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Forms and Aesthetics of Bridges

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ABSTRACT

The objective of a bridge design is to produce a safe bridge that is elegant and satisfies all functionality requirements, at a cost that is acceptable to the owner. A successful bridge design must be natural, simple, original, and harmonious with its surroundings. Aesthetics is not an additional consideration in the design of a bridge, but is rather an integral part of bridge design. Both the structural configuration and the aesthetics of a bridge must be considered together during the conceptual design stage. To achieve such a task, the bridge design engineer must have a good understanding of structural theory and bridge aesthetics.

1. Introduction

Humans are separated from wild animals by the existence of civilization. Elephants today still roam the earth with lives that are similar to those of elephants of thousands of years ago, but we humans have significantly improved our lifestyles—thanks to civilization!

What is civilization? The Merriam-Webster Dictionary defines "civilization" as "modern comforts and conveniences, as made possible by science and technology." Convenience can thus be achieved through technological advancement. Comfort, however, can only be achieved by improving the quality of our environment, which includes the form and aesthetics of the things surrounding us. Without quality in our environment, we cannot have quality and comfort in our life.

Approximately 2000 years ago, the great architect Marcus Vitruvius Pollio advised the Roman Emperor that "Structures shall be safe, functional, and beautiful!" [1]. Although these requirements are still valid today, we must add economy to the list. Therefore, today's standard should be that "Structures shall be safe, functional, economical, and beautiful!"

Cost was less important for Vitruvius because he worked for the Emperor. We engineers of today do not have that kind of luxury. Aside from that, not much has changed in how we define a successful bridge, or any successful structure. Beauty has never ceased to be one of the basic requirements of a successful bridge.

A successful bridge that is "safe, functional, economical, and beautiful" will provide both comfort and convenience.

2. Form follows function

A bridge makes up one element of a highway or a city street, which in turn is an element in the master plan of a city or a community. Hence, the function of a bridge is not defined by a bridge engineer. When the need arises to cross a river or a valley, or to connect two points, the planning calls for the design and construction of a bridge. This need drives the purpose of the bridge design. The purpose further defines the function of the bridge. The function of a bridge is established based on traffic planning, in conjunction with socioeconomic and urban studies. These studies identify how much traffic is predicted for a certain design life of the bridge. The traffic engineer determines the number of lanes required based on the volume of the predicted traffic and the design speed. The local topography and other local conditions then determine the desired geometry of the deck including the length, minimum span length, maximum grades, and minimum clearances.

Once the function of a bridge is determined, the bridge engineer selects the form of the bridge to satisfy the given function—hence the motto "form follows function." However, before establishing the form of the bridge, the engineer must understand what

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material is available for the construction of the bridge. This process is represented in Fig. 1.

Aesthetics is another ingredient used in finalizing the bridge design. We shall not build ugly bridges. An ugly bridge pollutes the environment.

3. Historic evolution of bridge forms

Bridges all over the world can be placed into four basic categories: girder bridges, arch bridges, cable-stayed bridges, and suspension bridges. All of these major bridge types are almost as old as human civilization. In some primitive form, all were first built many, many centuries ago. However, the evolution of today's more sophisticated and versatile bridge forms can be traced to the introduction of various construction materials of different times.

Some 4000 years ago, and until the beginning of the 19th century, the only construction materials available were wood and stone. Wood from tree trunks could be used as girders; therefore, felled trees were used to create bridges. For larger crossings, stone piers were created so that tree trunks could span between them; however, these bridges were not sturdy. They did not last long and could not encompass large spans.

Stone is much stronger than wood, albeit only in compression. It is also more weather resistant. All early Egyptian and Greek buildings were built of stone. Because stone cannot sustain high tensile stresses due to bending, these buildings have very closely spaced columns. Brick, which is also a compression material, was later produced to replace stone in some applications.

The arch bridge was the most ingenious invention by the Romans and the Chinese that fully utilized the compressive strength of stone. The Romans built the barrel vault by connecting successive arches together to create a large inner space. The dome was created by rotating the arch around its vertical axis. Using the dome, the arch, and the vault, the Romans built many spectacular structures. The Pantheon, with its 43.3 m diameter dome, was the largest dome in the world for about 1800 years. The arch allowed the Romans to build many bridges and viaducts, some of which are still in existence today.

Iron, with its greater strength and formability than stone, provided chains to build iron chain bridges, which are a type of "stress-ribbon bridge"—that is, an early form of suspension bridge. The very first major iron chain bridge is reported to have been built in China around 60 AD: the Lan Chin Bridge [2] in Yunnan Province, which has a main span of about 60 m. Many iron chain bridges were constructed in China, some of which are still accessible today. One of the longest span iron chain bridges, the Luding Bridge [2] in China, was built about 400 years ago. Iron chain was also used as the main cables of suspension bridges; however, these bridges tend to be smaller structures because, like stone, iron lacks high tension capacity.

