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Research on the Bridge Type Quadrant Diagram in Building Superlong-Span Bridges

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Abstract: With the increasing demand for global connectivity, research on superlong-span bridges has received increasing attention. This study revealed that the absence of internal forces and infinite structural stiffness are the basic conditions for building bridges with infinite spans. Based on this, three types of superlong-span collaborative bridge systems were built using the bridge type quadrant diagram and the characteristics of superlong-span bridges and specific measures to improve bridge stiffness were summarized. The bridge type quadrant diagram provides not only a simple approach for building structurally complex collaborative bridge systems but also a method for building superlong-span bridges. The results show the existence of three collaborative system bridges: the stayed cable-umbrella truss collaborative system bridge, the suspension-arch collaborative system bridge, and the stayed cable -suspension-arch- umbrella truss collaborative system bridge. Those collaborative system bridges meet the conditions of relatively ideal bridges and have the potential to become superlong-span bridges. The symmetry and force transmission paths of the bridge quadrant diagram reveal the construction characteristics of superlong-span bridges.

Keywords: ideal bridge; the bridge type quadrant diagram; relatively ideal bridge; superlong-span bridge

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1 Introduction

With the development of China's transportation industry, the demand for large-span bridges is constantly expanding, and the construction of large-span bridges is in full swing [1]. Among the five basic bridge types (beam bridge, cable-stayed bridge, suspension bridge, arch bridge, and umbrella truss bridge), only the main spans of cable-stayed bridges and suspension bridges have exceeded 1,000 m, and their spans are still increasing [2]. For example, the cable-stayed bridge of the Changtai Yangtze River Bridge under construction has a main span of 1,176 m, making it the cable-stayed bridge with the largest span in the world. The suspension bridge of the South Navigation Zhangjinggao Bridge under construction has a main span of 2,300 m, making it the bridge with the largest span in the world.

Compared with the bridge types in basic bridges, collaborative system bridges can improve the structural performance of bridges by cooperating internally with beam, stayed cable, suspension, arch, and umbrella truss, thereby significantly increasing the span of bridges. Collaborative system bridges are among the most promising options for superlong-span bridges (bridges with spans ≥ 3,000 m), but they also face a series of challenges, such as complex structural design and stress analysis [4, 5].

Among collaborative system bridges, the stayed cable-suspension collaborative system bridges are the strongest in terms of spanning ability. In the United States, the Brooklyn Bridge, completed in 1,883, was designed as a suspension bridge and later strengthened by stayed cables to form a stayed cable-suspension collaborative system bridge, with a main span of 486 m. The Third Bosphorus Bridge in Turkey, which was completed in 2016, has a main span of 1,408 m. In China, for example, the G210 Wujiang Bridge in Guizhou Province completed in 1997 was the world's first bridge designed and successfully implemented according to the stayed cable-suspension collaborative system bridges, with a main span of 288 m. The G3 Tongling Yangtze River Bridge (highway-railway combination bridge) and the Yonzhou Xihoumen Bridge (highway-railway combination bridge) under construction have main spans of 988 m and 1,488 m, respectively.

Certainly, the construction of large-span bridges needs to consider factors such as the local economy, transportation functions, and bridge safety [6,7]. Whether cable-stayed bridges or suspension bridges have the strongest spanning ability among the basic bridge types or stayed cable-suspension collaborative system bridges are theoretically more structurally optimal and have stronger spanning ability, the main spans of these bridges currently have not reached the standard of superlong-span bridges, and the gap between them is large. In the context of the increasing need for global connectivity and humanity's pursuit of the ultimate span of bridges, the demand for superlong-span strait bridges spanning wide seas is becoming increasingly urgent. For example, the possible main spans of the Messina Strait Bridge in Italy and the Gibraltar Strait Bridge connecting Europe and Africa are expected to exceed 3,000 m and 6,000 m, respectively, making them part of the category of superlong-span bridges. Currently, research on superlong-span bridges is limited and has focused mainly on special materials, structural stress, bridge wind resistance, and earthquake resistance applications [8-11]. There is a lack of research data on superlong-span bridges from the perspectives of basic bridge types, structural systems, and force transmission paths, and it is urgent to conduct research on bridge types with superlong-span potential to provide a theoretical basis for the selection of bridge types for superlong-span bridges.

