Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Self-forming pedestrian arch bridge based on bending-active concept

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Abstract

Bending active is commonly used to describe bent components whose geometric shapes are achieved through elastic deformation from initially straight or flat ones, such as rods, cables, and flexible membranes. Based on the bending-active concept, this paper proposes the design process, specific component details, and construction procedures of a pedestrian arch bridge. Initially, the development of bending-active structures is briefly reviewed, and a novel self- forming approach is introduced that the cross-sections of arch ribs can vary to correspond with the intended design shapes. Subsequently, this paper introduces the design scheme of the arch bridge, including its specific dimensions and components. Furthermore, the specific construction details of the arch ribs, joints, and base are presented. Finally, a detailed account of the construction process of the bridge is provided. All in all, the proposed self-forming pedestrian arch bridge offers several advantages: low transportation cost, short construction period, polished appearance, environment protecting and low maintenance requirements during service.

Keywords: bending-active, pedestrian arch bridge, self-forming, glass fiber-reinforced polymer (GFRP), construction process.

1. Introduction

The concept of bending-active is proposed by Frei Otto, a world-renowned German engineer. In 1962, he built Essen Pavilion with a span of 15 m, which is the first bending-active gridshell in the world. Then in 1976, Frei Otto designed the multi-purpose Mannheim Hall, whose span is four times than that of Essen, reaching about 60 m [1, 2]. With the development of computer technology and construction methods, the application of bending-active concept in civil engineering is increasing. Up to now, the more famous bending-active buildings include Downland Museum (England), Savill Garden (England), Accoya Gridshell (Australia), Airshell (Italy), etc. [3-7].

Since bending active requires large deformation during the forming process, materials need to have a high elastic limit to prevent damage during the bending process. Precisely for this reason, all the above buildings are mainly made of wood or steel with strong elasticity. In recent years, fiber-reinforced polymer (FRP) has been widely used due to its advantages of strong elasticity, high strength/weight ratio, as well as their outstanding fatigue performance and high corrosion resistance [8]. The ultimate rupture strain of FRP is around 1.5%–3%, making it suitable for large deformation [9, 10]. FRP has already been applied in some bending-active engineering applications, including Soliday Pavilion (France), SheltAir (Germany), Mobius Pavilion (China), etc. [11-13]. However, it is worth noting that FRP cannot be welded, which requires the continuity of FRP components at joints. Besides, joints are relatively difficult to deal with and usually need special design.

In addition to the above-mentioned gridshells made of wood, FRP or other materials, the bending-active concept can also be applied to other structures such as bridges (only three cases can be found up to now). First, Carlos Lázaro et al. constructed a UHPFRC pedestrian bridge with a span of 5.4 m by adopting the Paxton drainage construction designed by Joseph Paxton [14]. The bending of the bridge is achieved through pre-tensioning the steel cables below the deck [15]. Juan Bessini et al. bent GFRP straight rods into an arch shape in like manner by steel cables and three pairs of supports to form a 5 m long experimental pedestrian bridge [16]. In addition, Jean-François Caron et al. bent GFRP circular tubes through pre-stressed cables, and combined them with other components such as the bridge beam and deck to form a 4 m long (1/10 scaled model) pedestrian arch bridge [17].

Obviously, most of the existing bending-active structures are spatial latticed ones, and few cases of bridges through this concept have been currently constructed and analyzed, especially large-curvature arches. In this way, a bending-active pedestrian arch bridge has been designed to fill this gap in this paper. If the prefabricated construction method is adopted for arch bridges, the transportation cost for a whole bridge will be high due to the large size and complex shape of arch ribs. Therefore, the bending-active concept is introduced to solve this problem — the arch ribs in this bridge are formed by multiple GFRP rods after bending. According to the relative position of arch ribs and deck panel, arch bridges can be divided into upper, middle, and lower arch bridges, as shown in Figure 1, and the second form is adopted in this paper. Besides the bending-active concept, a self-forming concept is also employed in the design process of such bridge. The main idea is to correspond with the intended design shape by varying the cross-sections of arch ribs. For such pedestrian arch bridge, the cross-sections of arch ribs are designed (thick on both sides and thin in the middle) to make pedestrians pass smoothly through connecting components.

