EVOLUTION OF BRIDGE TECHNOLOGY

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SUMMARY

The evolution of bridge technology can be divided into two major eras: The Arch Era, from 2000 BC to the end of 18th century, was dominated by the Roman structures. They were practically all stone arches. The Contemporary Era that followed and continues today, flourished after steel was commercially available as a construction material in the mid 19th century. All modern bridge types including girder bridges, cable-stayed bridges, suspension bridges and arch bridges, especially those with larger spans, have been possible only because of the high strength of steel, both in compression and in tension.

Keywords: bridges, bridge evolution, stone bridges, steel bridges, concrete bridges, bridge technology

1. INTRODUCTION

If we observe the anatomy of all structures in the world, we find that there are basically only three types of structural elements: those that transfer the forces that act upon it by **a**xial force, by **b**ending or by **c**urvature. A member in a truss is an axial force element. A beam is a bending element. And, arch ribs and suspension cables are curvature elements. These can be defined as the "ABC of structures", Fig. 1.

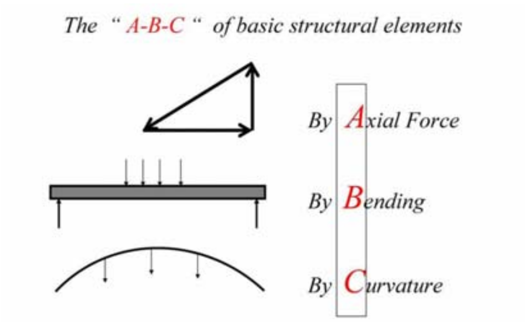

Fig.1 Basic Elements in Structures

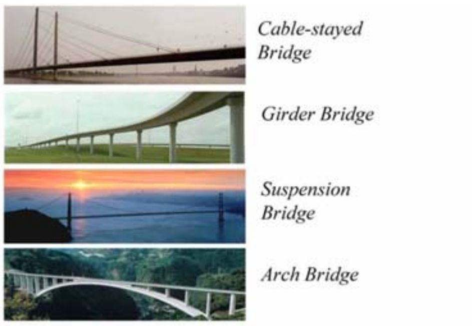

Fig.2 Four Types of Bridges

Every structure is a combination of these three types of elements. Some elements may have one type as its primary function and the other as secondary, such as the girder of a cable-stayed bridge. It is primarily an axial force element, but due to strain compatibility, it also must carry loads by bending.

Looking closely, we also find that each of these elements takes one of the four basic forms: a truss, a box, a stiffened plate, or a solid member.

Going one step further, we can conceptually group all bridges in the world into four basic bridge types: girder bridges, cable-stayed bridges, arch bridges and suspension bridges, Fig. 2. Some bridges are a combination of two or more types, such as an extradosed bridge, where the girder is the primary carrying member and is further strengthened by cable suspensions.

2. EVOLUTION

Engineering is an art, not a science. As an art, its practice precedes its theory. History shows that the application of the three types of structural elements and formation of the four bridge types existed in very ancient times, even though there was no theory to guide their design. Structural theory emerged only a few centuries ago. In ancient times, tree trunks were used as a girder to bridge gaps in roads. Vines and ropes were used to span larger distances forming the early suspension bridges. These types of "structures" were intuitive and their construction materials were readily available in nature.

In other words, all four types of bridges have existed for several millennia already. In the last few thousand years, we really have not "invented" any new bridge types. Rather, we have just been improving upon the existing types. As civilization has advanced, the bridges we built have become more sophisticated, bigger, stronger and more durable. It has been a process of evolution!

3. CIVILIZATION

Advances in civilization proceed on multiple fronts. In the construction industry, progress in structural theories, construction equipment improvements, as well as the introduction and improvement of new construction materials have all played a role in the evolution of bridge technology. However, close observation of how ancient Egyptians built the Pyramids and how the Romans built the domes and bridges reveals that the one most important factor in the evolution of bridge technology is the advancement in materials. The Egyptian and Romans did not have major construction equipment. But the structures they built were spectacular. The Great Pyramid of Gizeh has over 2 million pieces of stone blocks weighing about 2.5 tons each. The accuracy of its dimensions is better than 1 to 1000. Hence, we may conclude that human beings are very innovative. Whenever a new construction material becomes available, engineers are able to utilize it to build structures.

