# Structural Form of Bridges Reflecting the Construction Processes

Yusuke Mizuno*, and Yoshiaki Kubota
mizuno.yusuke.54v@st.kyoto-u.ac.jp, kubota.yoshiaki.8w@kyoto-u.ac.jp
Department of Civil and Earth Resources Engineering, Kyoto University, Japan

**Abstract:** The structural form of a completed bridge is strongly affected by its structural form during construction. It follows that innovative construction processes sometimes produce innovative bridge designs. It is important to consider the construction process in conjunction with bridge design methods. This approach could be applied not only to new construction but also to replacements, reconstructions, or reinforcements. One of the authors has systematized the structural forms of bridges and clarified the principles underlying them. This paper aims to extend these principles to construction systems. In other words, changes in the structural systems of the construction processes and systematization of the relationship between a completed bridge and construction process in a design are illustrated. This systematization enables the application of a variety of conventional construction methods in a system. This would be helpful in developing new construction methods and designs for bridges.

**Keywords:** Systematization, Construction Process, Innovative Bridge Design.

## Introduction

The structural form of a completed bridge is strongly affected by its structural form during construction. Therefore, innovative construction processes sometimes produce innovative bridge designs. It is important to consider the construction process in conjunction with bridge design methods. For example, King's Gate Bridge (figure 1) located in Durham, UK and designed by Sir Ove Nyquist Arup, elegantly represents the construction process of the bridge in the completed form, wherein it connects two sides of a valley. During the construction of this bridge, bents and scaffoldings were not used in the river to protect the river ecosystem. Instead, at each side of the river, one half of the bridge (which was composed of a concrete V-shaped rigid frame pier and beam) was constructed on a cylindrical foundation parallel to the river. It was then rotated by 90º and completed. This is an example of an outstanding design approach where the construction process led to the invention of a new construction method to solve a specific problem at the site. The result is a fine-looking structure.

**Figure 1.** King's Gate Bridge (Source: Zokei 1996)

In this manner, the design approach, which also considers the construction process, could be applied not only to new construction but also to replacements, reconstructions, or reinforcements.

## Background and Purpose of This Research

Researchers such as Frei Otto, Mike Schlaich, and others have advanced the systematization of structures. One of the authors, Yoshiaki Kubota, has systematized the structural forms of bridges and clarified the principles underlying them on the basis of the types of acting forces to bridge members. To date, research has mainly focused on the structural forms of completed bridges.

This paper aims to extend Kubota's method to include the construction systems. In this research, changes in the structural systems during the construction processes and systematization of the relationship between a completed bridge and construction process in a design are illustrated.

## Basic Theory

This work relies on Kubota's research, which describes force and form of fundamental bridge types. A new method will then illustrate the transition of structural form in the construction process.

**Table 1.** Dimensions of acting forces, structural systems, and the fundamental bridge types

| Acting force | 1 dimension | 2 dimensions | 3 dimensions | Typical Structural systems | Fundamental bridge types |
|---|---|---|---|---|---|
| Tension force | * | * | * | Suspension system | Suspension bridge |
| Compression force | * | * | * | Arch system | Arch bridge |
| Bending moment | | * | * | Beam system (Web system) | Girder |
| Shear force | | * | * | Beam system (Diagonal system) | Truss bridge |
| Torsional moment | | | * | – | – |

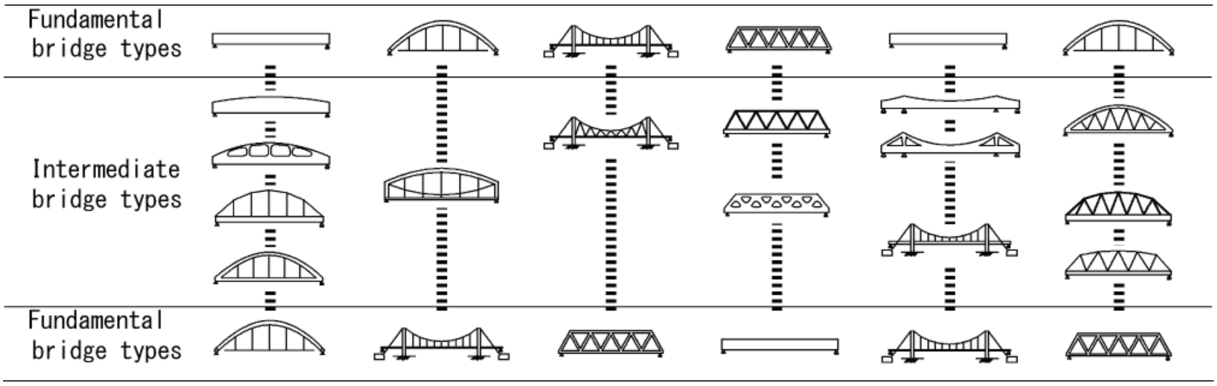



**Figure 2.** Continuous relationships between fundamental bridges

**Relationship between force and form of fundamental bridge types**

Generally, there are five forces that can be imposed on a bridge. These can be classified as follows according to the dimensions of the space where they can exist: axial force, that is, tension and compression, for one dimension; bending moment and shearing force for two dimensions; and torsional moment for three dimensions. Table 1 shows the forces acting on a bridge, the dimensions the forces can exist within, the typical structural systems that resist these forces, and the corresponding fundamental bridge types. As ordinary bridges are usually constructed to cross at a right angle to obstacles, such as rivers, roads, or railways, and cross straight to the other side, torsional moment seldom becomes a major factor when selecting the bridge type. Thus, torsional moment does not correspond to any of the structural systems and bridge types in this table. Of course, there are more bridge types in practical use. In addition, the forces that a real bridge is subjected to are more complicated as several types of forces often act on a member simultaneously. However, it is important to understand that the dominant force imposed on a structure has a great influence on the form of the bridge. Therefore, this analysis pairs four bridge types (suspension, arch, girder, and truss) with their corresponding forces.