It was steel that revolutionized bridge construction, because steel can take both high tension and compression. Once the mass production of steel became possible in the mid-19th century, engineers were able to build long-span girder bridges, truss bridges, and large and slender arch bridges. By combining steel with concrete, we have also been able to build many long-span reinforced concrete bridges.

High-strength steel wires are produced by a cold drawn process. The high strength of these wires makes long-span suspension bridges possible. Before high-strength steel wires were commercially available, suspension bridges were built using steel chains and eye bars; however, the span length of such bridges was limited.

The introduction of high-strength steel wires also stimulated the development of cable-stayed bridges. A cable is not effective if the sag due to its own weight is too large. The sag is a function of the tension in the cable. Therefore, a cable can only be effective if it can be stressed to a very high force under permanent load conditions, which is possible only if the cable is made of very high-strength materials so that it can still have reserved capacity to carry live loads. High-strength steel wires also improved the economy and versatility of prestressed concrete. As a result, many prestressed concrete bridges have been built.

It is evident that the availability of specific materials affects the selection of bridge forms. Thus, bridge development can be divided into two eras: the arch era, and the contemporary era with all four types of bridges. The arch era spans over 4000 years, while the contemporary era is less than 200 years old.

Looking to the future, many new materials such as carbon fibers, ultra-high-performance concrete, and nano materials may be useable in the development of new bridge forms. However, these materials are not yet ready for large-scale applications. Therefore, we can conclude that in the last four to five millennia, humans have only invented four bridge forms, as identified in Fig. 2.

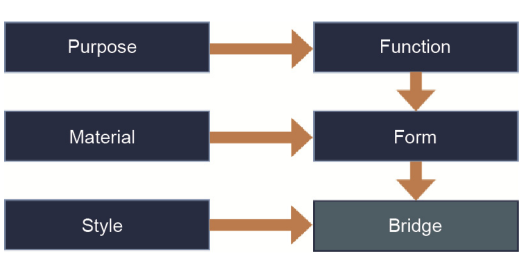

Fig. 1. Bridge design flow chart.

4. The basic structural elements: The ABCs of structures

Even though the four basic forms of a bridge—girder, arch, cable-stayed, and suspension (Fig. 3)—may look very different from one another, each of these bridge types is comprised of only three basic structural elements: axial, bending, and curved elements (the ABCs of structures). By combining and mixing these three types of basic structural elements, different bridge configurations can be created.

For example, a truss bridge mainly consists of axial elements. Bending moment may exist, but it is secondary. The same is true for a cable-stayed bridge. However, an arch bridge carries its load by the change of curvature, and this is also the case with the main cables of a suspension bridge. In comparison, a girder bridge is mainly a bending element (Fig. 4).

5. Engineering is an art, not a science

Engineering is not a science. The aim of science is to discover truth, which is unique. Therefore, science is rigid because it is not possible to change truth. Science is either right or wrong, and there are no "good" or "bad" sciences. Unlike scientists, engineers do not make discoveries; rather, engineers create things based on their subjective experiences and preferences. Therefore, engineering is flexible, and this flexibility affords engineers the possibility to select, or even to create, new structural forms that satisfy the given function of a bridge, within certain limitations. This process of selection and creation is an art!

Engineering is not an applied science either. When building the pyramids and the Great Wall, what science was applied? Science was a mere tool used by engineers to judge and explain the behavior of a structure. In addition to understanding science, engineers require knowledge and skills in many other fields such as economics, aesthetics, and politics in order to be successful bridge designers.

Fig. 2. The introduction of steel stimulated the development of new bridge forms. (a) Iron did not change the bridge form much (Coalbrookdale Iron Bridge by Pritchard); (b) high-strength steel wires stimulated new bridge types; (c) after high-strength steel wires became available, bridge construction started a brand new chapter.

In engineering, the question is always, "Does it work?" Engineering can be either good or bad, but never right or wrong.

We already know that all possible forms of bridges are comprised of only three basic structural elements: axial, bending, and curved elements. The art of bridge engineering lies in knowing how to integrate these elements in order to arrive at the best structure that satisfies the fundamental requirements of "safe, functional, economical, and beautiful" features. This is similar to a cook combining various ingredients in a certain way so the food will taste best.

However, in practice, the task of coming up with a good combination requires experience and training, just as in cooking, playing piano, or playing golf. Although the basics are simple, playing the piano well requires many years of hard work and practice.

Besides, there are limitations to what we can do. To extend the analogy of playing piano, it is impossible to have a piano produce a human voice. Thus, it is important to understand these limitations before practicing combinations of the ABCs.

