Scientific Research

The Bridge Type Quadrant Diagram and New Basic Bridge Type: Umbrella Truss Bridge

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Abstract: The structural characteristics of four basic types of bridges, beam bridges, arch bridges, cable-stayed bridges, and suspension bridges, were summarized in this paper. A bridge type quadrant diagram was constructed using the orthogonality of beams and piers (towers) and the symmetry of bridge structures. Based on the bridge type quadrant diagram: It was proven that there are only five basic bridge types; The structure and mechanical characteristics of the fifth type of bridge, called the umbrella truss bridge, were summarized; The structural features of the umbrella truss bridge were analyzed and optimized, leading to the identification of a corresponding real bridge after optimization. The real bridge not only verified the authenticity of the fifth basic bridge structure derived from the bridge type quadrant diagram but also validated the bridge type quadrant diagram proposed in this study. The results of this study provide a valuable attempt and discussion for perfecting and guiding the research and development of theoretical bridges.

Keywords: Basic bridge type; symmetrical characteristic; the bridge type quadrant diagram; umbrella truss bridge; theoretical bridge

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1 Introduction

In the process of understanding and transforming nature, humans gradually mastered and utilized natural materials such as stone, wood, and vines, initially forming three basic bridge types: beam bridges (stone beam bridges, wood beam bridges), arch bridges (stone arch bridges, wood arch bridges), and suspension bridges (vine suspension bridges, grass rope bridges) [1,2]. With a deeper understanding of the structural characteristics of bridges and the use of artificial materials such as concrete, iron, and steel, the first modern cable-stayed bridge was constructed in Sweden in 1956 with a main span of 182.6 meters [3]. The internationally recognized basic bridge types have evolved from three to four: beam bridges, arch bridges, suspension bridges, and cable-stayed bridges.

Since the appearance of the fourth basic bridge type, the cable-stayed bridge, almost 70 years ago, there has been no further development in the number or theory of basic bridge types. Questions such as whether there are fifth, sixth, or higher basic bridge types, whether the types of basic bridge types are finite or infinite, whether there are inherent connections between seemingly disparate basic bridge types, and how to express these connections in a simple and intuitive way remain unresolved issues that urgently need to be addressed in further development and fundamental theoretical research on bridge types.

In-depth research on the forms of bridge structures has been conducted worldwide. The research has primarily been focused on breakthroughs in specific types of bridges or collaborative system structures in areas such as seismic resistance [4], span [5,6], and research on materials [7], and construction [8,9]. However, relatively less theoretical research has been conducted on the fundamental structural forms of bridges. The comprehensive exposition of bridge systems in "Design Concepts and Development of Modern Long-Span Bridges" [10] is one notable exception. In this work, the classification of bridges differs from the traditional bridge classification (four categories: beam bridges, arch bridges, cable-stayed bridges, and suspension bridges). The results are presented in tabular form. Additionally, the bridge types in the article are distinguished by the types of primary force structures in the upper and lower parts of the bridge, resulting in the derivation of nine bridge types. For example, two types of arch bridges are considered: center-supported arch bridges and underbraced tied arch bridges. According to the argument in the paper, these two bridge types are different. However, under traditional classification, both are classified as arch bridges.

2 Transmission Paths of Basic Bridge Types

To study basic bridge types, it is necessary to investigate the transmission paths and summarize the stress characteristics of these basic bridge types. Bridges are structures designed primarily to overcome various loads and effects while spanning obstacles. The structures of bridges must exhibit two main attributes: ① The ability to achieve the maximum span across obstacles, which is the primary attribute of the beam; and ② The ability to overcome the gravitational force of the structure itself, as well as the loads from vehicles and pedestrians on the bridge deck, which is the primary attribute of the piers, abutments, and towers.

The direction of gravitational force always points toward the center of the Earth and is vertically downward. As a result, lower structures, such as piers, abutments, or towers, are primarily subjected to compression and theoretically vertical with the shortest possible transmission path. On the other hand, upper structures, such as beams, need to resist bending and are theoretically horizontal to achieve the maximum spanning capability. Therefore, the lower structures (piers or towers) and upper structures (beams) of bridges exhibit orthogonal characteristics.

For the analysis of transmission paths, we selected four common types of basic bridges with two spans: beam bridges, arch bridges, suspension bridges, and cable-stayed bridges. Schematic diagrams of the transmission paths (indicated by arrows) for these basic bridge types are shown in Figure 1 (a: Beam Bridge, b: Arch Bridge, c: Suspension Bridge, d: Cable-Stayed Bridge). These simplified diagrams illustrate that the following:①In the simplified force transmission path diagrams of beam bridges, arch bridges, cable-stayed bridges, and suspension bridges, the bridge deck and piers (towers) are all vertically orthogonal. This illustrates the orthogonality characteristics between the lower piers (towers) and upper beams of the bridge structure. ② Each basic bridge type is composed of the main structural diagram, the main internal force types of the components, the main component force transmission paths, the control constraints, and the positions; these are referred to as the four elements of the basic bridge type.

