Scientific Research

Research on the Bridge Type Quadrant Diagram in Building Collaborative System Bridge Diagrams

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Abstract: To promote the development of collaborative system bridges, a bridge type quadrant diagram is utilized in this study to build and validate multiple existing collaborative system bridges. Through the bridge type quadrant diagram, various new types of collaborative system bridges with different structures are built. The research indicates that collaborative system bridges are complex structures based on five basic bridge types. Using the bridge type quadrant diagram, various structural types of collaborative system bridges can be arranged and combined. Considering the characteristics of collaborative system bridges, a specific collaborative system bridge scheme is proposed to address mid-span deflection issues in large-span beam bridges. The bridge type quadrant diagram can be used to develop a simple and efficient method for the design and research of collaborative system bridges in the future.

Keywords: the bridge type quadrant diagram; collaborative bridge; arrangement; combination; building

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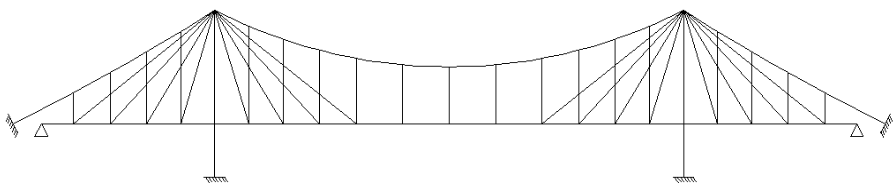
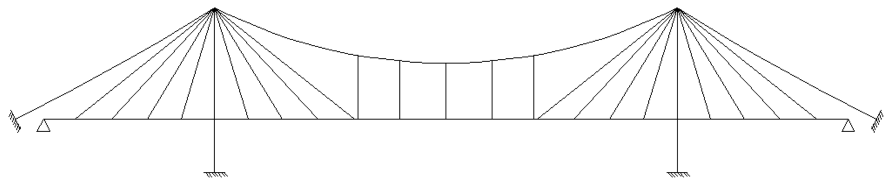
1 Introduction

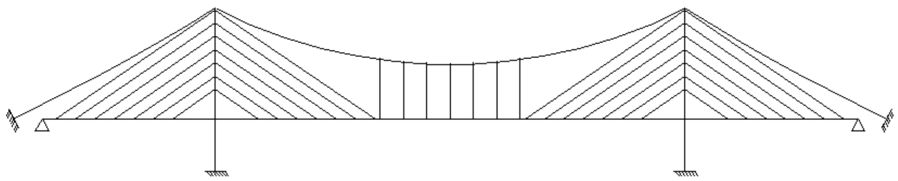
With the growing demand for developing China's transportation systems, the functional requirements for bridges have further increased. However, the development of basic bridge type structures is constrained by factors such as the materials used and the forces acting on the structure [1]. In comparison to basic bridge type structures, collaborative system bridges can use the force characteristics of various basic bridge type structures, collectively sharing the load. They exhibit significant advantages in aspects such as ultra-large-span bridges and optimized structural forces, making them more favorable in the field [2-4]. The stayed cable-suspension collaborative system bridge, due to its integration of the characteristics of the stayed cable bridge and suspension bridge, holds great potential in the development of ultra-large-span bridges. This approach has gained favor from bridge researchers worldwide, and various stayed cable-suspension systems have been proposed [5-7], as shown in Figure 1. In addition, various collaborative system bridges, such as stayed-cable-beam collaboration, are being constructed and developed in different parts of the world [8, 9].