The abovementioned four fundamental bridge types are related to each other. The relationships are illustrated in figure 2. There are six combinations of two bridge types. In this figure, the relationship between the suspension bridge and arch bridge is expressed as continuity. However, it could also be expressed as symmetry. In figure 3, the relationships between the four fundamental bridge types are integrated into a diagram with six arrows indicating the continuity or symmetry in structure and form among them. This figure also shows three classifications of structural systems: a suspension system, beam systems, and an arch system. Figure 3 illustrates the interrelationships among the four fundamental bridge types related to the acting forces.

We can consider not only the linear relationships shown in figure 3, but also more complex relationships among the various bridges. The relationships shown in figure 3 are altered to obtain two (upper and lower) triangular coordinate systems with bilateral symmetry in figure 4. Furthermore, the vertical position of the main structure and the floor system is illustrated in the depth direction of the figure. A bridge consisting of a suspension system, a web system, and a diagonal

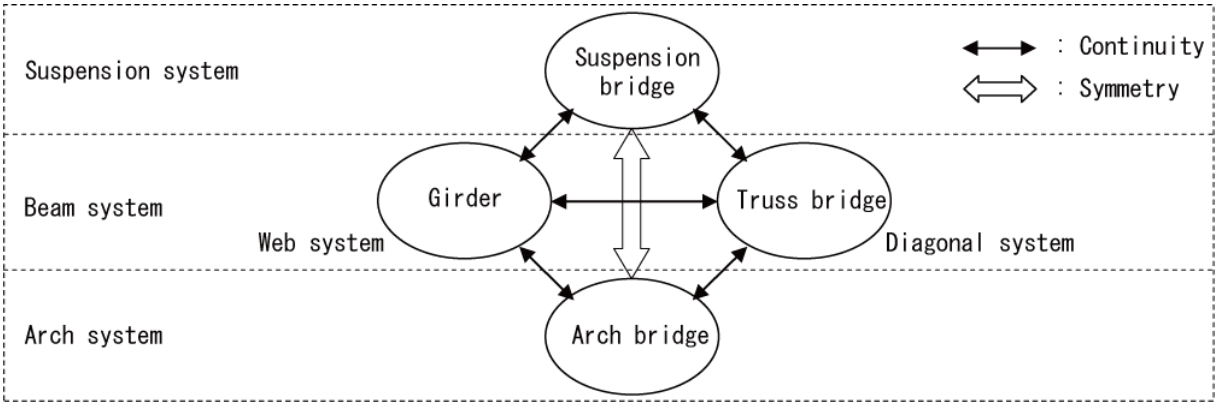



**Figure 3.** Interrelationships among four fundamental bridge types

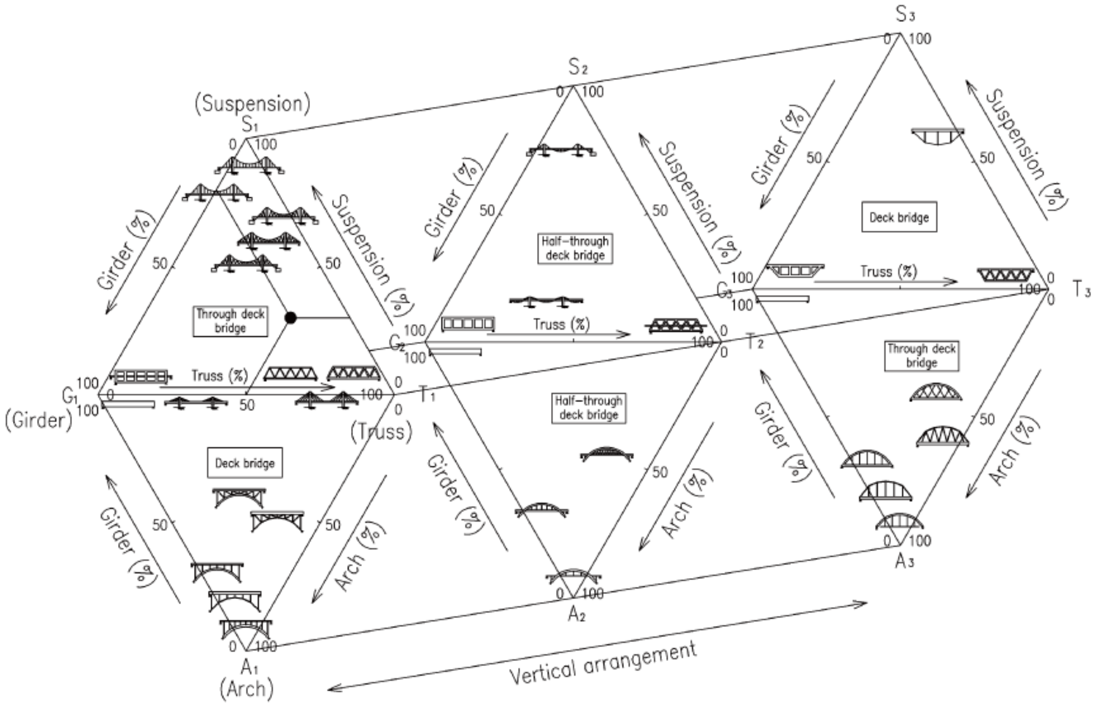



**Figure 4.** Correlation chart expressed by triangular coordinate systems

system is shown in the upper half of the figure (triangular prism $S_1G_1T_1$-$S_3G_3T_3$), while a bridge consisting of an arch system, a web system, and a diagonal system is shown in the lower half of the figure (triangular prism $A_1T_1G_1$-$A_3T_3G_3$). The bridges that have a symmetrical relationship in structure and form would be placed at symmetrical points with respect to the central plane ($G_1T_1T_3G_3$), as shown in figure 4.

### Transition of Structural Form

The structural form changes during the life cycle of a bridge. In this paper, the states are separated into three parts: constructed state, completed state, and retrofitted state. Furthermore, retrofitting is defined as a new structural system applied to an existing structure.

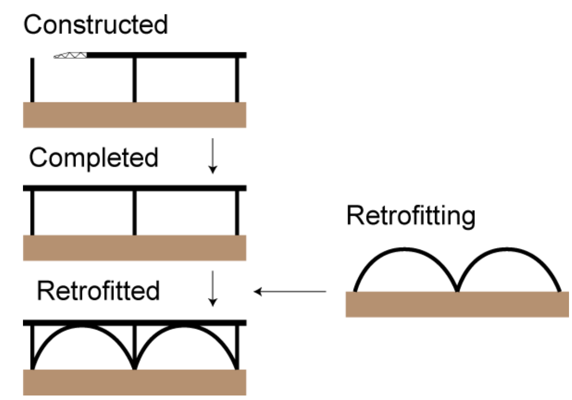