2 Research Ideas

The bridge type quadrant diagram is based on five basic bridge types: beam bridge, cable-stayed bridge, suspension bridge, arch bridge, and umbrella truss bridge. The beam and pier of the basic beam bridge are used as the horizontal and vertical coordinate axes, respectively. According to the force transmission characteristics of the other four basic bridge types (cable-stayed bridge, suspension bridge, arch bridge, and umbrella truss bridge), the cable-stayed bridge, suspension bridge, arch bridge, and umbrella truss bridge are placed in the first to fourth quadrants of the plane, as shown in Figure 1. This diagram facilitates the study of the force characteristics of various bridge types and collaborative system bridges.

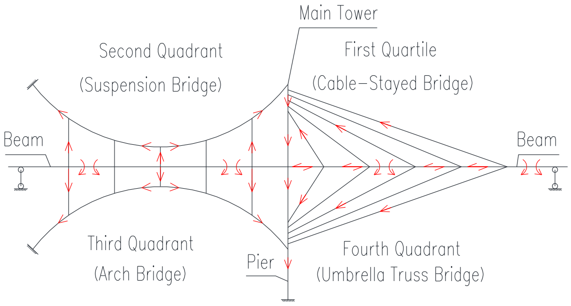

Figure 1 The bridge type quadrant diagram

This study first defines an ideal bridge structural system with an infinite span and then uses the bridge type quadrant diagram [12] as a research tool to explore the basic bridge types and collaborative system bridges that may become ideal bridges. Although under conventional conditions, an ideal bridge with an infinite span is impossible, relatively ideal bridges with extremely large spans that meet certain conditions can exist in practice. By studying the force characteristics of relatively ideal bridges, the aim is to identify the limiting conditions of superlong-span bridges and propose corresponding improvement measures.

3 Ideal Bridges under Special Conditions

Theoretically, a bridge with an infinite span is defined as an ideal bridge, which needs to meet two basic conditions: (1) the structural system has no internal forces; and (2) the total stiffness of the structural system is infinitely large. If a bridge structural system has no internal forces, then the structure is not stressed, and the span of such a bridge can be infinite. To control the deformation of the bridge structure, such a stress-free, infinitely large-span bridge also needs to have complete structural system stiffness. Therefore, the stiffness of the bridge needs to be infinitely large.

Figure 1 shows that the force transmission paths of the basic bridge types in the bridge type quadrant diagram all start from the horizontal axis beam and then transmit upward or downward along the other components of the bridge, finally ending at the external constraints (supports) of the bridge. If there are no internal forces in the bridge structural system, the source of the force transmission path is inside the beam, and there are no internal forces in the bridge members along the force transmission path. Thus, such a bridge has no force transmission path, and the span of a bridge with no force transmission path can be infinite.

The horizontal axis beam mainly bears its own weight, which is vertically downward. According to the above analysis, through the structural design of the beam, the self-weight of the beam can be made equal to the upward force it receives (such as buoyancy) everywhere to achieve the goal of no internal forces in the beam body, which is the source of the force transmission path in the structural system of the bridge mentioned above. When the beam body bears external loads such as cars, the beam body or its associated components can sink to achieve a new equilibrium.

All ancient and modern floating bridges (with boats or pontoons under the beam or with the beam and pontoons combined) are constructed using this force characteristic. The length and span of a floating bridge are not limited; only horizontal or stayed cables are required to fix the position of the floating bridge. Therefore, the bridge quadrant diagram reveals the simplest and most basic bridge type—the beam bridge—which has the potential to be an ideal bridge under special conditions (such as a floating bridge on water). The new SR-520 highway bridge in Washington State, USA, has a length of 2,350 m (Figure 2).

Figure 2 New SR-520 Highway Bridge, USA

4 Ideal Bridges under General Conditions

For basic bridge types other than beam bridges, whether they have the potential to be ideal bridges under general conditions (realistic conventional bridge construction conditions) requires further investigation. The requirement of no internal forces in the structural system of an ideal bridge can be achieved through the following two approaches:

In Approach 1, where the internal forces of all members within the entire bridge are zero, such a bridge is called an absolute ideal bridge. Obviously, it is difficult for such a bridge system without force transmission paths to exist in the real world because self-weights always exist without other external forces to counteract; therefore, force transmission paths must exist. Hence, a bridge without force transmission paths is meaningless.

In Approach 2, although the internal forces of all members within the entire bridge are not zero, if the internal substructures of the bridge's structural system are completely symmetrical and if the internal forces within symmetrical substructures are equal in magnitude and opposite in direction such that the sum of the internal forces of all substructures of the entire bridge is zero, then such a bridge is called a relatively ideal bridge.