6. Span length

When a large river or bay needs to be crossed, the question that always comes up is "How long of a span can we build?" History may provide some help in answering this question. Table 1 identifies the top three longest spans in the world for each bridge type today. Fig. 5 identifies how the maximum span of each bridge type has evolved. All of these curves show a trend: The maximum span length is increasing.

Knowing that the state of the art is changing with time, we should be humble in predicting the future. New materials are showing promise for construction, such as composite materials. However, the actual application of these new materials will require more testing and an actual record of performance before the materials can be used in a very long-span bridge design and construction; a bridge is inherently a major investment that usually calls for more conservatism.

Given what is available today, high-strength steel is still the only real high-strength material suitable for long-span structures. Thus, the question becomes: "What are the limits of steel bridges?"

Steel with a higher strength is currently available for bridge construction. In the late 1960s, a cable-stayed bridge—the Duisburg-Neuenkamp Bridge in Germany (Fig. 6)—used a very high-strength steel for the towers, which are predominantly compression members. The steel had a yield strength of about 700 MPa. The bridge has been performing well, so we may consider using this steel strength for future bridges, especially for compression members. Steel wires with a breaking strength of up to 2000 MPa are now available. Based on these steel strengths, the maximum span length of a suspension bridge can be 10 000 m, the maximum span length of a cable-stayed bridge can be 5500 m, and the maximum span length of an arch bridge can be 3500 m. There are no distinct criteria for a girder bridge. However, practical and economic considerations most likely limit the span length of a girder bridge to approximately 550 m.

Fig. 3. Bridge types. (a) Acosta Bridge (girder); (b) Old San Francisco-Oakland Bay Bridge (truss); (c) Crooked River Bridge (arch); (d) Talmadge Memorial Bridge (cable-stayed); (e) Golden Gate Bridge (suspension).

Having the ability to build a very long span does not technically mean that we can freely choose longer spans even if they are not necessary. Longer spans usually cost more. Since economy is one of the basic considerations for the success of a bridge design, it must be kept in proper perspective. Therefore, we must address the cost of a bridge as part of the design. If a bridge is not economically feasible, it will not be built.

7. Value versus cost

A bridge is economically feasible if its value is equal to or higher than its cost. The value of a bridge is the sum of several components—generally, these include its functional value, social value, and aesthetic value.

The value of function is obvious. Because of the bridge, a user can reduce the time required to travel from point A to point B. This convenience saves money and time, which can be represented by a dollar value. Multiplying the value of the bridge to an individual by the number of users yields the functional value of the bridge. As the standard of living in a society increases, the value of this convenience also increases. A bridge project that was not economically feasible in the past may become feasible today.

A bridge connects not only places, but also people. Very often, a bridge is built to symbolize a unification, friendship, or other bond between two communities. The value of this symbolism is difficult to determine numerically; however, under certain circumstances, it can be very significant, and can even be the sole reason for the construction of a structure.

Consider this famous saying: “Beauty is in the eye of the beholder.” Although beauty is very subjective, it has value. As an analogy, most people do not simply wear the cheapest clothing; in addition to considering cost, people choose clothing because

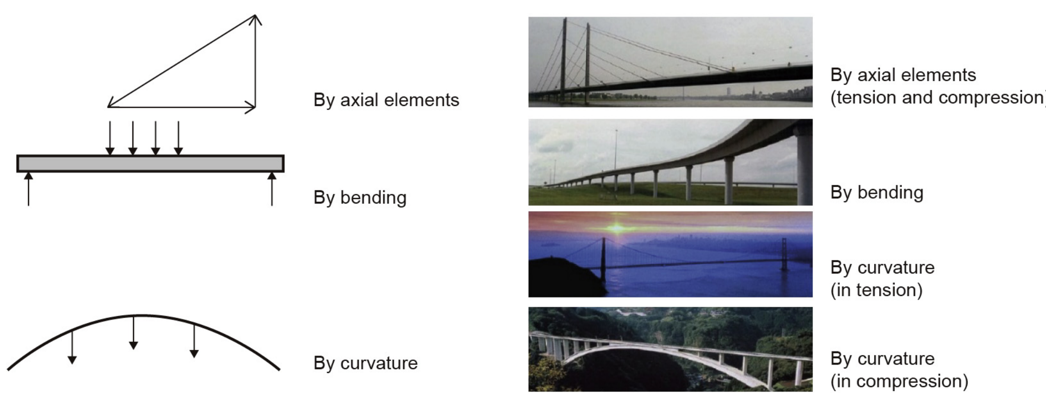

Fig. 4. The ABCs of structures.

Table 1
Longest bridge spans in the world for each bridge type.

