

DEVELOPMENT AND HISTORY OF STEEL BRIDGES

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ABSTRACT

The origin of iron can be dated back to the birth of the universe. The universe was thought to be born at the Big Bang which took place 13.7 billion years ago. Through the process of nuclear fusion, iron is born as the last stage product. Application of iron to the human life has also a long history. It was about BC 4000; a technique of iron production was invented by burning iron ore with charcoal. A piece of iron dagger was found from a tomb of Hittite King. It was supposedly made at about BC 3000.

The Industrial Revolution began in England. The early glorious founders of modern steel bridges include the following people: Telford, Thomas (1757-1834), Stephenson, Robert (1803-1859), Eiffel, Alexandre Gustave (1832-1923), Roebling, John Augustus (1806-1869) and Brunel, Isambard Kingdom (1806-1859). The Iron Bridge at Coalbrookdale has been described as the "Stonehenge of the Industrial Revolution".

With the introduction of truss bridges made of steel, the previous limits to span lengths were expanded. The span length of truss bridges recorded the world record when the Firth of Forth Bridge was erected in 1889, with a largest span of 521m and the Quebec Bridge across the St. Lawrence River was completed in August 1919 and renewed the record with the main span of 548.6m. In 1907, however, during the construction of the biggest cantilever bridge in the world, a tragedy occurred; later in 1916 the tragedy was repeated when the central portion was about to be completed.

It is due to the high tensile strength of steel in suspension bridges that made large spans possible. In the USA at the end of the 1800's and the beginning of the 1900's a number of striking suspension bridges were constructed. Since then the world record of the largest span length of suspension bridges has been continually renewed by Golden Gate Bridge, built in 1937 in San Francisco with the main span of 1280m and the Verrazano Narrows Bridge in New York (USA), built in 1964 and with the main span of 1298m. Currently, the bridge with the largest span length is Akashi Strait Bridge built in 1998 with the main span length of 1991m. As the larger the length of bridges becomes, nevertheless, the more they become vulnerable to aerodynamic instabilities. One of the most famous bridge collapses may be the Old Tacoma Bridge in 1940. On the other hand, bridges in the seismic area should be protected from earthquakes. Thus teachings learned from Hanshin-Awaji Great Earthquakes are invaluable.

After the German innovation just after the World War II, many cable-stayed bridges have been constructed as economical construction and recent increase of Chinese bridges is noted. The maximum bridge span length of cable-stayed bridges is becoming quite comparable to that of suspension bridges. Furthermore, floating bridges are drawing much attention. Such is the case of Yumemai Bridge of Osaka City. Besides, hybrid bridges made of steel and concrete are becoming more popular because of their better corrosion resistance and long life.

Presently, the importance of bridge management and maintenance is becoming widely recognized worldwide because of unavoidable long-term deteriorations. For such purposes, the asset management logistics are being utilized.

INTRODUCTION

The use of iron by mankind can be dated back to BC 4000 [1]. Basically, iron has been produced at first by nature and its origin can be dated back to 13.7 billion years ago when the universe was born with the "Big Bang". The characteristics of iron and steel are really amazing. In view of the evolution process of iron metal

starting from the cast iron to wrought iron and then to steel, steel can be thought to be the current main industrial material representing the iron group. It has a long history of reliability of usage, outstanding ductility, strength, stiffness, weldability, reasonable price and versatility for reuse or recycles.

Although in our highly advanced world of advanced materials such as carbon nanotubes and carbon fiber reinforced plastics nothing else but steel can be considered as the king of industrial materials. As a matter of fact, iron weapons proved to be superb when the Hittite battled with Egyptians. Iron was one of the leading characters of the industrial materials at the industrial revolution and from this time point [2], various iron bridges made remarkable appearances to the world. The desirable steel properties of outstanding ductility and strength contributed significantly to the arrival of the ages of large span bridges to conquer the battle against the gravity.

Of course nothing can be perfect. Steel has many drawbacks at the same time. Take for examples, steel may corrode quite easily if care is not taken. It is quite heavy. It takes a lot of energy and fuel when it is produced. It may lack in the warm touch of feeling as compared with wood. Most of these drawbacks have been successfully improved by innovations such as the inventions of stainless steel and hybrid materials.

It is really amazing to know that steel structures are considered to be much lighter than concrete structures, for an example. The average people may not understand this and think illogical since the specific weight of iron is 7.85 and that of concrete is something like 2.4. How on earth steel structures can be considered to be much lighter than concrete structures if this difference of specific weight is taken into account? Of course, structural engineers can give a good account of this illogical statement. In spite of much heavier specific weight, the steel can come up with much lighter structures than concrete structures thanks to much higher rigidity and stronger strength and easiness of forming cross sectional shape to compensate. Take for example; this structural lightness can be fully utilized when urban viaducts are built in big cities. Basically, big cities with some exceptions rest on soft basins. The soil of the basin can not withstand large weight because it undergoes the settlement and consolidations if any countermeasure is not taken. That is why in big cities like Tokyo and Osaka, the expressway viaduct is made of steel.

With the evolution of the steel material for better ductility and strength, large span bridges have been built in the world until the present time. Take for example, Akashi Strait Bridge completed in the year of 1998, the maximum span length reached 1991 m. One of the key innovations was the strength of the high strength of steel wire cables. The strength reached 1900 MPa, which proves to be much higher than the average strength of carbon steel of say, 400 MPa. Without this innovation, the Akashi Strait Bridge should have made a choice of using twin main cable as compared with the existing mono cable.