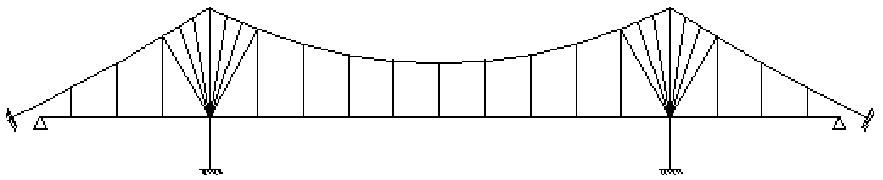
(a) Roebling system



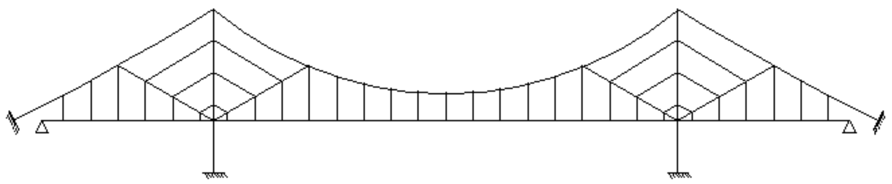
(b) Dischinger system



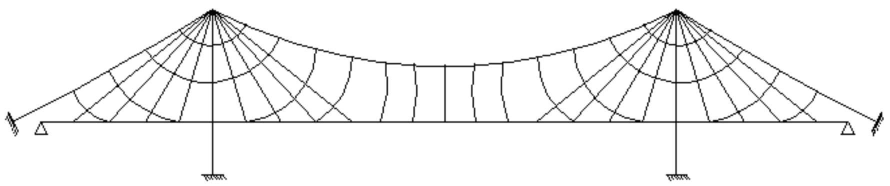
(c) The modified Dischinger system



(d) Steinman system



(e) Tung-yen Lin system



(f) Gimsing system

Figure 1 Diagrams of various types of stayed cable-suspension collaborative systems

Representative collaborative system bridges, both domestically and internationally, can be found in existing and ongoing projects, as shown in Figure 2. However, building collaborative system bridges that meet force transmission requirements and operationalization requires extensive knowledge of bridge theory and profound practical experience. This, to a certain extent, increases the difficulty of building collaborative system bridges. Currently, there is no unified and straightforward method or rule for building collaborative system bridges, greatly limiting their comprehensive development.

(a) Wujiang Bridge of the Zhanan line in Guizhou (stayed cable-suspension collaboration)

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(b) Xijiang Bridge of the Guangzhou-Zhuhai Railway (arch-rigid frame (beam) collaboration)

Figure 2 Collaborative system bridge cases in China

In the process of studying fundamental bridge types for many years, the author has summarized and proposed a simple diagram named the "the bridge type quadrant diagram" [10], as shown in Figure 3. As is well known, collaborative system bridges are complex structures based on fundamental bridge types, and they align with basic bridge types in a bridge type quadrant diagram. Therefore, the bridge type quadrant diagram is further used as a method for building and researching collaborative system bridges.

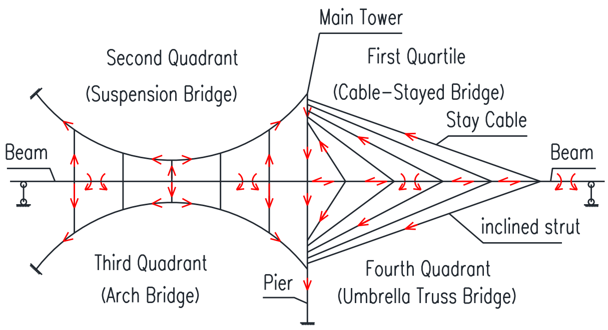


Figure 3 The bridge type quadrant diagram

2 Collaborative System Bridge Building Method Based on the Bridge Type Quadrant Diagram

2.1 The Bridge Type Quadrant Diagram: Definition and Characteristics

The bridge type quadrant diagram is a simple graphic representation with the beam of basic beam-type bridges as the horizontal axis and piers as the vertical axis. The basic bridge types, including cable-stayed bridges, suspension bridges, arch bridges, and umbrella truss bridges, are placed in the first to fourth quadrants, respectively, to study the simple relationships between basic bridge types.

The bridge type quadrant diagram is symmetrical: the basic bridge types in each quadrant are symmetric with respect to the horizontal beam and the vertical piers (towers). After symmetry about the horizontal beam, the basic bridge type changes; after symmetry about the vertical piers (towers), the basic bridge type remains unchanged, but this can increase the number of spans and improve the bridge's spanning capacity.

By applying simple operations such as translation, duplication, and rotation (within or outside the plane) to the basic bridge types and their components in each quadrant of the bridge type quadrant diagram, various existing collaborative system bridges, special structural bridges, and new collaborative system bridges can be built in a diverse and rich array of types.