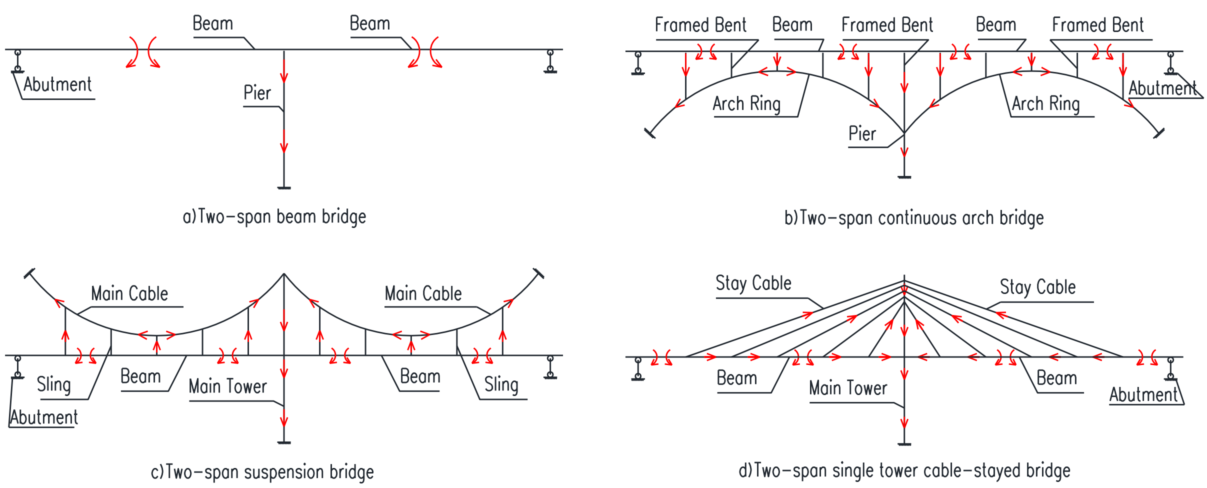

Figure 1 Schematic diagram of the force transmission paths of each basic bridge type

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3 Construction of the Bridge Type Quadrant Diagram

Comparing the simplified force transmission diagrams of the four basic bridge types in Figure 1 reveals that the two main components of the bridge exhibit a typical orthogonal pattern: the upper main structures (beams) are horizontal, while the lower main structures (piers or towers) are vertical. This conforms to the commonly used Cartesian coordinates. Therefore, Cartesian coordinates can be employed to study the various basic bridge types. Furthermore, as all four basic bridge types have horizontal beams and vertical piers (or towers), a connection between the four types can be established.

Analyzing the simplified force transmission diagrams of the four basic bridge types in Figure 1 reveals the following characteristics: ① All the basic bridge types in the figure have both beams and piers (or towers) in an orthogonal arrangement. ② Each basic bridge type in the figure is symmetric with respect to the vertical axis (in terms of structure, constraints, forces, and force transmission paths). Therefore, it is possible to study only half of the diagram without changing the nature of the bridge type. ③ Arch bridges are positioned below the bridge deck, while cable-stayed bridge structures are positioned above the bridge deck, and both are beam structures. ④ Cable-stayed bridges and suspension bridges are both located above the deck and are tower structures.

These four characteristics are completely consistent with the orthogonal coordinate system. In other words, in an orthogonal coordinate system, each quadrant has both horizontal and vertical axes, and adjacent quadrants share either the horizontal or vertical axis orthogonally. Therefore, the cable-stayed bridge, suspension bridge, and arch bridge can be placed in the corresponding quadrants of an orthogonal coordinate system, while the beam bridge serves as the coordinate axis for studying the relationships between various basic bridge types.

Based on the orthogonality between the beams and piers (towers) of bridges and the correspondence between the simplified force transmission paths and coordinate systems for each basic bridge type, a specialized diagram for studying basic bridge types is introduced. The main purpose of this diagram is to investigate the relationships between different basic bridge types and place them in the corresponding quadrants of a coordinate system for exploration. Therefore, this representation is named "the bridge type quadrant diagram".

The construction of the bridge type quadrant diagram for the four basic bridge types—the beam bridge, arch bridge, suspension bridge, and cable-stayed bridge—should adhere to the following principles:

(1) Among the four basic bridge types, the number of components varies, and the linearity of the components (including curves, slanted lines, and straight lines) can be complex. However, both the horizontal beam and the vertical pier (or tower) are shared by all four basic bridge types. To establish connections between the different basic bridge types, the shared and orthogonal beam and pier (or tower) should be used as the horizontal and vertical axes, respectively, in the bridge type quadrant diagram.

(2) Arch bridges, suspension bridges, and cable-stayed bridges should be placed within quadrants based on the characteristics of their respective force transmission diagrams and their relationships with beams and towers.

(3) Considering the characteristics of the force transmission paths and internal component relationships in arch bridges, which have the beam on top and other components below the beam, arch bridges should be placed only in the third or fourth quadrant under the orthogonal coordinate system. Similarly, suspension bridges and cable-stayed bridges, with the beam below and other

components above the beam, should be placed only in the first or second quadrant.

(4) Since the basic bridge type of the beam bridge serves as the horizontal axis, three other basic bridge types remain, and the orthogonal coordinate system has four quadrants, there seems to be an undiscovered fifth basic bridge type. Assuming this and considering that quadrants are conventionally arranged from smallest to largest, the undiscovered basic bridge type is placed in the fourth quadrant.