Talking about the future of steel structures, particularly bridges, however, many rooms for improvements are thought to exist. First of all, with regard to the construction of super long span bridges, the present concept of bridge design in use of steel can not be applied so easily. Especially, when the span length exceeds 3000 m, the present use of steel becomes significantly difficult. In exaggeration, bridges have to fight only with their own weight and neither external loads such as live vehicle loads nor natural loads such as wind, earthquake and snow load can possibly be carried! Many innovative engineers have proposed several revolutionary ideas such as the use of carbon fiber reinforced plastic to replace steel. It may be required to have much less specific weight, higher strength and higher resistance to corrosion. Nevertheless, as compared with the long history of iron and steel

over almost 6000 years of experience, this high performance material is lacking in the reliability because of only a very short history of usage. Furthermore, as the size of structures becomes larger and larger, there would be many hazard or barricade of aerodynamic instability, buckling and long-term durability particularly in the sea.

Of course one should consider other possibility. It may be too much a stubborn attitude to stick to the philosophy of conquering the gravity of the earth. What happens for example to the piers of Gibraltar crossing bridge project where the seabed may be as deep as 900 m. Even if the superstructure may be successfully designed and built using the high performance material such as carbon fiber reinforced plastics, how is it possible to build the piers exceeding one kilometer or so on the economical basis? In this regard, the concept of floating bridges would become a candidate. Usually the sea water is regarded as barrier to the bridge construction. However, in the case of floating structures, it can be regarded as if it is an elastic spring providing the buoyancy force.

Lastly, but not the least, people in the present world may not simply enjoy looking at the super long structures. They must also consider the priority of investment for other important facilities. Until quite recently the world was moving in the direction of "use and dispose". These days however people are realizing the importance of "sustainable development" which means positive evolution but great emphasis on "harmony with the environment".

In this humble paper, the historical development of iron and steel bridges are described with selected topics in the following text.

ORIGIN OF IRON

There exist no shining irons. They naturally rust away if no care is taken. The origin of iron can be dated back to the birth of the universe [3]. The universe was thought to be born at the big bang which took place 13.7 billion years ago. Hydrogen is the most abundant element in the universe. Most of hydrogen exists in the form of gas among stars, among galaxies and as constituent of stars or planets of the Jupiter type. After the big bang, the universe has evolved while stars are born and vanish repeatedly. The origin of the Earth, namely, the planet of iron can be dated back to 4.6 billion years ago. Iron is born as the result of the last stage product of the main activity of stars, namely the nuclear fusion.

As long as the size of the star is about that of the Sun, only Carbon and Oxygen can be produced from the fusion. Iron, however, can be produced only in the case of stars when they are about 8 to 30 times larger than the Sun. Through the process of nuclear fusion, iron is born as the last stage product. In the last stage, the stars emit the neutrino which is thought to hit the external atoms and causes big explosion. This is known as Nova. As a result, the products such as iron scatter and float in the universe. Thus, iron exists as one the most universal elements in the universe.

When the Earth was born, no oxygen existed but carbon dioxide, hydrochloric acid and sulfur dioxide filled the surface. The acid rain kept falling for extremely long time and the iron was dissolved and went into the ocean. In the early stage, no oxygen existed but bacteria which were close to alga were born 2.7 billion years ago

and started to produce oxygen through the photosynthesis. The oxygen was combined with iron and thus the iron oxide started to settle to form iron deposit.

IRON PRODUCTION BY MANKIND

Application of iron to the human life also has a long history. It was about BC 4000 [1]; a technique of iron production was invented by burning iron ore with charcoal. A piece of iron dagger was found from a tomb of Hittite King. It was supposedly made at about BC 3000. In BC 17th century, the Hittite built the empire in Asia Minor and destroyed the first Babylon dynasty with an iron weapon. In BC 15th century, the Hittite grew up as a great power with Egypt. The Egyptians disputed with the Hittite over Syria. A fight of the kaddish is known. The Hittite, however, died out by the invasions of "the citizen of sea" in BC 12th century. Table 1 shows the history of the use of iron.

Table 1 History of Use of Iron [1]