2.2 Building of Existing Collaborative System Bridges

Using Figure 3, the various collaborative system bridges shown in Figure 2 can be easily built (limited by space, only one example is provided, and readers can build others following the approach outlined in this paper; the same applies throughout). The building process is illustrated in Figure 4.

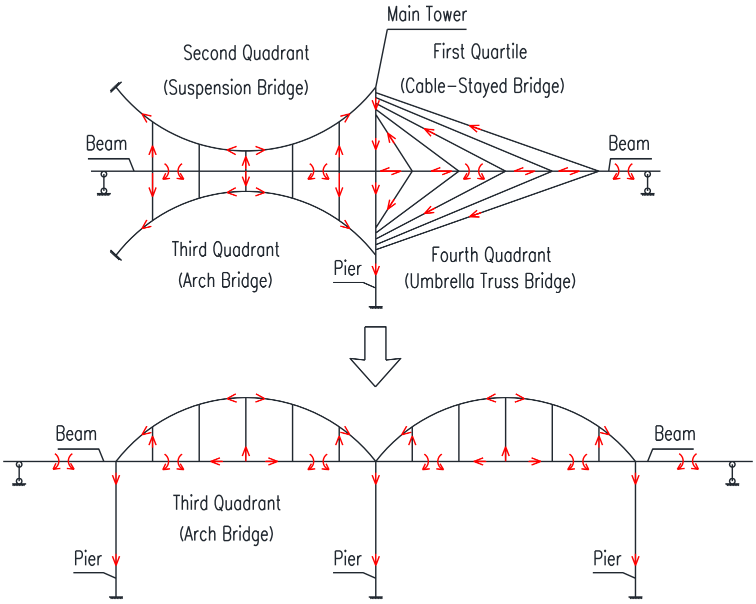


Figure 4 Xijiang Bridge of the Guangzhou-Zhuhai Railway (arch-beam collaboration)

The building process is as follows: Due to the collaboration of only arch and beam elements, the bridge type is an arch-beam collaborative system bridge. ① With the beam as the horizontal axis, cable-stayed bridges, suspension bridges, and umbrella truss bridges are deleted in the first, second, and fourth quadrants. Within the third quadrant, the arch bridge is vertically supported along the beam's horizontal axis, forming a sling cable (notably, the arrow direction needs to be changed after symmetry); ② the arch rib is translated in the third quadrant upward to intersect with the beam's horizontal axis at the arch foot, and the arch foot constraint is released; however, additional tension in the beam is required to maintain balance; ③ symmetrical along the vertical axis of the pier, a two-span T-shaped truss-cable arch collaborative system is formed; and ④ the axial lines of the beam is extended at both ends and symmetrically along the vertical axis of the pier to obtain the other two piers.

The bridge near the WWII bunker in Fronhoven, Belgium, has spans of 40+107+48 m. The bridge deck includes two 3.25 m long lanes and nonmotorized lanes on both sides, with a width of 18.45 m. The bridge design is novel and lightweight, featuring a rigid cable-stayed stayed cable-umbrella truss collaborative system bridge, as shown in Figure 5. It is also possible to rotate one of the collaborating bridges in the collaborative system in a planar manner to obtain an orthogonal spatial collaborative system bridge, such as the Zhoudaiyadong Bridge in Zhejiang Province, which has a main span of 2×65 m and a cross beam length of 50.8 m, as shown in Figure 6. Due to space limitations, readers can build their own bridges based on the bridge type quadrant diagram.

Figure 5 Fronhoven Bridge (cable-stayed - umbrella truss collaboration), Belgium

Figure 6 Zhoudaiyadong Bridge (arch-beam collaboration), China

2.3 Buildings of Existing Special Structure Bridges

The actual bridge is shown in Figure 7 after replacing the representative Dongkou Bridge in Shaoyang, Hunan Province, which has a length of 74 m, a designed span of 70 m, a rise span ratio of 1/9, and a bridge deck width of 4.5 m. Utilizing the symmetry in the bridge type quadrant diagram, starting with various arch bridges, a structural model for the Dongkou Bridge is built, as shown in Figure 8(c2), which is a superstructure-supported strut cable-stayed bridge.