(5) Comparing the force transmission paths of basic bridge types for arch bridges and suspension bridges (see Figure 1) reveals that in the fundamental bridge type of arch bridges, the arch ring is curved, the struts are vertical, and the force is transmitted downward along the path. In contrast, for suspension bridges, the main cable is curved, the slings are vertical, and the force is transmitted upward along the path. Both types exhibit strict symmetry about the horizontal axis (beam). To facilitate the identification of relationships between basic bridge types, suspension bridges, which are symmetric about the horizontal axis, should be placed in the second quadrant above the horizontal axis.

(6) Based on points (3) and (5), with suspension bridges occupying the second quadrant, only the first quadrant remains above the horizontal axis. Therefore, cable-stayed bridges should be placed in the first quadrant.

(7) Considering the symmetry discovered in point (5) between the arch bridges and suspension bridges about the horizontal axis, to easily identify the relationships between basic bridge types, the arch ring and struts in the arch bridge basic type and the main cables and slings in the suspension bridge basic type must be strictly symmetrical about the horizontal axis.

The selection of the conventional two-span bridge structures corresponding to the four basic bridge types for constructing the bridge type quadrant diagram is based on three points: ① Conventionality: The chosen bridge structures should be conventional and have a certain representativeness. ② Representation of Piers (or Towers): The diagrams must include piers (or towers); hence, there should be at least two spans. A two-span configuration is both compliant with these requirements and simple, making it convenient for studying bridge quadrant diagrams and drawing conclusions. ③ Special, single-span, multispan, or multitower configurations of the same basic bridge types can be obtained by symmetrically, translationally replicating, rotating, or adding/deleting structural elements within the corresponding conventional two-span bridge structures. By following these principles, the selected conventional two-span bridge structures can effectively represent the essential characteristics of the four basic bridge types in the bridge type quadrant diagram.

The bridge structures corresponding to each basic bridge type, whether special, single-span, multispan, or multitower, can be unique or complex. However, relative to those of conventional two-span bridge structures, the four essential elements of the basic bridge types remain unchanged. Therefore, they should be regarded as the same basic bridge type and classified into the respective coordinate quadrants and axes of the bridge type quadrant diagram, representing the same type of bridge.

Following the principles and approach outlined for constructing the bridge type quadrant diagram, the author created the diagram below. Using the beam of the beam bridge in the basic bridge types as the horizontal axis and the pier (or tower) as the vertical axis, half of each basic bridge type from Figure 1 is placed in the first to third quadrants (Due to the symmetry with the vertical axis in each basic bridge type in Figure 1, the four essential elements of the basic bridge type in half of the structure remain unchanged. Therefore, taking half of the structure does not alter the fundamental nature of the bridge type, but it significantly simplifies the illustration for ease of study.). The new basic bridge type is placed in the fourth quadrant, yielding the bridge type quadrant diagram, as shown in Figure 2.

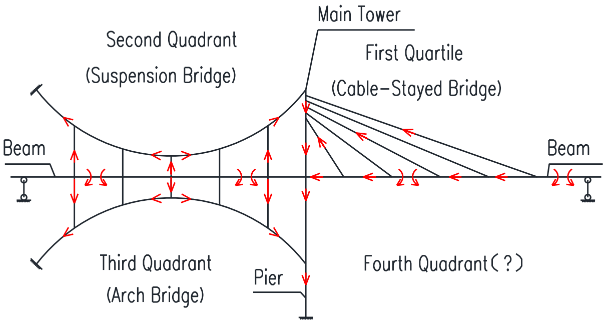

Figure 2 The bridge type quadrant diagram

4 Characteristics of the Bridge Type Quadrant Diagram

4.1 Three Characteristics of the Bridge Type Quadrant Diagram

As shown in Figure 2, the bridge type quadrant diagram exhibits three major characteristics: orthogonality, uniqueness, and symmetry.

4.1.1 Orthogonality

The horizontal beam and the vertical pier (tower) form a 90-degree orthogonal relationship, demonstrating orthogonality.

4.1.2 Uniqueness

Based on the load characteristics of the basic bridge types and their relative positions to the horizontal beam, each type of basic bridge has a unique corresponding quadrant or axis in the bridge type quadrant diagram, ensuring uniqueness.

4.1.3 Symmetry

The symmetry of the bridge quadrant diagram is expressed as follows:

(1) In quadrants one through three, if the vertical axis (pier/tower) is considered the axis of symmetry, Figure 1 holds. The transition from a single span to a double span can be observed, forming structurally equivalent multispan bridge configurations. With respect to the symmetry about the vertical axis (pier/tower), the bridge's span capability and length increase, but the basic bridge type remains unchanged.

(2) In the second quadrant, which represents suspension bridges; and the third quadrant, which represents arch bridges, the internal components strictly exhibit symmetry about the horizontal axis (beam); however, their internal force transmission paths are entirely opposite, creating tension or compression.

(3) Suspension bridges in the second quadrant and arch bridges in the third quadrant display macroscopic symmetry about the horizontal axis (beam), but they are two distinct basic bridge types. Regarding the symmetry about the horizontal axis (beam), the force transmission paths in the bridge change, changing the basic bridge type after symmetry.

