

Research on the structural behavior of special-shaped arch bridges

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Abstract. With the social progress and the rapid development of people's economic level, people pay more and more attention to the external image of bridges, which greatly promotes the emergence and development of special-shaped arch bridges. But because of the particularity of the special-shaped arch bridge structure, its plane stress characteristics, which are different from the traditional arch bridge, become more complex. In this paper, three types of arch bridges commonly seen in special-shaped arch bridges: leaning type, inclined span type and butterfly type arch bridges are selected for a brief structural stress analysis. The results show that most of the arch structures of special-shaped arch bridges only play an auxiliary role in bearing loads, and due to the more complex stress, the finite element analysis software needs to be used to optimize the structure for many times to reach a relatively reasonable range. In addition, some arch structures are used more for aesthetic purposes than to bear loads, and their mechanical performance is basically zero.

Keywords: special-shaped arch, bridge engineering, structure analysis, stress characteristics, arch structure.

1. Introduction

At present, with the improvement of people's pursuit of bridge aesthetics, bridge structures not only meet the most basic functional requirements of spanning, but also meet people's needs for the aesthetic effect of structural modeling. In recent years, the application and popularization of new materials and processes have provided convenient conditions for realizing this requirement [1,2]. The main alienation forms of these special-shaped arch bridges include the alienation of arch ribs, the alienation of suspender arrangement and the alienation of main beam structure [3].

The appearance of special-shaped arch bridges enriches the structural forms of arch bridges and better realizes the purpose of coordinating the bridge structure with the natural environment and social environment. However, due to the special shape of the arch structure, its mechanical characteristics are quite different from those of conventional arch bridges. In this paper, the development and research status of special-shaped arch bridges will be simply summarized. The mechanical characteristics or structural behavior of three main special-shaped arch bridges (leaning type, diagonal span type, butterfly type arch) are briefly analyzed. The results have a certain degree of engineering practical value, and provide a reference for the design of future special-shaped arch bridges.

2. Development of special-shaped arch bridge

With the development of structural calculation theory and construction technology, special-shaped arch bridges are produced to meet people's requirements for bridge landscape. They represent the process of structural alienation [4]. The early special-shaped arch bridge was Bacde Roda Bridge (Fig.1) designed by Spanish architect Santiago Calatrava in 1987 [5]. The total length of the bridge is 129m, which is a spatial stress system composed of the vertical main arch in the middle and the oblique auxiliary arches on both sides. The Danxi Bridge in Yiwu (2004, Fig.2) and the Yufeng Bridge in Kunshan (2005, Fig.3) built in recent years all refer to the design of the Bacde Roda Bridge, which is also known as the Diagonal arch bridge. The Daejeon World Expo Bridge (Fig.4), which was born in 1993, is another common type of special-shaped arch bridge - diagonal span arch bridge [6-8]. This bridge has a span of 70m, and part of the bridge deck is supported by slings connected to the two arches across the bridge diagonally. The Hulme Arch Bridge, built in 1997, and the Ponte Juscelino Kubitschek Bridge, built in 2002, are both similar to this bridge [9]. The special-shaped arch bridges with butterfly arch are few. The well-known Gateshead Millennium Bridge (Fig.6) and the Butterfly Bridge (Fig.7) belong to this category [10,11]. The arch ribs on both sides incline outward to support the bridge deck. In addition to the above types, there has special-shaped arch bridges of other structures, such as The Campo Volantin Foot bridge (Fig.8) [12].



Figure 1. The Bacde Roda Bridge.



Figure 2. The Danxi Bridge.



Figure 3. The Yufeng Bridge.



Figure 4. The Daejeon World Expo Bridge.



Figure 5. The Ponte Juscelino Kubitschek Bridge.



Figure 6. The Gateshead Millennium Bridge.



Figure 7. The Butterfly Bridge.



Figure 8. The Campo Volantin Footbridge.

The special-shaped arch bridge is different from the general arch bridge in the structural form and layout, mainly through the dissimilation of the shape or layout of arch ribs, main beams, slings and other structural components to achieve a stronger visual impact. However, it is also because of the complexity of the structure caused by structural alienation, which leads to construction difficulties and cost increases [2,13]. At present, most of the special-shaped arch bridges at home and abroad are pedestrian bridges, bicycle bridges or small span and small-scale vehicle bridges. Therefore, the research and design of bridge structures that can achieve the perfect combination of economy and aesthetics is one of the important topics in the current design of special-shaped arch bridges.