Figure 7 Dongkou Bridge in Shaoyang, Hunan Province

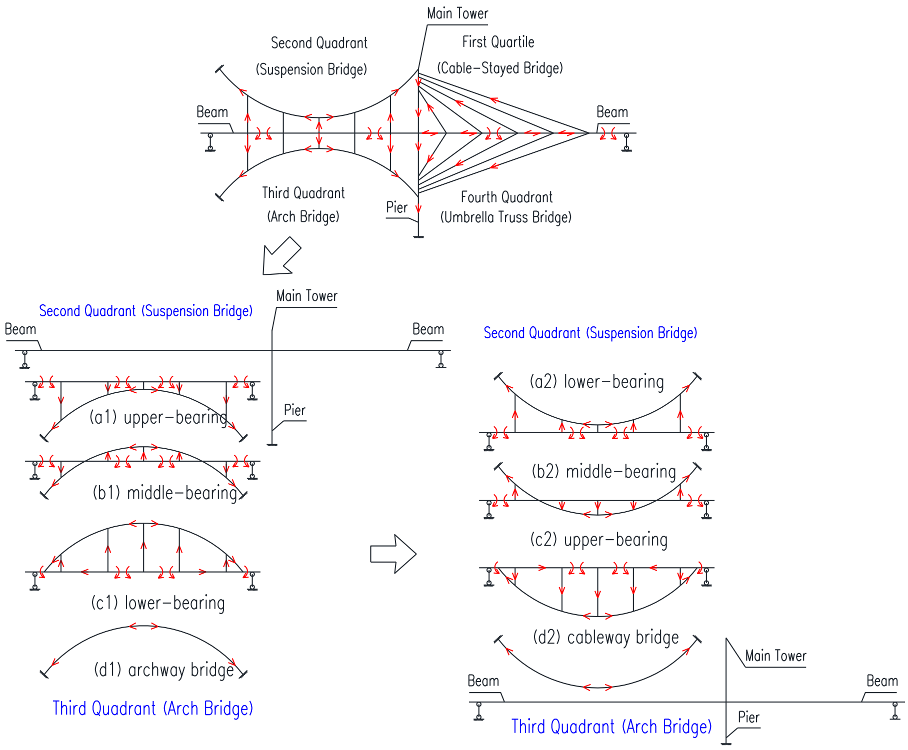


Figure 8 From various arch bridges to various types of suspension bridges

From the above, the bridge type quadrant diagram retains only the arch bridges in the third quadrant, excluding other bridge types from the residual quadrants. Following the building approach of the Xijiang Bridge (arch-rigid frame (beam) cooperation, see Figure 2(b) in this paper), one can utilize the upper-bearing arch bridges in the third quadrant of the bridge type quadrant diagram to build middle-bearing arch bridges, lower-bearing tied-arch bridges, and archway bridges (where the bridge deck and the arch form a single structure and pedestrians walk on the top surface of the arch). All the various arch bridges mentioned above are drawn in the third quadrant of the bridge type quadrant diagram, and by using the symmetry of the bridge type quadrant diagram, all the suspension bridge types in the second quadrant can be obtained. Figure 8 shows that due to symmetry, the upper bearing arch becomes a lower bearing suspension, which is the most widely used general suspension bridge. The lower bearing tie arch becomes an upper bearing strut suspension. Because the beam's horizontal axis is symmetric, the tie rod needs to become a strut rod. The above steps clearly reveal that the Dongkou Bridge is a rare upper-bearing strut suspension bridge, which is a special type of suspension bridge. By utilizing the symmetry of the bridge type quadrant diagram, various types of suspension bridge configurations can be obtained, as shown in Table 1, by combining arch bridge and suspension bridge configurations.

Table 1 Symmetric transformation table of all arch and suspension bridge types

Item	Symmetric bridge type transformation	
a	Upper-bearing arch bridge	General suspension bridge (lower-bearing)
b	(Thrust) Middle-bearing arch bridge	(Tension) Middle-bearing suspension bridge
	Self-anchored middle-bearing arch bridge	Self-anchored middle-bearing suspension bridge
c	Lower-bearing tied-arch bridge	Upper-bearing strut suspension bridge
d	Archway bridge	Cableway bridge

Note 1: In Table 1 item b, the (thrust) middle-bearing arch bridge and (tension) middle-bearing suspension bridge correspond to the illustrations in Item b) of Figure 8.