4.2 Analysis of the Characteristics of the Bridge Type Quadrant Diagram

(1) Bridges possess two fundamental attributes: the ability to span obstacles and the capacity to overcome various loads or effects. Bridges constructed on Earth are primarily designed to overcome gravity (self-weight), with gravity acting vertically. In Figure 2, the vertical axis (main tower/pier) is parallel to gravity. Symmetry along an axis parallel to gravity merely alters the bridge's spanning

capability (resulting in a multi span bridge resembling a force structure model). However, the force characteristics of the internal components within the bridge remain unchanged, causing these bridges to be the same basic bridge type.

(2) The horizontal axis (beam) is perpendicular to gravity, and gravity always points downward toward the center of the Earth. When the direction of force transmission within the bridge's internal components aligns with gravity, the bridge components primarily experience compression; otherwise, they primarily experience tension. The basic bridge types are named based on the force characteristics of the main force-bearing components within the bridge (bending, tension, compression, etc.). Instead of the position or appearance of the components, symmetry about the horizontal axis (beam) results in the second quadrant (suspension bridge) and the third quadrant (arch bridge), which represent two distinct basic bridge types.

(3) As the axis lines of the main beam and the main pier (or tower) are either perpendicular or parallel to the gravitational line acting on the bridge, they precisely correspond to the horizontal and vertical axes in the quadrant coordinate system.

(4) Considering that the beam and pier constitute the most fundamental horizontal and vertical axes, respectively, in the bridge type quadrant diagram and are perpendicular or parallel to the gravitational line acting on the bridge, possessing stable structures, the beam bridge is the most fundamental and simple basic bridge type. Therefore, it should be considered one of the most fundamental bridge types.

5 Discussion on the Total Number of Basic Bridge Types

The bridge type quadrant diagram (Figure 2), which includes orthogonal vertical and horizontal axes, divides the plane into four quadrants, collectively forming the entire space. Therefore, there are only five basic bridge types (the beam bridge type along the coordinate axes + one basic bridge type in each of the four quadrants).

According to the traditional viewpoint, each bridge can be simplified into a force transmission diagram within the plane for force analysis, which uniquely corresponds to a basic bridge type in the quadrants or horizontal axis (beam bridge). The bridge type quadrant diagram shows that the beam bridge types with orthogonal characteristics on the horizontal and vertical axes, plus the types in the four quadrants, fill the entire space without any blank areas. Therefore, in theory, the total number of basic bridge types is only five (one vertical and horizontal axis + four quadrants).

6 Derivation of a New Basic Bridge Type—the Umbrella Truss Bridge

As illustrated in the bridge quadrant diagram in Figure 2, the fourth quadrant is blank. Based on the symmetry characteristics about the horizontal axis in the bridge type quadrant diagram, the force characteristics of the bridge types in the fourth quadrant can be deduced:

(1) The structural type and force pattern are opposite to those of the types in the first quadrant, which are the cable-stayed bridge types.

(2) Due to the symmetry about the horizontal axis, the force transmission paths of the bridge structures are reversed, leading to a change in force. Hence, this bridge represents a new basic bridge type.

This fundamental bridge type has not been discovered to date, and its force characteristics have not been fully elucidated. According to the bridge type quadrant diagram, utilizing the symmetry about the horizontal axis of the cable-stayed bridge's basic bridge type leads to the derivation of a new basic bridge type. The structural diagram and force transmission path after force application in the fourth quadrant are illustrated in Figure 3 (notably, the arrows on the horizontal axis beam represent opposing compression and tension arrows on the main beam; for simplicity, only half of the arrows are shown for corresponding purposes).

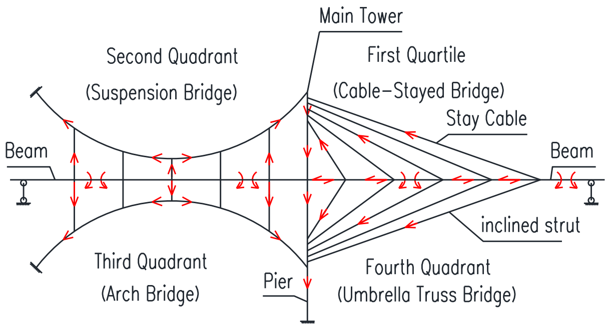

Figure 3 Umbrella truss bridge in the fourth quadrant

The structural diagram and force distribution in the new basic bridge type within the fourth quadrant of Figure 3 closely resemble the traditional Chinese umbrella shape, exhibiting a consistent force transmission path. Therefore, the new basic bridge type in the fourth quadrant is named the "Umbrella Truss Bridge," as depicted in Figure 4 (half of the bridge is shown).

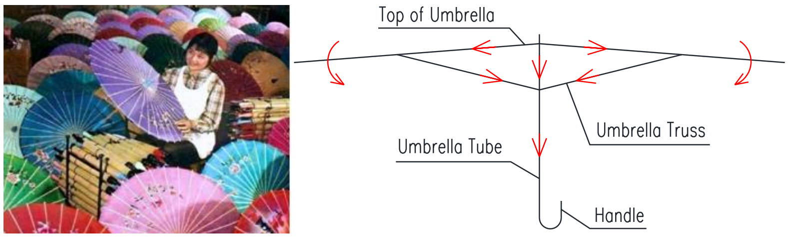

Figure 4 Traditional Chinese umbrella and structural force transmission path diagram

Analysis of the new basic bridge type in the fourth quadrant reveals several characteristics:

(1) There is no main tower above the bridge deck; only bridge piers are present. Due to the symmetry about the horizontal axis, the main tower on the bridge deck overlaps with the bridge piers, combining into a single pier.