3. Research status of special-shaped arch bridge

In the process of structural alienation, there are more and more researches on special-shaped arch bridges, which are mainly concentrated in the following aspects. First is the design and optimization of arch axis. The design of the arch satisfies people's aesthetic pursuit of bridges and the coordination of natural and social environments, while ensuring the rationality of the stress on the arch axis. The second is structural stability. The stability of the arch is an important factor affecting the structural safety of the arch bridge [3,14]. The special-shaped arch structure will inevitably sacrifice some rationality under stress, leading to a reduction in structural stability. The third is the local stress of key parts. Abnormal arch structures often produce excessive local stress. Last are the construction methods and technology. The traditional construction technology may not be suitable for the construction of special-shaped arch structures, and new construction technology needs to be studied.

At present, the research on aesthetic value, design and construction technology of special-shaped arch bridges has made progress, but the research on whether the construction cost brought by structural alienation meets the economic conditions and the applicability of existing design theories and calculation methods in the alienation structure is rarely involved [4].

4. Structural stress characteristics of special-shaped arch bridge

The main structural feature of the arch bridge is to bear the load by pressing the arch ribs. However, in the alien arch bridge, the alienated arch structure becomes a typical spatial stress system, and the main beam and arch ribs of its structure are in a complex spatial stress state. The stress characteristics of the three typical special-shaped arch bridge will be briefly analyzed below.

4.1. Leaning type bridge (The Kunshan Yufeng Bridge)

The leaning arch bridge is a spatial stress system composed of two vertical main arches and two inclined arches, as shown in (Fig.9). The middle parallel arch rib is the main load-bearing structure, and the inclined arch and the main arch form a spatial stability system to ensure the stability of the structure. Among the built leaning arch bridges, there are mainly two structural forms: one is the thrust free system for the main arch, and the other is the thrust system for the inclined arch, which is suitable for areas with good geological conditions. Another type of structure is that the main arch and inclined arch adopt thrust free system, which is more suitable for soft soil foundation [15,16].

Because Kunshan area is a typical soft soil foundation, the main arch and inclined arch of Yufeng Bridge are thrust free systems. The bridge span is 110m, and the rise span ratio of the main arch ring is 1/5.5. The rise span ratio of the inclined arch in the arch ring plane is 1/5.4 (Fig.10), and the arch axis of the two arch rings adopts a quadratic parabola [17]. The main dead load and live load of Yufeng Bridge are mainly borne by the main girder. The inclined arch is longitudinally equipped with horizontal tie bars to overcome the horizontal thrust generated by its dead load and live load. The transverse horizontal force generated by the inclined arch is borne by the end beam. There are 13 transverse beams between the main arch and the inclined arch to ensure the stability of the whole structure. The vertical force of the superstructure of the main bridge is transferred to the foundation by the inclined arch pier column and the end beam pier. The out of plane component force generated by the dead weight of the inclined arch is balanced by the partial tension of the inclined arch sling, so as to reduce the out of plane bending force of the main arch and the inclined arch, and improve the stress condition of the whole structure. In the design of Kunshan Yufeng Bridge, the bridge deck is arranged at the centroid of the main tie beam, which greatly reduces the impact on the bridge deck caused by the bending of the main tie beam [17].



Figure 9. The leaning arch bridge's 3-dimensional model.

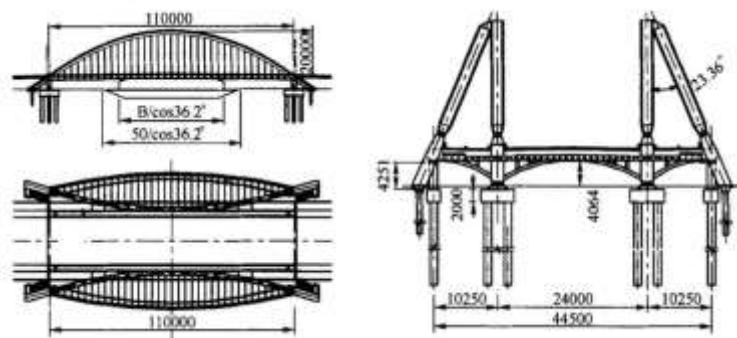


Figure 10. The general Layout of Yufeng Bridge.