Conclusively, this paper extends the application scope of bending-active structures to large-curvature arch bridges. As an engineering demonstration of FRP materials and bending-active & self-forming concepts, the proposed arch bridge poses several advantages, including low transportation cost, short construction period, polished appearance, environment protecting, and low maintenance requirements during service, which can serve as a design reference for similar future engineering cases.

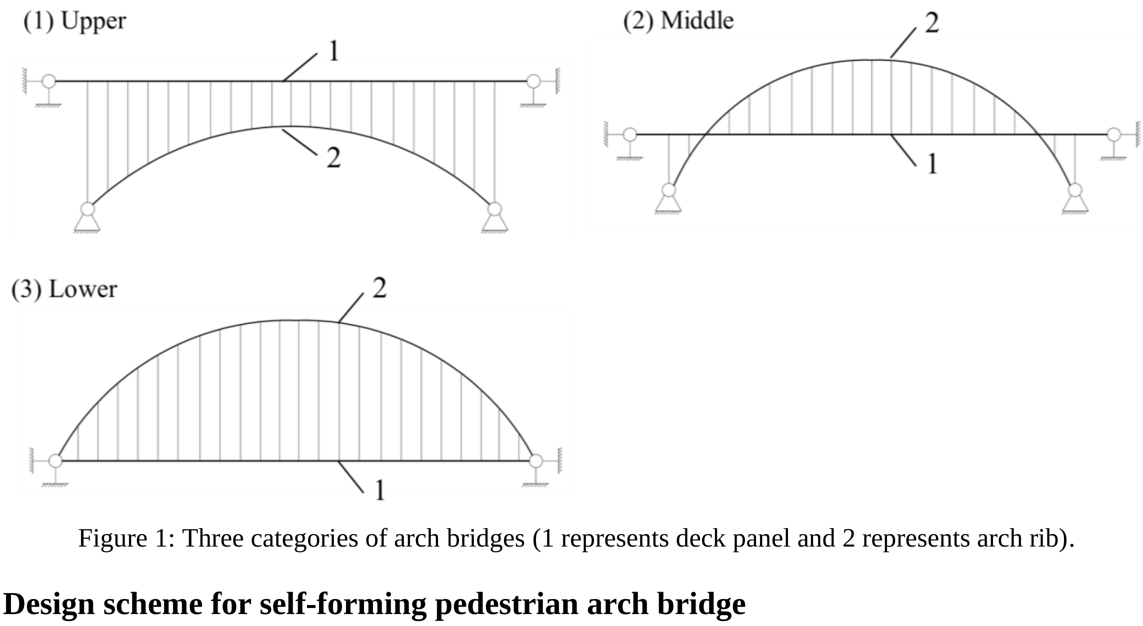


Figure 1: Three categories of arch bridges (1 represents deck panel and 2 represents arch rib).

2. Design scheme for self-forming pedestrian arch bridge

This section introduces the design scheme of the self-forming pedestrian arch bridge, as shown in Figure 2. The bridge was designed with a whole span length of 6800 mm, a width of 1800 mm, and a mid-span height of 3800 mm. The main structure of the arch bridge (arch rib) was divided into two pieces along the inner direction, and each piece was arranged with four slings. The length of the middle two slings was 3160 mm, and 2020 mm for the other two. The distance between the cables was 1637.5mm.

Each arch rib was composed of 16 glass fiber reinforced polymer (GFRP) components, with each component consisting of varying numbers of GFRP rods. The total length of the components was 11 m, with the thicker section composed of three rods (each 5 m long) and the thinner section composed of two rods (each 1 m long). The diameter of each rod was 16 mm. Both ends of the component were inserted into steel supports with a depth of 300 mm. The integration of the two arches was facilitated by four sets of GFRP connecting components (the blue part in Figure 2). Besides, there were four sets of under deck girders with a length of 1850 mm, positioned vertically in alignment with the suspension cables. The bridge deck was positioned 500 mm above the ground and laid on the girders mentioned above, with a length and a total width of 6550 mm and 1500 mm, respectively. The components that make up the bridge are described in detail in Section 3.

