areas, which the static structure cannot successfully achieve.

A deployable mechanism always owns one or several degrees of freedom, making related movement among several mechanism members possible. Via rotating, sliding, and rolling, it can make the achievement of configuration folded and unfolded to satisfy some specific demands.

In the field of architecture and civil engineering, A large number of research and study literature about the deployable structure have been published to solve a series of problems and make civil engineering constructions more multifunctional and aesthetically pleasing, etc. There is a lot of structural applications of using the deployable theory, such as retractable plate structures [1], rolling bridge[2], space enclosures [3], etc.

As time passed, the topic of deployable structure has become an old topic, while the origami and kirigami theory is going to be a new approach to the old topic. The term origami refers to the commonly known ancient art of paper folding[4], which uses one square sheet of paper with no cuts [5]. This process of seeing and understanding may be divided into two processes: one is to determine the possible three-dimensional configurations from the picture, while the other is to match them with some general concepts, especially the origami-inspired mechanisms offer enhanced flexibility in performance [6,7]. When we use paper to fold up and down, it will form some bulge and depressing creases, which are called "Mountain Fold" and "Valley Fold". Through these simple folds, some simple origami objects will be created. Then consider each part of the origami object surrounded by creases as a rigid panel while the creases are the connectors (such as a revolute joint); this is the fundamental theory of panel-structure folding. However, when it is denoting the panels' thickness, lots of deployable structures may have uneven surfaces. This is the reason why the kirigami theory is

published. Kirigami theory aims to cut off the paper (there will be somewhere no linkage between some panels) rather than solely folding the paper up and down. It is no difference when the thickness is zero, but it matters a lot when taking actual thickness into consideration. As the condition when some connections between panels are substituted by the voids (equivalent to splitting one rigid thick panel into two pieces of rigid thick panels), it will be possible to make any deployable structures with even surfaces be folded up successfully via the specific folding method. In other words, every existing functional structure all have the possibility to be folded up and down by using the origami and kirigami theory.



**Figure 1.** An example of an array panel structure folding by using origami theory [8]

The paper focuses on a new design of deployable pedestrian bridge deck whose basic model is simply supported girder bridge and purposing to solve the clearance limitation below the pedestrian bridge via using a folding method of origami and kirigami theory. And through designing the special linkage between two bridge deck elements to achieve configuration being expanded and folded successfully. The subsequent parts of the thesis will be developed in following four sections. Section 2 shows the design method and presents the force calculation analysis and configuration of the model. The results of force analysis and mechanism folding position analysis will be summarized in section 3. Then section 4 gives the whole conclusion of the model configuration design and deployable bridge folding method.

## 2. Methods

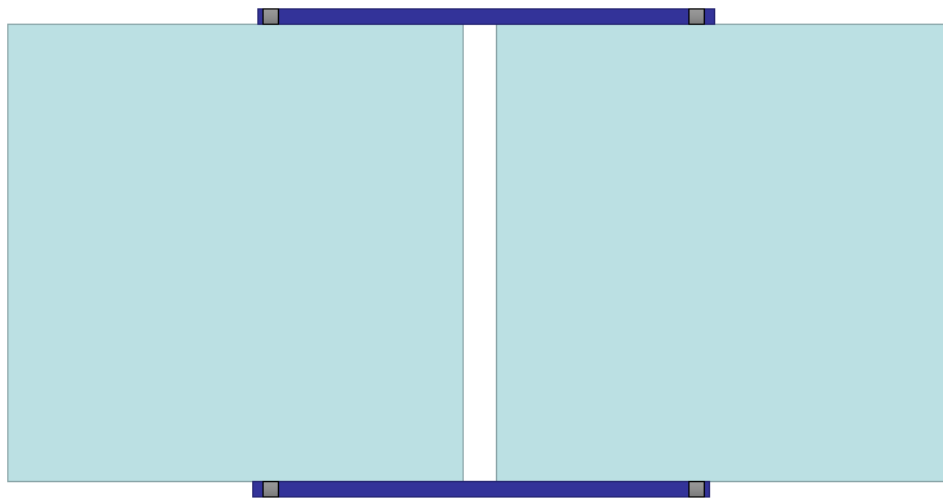
The design mainly uses structural folding position relationship analysis, origami and kirigami theory of deployable structure. Based on the Domestic Market Seagoing Ship Construction Code, the sightseeing boat width is usually designed as 6 m. Then the length of the deployable bridge will be created as  $L=12$  m. And the deck of the bridge will be separated into several square pieces which have identical shapes on upper and lower surfaces, while the cross-section of deck panels are different, as it will make the combination of a slider and a revolute joint work successfully between two adjacent deck panels on longitudinal and cross-orientation. The width of the bridge deck will be designed as  $w=9$  m, which will be separated into three panels.