**Figure 5.** Transition of structural form in a typical life cycle of a bridge

## Classification of Elements of Transition of Structural Form

A coordinate system for a bridge incorporates the movement, which occurs when the bridge is under construction. This is described by a combination of six degrees of freedom in three-dimensional space (figure 6). The x-axis is the bridge's axial direction, the y-axis is the direction in a horizontal plane at right angles to the x-axis, and the z-axis is the vertical direction. The coordinate origin is set at the point where the rotation of the structural system is the simplest on the x-axis. Rot-x can support small rotations such as when the structure supports a dead load, but this ability decreases drastically as the rotation angle becomes large. Rot-y is effective in beam systems, but in spanning systems (suspension and arch) it cannot achieve cantilever status so its support base such as suspension tower and bearing moves vertically. Rot-z can occur only in a beam system (diagonal system structure and web system structure) because it can become a cantilever system.

The element variations of structures include four typical structural systems as shown in table 2: suspension system, web system, diagonal system, and arch system. First, the structural condition of bridges is classified into "spanning system" and "cantilever system" in table 2. Then, "spanning system" is classified into rotation free condition (Rot) and rotation fixed condition (Fix) of the end point in the y-z plane. This classification can describe typical structural condition of bridges such as simple structure, consecutive structure, both-ends-fixed structure and cantilever structure. Thus, all structural conditions can be described in the area enclosed by a heavy line in table 2.

Basic transition of structural form in the construction process can be explained as a combination of them.

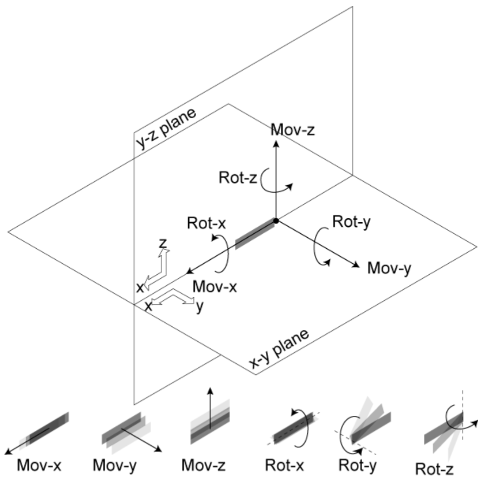



**Figure 6.** Movement and rotation of the bridges

## Analysis of Examples

### Illustration Method of Transition of Structure

In figure 7, each transition of structural form for constructed, completed, and retrofitted states in the life cycles of bridges is illustrated by the correlating diagram of structural system. When the structural system changes during the construction process life cycle, the "Structural Form Correlation Chart" also changes. Moreover, lines representing bridge materials in the diagram sketches are indicated in the figure 8 to 13 by color.