Under general conditions, according to the requirements of ideal or relatively ideal bridge structural systems, the five individual basic bridge types (beam bridge, cable-stayed bridge, suspension bridge, arch bridge, and umbrella truss bridge) in Figure 1 can be initially excluded because these five basic bridge types all have obvious force transmission paths. The structural configurations within these basic bridge types along the longitudinal axis piers (towers) are symmetrical, but the internal forces of various components within the bridges are the same in magnitude and direction and cannot cancel each other out. Therefore, the sum of the structural internal forces of the entire bridge is not zero.

Utilizing the symmetry characteristics of the bridge type quadrant diagram, as shown in Figure 1, the force transmission paths of various basic bridge types are transmitted upward and downward along the horizontal beam and are symmetrical about the horizontal beam. If the bridge type quadrant diagram is regarded as an illustration of a collaborative system bridge, namely, the stayed cable-umbrella truss two collaborative system bridge, it can be seen that the force transmission paths between the cable-stayed bridge in the first quadrant and the umbrella truss bridge in the fourth quadrant are symmetrical about the horizontal beam and opposite in direction. If they are equal in magnitude, they can cancel each other out. Thus, although there are force transmission paths within the bridge, the internal forces between the substructures (the stayed cable substructure in the first quadrant and the umbrella truss substructure in the fourth quadrant) can cancel each other out, satisfying the conditions of a relatively ideal bridge, i.e., the sum of the structural internal forces of the entire bridge is zero.

Similarly, the suspension bridge in the second quadrant and the arch bridge in the third quadrant form a suspension-arch collaborative system bridge, and the cable-stayed bridge in the first quadrant, the suspension bridge in the second quadrant, the arch bridge in the third quadrant, and the umbrella truss in the fourth quadrant form a stayed cable-suspension-arch-umbrella truss collaborative system bridge. The substructures of these three collaborative system bridges are all symmetrical along the horizontal beam, with the internal forces of various components within the bridges being opposite in direction. If properly designed to make the internal forces of symmetric components equal in magnitude, the sum of the structural internal forces of the entire bridge becomes zero, satisfying the conditions of a relatively ideal bridge. Theoretically, infinite span bridges can be achieved using these three collaborative system bridges. When building bridges using these three collaborative system bridges, the sum of the stiffness of the entire collaborative system bridge is infinite (the stayed cable and suspension in the collaborative system bridge are generally flexible cable; if their cable forces are ignored, the stiffness is zero, while the arch and umbrella truss in the collaborative system bridge are under compression, generally using rigid structures such as concrete structures, steel structures, or steel–concrete composite structures, so the stiffness can approach infinity). Therefore, these three collaborative system bridges not only satisfy the condition that the sum of the internal forces of the structural system is zero but also satisfy the condition that the total stiffness of the relative structural system is infinite. Therefore, these three collaborative system bridges all have the potential to become ideal bridges.

When the bridge type quadrant diagram is viewed as a dedicated illustration of the collaborative system bridge, the three collaborative system bridges (stayed cable-umbrella truss, suspension-arch two collaborative system bridges, and stayed cable-suspension-arch-umbrella truss four collaborative system bridges) directly displayed by this illustration are all relatively ideal bridges, all with the potential to become ideal bridges. This is also a characteristic of the bridge type quadrant diagram in expressing collaborative system bridges.

5 Characteristics of Relatively Ideal Bridges

According to the bridge type quadrant diagram in Figure 1, among the above three collaborative system bridges, although the force transmission paths between the symmetric substructures along the beam transverse axis are opposite in direction and equal in magnitude and the internal forces between the substructures of the collaborative system bridge cancel each other out, bending moments and shear forces still exist within the beam transverse axis of these bridges. Only when the distance between the suspension point above the beam and the support point below the beam is infinitely small are the bending moments and shear forces within the beam transverse axis of the bridge both zero, making the beam transverse axis of the source of force transmission free from internal forces. Theoretically, these three collaborative system bridges can achieve infinitely large span bridges; hence, they can be regarded as superlong-span bridges. According to the bridge quadrant diagram, relatively ideal bridges have the following characteristics:

(1) The arch collaboration in the third quadrant of Figure 1 and the umbrella truss collaboration in the fourth quadrant consist of members that are all compression members. Only when special materials with extremely low density, high compressive strength, and high elastic modulus are developed can they accumulate internal forces at a rate and magnitude approximately equal to those of the cables in the stayed cable collaboration in the first quadrant and the suspension collaboration in the second quadrant during the process of force transmission, thus cancelling out the internal forces between the symmetric substructures along the beam horizontal axis and satisfying the requirement that the sum of the internal forces of the relative ideal bridge structural system be zero. Currently, such special materials have not yet been developed, which is also the reason why the above three collaborative system bridges are difficult to realize.