It is worth mentioning that the design process of the bridge introduced the concepts of bending-active and self-forming. On one hand, the GFRP rods that make up the arch ribs were thin and straight round rods, which were made by pultrusion process. These rods need to be bent and formed on the construction site under external forces and moments, which reflects the bending-active concept. The specific construction process is described in Section 4. On the other hand, the two sides of the arch rib were composed of 48 rods, and the middle part was composed of 32 rods, which leads to greater flexural stiffnesses and less deformations on both sides, embodying the self-forming concept. The structure of the arch rib ensured that left and right sides of the connecting components are high enough for pedestrians to pass through, and also offered enough stiffness to bear the bending moment and horizontal reaction (because the supports are not hinged).

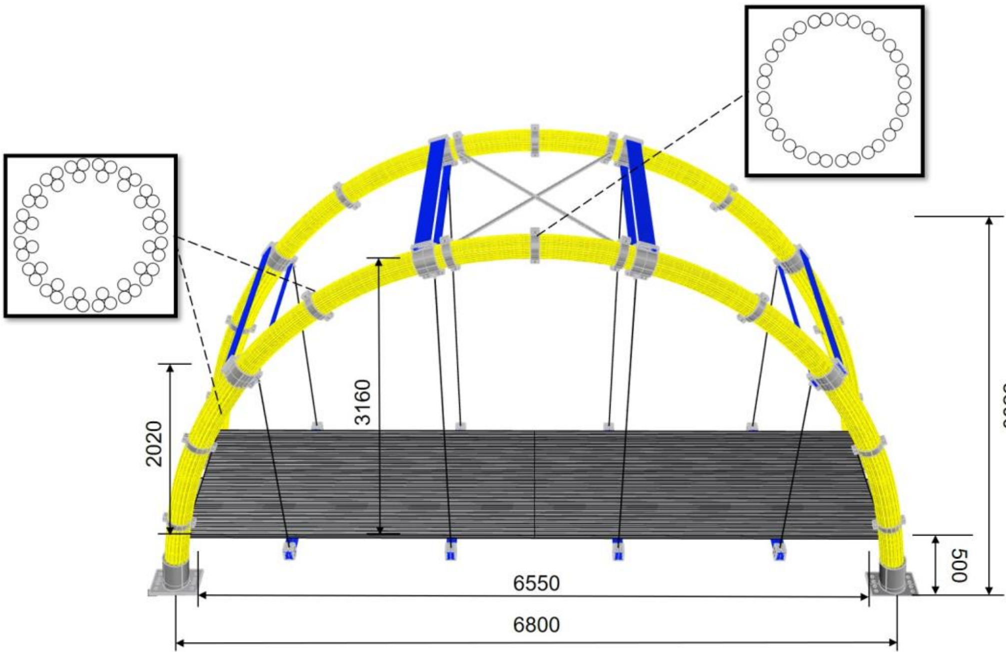


Figure 2: Design sketch of the self-forming arch bridge (with larger cross-sectional areas of arch ribs at both sides compared to the middle one).

3. Material selection and construction details for self-forming pedestrian arch bridge

3.1. Arch ribs and connecting components

The two arch ribs are made of GFRP with an axial tensile strength exceeding 300 MPa and tensile modulus exceeding 23 GPa. A bending test was carried out on a GFRP rod to observe the ductility and formability, by gradually reducing the distance between the endpoints of a GFRP rod with a diameter of 16 mm, as shown in Figure 3. When rods are bent to 100 times of the diameter (100d), crushing or tensile cracking were not observed on the inner and outer sides of the rods, which indicated the GFRP rods have adequate bending capability.