YEAR	PLACE	DESCRIPTION
BC 4000	Syria	A technique of iron production was invented by burning iron ore with charcoal.
BC 3000	Syria	A piece of iron dagger was found from a tomb of Hittite King.
BC 2890	Egypt	A fragment of iron found from a Pyramid
17th century BC	Asia Minor	The Hittite built the empire and destroyed the first Babylon dynasty with an iron weapon.
BC 1500	Egypt	An iron sickle (scythe) was found at Karnak Palace
BC 1400	Syria	Assyrian and Greek used iron.
BC 1350	Egypt	King Tutankhamen's Iron found.
BC 1285	Syria	Battle of Kadesh between Hittite & Egypt
BC 500	China	China made pig iron from iron ore.
BC 300	Europe	Bellows was used to produce iron.
BC 200	Japan	Forged Iron tool was found at Yoshinogasato (Yayoi period)
0	Nobeoka, Miyazaki Prefecture, Japan	Remain of iron production found.
319	Delhi, India	Iron post was made.
342	Ikaino-tsu, Osaka, Japan	The oldest record of Japanese bridge was found.
700	China	A suspension bridge was built with iron chains.
954	China	Iron lion was made.
1596	across Jintsu river, Japan	Pontoon Bridge was built.
1603	Tokyo, Japan	A wooden bridge: Nihon Bashi was built.
1698	Tokyo, Japan	A wooden bridge, Eitai Bridge was built.
1700	England	Blast furnace, refining and casting factory were built.
1734	Prussia	First European chain suspension bridge was built.
1779	England	Abraham Darby built the first iron bridge, Coalbrookdale Bridge over Severn River.
1857	Kyoto	Shijo Bridge was built.
1868	Nagasaki, Japan	Kurogane Bridge: 1 st Plate girder bridge in Japan
1869	Yokohama, Japan	Yoshida Bashi: 1 st Iron truss bridge in Japan
1873	Osaka, Japan	Shinsai Bashi Bridge: Imported truss bridge with wrought iron.
1877	Tokyo, Japan	Rokugogawa Railway Bridge: The oldest existing railway bridge in Japan.
1878	Tokyo, Japan	Danjou Bashi: 1 st bridge produced by Japanese.
1911	Hyogo, Japan	Amarube Iron Railway Bridge.

Three Different Iron Metals: Cast Iron, Wrought Iron and Steel

Cast iron can be made by filling molten iron into a mold. It can take any shape [2]. The compressive strength is extremely high; but the tensile strength is relatively low and brittle. Wrought iron is mild and tough. It has higher tensile strength and compressive strength. Thus wrought iron is safer than cast iron when it is used for a beam. However, since it can not be in the perfect mold state and the casting is limited only to rolling or forging, there are limitations on the shape of members. The characteristics of mild steel are similar to wrought iron but stronger in general in strength and casting is possible. However, it is not better than wrought iron either in corrosion resistance or formability. Table 2 shows the comparison of strength of cast iron, wrought iron & steel and carbon content.

Table 2. Strength of Cast Iron, Wrought Iron & Steel and Carbon Content [2]

MATERIAL	CARBON CONTENT (%) MELTING POINT (°C) PROPERTY	ULTIMATE STRENGTH	
		COMPRESSION (MPa or N/mm ²)	TENSION (MPa or N/mm ²)
Cast iron	2.25-4.0% 1200 (°C) Stiff but brittle	400-1000	100-150
Wrought iron	0.02-0.05% 1530 (°C) Mild and tough	250-400	250-400
Standard Steel (weldable)	0.2-1.0% 1400 (°C) Stiff and reasonably tough	350-700	350-700

INDUSTRIAL REVOLUTION

From Working on Land to Manufacturing

The Industrial Revolution was a 'revolution' that began in Britain which saw a move from people mainly working on the land to people mainly working in manufacturing [2]. Many people moved to cities looking for jobs. New methods of manufacturing implied things could be produced far cheaper and quicker than before.

There were many new inventions, ideas and methods. These developments meant things could be produced far more efficiently and reasonably. The use of new materials such as iron and coal was very important, leading to the invention of the steam engine. Thus, the Industrial Revolution saw an enormous increase in efficiency through the use of new methods and materials. In England, the industrial revolution gradually proceeded for relatively long time, say from 1760 to 1830.

Evolution of Iron

Black smith iron

Mankind became aware of the existence of iron 3000 years ago and has been utilizing it. In about 1500AD blast furnace was invented and the iron started to be produced in the molten state. China is believed to have a longer history of molten iron. In Europe, people became aware of the molten iron after the innovation of the blast furnace. Some people believe that Ancient Romans knew how to produce cast iron. Even if this is true, however, the know-how of such production was totally lost in the long history.

Before the invention of the blast furnace, iron was extracted from the iron ore in simple but small furnaces through the deoxidization process. Naturally, the production scale remained very small and laborious. The produced iron was far from being "liquid" but in the state of "paste". Craftsman used to refine the iron paste and hammer it for the casting. Thus, the iron may be called black smith iron.

Cast iron

Before 16th century, the mass production of iron product was impossible until the charcoal was replaced by more powerful coke as the main fuel. The size of the furnace was limited in case of charcoal; because of the fact that when the furnace becomes larger, the fuel was smashed due to the heavy weight of iron ore and thus the bellows did not function well. Abraham Darby (1678-1717) is believed to have established the iron production using coke. It was in 1709; however it took further considerably long time before this method became the main method of iron production. This method became quite popular only after 1750 in England and even later in the other European countries.

Wrought iron in mass production

In 1793, Henry Cort (1740-1800) finally was awarded with the patent of Puddling Process. Taking this opportunity the mass production of wrought iron became possible. In the Puddling Process, the carbon can be burned out in the reverberating furnace and the impurity is removed by the "puddling". With repetition of this process, the purity of iron is improved, the melting point and the toughness are increased and finally the iron can be extracted from the furnace to get ready for rolling and forging. This innovation proved to be epoch making since the quality of iron thus produced was good enough and did not differ from the black smith's product of good quality. Alongside with this, Henry Cort also came up with the idea of rolling with grooves. This made it possible to roll out channels, angles and T bars, and later light gauge and I members.

Steel

The origin of the steel now in use can be dated back to 18th century. Most of people believe that the utilization of steel could be dated back to Henry Bessemer's converter which was invented in middle of 1850. However, the drastic popularization of steel in the area of construction and shipbuilding can be attributed to Siemens-Martin's open-hearth steel production method.