(2) Based on the current state of materials, the above three collaborative system bridges that meet the requirements of relatively ideal bridges degenerate into basic cable-stayed bridge, basic suspension bridge, and stayed cable-suspension collaboration system bridges. Before the appearance of the special materials mentioned above, only cable-stayed bridge, suspension bridge, and stayed cable-suspension collaboration system bridges have the potential to become superlong-span bridges.

(3) When constructing superlong-span cable-stayed bridge, suspension bridge, and stayed cable-suspension collaboration system bridges, efforts should be made to reduce the longitudinal distance between the cables to reduce the self-weight and internal forces of the beam, thereby increasing the span of the bridge.

(4) Due to the elimination of the arch collaborative system and the umbrella truss collaborative system with high stiffness in superlong-span cable-stayed bridge, suspension bridge, and stayed cable-suspension collaborative system bridges, the bridge stiffness sharply decreases, no longer meeting the condition that the total stiffness of an ideal bridge structure system be infinitely large. Therefore, when the spans of cable-stayed bridge, suspension bridge, and cable-stayed-suspension collaborative system bridges are too large, these three types of bridges may encounter the problems of insufficient stiffness and poor stability of the bridge structure system, requiring early corresponding research and solutions.

(5) By utilizing the characteristics of the internal forces in the substructures of collaborative system bridges, where the forces are equal in magnitude and opposite in direction and can offset each other, collaborative system bridges with special properties can be derived. In stayed cable-umbrella truss collaborative bridges, suspension-arch collaborative bridges, and stayed cable-suspension-arch-umbrella truss collaborative system bridges, the entire collaborative system bridges

can achieve self-balancing to theoretically optimize the structure of the collaborative system bridges. For instance, in the suspension-arch collaborative system bridge, by offsetting the tension in the main cable end of the suspension substructure with the thrust at the arch foot of the arch substructure, the anchorage and arch seat structures in this collaborative system bridge can be eliminated; similarly, in the stayed cable-suspension-arch-umbrella truss collaborative system bridge, by adjusting the states of each structure, even the axial force of the main beam can be balanced to zero.

In conclusion, the stayed cable-umbrella truss collaborative system bridge, suspension-arch collaborative system bridge, and stayed cable-suspension-arch-umbrella truss collaborative system bridge with super long-span potential derived from the quadrant diagram in Figure 1 ultimately degenerate into cable-stayed bridge, suspension bridge, and stayed cable-suspension collaborative system bridge, which are the only bridge types domestically and internationally that have realized large-span actual bridge structures. This is consistent with the conclusions derived from utilizing the bridge type quadrant diagram to study super long-span bridge types, proving that using the bridge type quadrant diagram to study super long-span bridge types is correct.

6 Classification and Stiffness Characteristics of Relatively Ideal Bridges

6.1 Classification of Relatively Ideal Bridges

The collaborative system bridge types that may become superlong-span bridges derived from the bridge type quadrant diagram can be divided into the following categories:

6.1.1 Relatively Ideal Standard Structural Bridges

According to Figure 1, for these three collaborative system bridges to meet the condition that the internal forces of the relative ideal bridge structure system are zero, it is necessary to have equal and opposite force transmission paths in the collaborative system substructures above and below the horizontal transverse beam. Under the premise of ignoring the accumulation of internal forces on the transmission path, this conclusion can only be valid when half of the gravity borne by the horizontal transverse beam is transmitted upward, and the other half is transmitted downward. When flexible substructures such as the stayed cables and suspension in the upper part of the transverse beam bear half of the self-weight of the transverse beam and the gravity stiffness resulting from internal forces is ignored, rigid substructures such as the arch and umbrella truss in the lower part of the transverse beam must bear not only the other half of the self-weight of the transverse beam but also the entire stiffness of the collaborative system bridge. In this way, the bridge type satisfies the conditions of a relatively ideal bridge structure and has the potential to become a superlong-span bridge. Figure 3 shows the relative ideal standard structural collaborative system bridge (the structure below the horizontal transverse beam is indicated by a downward arrow, representing compression). Comparing Figure 1 in this paper with Figure 3, Figure 3 shows the basic bridge types from Figure 1 in the four quadrants transformed into corresponding collaborative bridge substructures.