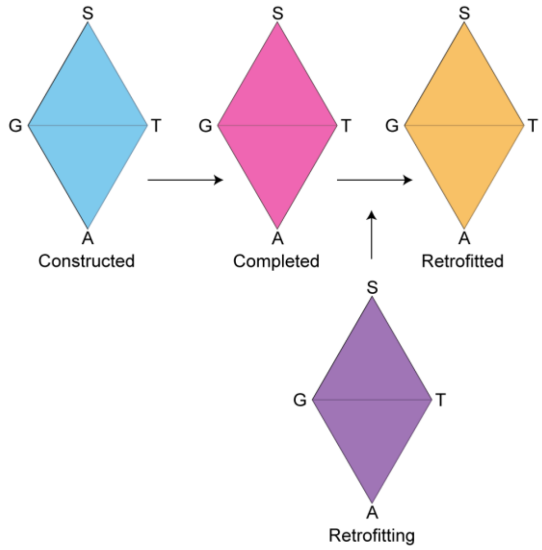



**Figure 7.** Construction states

**Table 2.** Adaptability to spanning/cantilever systems and movement within six degrees of freedom

| Structure system \ The Elements | | Spaning System – Boundary Condition: Rot | Spaning System – Boundary Condition: Fix | Cantilever System | Mov-x | Mov-y | Mov-z | Rot-x | Rot-y | Rot-z |
|---|---|---|---|---|---|---|---|---|---|---|
| Suspension System | | ○ | × | × | × | ○ | ○ | △ | △ | × |
| Beam System | Web System | ○ | ○ | ○ | ○ | ○ | ○ | △ | ○ | ○ |
| | Diagonal System | ○ | ○ | ○ | ○ | ○ | ○ | △ | ○ | ○ |
| Arch System | | ○ | × (*) | × | × | ○ | ○ | △ | △ | × |

・○ ; avilable, × ; unavilable, △ ; aviilable under the specific condition
・Though arch bridge can transfer bending moment at the endpoints because of the bending rigidity, column (*) is filled with "I" because a pure arch system can transmit only axial compression force.

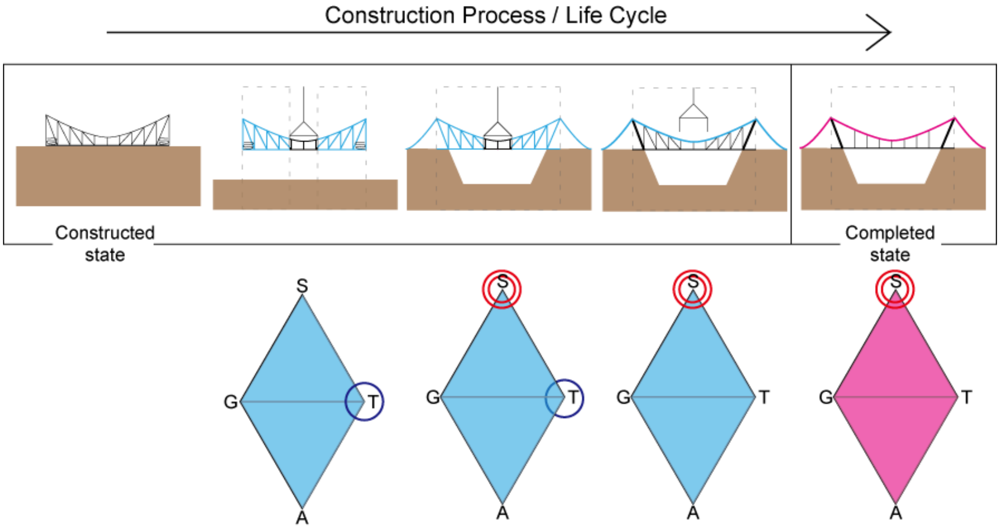



**Figure 8.** Single-operation method of the suspension bridge (Halgavor Footbridge)

The four colored shapes from the triangular coordinate system correspond to four types of life cycle states. Constructed state is in light blue, completed state is in magenta, and retrofitted state is in orange. Retrofitting state is in purple.

**Table 3.** Removability and Spanning/cantilever

| | Permanent | Removal |
|---|---|---|
| Spanning | ◎ (red) | ◎ (blue) |
| Cantilever | ○ (red) | ○ (blue) |

Table 3 illustrates the removability and spanning /cantilever states of structures as follows.

- A red circle means that the structure is permanent.
- A blue circle means the structure is a removal.
- A double circle indicates a spanning structure
- A single circle indicates a cantilever.

The member which is in the constructed state is shown in light blue, completed state is in magenta, retrofitted state is in orange and retrofitting state is in purple. The construction process proceeds from left to right. We examined six examples of construction processes illustrated below.

**Single-operation Method of the Suspension Bridge (figure 8)**

This construction method has an innovative idea in the construction process. When hung up, the temporary compression diagonal members enable the structure to function as a cantilever truss balanced at the both endpoints. After set, while the structure is hung up, the cables, which are left at both the endpoints, are fixed at the anchor. As the temporary diagonal members are removed, the structural system becomes the suspension system. Thus, the structure supporting the dead load changes from the cantilever system to the suspension system. This bridge needs few temporary diagonal members to function as it is made of fiber reinforced plastic. Thus, this method is an example of a simple, single-operation method for small and medium sized bridges using only one crane. The bridge's aesthetics are also innovative. Part of the diagonal members, which function as truss system in the constructed state, remained as pylons of the suspension bridge; thus, the pylons incline to the outside of the span. This design hides the pylons in the trees and vegetation so that drivers under the bridge can see only the slender bridge girder.