Note 2: In Table 1 item b, the self-anchored middle-bearing arch bridge (also known as the swallowtail arch bridge) and the self-anchored middle-bearing suspension bridge type are included; although there is no corresponding illustration in Item b) in Figure 8, the bridge can be built using the upper-bearing arch bridge from the third quadrant of the bridge type quadrant diagram through symmetry and translation.

The self-anchored middle-bearing suspension bridge in Table 1 is derived from the basic arch type in the third quadrant of the bridge type quadrant diagram through symmetry operation, and it is quite rare among suspension bridge types. The pedestrian bridge at Muchengtang Reservoir in Dalian city spans 62.4 m, the main cable sag height is 3.1 m, and the main beam is made of a steel truss. This bridge represents a more specific case of a self-anchored middle-bearing suspension bridge, as shown in Figure 9.

Figure 9 Pedestrian bridge at Muchengtang Reservoir

2.4 Building of New Collaborative System Bridges

By utilizing the bridge type quadrant diagram, it is possible to derive various collaborative system bridges, such as the currently nonexistent asymmetric triple collaborative system bridge and the novel stayed cable-stayed-arch-umbrella truss system bridge, as shown in Figure 10:

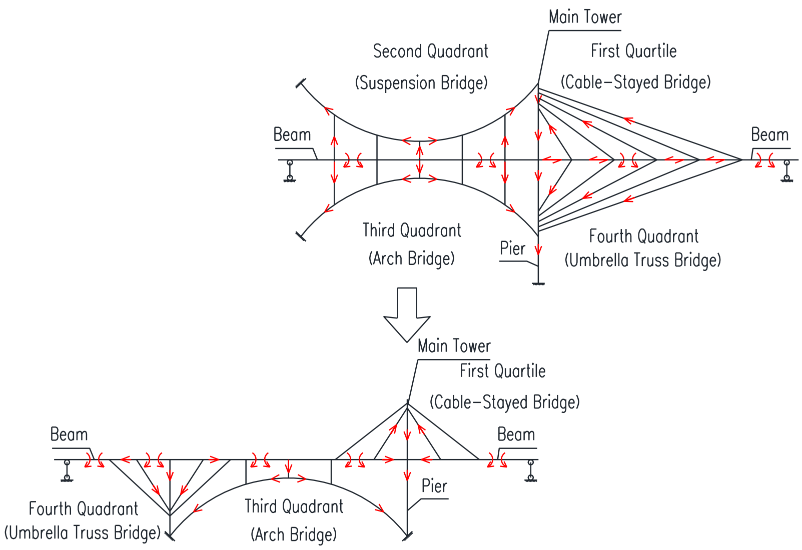


Figure 10 Asymmetric new stayed cable-stayed-arch-umbrella triple collaborative system

The building process of this bridge type is as follows: ① Delete the second quadrant of the cable-stayed bridge; move the fixed support at the bottom of the pier along the arch foot; ② remove the high strut near the arch foot in the third quadrant and the three outermost cables and struts in the first quadrant of the cable-stayed bridge and the fourth quadrant of the umbrella truss bridge; ③ symmetrically arrange the remaining stayed cables and struts along the pier (tower) vertical axis; ④ remove the single umbrella truss bridge at the pier symmetrically along the vertical axis of the arch bridge in the third quadrant; and ⑤ remove all the stayed struts at the pier.

Based on the derivation of collaborative bridge buildings using the bridge type quadrant diagram, the following conclusions can be drawn using the characteristics of the bridge type quadrant diagram:

(1) Although the bridge type quadrant diagram represents only the five basic bridge types, its characteristics, such as symmetry and translation, can be utilized to construct complex collaborative bridge systems.

(2) The core of the building process for each collaborative bridge system is the different arrangements and combinations of the five basic bridge types as the foundation of the bridge type quadrant diagram.

(3) When building collaborative bridge systems, the five basic bridge types from the bridge type quadrant diagram can be treated as modular components that can be freely combined. Different combinations result in diverse and complex collaborative bridge systems.