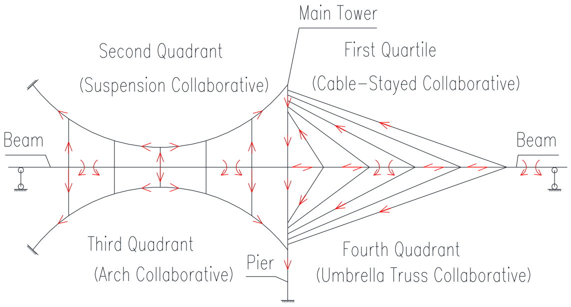

Figure 3 Relatively ideal standard structural collaborative system bridge

6.1.2 Relatively Ideal Rigid Structural Bridges:

In Figure 3, when the loads borne by the stayed cables and suspension collaborative substructures above the horizontal transverse beam in the bridge type quadrant diagram reach their entire self-weight, a collaborative system bridge is obtained where the arch and umbrella truss substructures below the horizontal transverse beam in the bridge type quadrant diagram only provide all stiffness of the entire collaborative system bridge, without bearing the weight of the transverse beam. That is, the arch and umbrella truss substructures are in a state of zero internal forces providing only the stiffness of the entire bridge, as shown in Figure 4 (note that the structure below the transverse beam has no arrow, indicating no internal forces).

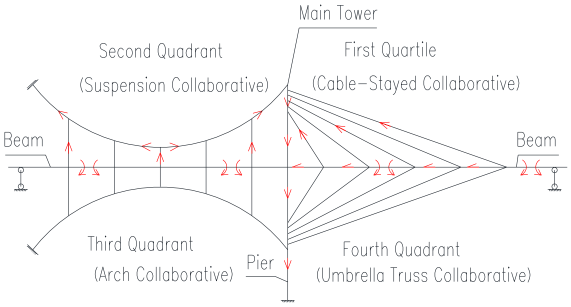

Figure 4 Relatively ideal rigid structural collaborative system bridge

In Figure 4, because the arch and umbrella truss collaborative substructures below the transverse beam only provide stiffness, they can be designed to be structurally simple and easy to construct, such as rigid piers and pillars that provide only stiffness constraints.

6.1.3 Relatively Ideal Flexible Structural Bridges

Continuing from above, by further increasing the load of the stayed cables and suspension structure located above the transverse beam in Figure 4, the arch and umbrella substructure below the transverse beam are transformed from a state of zero internal forces to a state of tension, as shown in Figure 5 (note that the structure below the transverse beam is represented by an upward arrow, indicating tension).

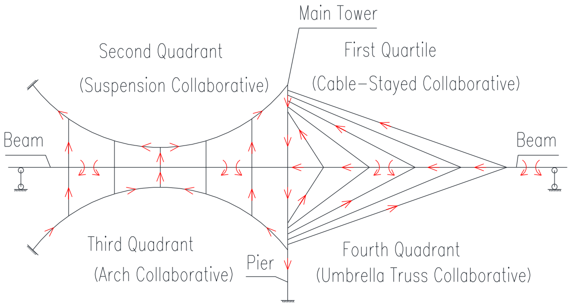

Figure 5 Relatively ideal flexible structural collaborative system bridge

Figure 5 shows that due to the tension in the arches and umbrella truss below the transverse beam, the tension in the stayed cable and suspension substructures above the transverse beam will be greater. In Figure 5, the stayed cable-umbrella truss and suspension-arch two collaborative system bridge and the stayed cable-suspension-arch-umbrella truss four collaborative system bridge can adjust the tension of the flexible cables above and below the transverse beam to coordinate the overall stiffness of the bridge to ensure the stability of the bridge's overall structure. Because the substructure below the transverse beam in Figure 5 is under tension, it is a flexible cable arch substructure or cable umbrella truss substructure, and the tension and structural stiffness are generated by the increased tension in the stayed cable and suspension structures above the transverse beam. If the stayed cable or suspension structure above the transverse beam is removed, the structural characteristics will change, and the stiffness cannot guarantee the stability of the structure itself. Therefore, such bridges cannot be called arch and umbrella truss collaborative system bridges but can only be called cable-arch suspension bridge, cable-umbrella cable-stayed bridge, or cable-arch-umbrella truss with stayed cable-suspension collaborative system bridge.