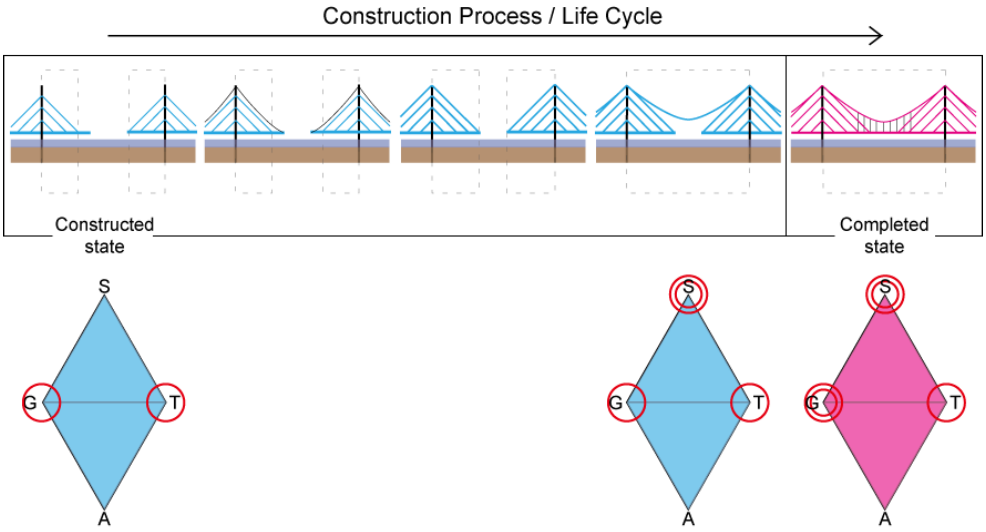



**Figure 9.** Construction method of Dischinger-type bridge (Third Bosphorus Bridge)

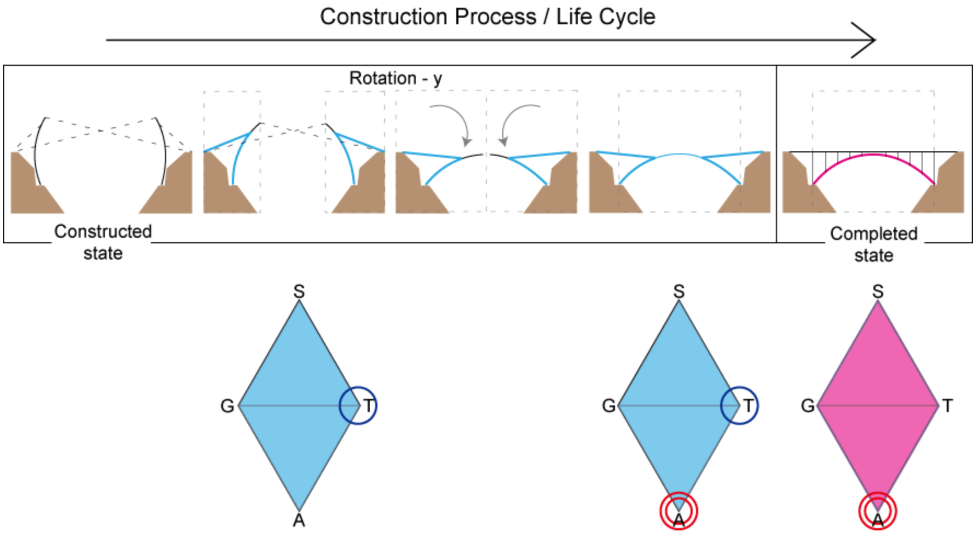



**Figure 10.** Lowering Method (many examples)

**Construction of Dischinger-type Bridge (figure 9)**

At first, cable-stayed bridges are constructed to overhang from the pylons. It is designed as a diagonal system - the truss system. After that, the pylons for making a cable-stayed bridge are used just as they are for the suspending of the suspension cables. Thus, live load and dead load of the floor construction beam are supported by the combination of a cable-stayed system as one of the truss systems and a suspension system. In this method, there are no huge temporary support structures. Thus, this method is efficient because of material efficiency and is suitable for long-sized bridges. This Dischinger method is the best method to make the longest span bridge today. Although the cables visually clash with each other and look complicated on the spot where both structural systems overlap, the completed bridge looks light because many cables are used in the cable-stayed system and the suspension system.

**Lowering Method (figure 10)**

In the lowering method, precast arch rib members are rotated on the hinges installed on both banks and eventually make up the arch system. In the rotation process, cables that receive a reaction force from the outside of the system and arch rib members constitute a cantilever truss system which looks like triangles. The truss system changes its stress state during the rotation process. Finally, the arch rib members are closed and function as arch system. In this method, the material efficiency is good because no huge temporary support structure is used during construction. However, the axial force occurring in the arch rib members in the rotation process is converted into the bending moment because their shape bends in relation to the arch structure. Thus, this method is not suitable for so long bridges because the truss system is not structurally efficient. Almost nothing from the rotation process remains in the constructed state. Nevertheless, the stress analysis at every angle is necessary because internal stress is