As mentioned before, the variable cross-section components were arranged in 16 sets of circular arrays around the center to form arch ribs with a radius of about 100 mm. Specifically, the components at the thicker cross-section were formed by three GFRP rods per set, while those at the thinner cross-sections consist of two rods per set, as illustrated in Figure 4. Carbon plate adhesive was applied to the inner walls of the joints to fix the components, and the remaining internal space is filled with 3D printed cores to prevent inward bending of components during loading. Connecting components were made of the same material as arch ribs, which comprised multiple 16 mm-diameter GFRP rods with a length of 1850 mm.

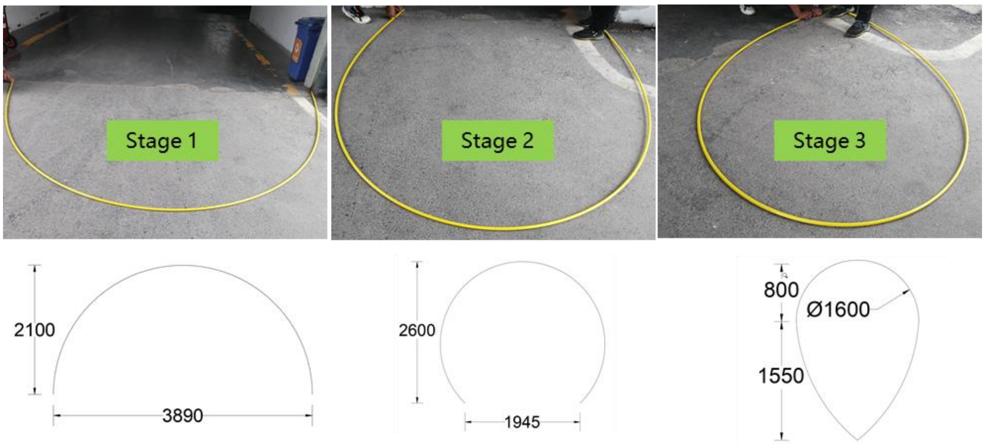


Figure 3: The bending test of a single GFRP rod.

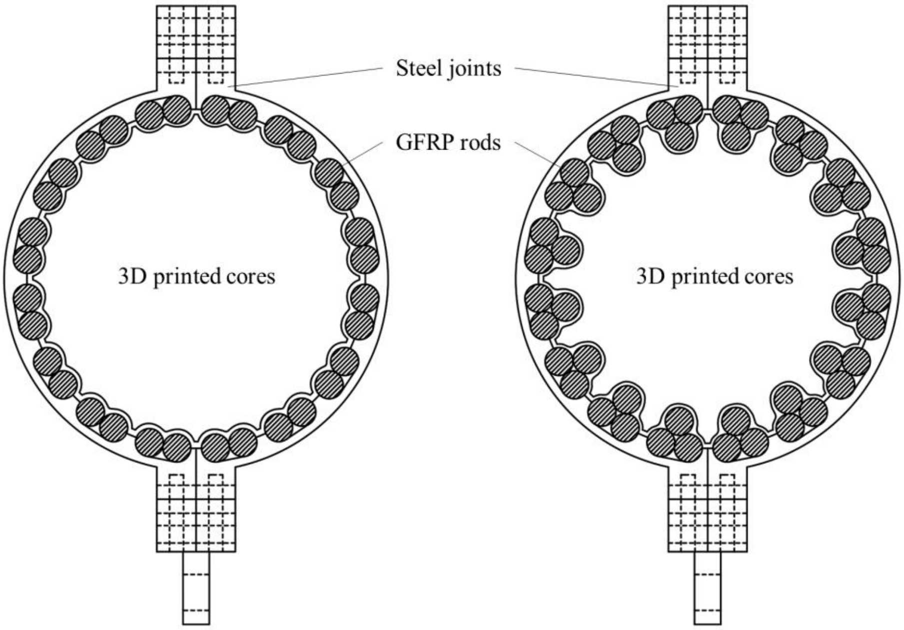
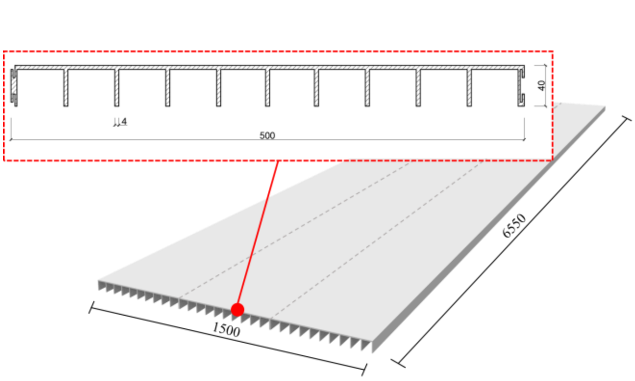