From tree trunks to precut lumber, wood has been available in nature all along. Hence, wood has steadily been a construction material for bridges over the last several thousand years, and many wood bridges are still being built today. But all ancient pure wood bridges were of minor span bridges, and did not last very long. In fact, most of them had already disappeared, preserved only in paintings or illustrations. The ancient bridges that have lasted until today are exclusively stone bridges.

Aside from wood, the three materials that significantly influenced bridge evolution are concrete, stone and steel. Concrete is a mixture of various sizes of stone aggregates, cement and water. The Minoans started to use lime mortar, or a kind of early cement, around 2000 BC. The Greeks used it too. But this material dissolved in water and was, therefore, not very weather resistant. The Romans made a significant improvement to it by adding a volcanic ash from the town of Pozzuoli. We may consider this as a primitive form of concrete. The Roman used it, together with stone, to build many coliseums, palaces, temples, viaducts and bridges. But both stone and this “concrete” are compression materials that can not carry tension, which limits their application.

Iron is of a higher strength, but is still mainly a compression material. Its tensile capacity is very limited. Steel was widely available around mid 19th century after it could be mass produced by the then newly developed processes. Steel was the first material that was good for both tension and compression. With its development, bridges with major spans became possible.

Portland Cement was officially introduced by Josepf Aspdin in 1824 and reinforced concrete was first patented by W.B. Wilkinson in 1854. Accordingly, even though most bridges today are reinforced concrete bridges, the history of reinforced concrete is only about 150 years.

4. MATERIALS AND BRIDGE FORMS

As mentioned above, there are only three basic types of structural elements. Each element can be stone, wood, iron, concrete or steel, or whatever new material we may have. With these elements, we conceptualize the form of a bridge. Consequently, we may develop a flow chart on how a bridge comes into being as shown in Fig. 3. When the need arises, we establish the purpose of a bridge, from which we define its function. The function determines the applied loads, the size and the location of the structure. Before we can conceptualize the form of the structure, we must know the availability and capacity of the construction material we can use.

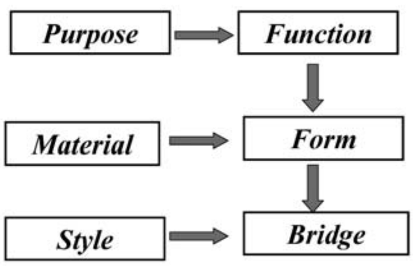

Fig.3 Flow Chart

Certainly, some people may find it unconvincing to define those tree trunks, stone slabs and vine suspensions as bridges due to their very primitive form, even though their function was to bridge over an existing gap. We may want to call a structure a bridge only if it is of certain size and capacity. If this is the case, then arches are the only bridge type that existed until very recently in history. Based on this assumption, we can divide the evolution of bridges into two major periods within the last four thousand years: the arch era form 2000 BC to about end of 18th century and the contemporary era since then.

5. ARCH ERA

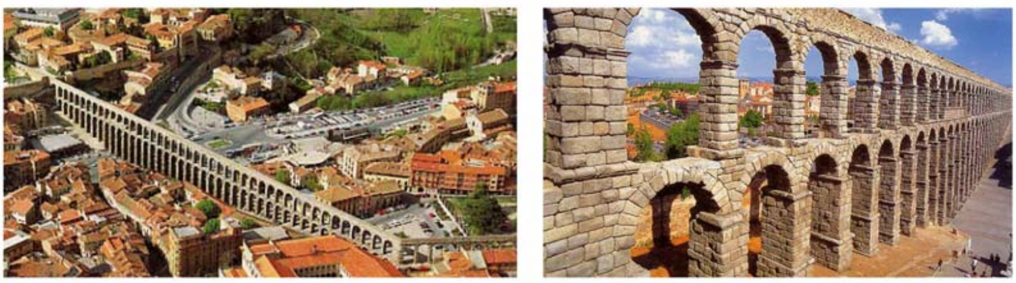

Fig.4 Roman Viaduct in Segovia

Arch is the perfect form for compression materials such as stone, brick and concrete, materials that were available a few thousand years ago. A properly configured arch can avoid any tensile stress in the structure. That is the reason why only arch bridges were built before iron and steel were commercially available for construction.