(4) There are five basic bridge types, and they can be arranged and combined to create two collaborative and even more complex three, four, or five collaborative bridge systems. The variety of collaborative bridge systems formed by the five basic bridge types and their derived subtypes (such as the lower, middle, and upper-bearing arch bridge types derived from the basic arch bridge type) is extensive. In theory, the maximum number of collaborative bridge systems is five (beam, arch, cable-stayed, suspension, and umbrella truss).

(5) As shown in Table 1, arch bridges, suspension bridges, and beam bridges have multiple subtypes. Therefore, each subtype within each basic bridge type can

also be combined to form various types of collaborative bridge systems with different characteristics.

3 Bridge Reinforcement Design Based on the Bridge Type Quadrant Diagram

Analysis of the force and structural characteristics of the collaborative bridge system indicates three main directions for the development of collaborative bridge systems:

(1) Less common, complex, and aesthetically pleasing urban landmark bridges can be designed by using the various characteristics of collaborative bridge systems.

(2) Super-span bridges can be designed by taking advantage of the symmetrical and opposite force characteristics of different basic bridge types, as indicated by the bridge type quadrant diagram.

(3) Bridges suitable for special conditions, including bridges with large spans and small beam heights due to construction constraints, can be built. Second, specialized collaborative bridge systems for reinforcing bridges with large-span beam deflection at the midspan can be developed.

In the context of the application of bridge reinforcement among the abovementioned development directions, the following design considerations are proposed. Deflection issues are common in large-span beam bridges, and effective reinforcement solutions are currently lacking. Conventional methods such as adding external prestressing tendons inside the box have proven ineffective for mitigating midspan deflection in large-span bridges [11]. The bridge type quadrant diagram can be employed to design specialized collaborative bridge systems (Arch-beam cooperation system bridge, Suspension-beam cooperation system bridge, Arch-suspension-beam cooperation system bridge.) for reinforcing large-span beam bridges with midspan deflection issues, as illustrated in Figure 11.

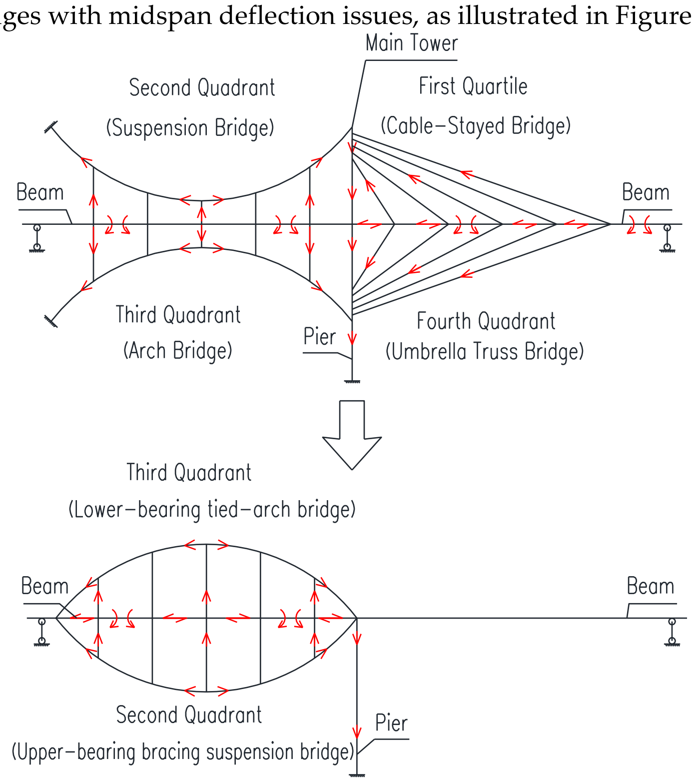


Figure 11 Specialized collaborative bridge for reinforcement

The characteristics of the specialized collaborative bridge for reinforcement are as follows:

(1) Except for the ends of the beam's horizontal axis, external supports are provided at the bottom of the pier along the vertical axis, and there are no external