Figure 4: The diagram of arch ribs' cross-section form: thinner (left) and thicker (right) cross sections.

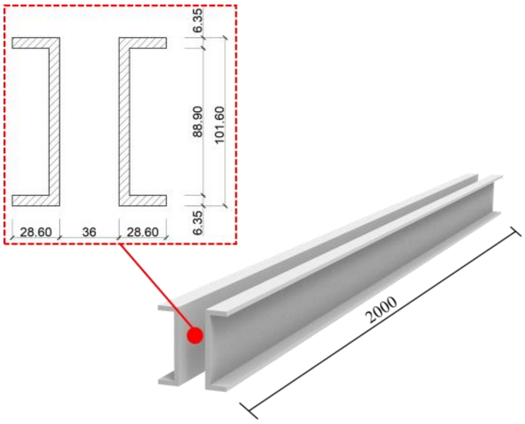
3.2. Deck panels and girders

The bridge deck panels and girders were both fabricated through GFRP pultrusion process. The dimension of the deck section was 1500×40×4 mm, consisting of three panels with a width of 500 mm each, as shown in Figure 5 (a). Those three pieces were jointed together by tenon-and-mortise joints at the edges in the construction site. Its longitudinal tensile strength and modulus exceeded 200 MPa and 17 GPa, respectively.

Figure 5 (b) shows the bridge girders channel sections, measuring 101.6×28.6×6.35 mm. Each group of girders comprised two channel beams, providing stiffness and strength equivalent to those of GFRP rods.



(a) The diagram of bridge deck panel.



(b) The diagram of bridge girder.

Figure 5: The cross-section shapes of bridge deck panel and girder.

3.3 Vertical cables

The tensile strength of carbon FRP (CFRP) cable used in this bridge exceeds 3000 MPa, with an elastic modulus of 170 GPa, whose tensile failure is primarily brittle. Figure 6 depicts the stress-strain relationship of such CFRP cable. The fracture elongation of CFRP cable can exceed 1.6%. Currently, research on anchoring systems for small-tonnage CFRP cable is relatively well-developed. The cable construction adopted for this arch bridge is depicted in Figure 7, which consists of CFRP cable, upper and lower rings, anchor system, screws, and regulating sleeve. Among them, the regulating sleeve can provide certain degree of flexibility to adjust the shape of the bridge.

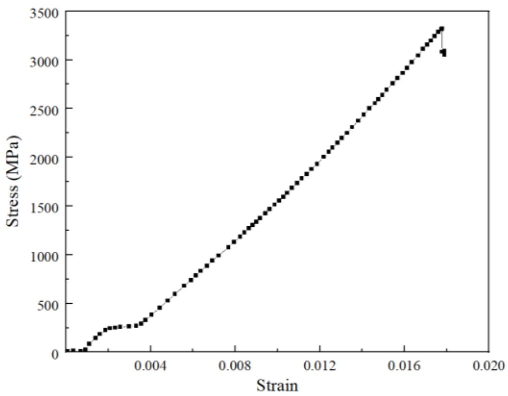


Figure 6: The cable's stress-strain relationship.