4.2. Diagonal span arch bridge (The Hulme arch Bridge)

Diagonal span arch bridge adopts the spatial layout form of single arch rib crossing the main beam obliquely. The arch rib has asymmetry with respect to the longitudinal plane. The arch feet are located on both sides of the main beam, and the arch rib and the main beam are connected by slings (Fig.11). Based on the spatial location of the arch, the current layout of slings are mainly divided into three types (Fig.12): separated type, cross type and pair anchor type [18,19]. Due to the spatial arrangement of slings, the arch rib is subjected to both out of plane and in-plane actions, and the main beam will be subjected to bending moment, axial force and torque at the same time.

The Hulme arch bridge (Fig.13) in England is a typical diagonal span arch bridge [20]. The bridge deck is supported by 22 slings connected to an arch 25 meters high. The slings are arranged separately. The two cable planes are evenly anchored to the center line of the arch rib without crossing at the arch crown. Due to the asymmetric arrangement of slings, the main beam tends to rotate in the plane, and

the arch structure also suffers from a considerable out of plane asymmetric bending effect (Fig.14). The combined action of axial force and horizontal and vertical axis bending of the section forms axial stress in the arch section. These stresses need to be carried out around the curve of the arch crown and arch web, and this effect is resisted by the longitudinal stiffeners and diaphragms inside the arch [21].

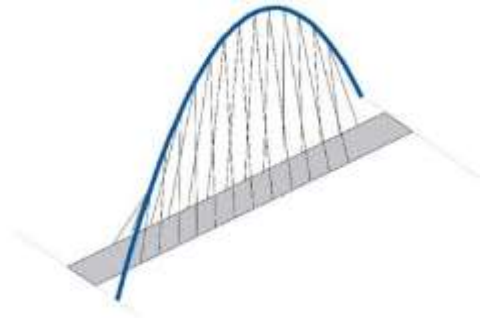


Figure 11. The diagonal span arch bridge's 3-dimensional model.

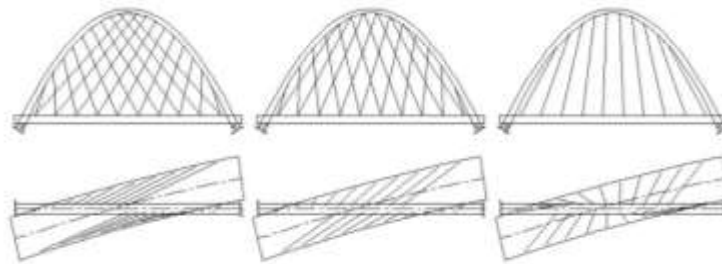


Figure 12. Three types of current layout of slings.



Figure 13. The Hulme arch bridge.

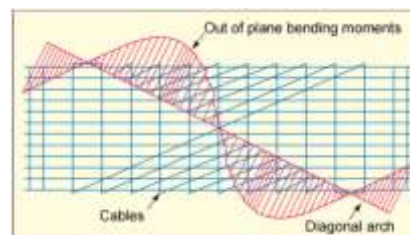


Figure 14. The bending effect diagram of arch.

4.3. Butterfly-shaped arch bridge (Nanning Bridge)

Butterfly arch bridges (Fig.15) usually adopt thrust free systems such as arch beam combination and tied arch. The arch ribs of the butterfly arch bridge incline outwards, making the suspenders not in the vertical plane. Therefore, the cables will generate forces in two directions, which will lead to inward displacement of the arch ribs. Compared with traditional parallel tied arch bridges, the transverse displacement of the arch ribs of butterfly arch bridges is more prominent. In addition, the out of plane stiffness of butterfly arch bridge is less than the in plane stiffness. The instability mode is shown as out of plane instability, and the problem of structural lateral stability is prominent [22,23].



Figure 15. The butterfly arch bridge's 3-dimensional model.

5. Conclusion

The special shape and good aesthetic effect of the special-shaped arch bridge will be favored by more bridge designers. However, the dissimilated arch structure design will also be accompanied by a more complex stress system. Up to now, most of the special-shaped arches have only played an auxiliary role in bearing loads. Although the designer can constantly optimize the structure with the help of parametric software, try to make the structure stress reasonable. However, the alienation of arch structure makes it impossible to avoid the problem of low utilization of some of its structures, which leads to some problems of rising costs that cannot be solved perfectly at this stage. Parametric analysis and research shall be carried out in combination with modern technology. Under the condition of achieving the design effect, the cost reduction method shall be found as far as possible, which may bring further development to the special-shaped arch bridge, so that it is not restricted to small urban bridges but can be used for larger bridge projects.