Various arch forms were used to build temples and palaces in very early civilization, traceable back to 2000 BC. But arch as bridges and viaducts were really well developed by the Romans. The Romans built many spectacular arch bridges, and quite a few of them are still standing today. The viaduct in Segovia, Fig. 4 is over 2000 years old and is still intact. Another well preserved Roman bridge, the Ponte Quartro Capi, is undoubtedly a master piece, both structurally and aesthetically, even by today's standards

Roman arch bridges utilize semi-circular arch forms, a form that later came to be called the "Roman". The Chinese had first employed the partial circular arch at the Zhao Zhou Bridge, Fig.5, also called the An Ji Bridge, which has a span of 37m. This is an extremely elegantly shaped stone arch bridge. The bridge was completed around 600 AD, and it is still in use today.

Fig.5 Zhaozhou Bridge

The major difference between a semi-circular arch bridge and a partial circular arch, which is sometimes also called a segmental arch, is that the former has a rise to span ratio of 1 to 2 and the latter is much flatter. The Zhao Zhou Bridge has a rise to span ratio of 1 to 5.3 (7m rise and 37m span). This resulted in a much flatter bridge that is more comfortable for the pedestrian and an extremely elegant configuration. To lighten the load on the arch ribs, the spandrel of the Zhao Zhou Bridge is slightly open with additional arch openings. These openings not only reduced the weight of the structure, they also made the bridge look much more slender and delicate.

Fig.6 Natural Bridge

A modern arch bridge today would probably have a rise to span ratio of between 1:5 and 1:10, a testament to the innovativeness of the builder of the Zhao Zhou Bridge.

Many notable stone arches have been built around the world, in Europe, India, China, and other places. Many are still being built. Stone arches are very beautiful structures and are the one bridge form that is closest to a natural form. They blend very well into the natural landscape. This is especially true for flatter arches because such formations can be easily found in the nature, Fig. 6.

6. IRON BRIDGES

Iron is a higher strength material than stone. Its tensile capacity is low but is still significantly higher than any material available before steel could be mass produced. There have been many major bridge structures built with iron. It was reported that the very first major iron chain bridge was built in China around 600AD – the Lan Chin Bridge in Yunnan Province with a main span of about 60meters. (Joseph Needham, “Science and Civilisation in China.” Cambridge University Press, 1971). China built many iron chain bridges, some of which are still accessible today, Fig. 7. These very early suspension bridges were a special type of suspension bridge, what we call “stress-ribbon bridge” today. The deck was placed directly over a bundle of cables.

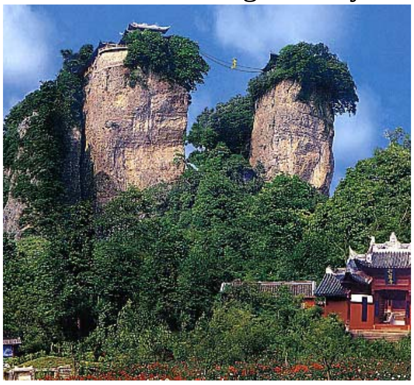

Fig.7 Iron Chain Bridge

It is generally recognized that one of the first modern suspension bridges was the Menai Strait Bridge designed by Thomas Telford based on the patent of James Findley of the United States. The 176m span was a major milestone in bridge construction. The bridge was completed in January 1826 with iron eye-bar chains as suspension cables. James Findley also built a number of suspension bridges himself but they were not successful. Many of these early suspension bridges did not stand the test of time. The problem had to do mainly with aerodynamics which was not properly understood until mid 20^{th} century. The Menai Bridge was seriously damaged by wind only 13 years after it was completed. It had to be rebuilt and then rebuilt again!

Thomas Pritchard recognized that iron was much stronger than wood, especially in compression. His design of the Iron Bridge at Coalbrookdale, Fig. 8, an arch bridge over the Severn River with a span of 100 feet (30.5m), is a classic by itself. Completed in 1779, the bridge’s slender arch ribs, which were stabilized by connectors, or struts, gave the bridge an extremely delicate appearance. More noteworthy was the short erection time of only three months after the iron casting was done.