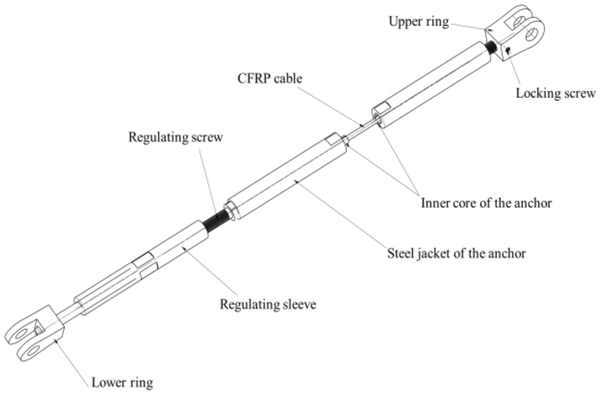


Figure 7: Construction details of CFRP cable.

3.4 Steel joints and supports

The pedestrian arch bridge comprises three types of joints and two types of supports, made of Q355 steel. Figure 8 depicts the distribution of joints and supporting conditions. Their specific constructions and functions are described as follows. Joint types 1 and 2 were mainly used to restrict the relative positions of the GFRP components in the arch ribs, while Joint type 3 was used to connect the deck girders and CFRP cables. A fixed support and a sliding support were utilized to fix the relative positions of the arch ribs and measure the horizontal forces of the bridge arch ribs.

The complex shapes of joints and supports were achieved through wire-electrode cutting. Figure 9 shows the on-site production process, which involved the following three steps: 1) Saw cutting: Steel (round bars or cubes) was cut into pieces according to the component sizes; 2) Preprocessing: The cut pieces were polished and finished to provide reference surfaces and longitudinal holes for inserting molybdenum wire; 3) Wire cutting: The pieces were then cut into the required components following planned paths.

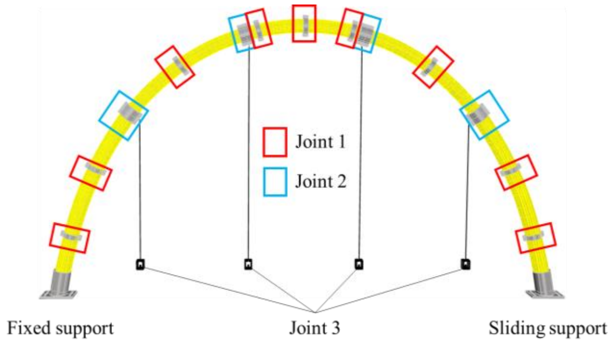


Figure 8: The locations of joints and supports.

Figure 9: The wire-electrode cutting process.

4. Specific construction process for self-forming pedestrian arch bridge

The self-forming pedestrian arch bridge utilized a bending-active construction method, allowing for the prefabrication and on-site assembly of all components within an estimated completion time of one week. The construction process is illustrated in Figure 10, and the specific details are elaborated as follows:

(1) **Fixing supports**: First, position four steel supports on the cement ground, with a lateral spacing of 1800 mm and a longitudinal spacing of 6800 mm. Then, secure the supports by driving expansion screws into the corresponding positions on the cement ground and inserting bolts into the holes. Finally, the heights of four supports can be measured by total station and adjusted by bolts, which should be at the same level.

(2) **Installing scaffolding**: Install scaffolding on both sides of the arch bridge to facilitate installation of arch ribs and mitigate the risk of lateral collapse during construction.

(3) **Assembling GFRP arch ribs**: Fix two 11 m long rods by nylon plastic ties, and then attach 5 m long rods at both ends of the assembled components to create sections with thinner middle and thicker ends. Repeat this process for a total of 32 components. Finally, insert the ends of the components into the corresponding holes of the supports. Note that 3D printed cores need to be placed inside the component bundles in advance.

- Assembling joint 1: Install joint 1 at the designated positions on the arch ribs one by one (from left to right). In this process, all components should be in correct orientation and position by fine-tuning the length of components inserted into the support.
- Assembling joint 2 & 3: Install joint 2 at the designated positions on the arch ribs to further stabilize the shape of the arch ribs, and attach it to a CFRP cable. Then, install joint 3 at the opposite end of the cable.
- Adhesive filling: Squeeze adhesive into gaps of all joints and supports to hold them in place.