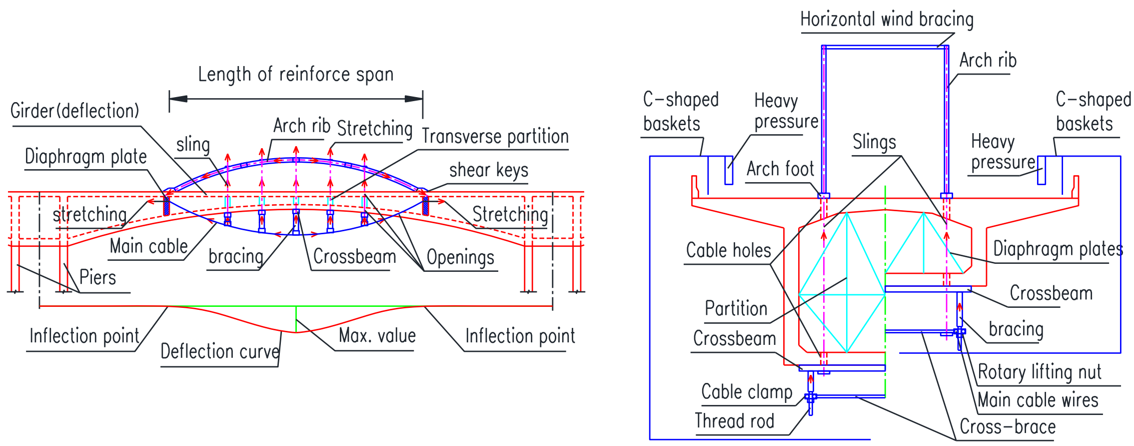
supports in the other quadrants, making it a self-anchored structure that meets the requirement of not having external support for the reinforcement scheme.

(2) A self-anchored collaborative bridge with the internal tensile and compressive forces of the horizontal axis beam offsetting each other is a collaborative bridge system of an arch (lower-bearing tied-arch bridge) and suspension (upper-bearing vertical bracing suspension bridge).

(3) In the collaborative bridge system of a lower-bearing tied-arch bridge and an upper-bearing vertical bracing suspension bridge, the internal force directions of the (arch) slings and the (main cable) vertical bracing struts are both vertically upward (completely coincident with the vertical direction of the beam's downward deflection, achieving the highest theoretical reinforcement efficiency) and orthogonal to the horizontal axis of the beam. Therefore, the arch-suspension collaborative system is an ideal solution for the optimal reinforcement of large-span beam bridges with mid-span deflection.

(4) When the space above the bridge deck is limited, only the upper-bearing suspension bridge scheme below the beam can be considered for reinforcement. When the bridge height is low and the clearance under the bridge is restricted, only the lower-bearing tied-arch bridge scheme above the bridge deck can be considered for reinforcement.

(5) When all conditions permit, a comprehensive reinforcement scheme using the arch-suspension collaborative system can be adopted. The reinforcement scheme is flexible and diverse. To reduce the self-weight of the reinforcement components, a steel structure is used for the compression components, and finished cable structures are used for the tension components, as shown in Figure 12.



a) Elevation plan of reinforcement scheme

b) Section diagram of reinforcement scheme

Figure 12 Schematic diagram of the specialized collaborative bridge for reinforcement

Arch-suspension collaborative reinforcement system bridge solution steps are as follows:

(1) The deflection curve of the bridge deck is measured and plotted along the longitudinal bridge direction, the inflection points of the curve are identified, and the reinforcement span of the reinforcement system, which should be greater than the distance between inflection points of the deflection curve, is determined.

(2) The number of traffic lanes should be reduced, or the width of lanes (limit speed) should be narrowed to add arch ribs on the bridge deck of the lower-bearing arch bridge.

(3) The top plate's below surface of box beam of the reinforcement bridge is used as the building position for the tension or compression member of the reinforcement system. When using the arch-suspension collaborative reinforce-

ment system, the tension and compression member forces cancel each other out, so there is no need to set tension or compression members.

(4) Since the arch foot at the bridge deck is under pressure and the compressive strength of the concrete structure of the box beam's top plate is high, there is no need to open holes in the top plate for the arch foot. Only shear keys should be set between the longitudinal and transverse prestressed reinforcement bars of the top plate, and transverse partitions should be added inside the box to continue transmitting arch foot pressure. At the bottom of the beam, the main cable is under tension, so small holes are needed in the bottom plate of the box beam for the passage of the main cable tendons. After installing solid transverse partitions inside the box, anchor and tension near the top plate of the box are applied. The remaining reinforcement components under the bridge can be built using C-shaped baskets hanging from the sides of the box beam bridge deck.