Fig.8 Coalbrookdale Iron Arch

Construction of iron arch bridges continued even after steel was available, most notably the iron arches by Gustav Eiffel. The 160m span Pia Maria Bridge in Portugal, completed in 1877 and his last arch bridge, the 165m span Garabit Viaduct in France, completed in 1884 are both master pieces.

In the first half of the 19^{th} century, before steel was available, the extensive railroad construction program had required many new bridges, especially in England. Some of these bridges were iron bridges.

7. CONTEMPORARY ERA

The introduction of steel completely changed the landscape of bridge construction. While arch bridges had dominated the last few millennia, for the last 150 years or so, a large number of spectacular bridge types were built. Long span girder bridges, suspension bridge, and finally cable-stayed bridges were well developed in one way or the other, all with the help of steel.

The influence of steel in modern bridge construction can be summed up in three categories: 1. the steel plates used for girders and bridge towers; 2. the cold drawn high strength steel wires used for cables in both suspension bridges and cable-stayed bridges; and 3. steel bars in reinforced concrete and the use of the high strength wires as prestressing tendons.

The 521m span Firth of Forth Bridge in England, completed in 1890, is certainly one of the most spectacular early steel bridges. It is still the world's second longest girder span, after the 549m span Quebec Bridge, completed 27 years later. The compression members in the truss structure are steel tubes. The bottom chords, for instance, are 12 feet (3.66m) diameter circular tubes. The bridge was built after the collapse of the Firth of Tay Bridge in December 1879. Probably for that reason, the design of the Forth Bridge appeared to be overly conservative, which made it look rather messy. For a long period of time, some people deemed it as one of the ugliest structures. But it has been successfully serving its purpose until today.

About the same time as the Firth of Forth Bridge was built, several beautiful steel bridges were constructed: the St. Louis Bridge over the Mississippi River by James Eads and several suspension bridges by the Roeblings in the United States, the most famous of which is the Brooklyn Bridge in New York.

The St. Louis Bridge was completed in 1874. The three main arch spans are 502 ft + 520 ft + 502 ft (153m+158.5m+153m). This was probably the first major steel bridge after the mass production of steel was made possible by the new processing methods.

More major arch bridges were built as steel was introduced to the industry. Gustav Lindenthal's Hell Gate Bridge in New York was a trend setting structure. The bridge has a main span of 298m and was designed for heavy railway loads. Completion of the Hell Gate Bridge prompted the construction of two very famous steel arch bridges: the 503m span Sydney Harbor Bridge in Australia, completed in 1932 and the 503.6m span Bayonne Bridge in New York, completed in 1931. The Bayonne Bridge, designed by Ottmar Amman, who had worked as Lindenthal's assistant, appeared to rival the Sydney Bridge. It was started later but finished earlier and with a span just a bit longer. A still longer span steel arch, the 1700 ft (518.3m) span New River Gorge Bridge in West Virginia, USA was completed in 1978, some 47 years after the completion of the Bayonne Bridge. The world record today is in China. The Lupu Bridge was completed in 2004 with a main span of 520m. Another steel arch is under construction in Chongqing, China with a main span of 552m, scheduled to be completed in 2009. The arch ribs of all these bridges, except Lupu, are truss members. The new generation of arches is much more slender. In such configurations, the old concept of having only compression in all members of an arch is no longer valid. There are both high tensile and compressive stresses in the arch ribs, which can be carried by steel members.

7.1 WIRE FOR CABLES

Development in wire technology made long span suspension bridges possible. Cold drawn wrought iron wires had been used to build several suspension bridges in the early 19th century. The "Grand Suspension Bridge" over the Sarine Valley in Fribourg, designed by Joseph Chaley, with a main span of 273m, was completed in 1834. But the real progress to ocme would be due to the use of steel wires, which have much higher strength than iron wires. Steel wires are also more resilient.

As mentioned above, the problem that plagued the long span suspension bridges in those days was wind. From Findley's design to Telford's Menai Bridge to Charles Ellet's Wheeling Bridge over the Ohio River, which had the world's longest span of 308m, all were troubled by wind action. John Roebling was the first to successfully stabilize a bridge against wind actions. Even though aerodynamics was not yet well understood in that time, his intuition to install inclined cables to stabilize the bridge against wind-induced oscillations was successful for the bridges he built. The collapse of the first Tacoma Narrow's Bridge in 1940 initiated a fury in the research in aerodynamics. This research has offered a way to design against wind actions for ever longer span suspension bridges today.