(4) **Installing girders and deck panels:** Insert the GFRP channel beams sequentially into joint 3. Assemble the panel pieces together and place them on the girders for the bridge deck.

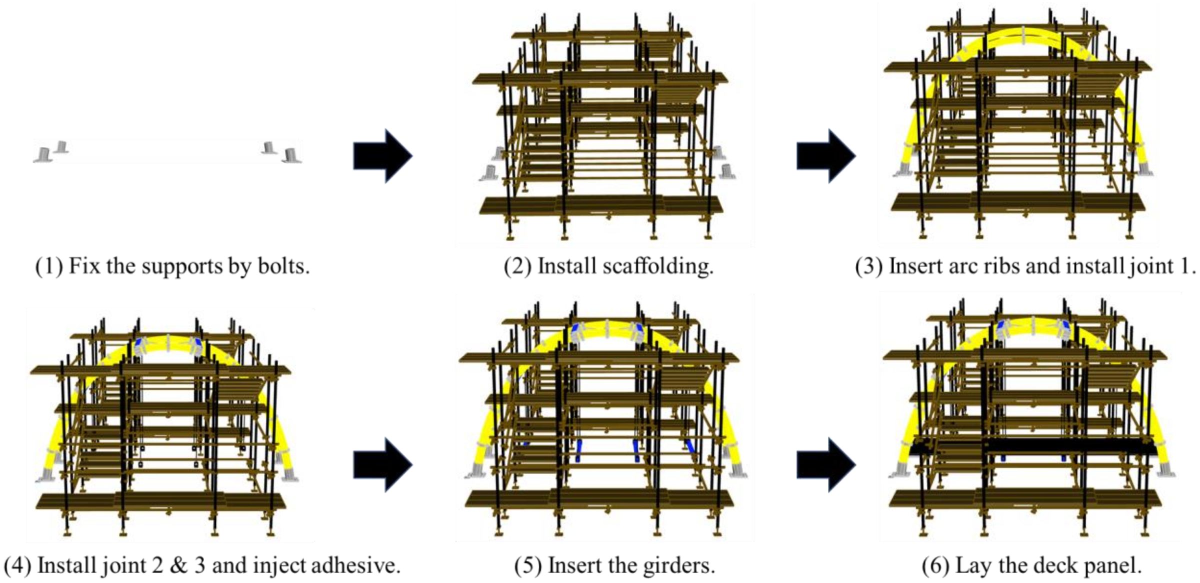


Figure 10: The entire construction process of the self-forming pedestrian arch bridge.

4. Conclusion

This paper presents a novel application of bending-active concept, showcasing a self-forming pedestrian arch bridge that utilizes FRP materials. The proposed arch bridge offers several advantages, including cost-effective transportation, a short construction period, a polished appearance, environmental sustainability, and low maintenance requirements during service. The key innovations can be summarized as follows:

(1) Efficient construction: The use of multiple bent GFRP rods in the arch ribs improves construction efficiency, reduces transportation difficulties and costs.

(2) Bending-active GFRP components: GFRP material used in the bending-active components enables large deformations, ensures a polished appearance, and requires minimal maintenance during service.

(3) Variable cross sections: Arch ribs with variable cross sections are realized achieved through the innovative construction of joints and supports. Strategically adjusting the flexural stiffness along the axis of the arch rib not only improves the bearing capacity of the structure, but also allows for shape adjustment of arch ribs, providing convenient passage for pedestrians.

Future research should aim to establish a finite element model to analyze the arch bridge's bearing capacity and stability. Additionally, conducting construction and mechanical testing of the bridge will provide valuable insights into its performance and behavior.

Acknowledgements

This research project has been supported by “CSCEC Technology R&D Program, CSCEC-2022-Z-8”.

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