Bridge type	Name	Span (m)	Country	Year of completion
Girder	Shibanpo Yangtze River Bridge	330	China	2006
	Stolmasundet Bridge	301	Norway	1998
	Presidente Costa e Silva Bridge	300	Brazil	1974
Arch	Chaotianmen Yangtze Bridge	552	China	2009
	Lupu Bridge	550	China	2003
	New River Gorge Bridge	518	USA	1977
Suspension	Akashi Kaikyō Bridge	1991	Japan	1998
	Xihoumen Bridge	1650	China	2009
	Great Belt East Bridge	1624	Denmark	1998
Cable-stayed	Russky Bridge	1104	Russia	2012
	Sutong Yangtze River Bridge	1088	China	2008
	Stonecutters Bridge	1018	China	2009

they want to look good, or at least appropriate. We decorate our homes because making them more beautiful enhances our love of life. We travel to places simply to enjoy looking at the beauty of the scenery and surroundings there. There is no doubt that people are always willing to pay for aesthetics, whether knowingly or unknowingly. An attractive building in a nice neighbourhood can demand a higher rent. Consequently, aesthetic considerations have always been important in the design of the exterior and interior of commercial buildings.

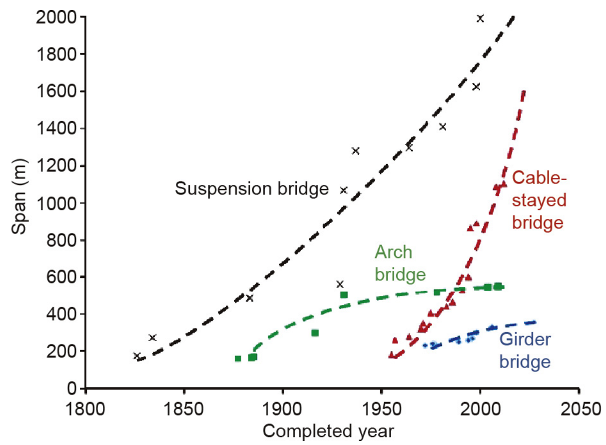

Fig. 5. Milestone maximum spans of various bridge forms.

Fig. 6. Duisburg-Neuenkamp Bridge.

Since most bridges are paid for by tax dollars, they are indirectly paid for by taxpayers or citizens. Consequently, it is the responsibility of the bridge engineer to understand what the taxpayers would do if they were to design the bridge. Considering that most taxpayers are willing to pay for aesthetics in their daily life, there is no reason why engineers should impose on taxpayers the cheapest bridge possible. Besides, the inclusion of aesthetics does not always cost money. Paying more attention to details can bring about a significant improvement in the appearance of a structure.

A visit to Paris may include visits to the Eiffel Tower, the Louvre and its famous paintings and sculptures, the Arc de Triumph, the Pont Alexandre III, and other beautiful structures (Fig. 7). Some of these structures have little or no functional value, such as the Arc de Triumph. However, tourists and locals remember and love them because they are beautiful; one need not be a bridge engineer to notice that the bridges across the Seine River are beautiful structures that are designed with thoughtful attention to aesthetics. It would be unthinkable for all of the bridges over the Seine River to be built in the cheapest way possible. The resulting Paris would not be the Paris we know today!

Obviously, it is difficult to estimate the value of beauty or a landmark; however, in 2012, the Monza and Brianza Chamber of Commerce of Italy made an effort to do just that. They evaluated the most well-known landmarks of the world, and concluded that the Eiffel Tower was worth about 544 billion USD to the French economy. Considering that the French GDP was 3380 billion USD in 2012, the economic value of the Eiffel Tower was estimated to be as high as 16% of the French GDP in 2012—an enormous value!

8. Bridge aesthetics

A successful bridge design must be natural, simple, original, and harmonious with its surroundings (Fig. 8). A bridge is usually a large and very visible structure within its environs. It should look natural and fit well into the landscape. It should also be simple and not look superficial. A structure looks more natural if it can convey an understandable impression to the public about how it works.

Fig. 7. Typical memories of Paris focus on the aesthetics of structures and other artwork, including the bridges across the Seine River.

Fig. 8. A successful bridge design must be natural, simple, original, and harmonious with its surroundings.

Uniqueness is an important factor in any piece of art. Likewise, each bridge should be unique in and of itself. Each structure has its own requirements and distinct surroundings. Each bridge design should be based on its own particular conditions. Therefore, each bridge should be original and have its own style, characteristics, and design. Like a painting, only an original bridge is valuable.

Being harmonious with its surroundings does not necessarily mean that the bridge must only blend well with its environment. It also means that the structure should be configured such that it "fits" well in its position. This may often mean that the bridge stands out from its surroundings, if doing so is more appropriate. A bridge is viewed from many different angles, so looking good from only one viewpoint is not sufficient.