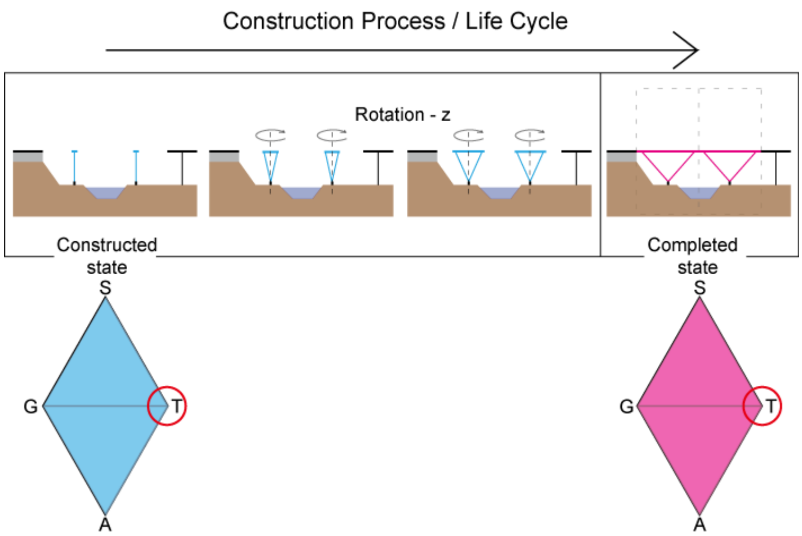



**Figure 11.** Horizontal Rotation Method (King's Gate Bridge)

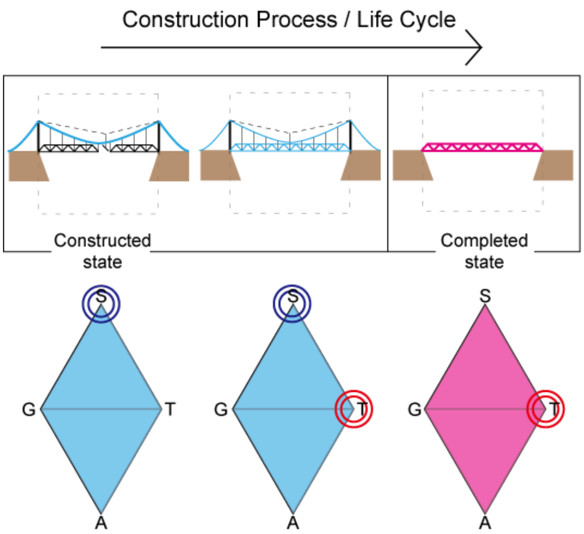



**Figure 12.** Vertical Cable Erection Method (many examples)

changing along with the form change of the truss structure.

### Horizontal Rotation Method (figure 11)

King's Gate Bridge is the pedestrian bridge that Ove Arup regarded as the masterpiece in his life. The V-shaped, rigid frame pier and beam, was constructed on a cylindrical foundation parallel to the river. It was then rotated by 90° and completed. During construction, the two V-shaped structures functioned as a cantilever truss system. Then, the final structural form appears by the rotation-z on the cylindrical foundation. The extremely slender V-shaped pier gives the impression of elegance and delicacy.

### Vertical Cable Erection Method (figure 12)

In this method, there are two types of suspension cables in the constructed state. Carrier cables transport the blocks of the bridge members and main cables hang vertically. After the truss bridge (the final structure) is completed, hanger ropes are removed and transference of the dead load occurs from a suspension system to a diagonal system – the truss system. This method requires many temporary structures such as pylons, carrier cables, main cables and so forth; however, there are many variations of structural form in the completed state because main cables work as if falsework takes charge of all load.

### Reinforcement by retrofitting the Middle Hinge PC Bridge with String Beam Structure (figure 13)

This rigid-frame middle hinge bridge has a striking deflection at the hinge located in middle of the span, so this method was used for restoring it. The bending moment at the hinge point is zero and the floor construction beam overhangs both endpoints beyond the post. Therefore, the span, which includes the repair part, is regarded as two cantilever girders butted against each other. Thus, the final structure

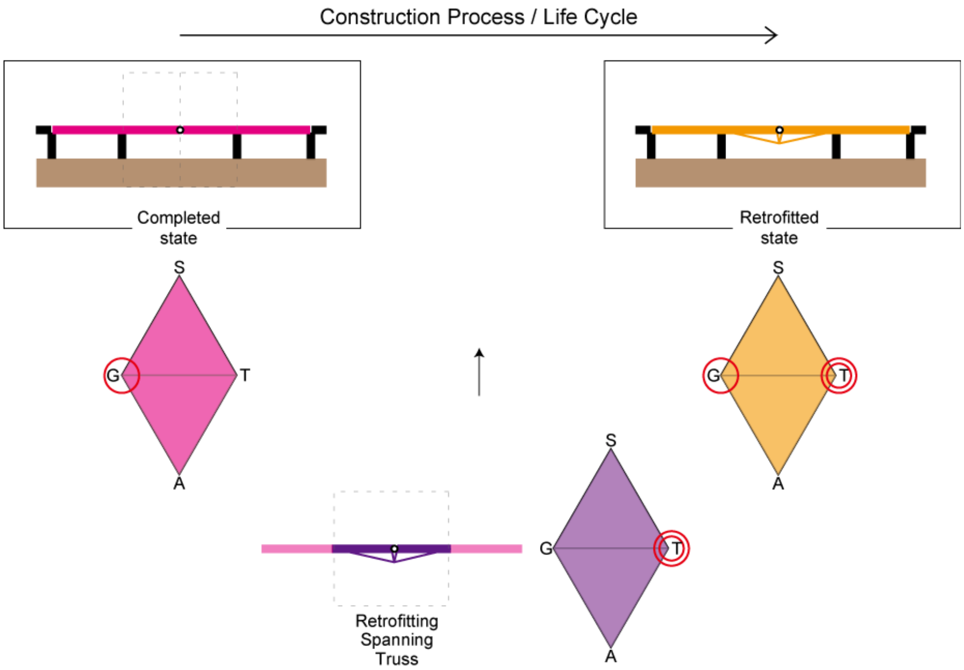



**Figure 13.** Reinforcement by retrofitting the middle hinge of a PC bridge with string beam structure (Kireuriwari Bridge)

system is a retrofitted cantilever girder with spanning system.