### 2.1. Basic unit element design

The design of the unit element of the bridge deck and the connector between two deck panels are shown in the following diagrams. As the configurations for which the displacements of the special-designed connector do not cause elongations of the combination of revolute joints and sliders to represent valid rigid origami configurations [9], the design and analysis shall not consider the internal deformation.



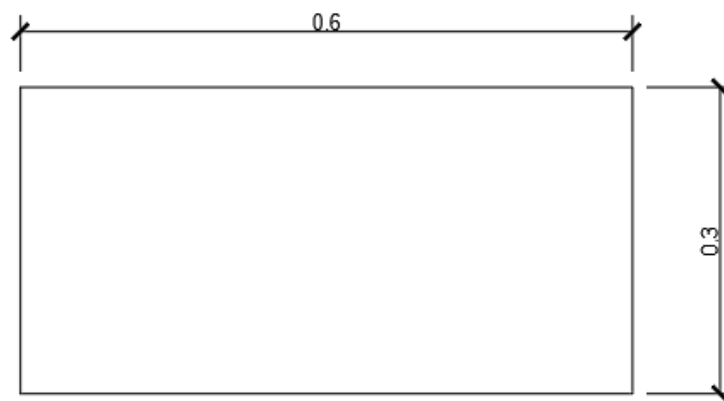
**Figure 2.** Main view of basic unit element.



**Figure 3.** Top view of basic unit element.

In the main view of the basic unit element, the hollow of a deck panel is a connector composed of a combination of a slider and a revolute joint. When the deployable bridge is folding, the deck panel will be folded up by sliding the slider and rotating the revolute joint to accomplish the overlap of two bridge deck panels. This connector is partially naked from the bridge deck, and the thickness of the connector can be negligible. The model size of the deck panel thickness is designed as  $D=40$  cm, while the thickness of the connector that is exposed from the bridge deck shown in the top view from the diagram is being designed as  $d=30$  cm, and its width is equal to the thickness.

The section of span centre is consisted of two approximately identical squares. Hence, section size diameters are shown as following diagram.

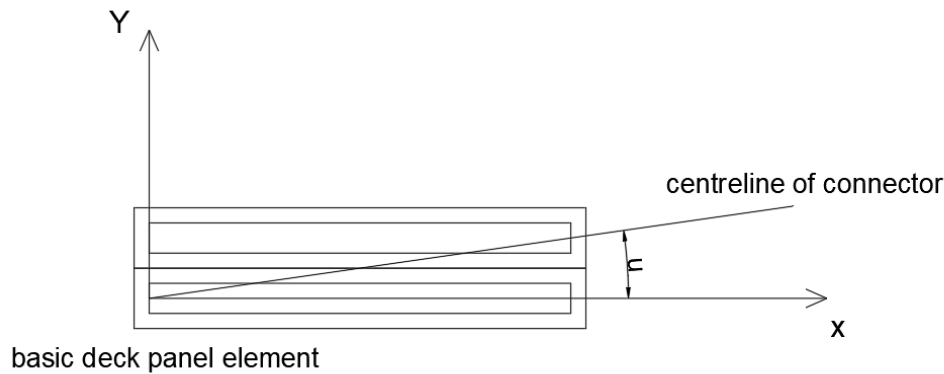


**Figure 4.** Dimensional values of span centre section (m)

### 3. Results

As the different properties of each fold state, such as shape, dimensions, etc., can make an allowance to a device based on a single origami crease pattern to perform multiple functions [10]. The results of the basic element configuration folding position analysis and mechanism folding processions are formatted as follows:

### 3.1. Results of mechanism folding position analysis



**Figure 5.** Location relationship presentation.

According to Figure 8, the relationship of location between the clamping angle of the center-line of the connector and X-axis ( $u$ ) and the center point of the left side of the connector position( $x$ ) is presented as follows.