Ages of Cast Iron, Wrought Iron and Steel

Achievement of structural iron and steel

Looking back the last 250 years of achievement of iron and steel structures, it may be convenient to classify the achievements in terms of the periods during which the three different kinds of iron metals took the principal roles although the classification may not be so sharply defined and the ages may overlap. The classification may be given by Table 3:

Table 3. Ages of cast iron, wrought iron and steel [2].

NAME OF AGE	PERIOD
Age of Cast Iron	1780-1850
Age of Wrought Iron	1850-1900
Age of Steel	1880-Present time

Age of Cast Iron

All of the early iron bridges are of arch type. Although the cast iron only replaced the masonry structure, the weight and the horizontal reaction forces were significantly reduced and this reduction resulted in improvements toward the more economical structures and shortened construction period.

The first iron bridge is Iron Bridge at Coalbrookdale completed in 1779 [2]. The Iron Bridge at Coalbrookdale (shown in Figure 1) has been described as the "Stonehenge of the Industrial Revolution". The original Stonehenge stands testament to long past history. The Iron Bridge, a magnificent and innovative design when first constructed, now stands testament to the marvels of the Industrial Revolution.



Figure 1. Iron Bridge at Coalbrookdale [2]. Courtesy of Kozai Club.

The Iron Bridge crosses the River Severn at the Ironbridge Gorge, by the village of Ironbridge, in Shropshire, England. It was the first bridge of its size in the world made of cast iron.

Although until early eighteenth century the only way to cross the Severn Gorge was by ferry, the industries that were growing in the area of Coalbrookdale and Broseley needed a more reliable crossing. In 1773, Thomas Farnolls Pritchard [1] wrote to a local ironmaster, John Wilkinson of Broseley to suggest building a bridge

using cast iron. By 1775, Pritchard had finalized the plans, and Abraham Darby III, an ironmaster working at Coalbrookdale in the gorge, was commissioned to cast and build the bridge. The characteristics of Iron Bridge are shown in Table 4 [4].

Table 4. Characteristic Values for Iron Bridge [4].

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Shropshire, England
Completion Date	1779
Length	30.5 m (100 feet)
Type	Arch
Purpose	Roadway (original), Pedestrian (Today)
Materials	Cast iron
Longest Single Span	30.5 m (100 feet)
Engineer(s)	Abraham Darby III, Thomas Farnolls Pritchard

Age of wrought Iron

This age may be well characterized by the rivet connection started to be used from the late 1840's. The birth of wrought iron may be attributed to the increase of questioning the safety of cast iron under bending action, the need for the improvement and the successful use of this type of iron in the shipbuilding industry. The most important reason for this popularity may be the successful implementations of Britannia and Conway tubular bridges as well as the progress of the rivet connection. Stephenson, Robert who designed the Britannia Bridge can be regarded to be one of the key persons.

Age of steel

Since steel is not only better than wrought iron in strength but also it can be produced in the molten state, it was made possible to produce large size rolled and forged members. The strongest impetus to change to steel from wrought iron may be attributed to its popularity in the shipbuilding industry. The Lloyds-register approved the use of the steel thick plates that could reduce the relative thickness by 1/5 as compared to the wrought iron counterparts. By 1908 it was even insisted that the steel to be used in the shipbuilding must be produced using the open-hearth steel production method.

Since the tendency of the age was for the larger and longer bridges, the initiative moved out of England and went to USA where the need for large bridges was the strongest in the world. All of the large bridges completed by 1945 including the Golden Gate, George Washington and Trans Bay are all made using the rivet connections and the use of high strength spiral steel ropes.

One of the revolutionary aspects of the steel may be the introduction of welding technology starting from 1930's or even before. Now, the rivet connections are almost gone to the past and now the time is for welding and bolted connection.

The Steel Revolution

With the introduction of truss bridges made out of steel, the previous limits to span lengths were

expanded. The span length of truss bridges temporarily culminated with the building of the Firth of Forth Bridge, erected in 1889, with a largest span of 521 m and the Quebec Bridge from 1917, with a main span of 548.6 m.

With respect to large spans, it is the utilization of the tensile strength of steel in suspension bridges that makes this feasible. In the USA at the end of the 1800s and the beginning of the 1900s a number of daring suspension bridges were constructed. In our time suspension bridges are being built in the USA, in Europe and in Asia, where the span length is continually being expanded. For example we can see the Verrazano Narrows Bridge in New York (USA), built in 1964 and having a main span of 1298 m, the Humber Bridge, built in 1981 with the largest span length of 1,410 m and Akashi Strait Bridge built in 1998 with the largest span length of the world of 1991 m. The cross-sectional profile of the Humber Bridge is noted for its closed tubular shape similar to airfoil representing the progress made in England in the area of aerodynamic stability in contrast with the truss structure of the American tradition.

Bridge Engineers in 18th And 19th Centuries

There are a number of bridge designers who contributed significantly to the early development of iron and steel bridges during the industrial revolution. The following people are among the big names.

Telford, Thomas (1757-1834) [5]

The English engineer who is well known and the first president of the Institution of Civil Engineers, England. Like others of his contemporaries he was very versatile, and engaged in many branches of engineering. He designed the Menai Suspension Bridge (Figure 2). It is a suspension bridge between the island of Anglesey and the mainland of Wales. It was completed in 1826; it is one of the first modern suspension bridges in the world.