Fig.9 Golden Gate Bridge

Fig.10 Gibraltar Strait Bridge

Several landmark suspension bridges have been successfully completed after the Brooklyn Bridge: the George Washington Bridge was the first to break through the 1000m span length in 1931; the ever legendary Golden Gate Bridge, Fig. 9, with a span of 4200ft (1280m), was completed in 1937; and the longest span today, the Akasi Kaikyo Bridge in Japan with a span of 1991m, was completed in 2000. The Messina Bridge in Italy, with a 3,300m span, is under construction while a twin span of 5,000m suspension bridge across the Gibraltar Strait, Fig. 10, proposed by the late T.Y. Lin, has shown that, with the steel wire and engineering knowledge we have today, a much longer span is technologically possible.

7.2 REINFORCED AND PRESTRESSED CONCRETE

As mentioned above, reinforced concrete was patented only about 150 years ago. With steel reinforcement carrying the tension and the concrete carrying the compression in a member is an ingenious way of fully utilizing the physical properties of each material. And pre-compressing the concrete using high strength tendons is another significant innovation that has propelled concrete to being the most popular construction material for bridges today. This pioneering idea by Eugene Freyssinet and the many practical applications developed by Ulrich Finsterwalder have offered us opportunities in the construction of many short, medium and long span bridges in prestressed concrete.

Cantilever construction started only in 1952 for the Balduinstein Bridge over the Lahn River in Germany. The method was already well developed in the early 1960s for the successful construction of the 208m span Bendorf Bridge, Fig. 11, over the Rhine in Germany. Since then, many long span concrete bridges have been completed all around the world.

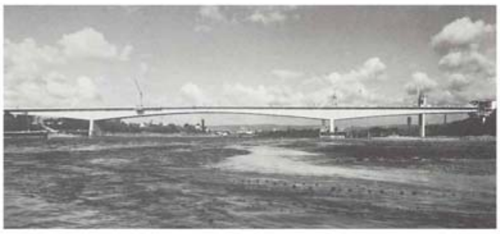

Fig.11 Bendorf Bridge

Fig.12 Second Shibanpo Bridge

Currently, the longest full concrete bridge is the 301m span Stolmasundet Bridge in Norway. The longest box girder span is the newly completed Second Shibanpo Bridge, Fig. 12, in Chongqing, with a main span of 330m. The Stolmasundet Bridge utilizes light weight concrete in the middle section of the main span to reduce weight. The Shibanpo Bridge has a 103m steel section in the middle of the main span for the same reason.

Obviously, prestressing is possible only after high strength steel is available. If the steel strength is not sufficiently high, creep and shrinkage of concrete, plus the relaxation of the steel itself would render the prestressing relatively ineffective. Again this is another example of how the availability of a specific construction material has changed the form of the bridge.

7.3 CABLE-STAYED BRIDGES

The idea of cable-stayed bridge is rather straightforward. But a cable is only effective if it is stressed to a certain minimum force to take out the effect of the sag. Consequently, the material of a cable must be able to carry high tension so that after the initial tension, it still has sufficient residue capacity to carry additional loadings. This explains why many attempts to build cable-stayed bridges were not successful before high strength steel was available.

The Stromsund Bridge in Sweden was recognized as the first modern cable-stayed bridge. Designed by Franz Dischinger, the bridge has a main span of 183m and was completed in 1955. Cable-stayed bridges were found to be very efficient for medium spans. In the ensuing two decades, a good number of major cable-stayed bridges were completed in post-war Germany. The span of cable-stayed bridges in Germany kept increasing, until the two world record spans of Knie Bridge (320m span) and the Neuenkamp Bridge (350m span), Fig. 13, were completed in the early 1970s.

Fig.13 Neuenkamp Bridge (left) and Knie Bridge

Since then, many long span cable-stayed bridges have been completed around the world, with the record span increasing to the 602m span Yangpu Bridge in China, completed in 1994, the 856m span Normandy Bridge in France, completed in 1995 and the 890m span Tatara Bridge in Japan, completed in 2000. Two superlong span cable-stayed bridges are currently under construction: the 1018m span Stonecutters Bridge in Hong Kong, to be completed in 2009 and the 1088m span Sutong Bridge in China, to be completed in 2008.