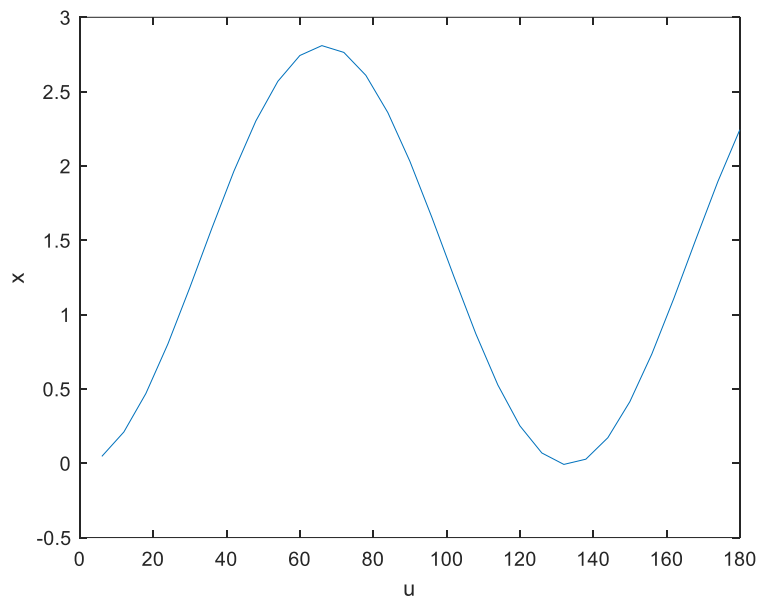
The length of connector is equal to  $l_0$ .

$$l_0 = \sqrt{(3 - 2 \times 0.1)^2 + \left(\frac{1}{2} \times 0.6\right)^2} = 2.82\text{m} \quad (1)$$

$$x = \frac{1}{2} \times (2.8 - l_0 \cos u) \quad (2)$$

As  $\arctan \frac{0.3}{2.8} = 6.11^\circ$ ,  $u = u_0$  shown in Figure 8 is equal to  $6.11^\circ$ . Then the range of value  $u$  is from  $180^\circ$  to  $6^\circ$ . And the velocities of two sliders are always kept at a value to make the line determined by the center point of the connector and the center point of the lower side deck panel perpendicular to the lower side deck panel.

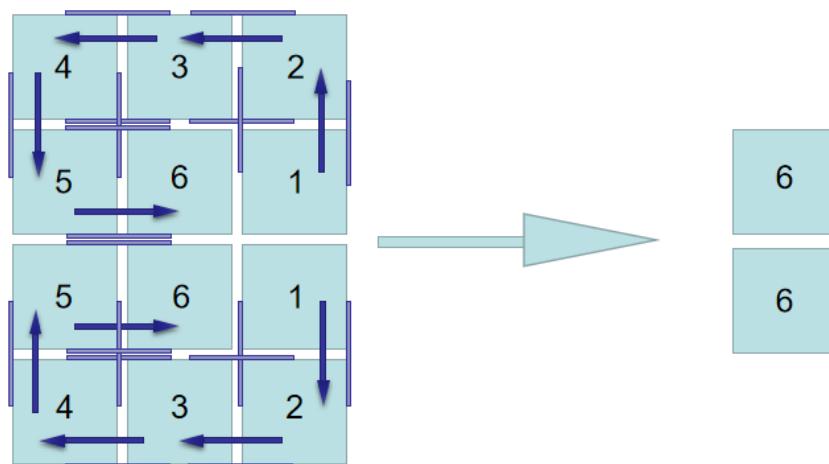
During the folding period, the first state of the basic element is that two identical deck panels are at the common thread, which keeps a negligible gap between each other, and the clamping angle  $u$  is equal to  $\pi$ . While the last state of folding period of the basic deck panel element is the moving deck panel is completely folded upon the other, and the clamping angle  $u$  is equal to  $6.11^\circ$  according to the prior computation. The exact data-driven relationship between the clamping angle and the exact position of the left side of connector on X-axis is shown as following diagram.



**Figure 6.** Location relationship based on figure 8.

### 3.2. Results of mechanism folding processions

The results of mechanism folding processions from the top view are shown in the following diagram. The whole deployable bridge deck is divided into 12 pieces, and the blue bar surrounding the deck panels are connectors that connect two identical panels and compose a basic element. The arrow pointing direction is the orientation that the deck panel folds up, while the number marked on the panels is the folding sequence. The shape of the fully-folded state of deployable bridge is as the right diagram of figure 7.



**Figure 7.** Result of mechanism configuration folding method.

## 4. Conclusions

According to the analysis of geometric position relationship analysis of the basic deck element, the paper is purposing to design a novel deploy approach of deployable bridge inspired by origami and kirigami theory. The design can efficiently complete the change from the fully-folded state to the deployed state, which will make it convenient for pedestrians and boat drivers. The design can also

be characterized by abundant replicability and reproducibility, which embodied in the size and material can be changed according to the specific situation. It also could be a kind of the beginning of retractable piers. However, the limitation of the origami-inspired deployable bridge is that it cannot be used in large-span or variable cross-section bridges for the reason of its special folding method. The impact on the kinematic relationship between the rotating angle and the position of two side tips of the connector has been discussed in the analysis part. Compared to the previous design of deployable bridges, the design characterizes a better expandability benefit from geometry of the connector design and folding method and ensures there are only two degrees of freedom on each basic element to make it possible to be folded up with a much simpler mechanism.

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