Figure 2. The Menai Suspension Bridge [5].

On February 28, 2005 the bridge was promoted to UNESCO as a candidate World Heritage Site, and, coincidentally on the same day one carriageway of the bridge was closed for six months restricting traffic to a single carriageway so that traffic now traveled to the mainland in the morning and to Anglesey in the afternoon. The bridge was finally re-opened to traffic in both directions on 11 December 2005 after its first major re-painting in 65 years.

Stephenson, Robert (1803-1859)

He is usually considered the co-inventor of the railway with his father, George Stephenson. His career covered engineering works of magnitude all over the British Empire, but he is best known for his Britannia Bridge over Menai Straits (Figure 2 shown previously). The original Menai Bridge was used for high speed trains. Britannia Bridge is a bridge across the Menai Strait [6] between the island of Anglesey and the mainland of Wales, originally a tubular bridge of wrought iron rectangular box-section spans, and now a two-tier steel truss arch bridge.

The opening of the Menai Bridge in 1826. The increasing popularity of rail travel necessitated a second bridge to provide a direct rail link between London and the port of Holyhead, the Chester and Holyhead Railway. Other railway schemes were proposed, including one in 1838 to cross Telford's existing Menai Bridge.

Railway pioneer George Stephenson was invited to comment on this proposal but stated his concern about reuse of the suspension bridge. By 1840, a Treasury committee decided to adopt Stephenson's proposals, with final consent to the route including Britannia Bridge given in 1845. Stephenson's son Robert was appointed as chief engineer.

The bridge was opened on 5 March 1850 [Figure 3(a)]. For its time, it was a bridge of "magnitude and singular novelty", far surpassing in length contemporary cast beam or plate girder iron bridges. One aspect of its method of construction was also novel; the box sections were assembled on-shore, and then floated out into position before being lifted into place. In spite of the heavier loadings placed on it in its later life, the bridge was "one of the most easily maintained and successful railway bridges" in the UK, and "as the first really large wrought iron bridge of the girder type it has unique significance in civil engineering history".

During the evening of 23 May 1970 the bridge was greatly damaged when boys playing in the bridge dropped a burning torch, starting a fire. As a consequence the bridge was completely rebuilt, with the spans supported by archways. The deck has two levels: the lower still carries the rail line, and the upper supports a single-carriageway section of the A55 road [Figure 3(b)].



(a). Original box section, in a circa 1852 illustration [2]. Courtesy of Kozai Club.

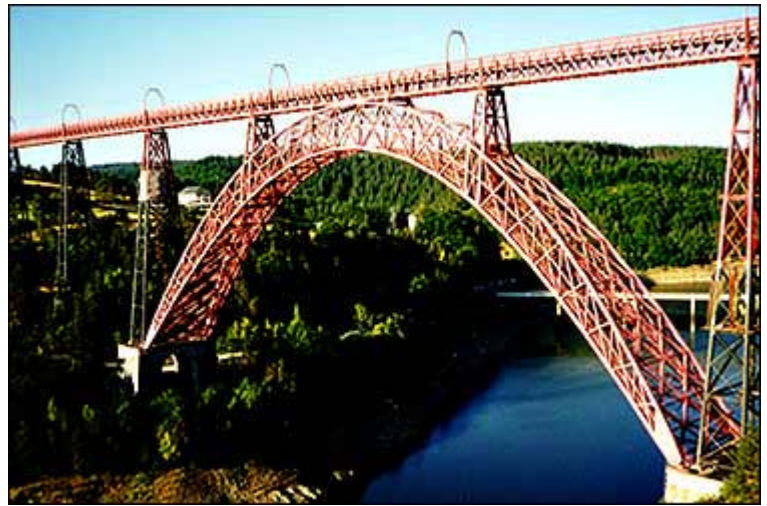


(b). The post 1970 Bridge retains Stephenson's Original Piers [6].

Figure 3. Britannia Bridge

Eiffel, Alexandre Gustave (1832-1923)

The famous French builder of bridges who designed and built the great Eiffel Tower [Figure 4(a)] for the French Exposition of 1889 built Garabit Viaduct Bridge [Figure 4(b)]. It is thought to be a wonderful masterpiece of his design. The characteristics of Garabit Viaduct Bridge are provided in Table 5 [7].



(a) Eiffel Tower in Paris [2] .
Courtesy of Kozai Club.

(b) Garabit Bridge, Massif Central, France [7].

Figure 4. Masterpieces of Eiffel, Alexandre Gustave

Table 5. Characteristic Values for Garabit Viaduct Bridge [7]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Massif Central, France
Completion Date	1884
Length	565 m (1,853 feet)
Type	Arch
Purpose	Railway
Materials	Wrought iron
Longest Single Span	Single Span: 165 m (541 feet)
Engineer(s)	Gustave Eiffel
Cost	

Roebing, John Augustus (1806-1869)

The builder of the Brooklyn Bridge (Figure 5) [8] as well as those at Cincinnati, Pittsburgh, and Niagara was a Prussian engineer, all of whose great work was done in the United States. The wire from his works was used on the Manhattan, Williamsburg, and 178 Street Bridges in New York. The characteristics of Brooklyn Bridge are shown in Table 6. It was unfortunate, however, to know that he died of an accident he met at his surveying. His son, Washington wanted to succeed him in this project. He also unfortunately met an accident at the site of pneumatic caisson and thus could not see the completion of the bridge either. His wife, Emily learned bridge engineering by herself and contributed to the completion of the bridge.