(2) Corresponding to the inclined tension cables in the first quadrant of the cable-stayed bridge, the new basic bridge type in the fourth quadrant should have multiple unconnected inclined upward struts.

(3) The presence of inclined struts requires high piers to cross large spans.

(4) With lateral constraints from the inclined struts, the high pier has significant stiffness, eliminating overall stability concerns. Therefore, the dimensions of the pier column can be minimized.

(5) In terms of force, this bridge differs from that of the cable-stayed bridge in the first quadrant. The inclined struts primarily experience compression, forming an inclined bracing structure. Inclined struts must use materials with high compressive strength and stiffness, such as concrete, steel, or composite structures; otherwise, the overall stability of the structure will be compromised.

(6) Within the range of inclined struts, the main beam is primarily under tension, including bending.

(7) Due to the multiple pairs of inclined struts on the bottom of the beam, the length of the bending section at the main span midpoint is reduced, alleviating the mid-span sagging issue common in long-span beam bridges.
(8) For two-span single-pier and multispan multipier umbrella truss bridges, the local zone extending from the connection point of the beam and the maximum inclined strut to the bridge abutment is considered a bending beam structure. The force calculation and structural measures of the structure must be considered based on the beam structure.

7 Optimization of the Umbrella Truss Bridge Structure

Based on the fourth quadrant umbrella truss bridge in Figure 3and combined with the diagram in Figure 1, the force transmission path diagram for the conventional two-span single-pier umbrella-beam bridge after symmetry can be derived with respect to the vertical axis pier, as shown in Figure 5.

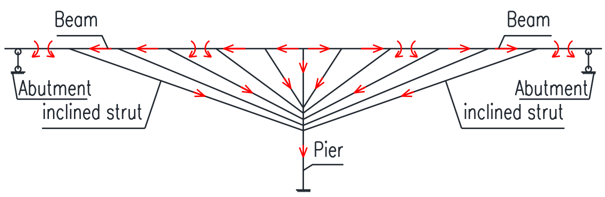

Figure 5 Schematic diagram of the force transmission path of the umbrella truss bridge

The conventional force transmission path diagram for a two-span basic bridge type is symmetric with respect to the vertical axis pier (or tower). Through operations such as symmetry, translation, duplication, rotation, addition, or deletion along the symmetry axis, single-span, multispan, or even more complex force transmission path diagrams can be generated. Consistent with other fundamental bridge types, similar operations on the conventional two-span single-pier umbrella truss bridge can also extend this type into single-span, multispan, or even more complex umbrella truss bridge configurations. These special, multispan, or multipier umbrella-beam bridge structures, although more unique or complex, have not exhibited changes in the four fundamental elements relative to the conventional two-span single-pier umbrella-beam bridge structure. Therefore, these trusses should be considered the same basic bridge type and classified into the fourth coordinate quadrant corresponding to the basic bridge type of the umbrella truss bridge.

Figure 5 shows that the conventional umbrella truss bridge has a complex structure, making construction challenging. It is necessary to optimize its construction, and the main optimizations include the following aspects:
(1) The main beams within the range of each diagonal brace are subjected primarily to tension-bending forces. To simplify construction, these main beam sections can be minimized in size and designed as constant or slightly variable height structures. If prestressed concrete is used, the prestress can be arranged in a straight formation, and a simple one-time casting construction process can be employed.
(2) The main beams, excluding the main beams between inclined struts, are bending structures. For small spans, constant-height beams can be used for ease of construction. For large spans, variable-height beams should be used to meet bending and shear resistance requirements [11].
(3) When the bridge is a multipier structure, for each pier top, excluding the main beam between the inclined struts, the main beams of the main span form bending compression or bending tension structures. This leads to hyperstatic secondary internal forces in the structure [12].
(4) To reduce the local stress concentration at the intersections of inclined struts with beams and piers, measures such as adding fillets at the connection points

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of inclined struts with beams and piers or increasing the beam and pier section thickness can be implemented for large-span umbrella-beam bridges.

(5) Due to the self-weight of the inclined struts, which are compression-bending structures, and the downward force of gravity, the inclined struts can be designed with a slight upward curve to minimize deformation.

(6) The main pier can be a single-column pier or a double-limb thin-walled pier. Given a double-limb thin-walled main pier, at each intersection of inclined struts with the main pier, horizontal tie beams need to be installed to cancel out the horizontal forces at the lower ends of each pair of inclined struts.

(7) Increasing the number of inclined struts leads to greater complexity in construction, force analysis, and structure construction at the nodes where the struts intersect with beams and piers. Therefore, efforts should be made to minimize the number of inclined struts in umbrella truss bridges. However, to ensure that the optimized bridge structure meets the four essential requirements of the basic bridge type, there should be no less than one pair of inclined struts on one main pier. Otherwise, the umbrella truss bridge may transform into another basic bridge type (beam bridge) due to changes in the main structural diagram (no inclined strut), primary internal force types (bending only, not tension or compression), or main components (between beam and inclined struts).