9. What are bridge aesthetics?

A bridge is mainly comprised of girders, piers, towers, and perhaps cables. The girders are relatively horizontal, and the piers and towers are generally vertical. A bridge typically has two abutments, one at each end. These are all the elements to be dealt with. Common sense recognizes the following:

- The soffit should camber upward to avoid a sagging appearance. A haunch girder should have a smooth curvature.
- Catenary, circular, and parabolic arch shapes each have different characters.
- The bridge alignment is usually straight. Curvature in a bridge always introduces some form of intrigue; however, curves must be handled with care. Curvature can create completely different impressions when looked at from different viewpoints.
- For box girders, sloping webs look lighter; however, this may create complex and messy lines when the bridge is in a curve.
- Symmetry looks more robust and traditional, but asymmetry offers a more intriguing appearance.
- Viewers may be located on the bridge, under the bridge, or looking at the bridge from any angle of its surroundings. Glorifying one view from a specific location and neglecting the other views is not desirable.
- Piers should express the flow of the load path. Textures can be used to reduce a monotonous appearance.
- Long cantilever slabs over box girders cast a shadow, which makes the girders look more slender.

Of course, the factors listed above are just commonsense observations, not rules. Most engineers are accustomed to following rules; however, even though not everyone agrees, most people have concluded that there are no rules for aesthetics. The Greeks devoted an extraordinary amount of time to aesthetics 3000 years ago. Their buildings were very meticulously designed and constructed, and the Parthenon has been recognized by many as the most perfect building in history. Careful investigation of the Parthenon has indicated that every detail was meticulously attended to in order to compensate for the perception of the human eye. For example, all the horizontal lines of the Parthenon are curved upward to make them look horizontal. The spacing between columns is not the same, in such a way that it appears the same to the human eye. The diameter of the columns is also very specifically not uniform, in order to make it look uniform. These technical details were given particular attention, even though they were based on common sense rather than on rules.

Many scholars have tried to establish rules for structural beauty, but none have succeeded. For example, the "golden section" concept, which is supposed to prescribe the proportion of the best-looking rectangle, has been studied and promoted by various architects for years. However, even today, after centuries of study and debate, no one can really say whether a rectangle with a proportion of the two sides of Φ ($\Phi = 1.61803$) definitely looks better than a square, under any circumstances.

In general, aesthetics is about proportion, balance, and harmony. The Italian Renaissance architect Alberti defined beauty as "a harmony of all the parts." When we look at an object, we do not go through any logical derivation to determine whether it is beautiful or not; our reaction is a more spontaneous one. Although human perception often changes with time, real beauty transcends time and style. A beautiful bridge can be dramatic and daring, but it can also be graceful and poetic. The basic idea of bridge design is to inspire an emotional response from viewers, and even a kind of surprise. How we achieve this is can be called an art.

Nature endorses simplicity; many of the important rules of nature are simple. Even the most important equations of nature in physics are extremely simple, such as $F = m{\cdot}a$, or $E = m{\cdot}c^2$. The human mind, which has historically been immersed in nature most of the time, is accustomed to simplicity. It has been repeatedly proven that the simplest configuration is usually the best-looking solution. It has been stated that in order to arrive at the most beautiful structure, the best method is to try to take away any component that can be taken away, in a process of simplification. Obviously, this requires experience and a good understanding of structure and aesthetics.

We teach our children to walk properly, talk properly, and move properly. A person with a good posture automatically emits a certain charisma—clothing style and accessories are secondary. Good posture costs nothing; once a person is well-trained in manners and attitude, it comes naturally. A similar premise applies to bridge design and, in fact, to any kind of art. If we disregard the skill of the artist or the designer, the actual cost of a good painting versus a bad one is basically the same and comprises the costs of the canvas, paint, brushes, and so forth. In the same way, the difference in the basic cost of a beautiful bridge versus that of a mediocre bridge may be very little. In reality, a well-designed, attractive bridge is usually more economical because it is more natural and simple; it follows the intentions of nature.

We should treat bridge design as an art. However, a bridge is not just a function of art: The basic purpose of a bridge is still to carry traffic. A sculpture may be created simply because it looks attractive, but a bridge is never built for the same reason. It is obvious that there are three distinct differences between bridge design and other art forms. First, a bad painting or other artwork will just end up gathering dust in a basement somewhere, whereas a bridge, once complete, will be prominently displayed in the public eye for hundreds of years. The community cannot escape being affected by it. Second, the fruits of success are rewarded to the painter or other artist, whereas in our present system, there is little incentive for a bridge engineer to spend additional effort to strive for the best-looking bridge form—his/her fee will probably be the same regardless. Finally, most other artists work more or less alone, whereas an engineer works in a group and must deal with many related parties, including economists and politicians, who may elect to impose their own ideas on the bridge design and designer.