References

- [1] Li, Q. and Li, L. (2001) Analysis of the internal force of different-type arch bridge structure. *Highway traffic technology*, 18(1):31-35.
- [2] Chen, B.C. (2004) Technical Achievements and Prospect of Arch Bridge. In: *Proceedings of the Second National Highway Science and Technology Innovation High Level Forum (I)*. Beijing. pp. 121-125.
- [3] Lin, Y.Z. (China), 2016. Analysis on Force Characteristics and Construction Control of Different Arch Bridge. <https://d-wanfangdata-com-cn-s.era.lib.swjtu.edu.cn/thesis/Y3060049>
- [4] Wang, W.J. (China), 2011. Analysis of arch ring parameters and local stress of special-shaped arch bridge. <https://d-wanfangdata-com-cn-s.era.lib.swjtu.edu.cn/thesis/Y1955821>
- [5] Winstanley, T. (United Kingdom), 2011. AD Classics: Bac de Roda Bridge / Santiago Calatrava. <https://www.archdaily.com/151187/ad-classics-bac-de-roda-bridge-santiago-calatrava>
- [6] Lv, B. (China), 2018. Commemorating the 40th Anniversary of Reform and Opening up, Spring and Autumn Festival of Light and Shadow. <https://news.zgyww.cn/system/2018/12/16/010148888.shtml>
- [7] Laobaixiao Bridge Collection. (China), 2022. Kunshan Yufeng Bridge. <http://www.china-qiao.com/ql16/szql/szql486.htm>
- [8] Zhao, W.C. (China), 2010. Looking Back at the World Expo - Everything Begins at the World Expo. http://ztpd.nmgnews.com.cn/system/2010/04/08/010413260_02.shtml
- [9] Diewald, C. (Flickr), 2002. The Juscelino Kubitschek Bridge in Brasilia, Brazil. https://www.flickr.com/photos/chris_diewald/445373729?rb=1
- [10] Duncan, C. (Thousand Wonders), 2022. Gateshead Millennium Bridge. <https://www.thousandwonders.net/Gateshead+Millennium+Bridge>
- [11] Speed, S. (structurae.net), 2016. Butterfly Bridge. <https://structurae.net/de/medien/251599-butterfly-bridge>
- [12] Janberg, N. (structurae.net), 2016. Compo Volantin Footbridge. <https://structurae.net/en/media/262671-campo-volantin-footbridge>

- [13] Du, G.(China), 2010. Structural stability and dynamic performance analysis of special-shaped arch bridges. <https://d-wanfangdata-com-cn-s.era.lib.swjtu.edu.cn/thesis/Y1956345>
- [14] Li, C.Q. (2000) Structural stability and stable internal force. People's Communications Press, Beijing.
- [15] Hu, F.(China), 2006. Mechanical performance analysis of leaning arch bridge. <https://d-wanfangdata-com-cn-s.era.lib.swjtu.edu.cn/thesis/Y947021>
- [16] Xiao, R.C., Sun, H.T. (2004). Leaning arch bridge. Shanghai Highway. 4: 22-26.
- [17] Xiao, R.C., Sun, H.T. (2005). Design and Research of Kunshan Yufeng Bridge - the First Large Span Thrust free Inclined Arch Bridge. Journal of Civil Engineering. 38: 78-83.
- [18] Aguilar, J., Jesus. (2021) The Diagonal Arch Bridge, a Particular Case of Spatial Arch Bridges. Applied sciences. 11: 1-24.
- [19] Li, C., Zheng, K.F. (2020) Research Status and Prospect of Skew Span Arch Bridge. Chinese and foreign highways. 40: 182-186.
- [20] McDermott, P. (Geograph Britain and Ireland), 2018. Hulme Arch Bridge. <https://www.geograph.org.uk/photo/5963935>
- [21] Hussain, N., Wilson. (1999) The Hulme Arch Bridge, Manchester. In: Civil Engineers. pp.2-13.
- [22] Luo, H.L. (2016) Development survey and design parameter analysis of butterfly arch bridge. Fujian Architecture. 01: 1-24.
- [23] Hu, L.X.(China), 2015. Mechanical characteristics analysis of butterfly arch bridge with special-shaped steel-concrete composite structure. <https://d-wanfangdata-com-cn-s.era.lib.swjtu.edu.cn/thesis/D01032385>.