(5) A steel crossbeam can be installed at the bottom of the beam. Holes can be set on the box beam's top and bottom plates. The slings pass through those holes and anchor slings on the crossbeam at the bottom of the beam. The vertical bracing rods of the lower-bearing suspension bridge also support the bottom of the steel crossbeam.

(6) At the bottom horizontal position of the box beam bridge near the bottom of diaphragm plates, a set of main cables are arranged on each set of hangers, and multiple main cables are symmetrically arranged. By setting a vertical thread rod (passing through the cable clamp) on the main cable, adjusting the length of the vertical brace using the rotary lifting nut, so as to balance and coordinate the vertical bracing force at each location of the reinforced box beam bottom.

(7) By installing steel crossbeams at the bottom of the beam and pulling up the arch bridge slings on the bridge deck and the cable ends inside the box, the deflection mid-span beam can be lifted (using the bridge deck arch slings) and lowered (using the bottom suspension bridge vertical bracing rods), achieving the goal of reinforcing the mid-span sag.

The abovementioned reinforcement collaborative system can not only be used in old bridge reinforcement projects such as truss arch bridge and truss combined arch bridge (whose force is essentially a single cantilever height-variable truss beam + intermediate hole-hanging height-variable truss beam type; due to the truss beam being heightened and the lower chord being solidified, so it has the force of an arch as well), but also can be used in the new construction projects of larger-span beam bridges.

4 Conclusion

Through the application deduction of the bridge type quadrant diagram in complex collaborative system bridges, the following conclusions can be drawn:

(1) The bridge type quadrant diagram establishes an organic connection between the five fundamentally different bridge types, allowing a unified study of these basic bridge types. This provides a foundation for the building of complex collaborative system bridges.

(2) The bridge type quadrant diagram reveals that collaborative system bridges are based on five fundamental bridge types. Through simple symmetry, duplication, and various arrangements and combinations of the basic bridge types within the diagram, various complex collaborative system bridges and special structural bridges can be built.

(3) The bridge type quadrant diagram can provide solutions and theoretical support for special scenario bridges. This diagram facilitates the development of specialized collaborative system bridge reinforcement solutions, such as those for mitigating mid-span deflection in large-span beam bridges.

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(4) The bridge type quadrant diagram offers a simple and efficient method for building and studying collaborative system bridges.

Conflict of Interest: All authors disclosed no relevant relationships.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Yu, upon reasonable request.

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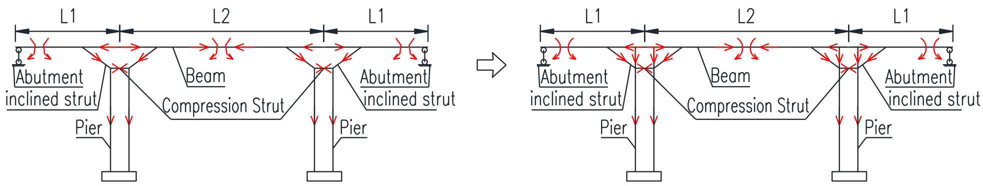
Clarification

This paper is an applied work based on the author's previously published paper titled "The Bridge Type Quadrant Diagram and New Basic Bridge Type: Umbrella Truss Bridge " (Yu, J. The Bridge Type Quadrant Diagram and New Basic Bridge Type: Umbrella Truss Bridge. *Prestress Technology* **2023**, *3*, 15-29. Doi: 10.59238/j.pt.2023.03.002). In the original paper, there was an error in Figure 7, depicting a double-armed thin-walled main pier umbrella arch bridge. The original illustration (left the arrow) and the corrected version (right the arrow) are presented in figure below (note the difference in the pier top positions between the two images). This clarification is provided to maintain consistency with the structural depiction in Figure 9 of that paper. For this, apologize to the editorial board and the readers.



The left figure is the original image, and the right figure is the modified schematic diagram