(8) Large-span umbrella truss bridges adapt well to higher main piers. Despite the overall height of the bridge piers, the free length is relatively small due to the constraints from inclined struts in the longitudinal direction. This yields higher stability safety factors for tall piers. Therefore, piers can be designed with higher standard numbers, and structural dimensions can be minimized.

(9) Inclined struts should be constructed with high compressive strength and stiffness. The pair of inclined struts near the top of each pier and the main beam have already formed a stable triangular structure. Therefore, the vertical part of the pier above the intersection point with the pair of inclined struts at the top of the pier can be eliminated to simplify pier-top construction, facilitate construction, reduce project volume, and reduce costs.

Based on the above optimization points, the simplest structure for an umbrella truss bridge is obtained: a three-span continuous umbrella truss bridge with two piers and a pair of inclined struts, as shown in Figure 6 (single-column main pier, optimized top of pier) and Figure 7 (double-limb thin-walled main pier, unoptimized pier top). The unoptimized single-column main pier and the optimized double-limb thin-walled main pier without an optimized pier top can be derived by readers based on the ideas presented in this paper.

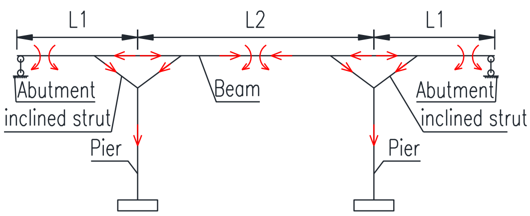

Figure 6 Single column main pier umbrella truss bridge

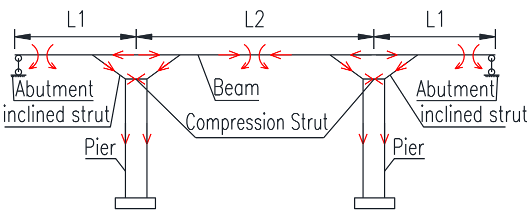

Figure 7 Double-limb thin-walled main pier umbrella truss bridge

8 Real Bridges of the Umbrella Truss Bridge

In this paper, based on traditional viewpoints, the bridge type quadrant diagram is established by using the four existing basic bridge types (beam bridges, arch bridges, cable-stayed bridges, and suspension bridges) as a foundation. Guided by the force transmission paths within the entire bridge structure, a quadrant diagram is constructed, and utilizing its symmetry, a new fifth class of basic bridge types—umbrella truss bridges—is deduced to exist in the fourth quadrant. Due to the complexity of the derived umbrella truss bridge structure and the associated construction difficulties, the structure is optimized. Two simplified forms of umbrella truss bridges are ultimately obtained, as shown in Figures 6 and 7.

To validate the accuracy of the bridge type quadrant diagram constructed in this paper and to confirm the authenticity of the newly derived umbrella truss bridge in the fourth quadrant, corresponding real bridges need to be found. Regardless of the bridge type, the simpler the structure is, the easier the bridge is to design and construct, making it more practically feasible and likely to be built as a real bridge. This is intuitive. Following this logic, the author, based on Figures 6 and 7, collected information on existing real bridges worldwide, identifying two simplified forms of umbrella truss bridges corresponding to the two simplest bridge types, as shown in Figures 8 (maximum main span of 64 m, single-column main pier, optimized pier top) and 9 (maximum main span of 290 m, double-limb thin-walled main pier, unoptimized pier top).

Figure 8 Minho River Bridge, Spain

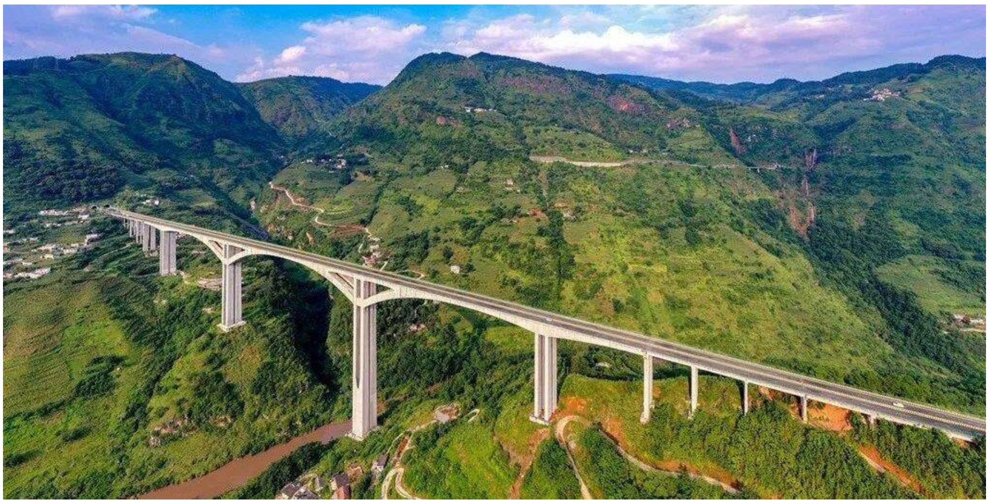

Figure 9 Guizhou Shuipan Expressway Beipanjiang Extra-large Bridge, China

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Analyzing these real bridges, the Minho River Bridge and Guizhou Beipanjiang Extra-large Bridge, shows that the bridge types of the two real bridges match the two simplest bridge types (see Figure 6 and Figure 7) derived from the fourth quadrant of the bridge type quadrant diagram. Additionally, the construction of the main force structure members in the upper and lower parts of the two real bridges aligns with the optimization points introduced in Section 7 of this article for the complex structure of conventional umbrella truss bridges. Therefore, the existence of two real bridges not only confirms the authenticity of the fifth class of fundamental bridge structures, the umbrella-beam bridge, derived from the bridge type quadrant diagram, but also demonstrates the correctness of the novel bridge type quadrant diagram constructed by the author.