Figure 5 Brooklyn Bridge, Manhattan and Brooklyn, New York, 1904 Picture Collection, The Branch Libraries, The New York Public Library [8].

Table 6. Characteristic Values for Brooklyn Bridge [8]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Manhattan and Brooklyn, New York, USA
Completion Date	1883
Length	1055 m (3,460 feet)
Type	Suspension
Purpose	Roadway
Materials	Steel, granite
Longest Single Span	486 m (1,595 feet)
Engineer(s)	John A. Roebling, Washington A. Roebling
Cost	\$18 million

Brunel, Isambard Kingdom (1806-1859)

He was the most prodigious engineer in England and achieved many works, which challenged and inspired his colleagues during the period, have survived to our own time and some are still in use. His father, Sir Marc Brunel is also well known as the great civil engineer of the Victorian age. He was the designer of Clifton Bridge which still exists (Figure 6) [9].



Figure 6. Clifton Bridge [2]. Courtesy of Kozai Club.

The bridge is across the Avon Gorge at Bristol, U. K. He submitted four designs for bridges at four sites along the gorge to the bridge design competition in 1830, and one of them was selected. In 1836 the foundation stones were laid but serious financial problems had occurred. Unfortunately, Brunel died in 1859. In 1860 the construction had been undertaken again for completing a monument to Brunel and removing a slur upon the Engineering talent of U. K. The bridge had been constructed using ironworks of other suspension bridge, designed by Brunel, and opened in 1864. The bridge has been utilized safely up to the present.

FOR LARGER SPAN LENGTH

Larger Steel Truss Bridges

With the introduction of truss bridges made of steel, the previous limits to span lengths were expanded. The span length of truss bridges recorded the world record when the Firth of Forth Bridge erected in 1889, with a largest span of 521m [4] and the Quebec Bridge across the St. Lawrence River completed in August 1919 renewed the record with the main span of 548.6m. In 1907, however, during the construction of the biggest cantilever bridge in the world, a tragedy occurred; later in 1916 the tragedy was repeated when the central portion was about to be completed.

Firth of Forth Bridge

More than 55,000 tons of steel were used, as well as 18,122 m³ of granite and over eight million rivets. The bridge was opened on March 4, 1890 by the Prince of Wales, later King Edward VII (Figure 7 & Table 7) [4]. The use of a cantilever in bridge design was not a new idea, but the design was extensively followed afterwards in different parts of the world. Much of the work done was without precedent, including calculations for incidence of erection stresses, provisions made such as for reducing future maintenance costs, calculations for wind pressures made evident by the Tay Bridge disaster and the effect of temperature stresses on the structure.



Figure 7. Firth of Forth Bridge [2]. Courtesy of Kozai Club.

Fast Facts:

- The Firth of Forth Bridge may not have been a bridge at all -- engineers considered building a tunnel, but abandoned the idea because it seemed too risky.
- The Firth of Forth was the first bridge built primarily of steel.
- It took 54,000 tons of steel; 194,000 cubic yards of granite, stone, and concrete; 21,000 tons of cement; and almost seven million rivets to build the Firth of Forth Bridge. Here's how this bridge stacks up against some of the longest-spanning bridges in the world.

Table 7. Characteristic Values for Firth of Forth Bridge [4].

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	South Queensferry and North Queensferry, Scotland
Completion Date	1890
Length	2524 m (8,276 feet)
Type	Cantilever
Purpose	Railway
Materials	Steel
Longest Single Span	521 m (1708 feet)
Engineer(s)	Benjamin Baker, John Fowler
Cost	\$15 million

Quebec Bridge

The Quebec Bridge in Canada crosses the lower Saint Lawrence River to the west of Quebec City. The Quebec Bridge is a riveted steel truss structure and is the longest cantilever bridge span in the world (Figure 8 & Table 8) [10]. The bridge accommodates three highway lanes (none until 1929, one until 1949, two until 1993), one rail line (two until 1949), and a pedestrian walkway (originally two); at one time it also carried a streetcar line. It has been owned by the Canadian National Railway since 1993.



Figure 8. Quebec Bridge [10]

Table 8. Characteristic Values for Quebec Bridge [10]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Quebec City, and Lévis, Quebec, Canada
Completion Date	1917
Length	987 m (3,239 ft)
Type	Cantilever
Purpose	Roadway & Railway
Materials	Steel, granite
Longest Single Span	549 m (1,800 ft)
Engineer(s)	Theodore Cooper
Cost	\$25 million

First design and Collapse of August 29, 1907

The Quebec Bridge was included in the National Transcontinental Railway project, undertaken by the federal government. By 1904, the structure was taking shape. However, preliminary calculations made early in the planning stages were never properly checked when the design was finalized, and the actual weight of the bridge was far in excess of its carrying capacity. The dead load was too heavy. All went well until the bridge was nearing completion in the summer of 1907, when the local engineering team under Norman McLure began noticing increasing distortions of key structural members already in place.

McLure became increasingly concerned and wrote repeatedly to supervising engineer Theodore Cooper, who at first replied that the problems were minor. The Phoenix Company officials were claiming that the beams must already have been bent before they were installed, but by August 27 it had become clear to McLure that this was wrong. A more experienced engineer might have telegraphed Cooper, but McLure wrote him a letter, and then went to New York to meet with him on August 29, 1907. Cooper then agreed that the issue was serious, and promptly telegraphed to the Phoenix Bridge Company: "Add no more load to bridge till after due consideration of facts." The two engineers then went to the Phoenix offices.