Without high strength wires, these cable-stayed bridges would not have been possible.

7.4 COMBINATION OF BRIDGE TYPES

It is possible to combine two of the four types of bridges; girder bridge, cable-stayed bridge, suspension bridge and arch bridge, into new bridge systems. Roebling's suspension bridge with stay cables was effective. But the stay cables were mainly used to stabilize the bridge against wind vibrations. They did not carry the intended 50% of the load because it was difficult to separate these two systems.

F. Dischinger proposed to have a real combination of the two cable systems, forming a bridge with partial cable-stays and partial suspension, Fig. 14, for superlong span bridges. Unfortunately, the concept has not been tried on a long span bridge yet, it has only been used on a few small spans.

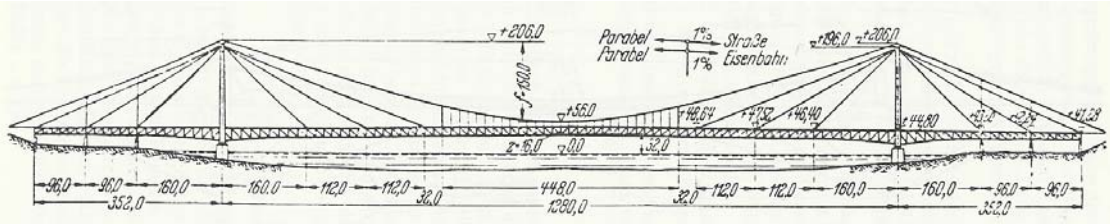

Fig.14 Dischinger's Combination of Suspension and Cable-stayed Bridge System

The concept of a partially cable-supported girder bridge was proposed by the writer recently and has been applied to the design of several medium span bridges in China. The idea is to fully utilize the capacity of the bridge girder while the supporting cable system is only designed only for the forces required to sufficiently supplement the girder capacity to carry the design loading. This is contrary to the concept of a conventional cable supported bridge, either a cable-stayed bridge, a suspension bridge or an arch bridge, where the cables are supposed to be the main load carrying members. These cables carry practically all the loads on the girder and transfer them to the towers or the arch ribs. The extradosed bridge is a special case of partially cable-supported girder bridge. But certain pre-requisite conditions on geometry must be satisfied so the cables can be designed as external prestressing tendons to achieve economy. If the towers are made taller, the bridge will not be qualified as an extradosed bridge anymore. But the general partially cable-supported girder bridge does have these restrictions. Fig. 15 shows a variety of possible configurations of partially cable-supported girder bridges.

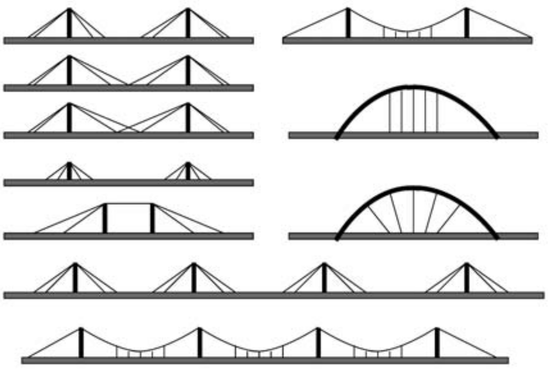

Fig.15 Partially Cable-supported System

8. OTHER INFLUENCES

It may be an interesting question to ask if the Egyptian or the Romans were given the materials, mainly the high strength steel we have today, but not the tools and equipment we use, would they be able to build the major spans we have completed? It appears that the answer would be positive considering what they had achieved two thousand years ago. The only exception is probably the knowledge in structural dynamics, especially aerodynamics. But Roebling had provided, intuitively, the stabilizing stay cables against wind vibrations without any theoretical investigations. They worked!

Hence, we may conclude that, even though structural theory does offer us a better understanding of our structures, it is not a pre-requisite for their realization. Construction equipment has simplified construction and expedited the evolution process. But the lack of modern construction equipment would not have inhibited the process of evolution.