9 Derivation of the Special Case of the Umbrella Truss Bridge

Furthermore, using the symmetry of the bridge type quadrant diagram, another special type of umbrella truss bridge can be derived from a specific type of cable-stayed bridge. Cable-stayed bridges include ground-anchored or tree-anchored cable-stayed bridges, such as the Sekayam River Bamboo Bridge in Indonesia. This type of cable-stayed bridge utilizes large trees along the riverbank or steep cliffs as the upper anchor point for the stay cables, with the lower end pulled up and anchored on the bridge deck, as shown in Figure 10.

Figure 10 Sekayam River Bamboo Cable-Stayed Bridge, Indonesia [13]

The structural force transmission path diagram of the Sekayam River Bamboo Cable-Stayed Bridge can be constructed using a quadrant diagram of the bridge type. The readers can follow steps such as moving the vertical axis and performing symmetrical operations about the vertical axis, modifying external constraints and changing the internal force direction of cables, or deleting redundant stay cables and replacing them with external constraints. The resulting diagram is shown in Figure 11, where for illustrative purposes, the multiple bamboo stayed cables on both banks have been removed, leaving only two. The external constraints at the beam ends are notable. In Figure 11, the external constraints at the beam ends do not restrict the horizontal direction, providing only vertical support.

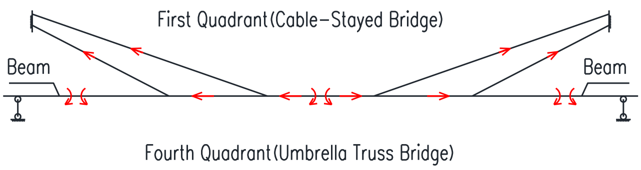

Figure 11 ForceDiagram of the Sekayam River Bamboo Cable-Stayed Bridge

Figure 11 shows that all the stay cables are in tension. Under the influence of the tensile force in the stay cables, the main beam within the range of the stay cables forms a tensile-bending structure, and the portions near the abutments are subjected only to bending. By utilizing the symmetry of the bridge type quadrant diagram and reflecting the special cable-stayed bridge in the first quadrant about the horizontal axis, a special type of umbrella truss bridge in the fourth quadrant with forces opposite to those in the special cable-stayed bridge can be derived, as illustrated in Figure 12.

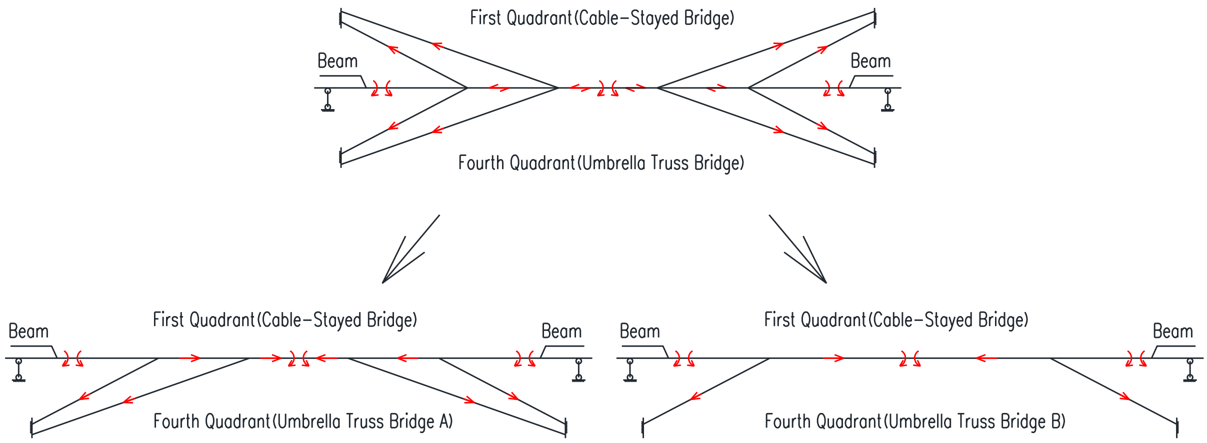

Figure 12 Force diagram of a special umbrella truss bridge

In Figure 12, the special cable-stayed bridge in the first quadrant is symmetrically reflected about the horizontal axis to obtain the umbrella truss bridge in the fourth quadrant. Both share the main beam, and the axial forces are opposite; hence, they are represented by the upper and lower halves of the arrow. Removing the special cable-stayed bridge from the first quadrant results in two different types of special umbrella truss bridges in the fourth quadrant, denoted as Umbrella Truss Bridge A and Umbrella Truss Bridge B. Based on the optimization of the umbrella truss bridge structure described in Section 7 of this paper, Umbrella Truss Bridge A and Umbrella Truss Bridge B in Figure 12 are the same bridge type. The main structural properties, force transmission paths, external constraints, etc., remain unchanged, and their only difference is the absence of one inclined strut on each side; as long as at least one inclined strut is retained, the overall structural properties and basic bridge type remain consistent.