But the message had not been passed on to Quebec, and now it was too late. That same afternoon, after four years of construction, the south arm and part of the central section of the bridge collapsed into the St. Lawrence River in just 15 seconds. Of the 86 workers on the bridge that day near quitting time, 75 were killed and the rest were injured.

Second design and Collapse of September 11, 1916

After a Royal Commission of Inquiry into the collapse, construction started on a second bridge. Three engineers were appointed: H.E. Vautelet, a former engineer for the Canadian Pacific Railways, Maurice Fitz Maurice from Britain, who worked on the construction of the Forth Bridge, and Ralph Modjeski from Chicago. Vautelet was President and Chief Engineer. The new design was still for a bridge with a single long cantilever span, but a much more massive one. On September 11, 1916, when the central span was being raised into position, it fell into the river, killing 13 workers.

Completion

Construction was ultimately completed in August 1917, at a total cost of \$25 million and 88 bridge workers' lives. On December 3, 1919, the Quebec Bridge opened for rail traffic, after almost two decades of construction. Its center span of 549 meters (1800 ft) remains the longest cantilevered bridge span in the world and is considered a major engineering feat.

Competition for Lager Suspension Bridges

It is due to the high tensile strength of steel in suspension bridges that made large spans possible. In the USA at the end of the 1800s and the beginning of the 1900s a number of striking suspension bridges were constructed. Since then the world record of the largest span length of suspension bridges has been continually renewed by Golden Gate Bridge, built in 1937 in San Francisco with the main span of 1280m and the Verrazano Narrows Bridge in New York (USA), built in 1964 and with the main span of 1298m. Currently, the bridge with the largest span length is Akashi Strait Bridge built in 1998 with the main span length of 1991m.

Golden Gate Bridge

Today, some call it the "most spectacular bridge in the world" (Figure 9 & Table 9) [11]. But a century ago, building the Golden Gate Bridge seemed like an impossible task. Any bridge in this location would have to withstand brutal winds, tide, and fog. It would also sit less than eight miles from the epicenter of the most catastrophic earthquake in history. Only one engineer was willing to gamble that his bridge could withstand such destructive power. His name was Joseph Strauss. Strauss used more than one million tons of concrete to build the anchorages -- the massive blocks that grip the bridge's supporting cables. The north pier, which supports the tower, was built easily on a bedrock ledge 20 feet below the water. But on the southern San Francisco side, Strauss had to build his pier in the open ocean, 100 feet below the surface. He built a huge water-tight cofferdam -- big enough to enclose a football field -- and pumped in hundreds of tons of concrete. By 1935, the towers were complete, and cable-spinning began. Two years later, the bridge was finished. Strauss completed the \$27 million bridge only five months after the promised date and \$1.3 million under budget. For his efforts, Strauss received \$1 million and a lifetime bridge pass. Here's how this bridge stacks up against some of the longest-spanning bridges in the world.

Table 9. Characteristic Values for Golden Gate Bridge [11]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	San Francisco and Sausalito, California, USA
Completion Date	1937
Length	2739 m (8,981 feet)
Type	Suspension
Purpose	Roadway
Materials	Steel, concrete
Longest Single Span	Single Span: 1280 m (4,200 feet)
Engineer(s)	Joseph B. Strauss
Cost	\$27 million



Figure 9. Golden Gate Bridge, San Francisco and Sausalito, California [11]

As the larger the length of bridges becomes, nevertheless, the more they become vulnerable to aerodynamic instabilities. One of the most famous bridge collapses may be the Old Tacoma Bridge in 1940. On the other hand, bridges in the seismic area should be protected from earthquakes. Thus teachings learned from Hanshin-Awaji Great Earthquakes are invaluable.

Akashi Strait Bridge (Pearl Bridge)

To connect the Islands of Shikoku, Awaji and Honshu was a long standing dream of people who lived around them. But, those who spoke out in earnest for it were called big mouths or crazy. It was actually impossible to build such a long bridge with the technology which Japan had at that time, and with her economical power. In 1889, Okubo Jinnojo, a representative to the Parliament of Kagawa prefecture stressed the importance of such a bridge in the local Parliament. In later years, many politicians insisted in its importance. The Diet member, Hara Kenzaburo was one of them. But, he was called the big mouth Ken. He continued insisting the importance of the bridge during many years. He served for a term as a chairman in the House of the Representatives and retired from political career in 2000 at the age of 93 years old, 2 years after the completion of the bridge. He said that his long life could allow him to see the long bridge.

In 1955, the former National Railway Corporation studied the feasibility of the construction of the bridge. In 1970, Honshu Shikoku Bridge Authority was established to build the bridges to link Honshu with Shikoku. This organization, however, gave priority to the building of other bridges to link Honshu with Shikoku according to the tight National budgets and policy of the Japanese government.

In 1986, the inaugural ceremony to start the building of the Akashi Strait Bridge was held. In 1998, the bridge was completed and was opened to the transit [12] (Figure 10 & Table 10). The total length of the bridge completed was 3,911 meters, and the distance between the bases of two main towers 1,991 meters, the longest in the world. The bridge with the second longest length between the towers is the Great Belt East Bridge in Denmark with its length of 1,624 meters.