Making the effort to search for the best-looking bridge alternative requires time and effort. However, once this practice becomes routine in design, the additional effort is not significant. Despite the abovementioned factors, it is still the responsibility of the bridge engineer to pay attention to aesthetics. An unattractive bridge is a kind of pollution to the community—one that will remain present for a very long time.

10. Decorations

Decoration is like cosmetics: True beauty does not need makeup. The most successful bridge is one that fully expresses itself through its structural form. The touching up of small details, such as adding covers to hide cable anchorages, is not decoration; installing statues or flowerpots is.

A bridge is a large structure. In most cases, the magnitude and form of the bridge itself are so powerful that decoration only makes the bridge look less impressive. However, if a bridge is built to symbolize certain events or a relationship, like the Pont Alexandre III in Paris, which was built to celebrate the friendship between the Russian Empire and France, decoration can convey certain meanings and impressions.

In general, city bridges tend to be more suitable for decorations, which can create more harmony with the bridge's surroundings. City bridges tend to be smaller in size as well. A bridge in a natural setting should be more natural and simple; decoration is usually not desirable.

11. Aesthetic lighting

Aesthetic lighting is an art in itself: It not only makes bridges visible, but also gives them vibrancy at night. However, it is important to differentiate between illumination and aesthetic lighting. Illumination simply makes a bridge visible; aesthetic lighting makes use of the interaction between light and the structure to create special effects and impressions (Fig. 9).

It is important for aesthetic lighting to be considered early on in the design so that all the physical facets of lighting can be properly accommodated in the structure. Some lighting elements may appear unattractive in the daytime if they are not properly located.

Fig. 9. Aesthetic lighting gives vibrancy to bridges at night.

12. Who designs the bridge—the engineer or the architect?

A bridge is not a sculpture; in addition to having a pleasing design, a bridge must be safe, functional, and economical. These matters are best dealt with by engineers. It is a bad idea to leave the aesthetics of a bridge to architects alone; architects cannot conceptualize a complete bridge because they do not have sufficient training in structural engineering to perform this task. It is also a bad idea, albeit one that is practiced by many engineers, to ask an architect to beautify a bridge after the engineer has finished the structural design. At that point, all an architect can do is add decorations, which may not always be appropriate.

Aesthetics are not an addition to a bridge, but are an integral part of the bridge design. Both structural configuration and aesthetics must be considered together during the conceptual stage of bridge design. To achieve such a task, the bridge engineer must have a good understanding of structural theory and bridge aesthetics. Unfortunately, most engineering schools do not teach aesthetics. A bridge engineer must learn aesthetics, whether inside or outside of his/her educational training. As a rule, the engineer must be the prime designer of a bridge. He/she must conceptualize the bridge to satisfy all structural and functional requirements with due consideration for aesthetics. As a compromise, he/she can also work together with an architect during the conceptual stage of the design.

13. Innovation

As discussed earlier, each bridge should be treated as a unique design. It is acceptable to borrow recognized concepts from existing bridges; however, each concept must be applied in a unique way. It is unacceptable to copy another bridge design. To make an analogy, although many great artists have painted roses, each artist painted roses in his/her own way. Therefore, each original painting of roses is unique. In contrast, a copy of a painting has little value because it lacks the creative spirit of art. Originality and uniqueness together form innovation; however, innovation also means something new and perhaps nontraditional. New and nontraditional designs are often met with resistance.

Although an artist creates a sculpture or a painting basically by himself/herself, the building of a bridge involves many parties: the owner, the managing agent, various engineers, the contractor, and others. The engineer may not always be the master of the project. As the saying goes, "The donkey was the product of a committee that intended to create the most beautiful horse."

Under such circumstances, uniqueness can often be met with resistance, whether from an owner who prefers to do exactly what others have done before, or—and surprisingly often—from fellow engineers. Some engineers can be very conservative and tend to prefer repeating what has been done before. These resistances are sometimes rational, and sometimes not.

Some great designs were never built because of the resistance of others. A group of engineering experts vetoed Thomas Telford's design of the London Bridge as unbuildable. Fortunately, the same design concept was used to build the beautiful Craigellachie Bridge in Scotland [3]. Similarly, when the Eiffel Tower was proposed, people denounced it as unbuildable and ugly. Today, 100 years later, it has become the jewel of Paris and the pride of French construction and ingenuity. In fact, the public has been in love with the Eiffel Tower since its opening.

Philosophers and fine artists can live in an intellectual world generations ahead of others. They do not have to seek approval, and they own their ideas and concepts. An engineering project, on the other hand, always includes an owner and a designer. Although a bridge engineer designs the bridge, the bridge engineer does not own the bridge. The owner represents the public, and the public has a right to ask for what it wants. Thus, a bridge engineer should never try to build a monument for himself/herself. A bridge engineer is there to serve the public with his/her best effort. Still, despite all these considerations, an engineer must not give up the responsibility to ensure that a bridge is beautiful, in addition to being safe, functional, and economical.