## Evaluation of Applicability and Efficiency of Structural Systems

There are many construction types in the life cycle of bridges including new construction, reinforcement, repair, and removal. New construction is a basic construction type used to consider all other types. The structural changes that occur in new construction are shown in tables 4 and 5. (Note: Table 4 and 5 are separated for want of space.) In addition, we analyzed the "Applicability of Structural System" which indicates the likelihood that a structural system will change to another system and "Efficiency of Material and Time" for table 4 and 5.

### Applicability of Structural System

The vertical cable erection method, which uses a suspension system, can make almost all types of bridges. The diagonal cable erection method or overhanging erection method, which use a diagonal system, can be applied to many types of bridges such as arch bridges, cable-stayed bridges, and truss bridges. If the special construction methods of the "Halgavor Footbridge" are used, we can also construct suspension bridges using a diagonal system. In this manner, a suspension system and a diagonal system have a high potential to make various types of bridges. On the other hand, while a web system can be used in the launching method as a beam system, the applicability of that structural system is comparatively low. An arch system is rarely used in the constructed state. In the constructed state, the applicability of a suspension system and a diagonal system is particularly good.

### Material Efficiency

Bridges which do not change their structural system from constructed to completed state throughout the cycle such as a suspension bridge or a cable-stayed bridge have high material efficiency because they do not need huge temporary structures.

### Time Efficiency

Bridges using a beam system have good time efficiency because they can be placed using parallel translation such as the launching-type erection method. In addition, a beam system can be hung up by a small number of cranes. However, these methods generally require many temporary structures in the constructed state, so material efficiency tends to be low. Nevertheless, we can try to improve material efficiency by using temporary structures several times.

## Efficiency in the Each Condition

Table 6 compares the efficiency between three types of structural systems including a suspension system, a beam system and an arch system; all with corresponding construction states: constructed, completed, retrofitted and retrofitting.

The suspension system is generally good at material efficiency, but in the retrofitted state, all efficiency is low because of difficulty of reinforcement. The beam system has better material efficiency because it requires a small number of temporary structures for cantilevering. In addition, it can also improve time efficiency by using the launching-type erection method. In the constructed state, it functions well, and in the retrofitting state it is efficient if a diagonal system is used for stiffening. The arch system is not efficient in the constructed state because it is not easy to build without another system's support. However, in the retrofitting state, it is an efficient way to reinforce the existing structure. In the retrofitted state, it can accept various types of reinforcement.

Thus, in the constructed state, the suspension system is efficient and the arch system is inefficient. In contrast, in the retrofitted state, the suspension system is inefficient and the arch system is efficient. The superiority of each structural system is dependent upon whether it is new constructed or reinforced.

**Table 4.** Structural change list for newly constructed bridges

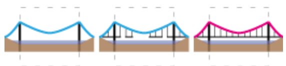
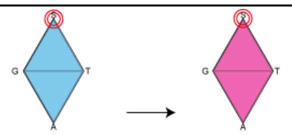
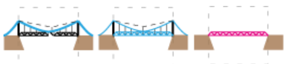
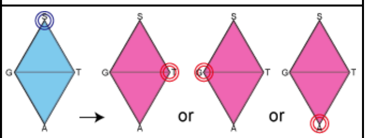
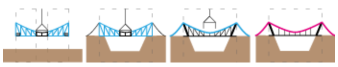
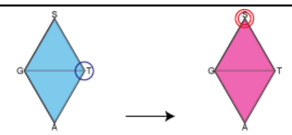
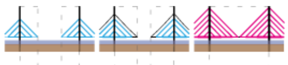
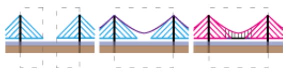
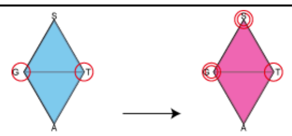
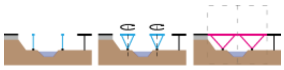
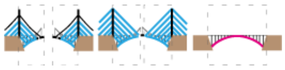
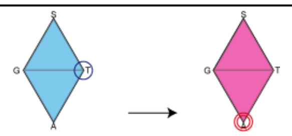
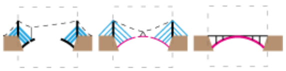
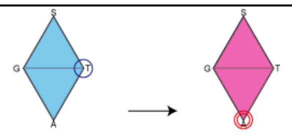
| Construction Method / Names of Completed Bridge | Efficiency (Dimensionless) | | Construction Process / Life Cycle | Transition |
|---|---|---|---|---|
| | Material | Time | | |
| Suspension Bridge | ◎ | ○ |  |  |
| Vertical Cable Erection Method | × | △ |  |  |
| Single-operation Method of the Suspension Bridge | ○ | ◎ |  |  |
| Cable-Stayed Bridge | ◎ | × |  |  |
| Dischinger-Type Bridge | ◎ | × |  |  |
| Vetrical Rotation Method | ◎ | ○ |  |  |
| Pylon Method | × | △ |  |  |
| Diagonal Cable Erection Method | × | △ |  |  |