Analyzing the umbrella truss bridges (the Umbrella Truss Bridge A and Umbrella Truss Bridge B) derived from Figure 12 reveals that these bridges correspond to two types of bridges found in reality: rigid frame arch bridges and inclined-leg rigid frame bridges. Due to the abundance of these bridge types in the current bridge-related literature and real bridges worldwide, specific examples with photos are not provided in this paper. The inclined legs on both sides and the main beam between the inclined legs of rigid frame arch bridges and rigid-legged truss bridges experience forces similar to those in the arch ring of an arch bridge (both have axial forces, and the mid-span section is primarily a bending component dominated by bending moments); additionally, they have similar structural shapes (the rigid joints in rigid frame arch bridges and rigid-legged truss bridges experience stress concentration, the nodes have larger dimensions, and the structures often include curved segments, making them appear like an arch ring. Some people even confuse rigid frame arch bridges, rigid-legged truss bridges, etc., with arch bridges). However, the construction process of these types of bridges reveals that such bridge structures are entirely unrelated to the basic arch bridge type. This also explains why specific parameters for arch bridge design, such as arch axis coefficients, do not apply to rigid frame arch bridges, rigid-legged truss bridges, or rigid-legged deck truss bridges. The forces on rigid frame bridges are related primarily to the inclination angle of the inclined legs, similar to the logical relationship between the forces on the main beam of cable-stayed bridges and the inclination angle of the stay cables. The structural forces on rigid frame arch bridges and rigid-legged truss bridges are closely related to conditions such as the inclination angle of the inclined legs and external constraints; changing these conditions alters the type of bridge.

By utilizing the bridge type quadrant diagram and its inherent symmetry characteristics, along with simple derivation, it is possible to identify bridge type nomenclature that differs from traditional viewpoints. Through the process of deduction, it is possible to clearly articulate the origin, force characteristics, and force transmission paths of the actual bridge types in reality. Consequently, accurately naming real-world bridge types and further understanding of their characteristics is achievable. This approach is beneficial for designing and constructing bridges of corresponding bridge types because it aids in grasping their specific features.

10 Conclusions

In this paper, the four most basic types of bridges (beam bridges, arch bridges, cable-stayed bridges, and suspension bridges) are described, and the inherent connections between these basic bridge types are analyzed. A specialized illustration for studying basic bridge types called the bridge type quadrant diagram is constructed. The construction of this diagram holds the following significance:

(1) The bridge type quadrant diagram establishes an organic internal connection between the four independently existing basic bridge types for the first time, providing a simple and concrete illustration. The construction of the diagram allows us to understand the relationships between basic bridge types.

(2) By analyzing the characteristics of the four basic bridge types in the bridge type quadrant diagram and utilizing the symmetry of the diagram about the horizonal axis, a new fifth basic bridge type—the umbrella truss bridge is derived and placed in the fourth quadrant. Its force characteristics are summarized.

(3) According to traditional views, all bridges can be simplified into a force diagram within a plane, and this force diagram is uniquely determined. Since the five fundamental bridge types already completely fill the entire plane of the orthogonal coordinate system, the theoretical model of the bridge type quadrant diagram thus theoretically shows for the first time that there are only five basic types of bridge structures.

(4) The basic bridge type of the umbrella truss bridge is the latest discovery derived from the bridge type quadrant diagram, completing the final piece of the puzzle. The bridge type quadrant diagram comprehensively showcases the basic structural system of bridges and establishes a unified illustration and theory for the five fundamental bridge types.

(5) By utilizing the bridge type quadrant diagram proposed in this paper as a dedicated tool for studying bridge types, one can easily derive special umbrella-beam bridge types with names distinct from traditional bridge types through simple deductions. This approach is crucial in accurately naming and understanding various bridge types in reality.

(6) Based on the theory of the bridge type quadrant diagram, during further exploration of the functionality of the diagram, the author discovered that the bridge type quadrant diagram can play a crucial guiding role in research on complex collaborative systems of bridges composed of various basic bridge

types, particularly in terms of structure and force, as well as in the investigation of super-span bridges.

In summary, the bridge type quadrant diagram is a valuable tool for understanding and categorizing different bridge types, providing a comprehensive and unified framework for the study of bridge structures.

Note: This paper is based on the author's previously published paper " Quadrant diagram of bridge and a new basic umbrella bridge " (JOURNAL OF TRANSPORT SCIENCE AND ENGINEERING, 2022, 38(3): 100-106), with further editing, modification, and improvement. The main modifications and improvements made in this paper are as follows: ① The chapters have been organized to provide a more comprehensive representation of the utility of the bridge type quadrant diagram. ② Additional content has been included, such as the derivation of special cases for umbrella truss bridges, to enhance the comprehensiveness of the research based on the bridge type quadrant diagram, facilitating a more comprehensive understanding for readers. The purpose of submitting this modified paper again is to present China's latest basic bridge type theoretical research and its progress to the international community. The author hopes to attract more attention from international peers to focus on fundamental bridge research, laying a certain foundation for the further development of bridges and basic bridge type theoretical research. The goal is to contribute and stimulate more discussions on this topic.

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