14. An example: Dagu Bridge, Tianjin

The Dagu Bridge may be a good example of a bridge design project (Fig. 10). This bridge, which is located at the center of the city of Tianjin, is part of the Downtown Redevelopment Project that revitalized the old city. One of the first goals of the Downtown Redevelopment Project was to have a signature structure that could become a symbol of the city of Tianjin.

The width of the river at this location is 96 m. The bridge was designed to avoid having any piers in the river, with the resulting design featuring a main span of 106 m. The bridge carries six lanes of traffic and two pedestrian paths, one on each side of the bridge deck. The minimum width of each of the pedestrian paths is 3 m. Two of the traffic lanes are 3.75 m wide, and the other four lanes are 3.5 m wide each. Along with the median divider, barriers, and railings, the required minimum width of the deck is about 30 m. The design speed for this city bridge is 60 $km{\cdot}h^{-1}$, and the live load is based on the Chinese city class A car loading [4].

Fig. 10. Renderings of the Dagu Bridge in Tianjin.

Both ends of the bridge connect to existing streets, so the deck elevation of the bridge is fixed. The bridge also accommodates future sightseeing boats on the river. These two requirements restrict the maximum girder depth to 1.38 m at the centerline of the bridge. The cross slope further reduces this to 1.3 m at the edge of the traffic lanes.

Tianjin is very close to Tangshan, where a major earthquake in 1976 caused very extensive damage and fatalities. Consequently, the Dagu Bridge was designed for the highest seismic forces in China. Unfortunately, the upper layers of soil are very soft, which eliminated all bridge types from consideration that required anchorages for horizontal forces.

14.1. The Dagu Bridge concept

Conceptual design is the most important step in the design of a bridge. A proper conceptual design solidifies the structural system, aesthetics, cost, and functionality of the bridge. It should also come with a construction method and solution for important details. Every bridge has certain restrictions. The conceptual design must properly consider and provide solutions for all these restrictions.

After it was determined that the Dagu Bridge was to be a tied arch bridge, the logic for the conceptual development that led to the final configuration was suggested (Fig. 11), as outlined below:

- Due to the river's navigational requirement, the arch must be above the deck.
- The minimum deck width is about 30 m, and the girder depth is restricted to 1.38 m at the centerline of the bridge, as shown in Fig. 11(a).
- The arch bridge should have two arch ribs, usually one on each side of the deck. These ribs should be over 32 m apart, as shown in Fig. 11(b).
- The girder is only 1.38 m deep; this is not sufficient to span a 32 m wide deck transversely, so the arch ribs cannot be located outside of the deck. As a solution, the two arches can be moved to the edges of the six traffic lanes (they ended up about 24 m apart, as shown in Fig. 11(c)).
- If the two arch ribs were not connected to each other, they would have to be quite bulky in order to avoid lateral buckling. This is aesthetically unpleasing and unacceptable; moreover, two vertical arch ribs would appear mundane.
- It is customary to tie the two arch ribs together with struts to stabilize them so they can be more slender, as shown in Fig. 11(d). However, this would look too messy because the bridge span is relatively short and the arches are rather small. This solution is also aesthetically unacceptable.
- To reduce the length of the braces, it is possible to incline the arch ribs inward to form a basket-handle arch, as shown in Fig. 11(e). However, for a relatively short, 106 m span, a basket-handle configuration appears too flat and bulky.
- Instead of the conventional transverse braces, a three-dimensional structural system employs two planes of hangers tying each arch rib to the deck girder. The two planes of hangers give support to the arch rib in both the vertical and transverse directions. This stabilizes the arch against lateral buckling. Thus, the ribs can be made very slender, as shown in Fig. 11(f).
- Now, with two planes of hangers stabilizing each arch rib, the arch ribs can be tilted in any way desired. Here, they are tilted outward. This offers a very open view looking from the deck.
- The surrounding landscape is very asymmetrical; therefore, the height of one arch can be increased to make it more intriguing. The taller arch is given a smaller inclination so that it does not lean too far outward.