**Table 5.** Structural change list No. 2 for newly constructed bridges

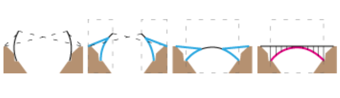
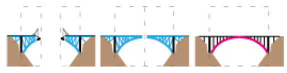
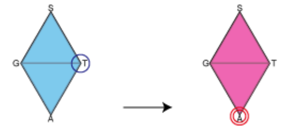
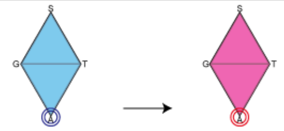
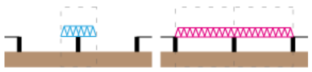
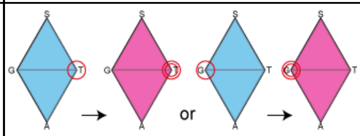
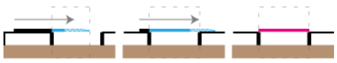
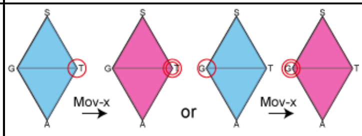
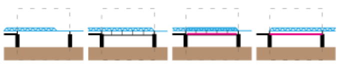
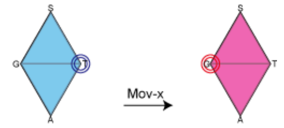
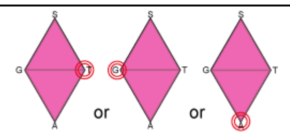
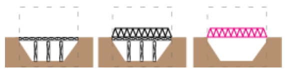
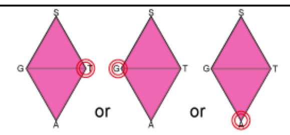
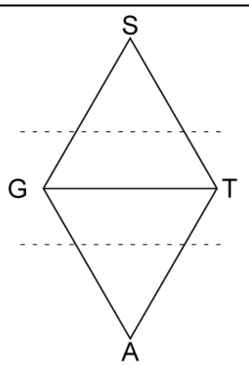
| Construction Method / Names of Completed Bridge | Efficiency (Dimensionless) | | Construction Process | Transition |
|---|---|---|---|---|
| | Material | Time | | |
| Lowering Method | ○ | △ |  |  |
| Overhanging Arch Erection Method with Truss | ○ | × |  |  |
| Arch Center Method | × | ○ |  |  |
| Balanced Cantilever Method | ◎ | △ |  |  |
| Launching Erection Method | △ | ◎ |  |  |
| Span by Span Construction Method | × | ◎ |  |  |
| Single-Operation Method with Floating Crane or Pontoon | × | ◎ |  |  |
| Fixed Timbering Erection Method | × | ◎ |  |  |

**Table 6.** Effectiveness in each structure system

| Triangular Coordinate System | | | Constructed | Completed | Retrofitted | Retrofitting |
|---|---|---|---|---|---|---|
| Suspension System (Spanning System) | |  | Efficient because of the material efficiency | More efficient because of the material efficiency | Low efficiency | Efficient because of the material efficiency |
| Web System (Beam System) | Diagonal System (Beam System) | | Efficient at both time and material because of being used as a cantilever | Efficient because of the material efficiency | Efficient | Efficient if being used as a diagonal system |
| Arch System (Spanning System) | | | Low efficiency | More efficient because of the material efficiency | Efficient | Efficient for Supporting exisiting spanning systems |

## Conclusion

In this thesis, we established an analysis method based on a "Structural Form Correlation Chart" which showed the change of structural form throughout the life cycle of the bridge including construction processes. We then systematized the relationships between the structural forms in the completed state and construction processes including retrofitting existing bridges. In addition, we revealed the peculiarities of four fundamental structural systems such as the applicability of structural system and the efficiency of material and time corresponding to the three states: constructed, completed and retrofitted. We will improve this theory to develop innovative construction processes and bridge design while being based on more example analyses.

## References


Kubota Y. (2009) Fundamental Study on the Method Used for the Operations on the Structure and Form of a Bridge, *Journal of the Japan Society of Civil Engineers*, Vol. 65, No. 1, pp. 64-76.

Kubota Y. (2010) Systematization of structures and forms of truss systems, *34TH International Symposium on Bridge and Structural Engineering*, pp. 1-5

Japan Construction Machinery and Construction Association (2016) Multiplication of bridge construction the 2016 version

Kenchiku Shiryo Kenkyusha CO., LTD. (1996) Zokei, pp 74-81

Sato T. et al., (2013) Adoption of the Lowering Construction Method of Raise type RC Fixed Arch Bridge Takatakinozawa Bridge, *The 57th Hokkaido development technology research presentation*

Yoda Y. et al., (2003) Concerning Dywidag Bridge's Repair Design, *the 58th annual academic lecture of Japan Society of Civil Engineers*