It is the availability of construction materials that is the dominant factor in the evolution of bridge technology!

9. PRE-CONDITION FOR EVOLUTION

As Darwinian theory implies, evolution is a response to the need of coping with the environment. As the flow chart in Fig. 3 shows, a bridge will only be built to serve a purpose, to satisfy the need in traffic. Looking back in history, there are several periods of time in which a large number of bridges were constructed: the Roman Empire, the era of industrial revolution, post-war Germany and today, in China, and soon, India and other developing countries, where a buildup of the infrastructure is pre-requisite for the modernization of the economy. Innovative ideas and inventions in each of the past periods had brought the evolution of bridge technology to a new height. The Romans perfected stone arch bridge construction. The industrial revolution brought us iron and steel as well as innovative concepts of long span suspension bridges. The reconstruction of destroyed bridges in post-war Germany, even though it occurred in only a short period of about 25 years, saw the development of the steel orthotropic bridge deck, cable-stayed bridges, cantilever construction, and modern stress ribbon bridges. It was a very productive era. In each of these past bridge building periods, there had been major developments in bridge technology. Today, we are in the midst of another bridge building era, in China and some other countries. We hope it will bring us another major advancement in the evolution.

10. COST VS VALUE

A construction project will be realized if, and only if, its value is greater than, or at least equal to its cost. Most of the time, it is not possible to determine either the cost or the value of a bridge accurately numerically. A lot depends on experience and empirical concepts. A great portion is probably perception. Nevertheless, in the mind of every decision maker, or stakeholder, there must be some sort of an equation on cost and value.

Toady, the cost of a bridge project can be estimated more accurately: planning, capital, construction, right of way, management, maintenance, and etc. It is not a science yet, but it looks more like a science.

The value of a bridge project is less clear. The value of a bridge consists mainly of commercial value, aesthetic value and political value. There have been bridges built mainly for political reasons such as a promise to connect two communities. It is certainly hard to put a number on the value of such a project. But some bridges offer political value besides commercial value.

Aesthetic value is usually a byproduct. Obviously no one would build a bridge just because it looks good. But a good looking bridge does contribute additional value to the environment. The value of the Golden Gate Bridge for the City of San Francisco, or even for the United States as a whole, is tremendous. Aesthetic value is usually not part of the equation when the bridge is originally conceived. But it should be the responsibility of the bridge engineer to assure that the bridge he/she is designing will add value to the environment, instead of degrading it.

The commercial value is simply the value we place on the convenience we get from using the bridge. If the user feels that it is worth paying $10 a day for the toll, multiply this by the number of passengers, and we will reach a figure that roughly represent the user's value of the bridge. To this we may add the effect of the traffic on the community and the commerce of the vicinities. The commercial value is usually the main reason why a bridge is built. It satisfies a need in the community.

As the living standard of a community increases, the commercial value of a bridge project also increases. We may find a toll of $10 acceptable today while it was not 10 years ago. Comparing the increase in living standard and the increase in bridge construction cost, we find that standard of living has increased faster than the construction cost. The two sides of the cost/value equation change with time. This means that certain bridges we build today may not have been commercially feasible in the past In turn, a bridge that is not affordable today may become feasible in the future.

11. CONCLUSION

The evolution of bridge technology can be divided into two major eras: the Roman era and the contemporary era. The Roman Empire, which occupied most of Europe, was very proficient in construction. Their representative bridge form was the semi-circular arch. Their basic construction material was stone. But for over one and a half millenniums after the Romans, the evolution was kind of stagnant. The contemporary era started during the industrial revolution, when expanding trades prompted the construction of a large amount of railroads, roads and bridges. This era began just about 200 years ago and continues still. This era is signified by the development of long span suspension bridges, segmental concrete bridges and cable-stayed bridges, which were all made possible by the introduction of steel.

Coming back to our flow chart in Fig. 3, bridge form follows the construction material available at the time. In the last few thousand years, two materials have influenced the bridge evolution most: stone and steel.

Today, we have new materials being introduced to the construction industry. We have built prototype bridges with high performance concrete with strength up to 200MPa. We have also built test bridges with composites of extremely high strengths. Will these materials write another chapter in the evolution of bridges?