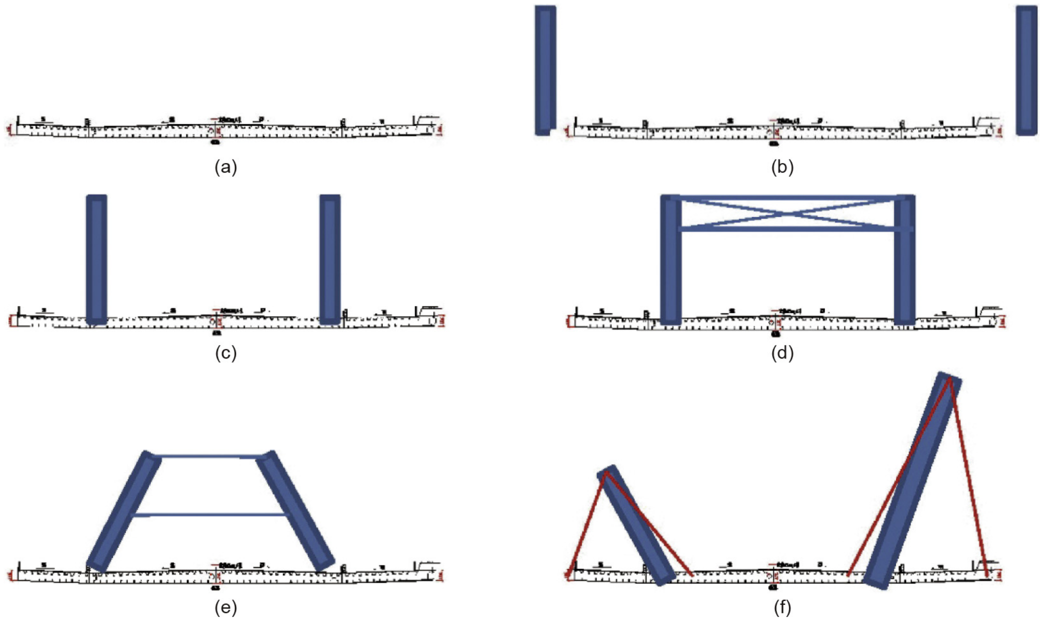

Fig. 11. Development of the Dagu Bridge concept.

14.2. Design of the Dagu Bridge

The owner metaphorized the development of the Hai River as a "golden dragon dance" because the Hai River runs diagonally across the entire city, a bit like a dragon's sinuous tail. The configuration of the Dagu Bridge symbolizes the sun with its large arch, the moon with its small arch, and the stars with the lights around the edges of the deck; all of these compliment the concept of the dragon (Fig. 12).

In this basic structural system, the arch ribs provide the vertical stiffness for the bridge; the deck provides the lateral stiffness, and the cables combine the two together into a compact system. The bridge itself is stable while supported on piles.

For a 106 m span, the rise of the arch ribs would usually be about 20 m. To introduce some architectural surprise and intrigue, the two arch ribs are of unequal heights, as mentioned earlier. The small arch is 19 m high and the large arch is 39 m high. To create further architectural interest, the pedestrian paths curve outward to offer additional space for pedestrians to rest and enjoy their surroundings.

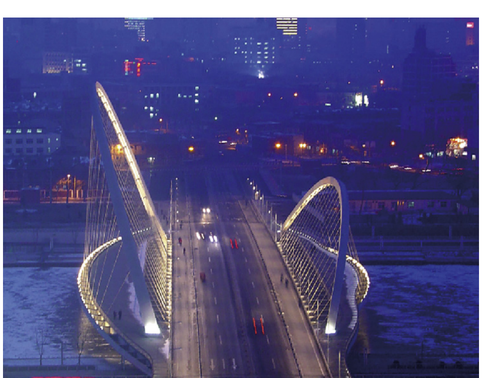

Fig. 12. The large arch of the Dagu Bridge symbolizes the sun, the smaller arch symbolizes the moon, and the lights around the edges of the deck symbolize the stars.

14.3. Aesthetic lighting

Three different sources of light illuminate the Dagu Bridge. The first light source is the streetlights on the bridge and along the riverbanks. The second light source is the spotlights on each hanger at a level slightly below the bridge deck. Two spotlights are installed at each hanger location in order to obtain a more uniform reflection on the arch ribs. These lights illuminate the arches and cables. The third light source is a set of lights under the edge plates at the outer rim of the pedestrian paths. These lights reflect the water underneath and horizontally through the holes in the edge plates. The intensity of these three light sources is well coordinated and expresses the elegance of the structure at night (Fig. 13).

Fig. 13. The Dagu Bridge. (Note: T.Y. Lin International provided the conceptual and preliminary designs of the Dagu Bridge. Tianjin Urban Construction Design Institute provided the construction plans.)

15. Summary

By taking advantage of the flexibility of engineering and by utilizing the three basic elements—the ABCs of structures—engineers should be able to create bridge forms to fit any occasion. Bridge design is not difficult; the design must be kept natural, simple, original, and harmonious with the landscape. A bridge engineer cannot neglect this responsibility.

If we want quality in our lives, we must have quality in our environment. If we want quality in our environment, we must pay close attention to the beauty of the structures we build, including all bridges. We must keep our world beautiful for the enjoyment of all of its citizens. This is the only world we have.

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