The Yimeng Mountain pedestrian cable-arch suspension bridge in Shandong Province is a representative of such bridges, with a main span of 420 m, as shown in Figure 6. The structure below the main beam in Figure 6 is made of steel wire ropes, a typical flexible structure. Through the above deduction, the stress characteristics of the Yimeng Mountain pedestrian cable-arch suspension bridge in Shandong Province and the origin of such bridges can be clearly derived theoretically. This also confirms the correctness of the above deduction and the guiding significance of this study on the bridge type recognition, bridge stress, and bridge force transmission paths of actual specific bridges.

Figure 6 Yimeng Mountain pedestrian suspension bridge in Shandong Province

6.2 Characteristics of Various Relatively Ideal Bridge Structures

According to the above analysis, the characteristics of various relatively ideal bridge structures are as follows:

6.2.1 Relatively Ideal Standard Structural Bridges

With the collaborative of the stayed cable-umbrella truss collaborative system bridge, the suspension-arch collaborative system bridge, and the stayed cable-suspension-arch-umbrella truss collaborative system bridge, these three collaborative system bridges have the potential for infinite spans. Special materials with extremely low density, high compressive strength, and high elastic modulus are needed to achieve this goal. Thus, such special materials are the key direction for the development of materials for superlong-span bridges in the future and indicate a research direction for materials for superlong-span bridges.

6.2.2 Relatively Ideal Rigid Structural Bridges

The arch and umbrella collaborative substructure located below the transverse beam (assuming that the self-weight of the components is neglected) are structures with no internal force and no need for force transmission paths. They only provide overall bridge stiffness, and their construction can be arbitrarily designed. Therefore, the collaborative system substructure below the transverse beam that only provides stiffness can be designed as rigid constraints adapted to bridge construction conditions, with simple structures such as rigid piers and columns, to optimize the structure, simplify force transmission, and facilitate construction.

6.2.3 Relatively Ideal Flexible Structural Bridges

(1) Since the substructures in this bridge structure are symmetric along the transverse beam and are all under tension (with different tension magnitudes), the bridge structure can maintain stability without relying on the gravity stiffness provided by the transverse beam (similar to spider webs in real life, where the weight of the web and the resulting gravity stiffness are negligible, but the web can remain stable in the air and can catch insects much heavier than the weight of the web itself). The main reason for this is that if there is tension in the cable structure, tension stiffness can be formed in the structure, which can keep the flexible cable structure stable. Thus, the concept of the tension stiffness of flexible cable structures, which is different from the gravity stiffness of flexible cable structures, is derived. In summary, the tension stiffness is another type of stiffness that is practical and can keep flexible cable structures stable.

(2) The tension stiffness can provide the required stiffness for bridge stability, and the structural tension stiffness is an actively adjustable stiffness. Tension is carried by flexible cables, which are cost-effective and economical, so they can be used to design superlong-span bridges.

(3) Flexible cable structures cannot rely only on the gravity stiffness formed by the self-weight of the structure to provide support and stability. Because gravity stiffness is a type of passive stiffness structure, the greater the amount of material used, the larger the mass, and the greater the gravity stiffness. Therefore, flexible cable structures that rely only on gravity stiffness are bulky, economically inefficient, and not very suitable for designing super-span bridges.

(4) The stayed cable-arch and stayed cable-umbrella truss located below the transverse beam mainly provide overall structural stiffness for the entire bridge, so they can flexibly adopt suitable and variable structural forms in combination with bridge site construction conditions.

(5) Figure 6 shows that several pairs of cable-stayed cables can be set at appropriate positions on the beam to replace the parallel cable-stayed cables and curved main cables below the beam, but it should be noted that for bridges with stayed cable-arch, stayed cable-umbrella truss and stayed cable-arch-umbrella truss system below the transverse beam, the tension in the cables will affect the overall structure of the bridge, so the specific structural form needs to be determined through calculations combined with the overall force situation of the bridge structure.

7 Conclusions

In-depth research on the bridge type quadrant diagram found that it can not only serve as a computational diagram for the study of collaborative system bridge types for superlong-span bridges but also provide theoretical guidance for specific research on superlong-span bridges (such as the development of special materials, overall structural stiffness and stability measures for bridge systems). This study theoretically deduces bridge types with superlong-span potentials and summarizes their characteristics to provide ideas and references for theoretical research on superlong-span 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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