The distance between the 297 meters tall tops of the two towers is 1,991 meters 9.3 cm. The difference of 9.3 cm at the tops doesn't mean that the towers have a slant. It comes from the fact that the Earth is round and not flat, and the bridge is very long and its towers are very tall. The tops of the two towers were directed exactly vertical to the center of the gravity of the Earth. The difference of 9.3 cm compensate for the Earth's spherical shape. The towers actually have not any difference in being vertical to the gravity center of the Earth. (See the diagram in the web page below shown of Honshu Shikoku Bridge Authority) For the construction of the bridge, 1,

420, 000 m³ of concrete was used for the anchorages and the two main towers. 200, 000 tons of steel were used as cables and for the passage of the cables. It was designed to withstand any natural disasters.

This area is the frequent route of typhoons, and is called Typhoon Ginza Street. The largest typhoon recorded which hit the Seto Inland Sea was the Muroto Typhoon in 1934. Its largest speed recorded was 84.5 meter per second, but the wind speed recorder was broken by the strong wind. Probably its speed was a little weekend when it entered the Seto Inland Sea. But, it caused a loss of 2,074 persons dead, 334 missing, and left 14,994 persons injured.



Figure 10. Akashi Kaikyo Bridge, Kobe and Awaji-shima. Courtesy of Japan Honshu-Shikoku Bridge Authority.

The Akashi Strait is a busy shipping port, so engineers had to design a bridge that would not block shipping traffic. They also had to consider the weather. Japan experiences some of the worst weather on the planet. Gale winds whip through the Strait. Rain pours down at a rate of 57 inches per year. Hurricanes, tsunamis, and earthquakes rattle and thrash the island almost annually.

How did the Japanese engineers get around these problems? They supported their bridge with a truss, or complex network of triangular braces, beneath the roadway. The open network of triangles makes the bridge very rigid, but it also allows the wind to blow right through the structure. In addition, engineers placed 20 tuned mass dampers (TMDs) in each tower. The TMDs swing in the opposite direction of the wind sway. So when the wind blows the bridge in one direction, the TMDs sway in the opposite direction, effectively "balancing" the bridge and canceling out the sway. With this design, the Akashi Kaikyo can handle 180-mile-per-hour winds, and it can withstand an earthquake with a magnitude of up to 8.5 on the Richter scale!

Here's how this bridge stacks up against some of the longest-spanning bridges in the world. (total length, in feet)

Fast Facts:

- The bridge is so long, it would take eight Sears Towers laid end to end to span the same distance.
- The length of the cables used in the bridge totals 300,000 kilometers. That's enough to circle the earth 7.5 times!
- The bridge was originally designed to be 12,825 feet. But on January 17, 1995, the Great Hanshin Earthquake stretched the bridge an additional three feet.
- The bridge holds three records: it is the longest, tallest, and most expensive suspension bridge ever built.

Table 10. Characteristic Values for Akashi Strait Bridge [12]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Kobe and Awaji-shima, Japan
Completion Date	1998
Length	3912 m (12,828 feet)
Type	Suspension
Purpose	Roadway
Materials	Steel
Longest Single Span	1991 m (6,527 feet)
Engineer(s)	Honshu-Shikoku Bridge Authority
Cost	\$4.3 billion

Tacoma Narrows Bridge

On the morning of November 7, 1940, the Tacoma Narrows Bridge twisted violently in 42-mile-per-hour winds and collapsed into the cold waters of the Puget Sound. The disaster -- which luckily took no human lives -- shook the engineering community and forever changed the way bridges were built around the world. Engineer Leon Moisseiff had designed the ultimate in slender bridges (Figure 11) [4]. The roadway was a mere 39 feet -- only eight teenagers lying head to toe would fit across the bridge! Moisseiff strengthened his narrow bridge with a solid steel girder beneath the roadway. But soon after it opened, the Tacoma Narrows started behaving strangely.

Wind caused the bridge to sway back and forth, and it also sent rippling waves along the deck. The Tacoma Narrows tore itself apart only four months later.

Years later, engineers found that the solid girders actually blocked the wind and caused the slender bridge to twist. The twisting bridge fanned the steady wind into a swirling motion, which caused the bridge to twist even more -- and eventually snap in two. The Tacoma Narrows Bridge was replaced in 1950 by a new bridge stiffened with a truss. Rather than blocking the wind, the open truss allowed the wind to blow through the new bridge. Here's how this bridge stacks up against some of the longest-spanning bridges in the world (Table 11).

Fast Facts:

- The bridge earned the nickname "Galloping Gertie" for its unusual rolling, twisting behavior. Many drivers complained of seasickness.
- Thrill-seekers often crossed the Tacoma Narrows just to experience the bridge in unusual rolling and twisting behavior. Drivers say crossing the bridge was like riding a roller coaster.
- In 1992, Gertie's sunken remains were placed in the National Register of Historic Places to protect them from being stolen.



Figure 11. Old Tacoma Narrows Bridge [4].

Table 11. Characteristic Values for Tacoma Narrows Bridge [4]

ITEM	DESCRIPTION OF CHARACTERISTIC VALUE
Location	Tacoma, Washington, USA
Completion Date	1940
Length	2254 m (7,392 feet)
Type	Suspension
Purpose	Roadway
Materials	Steel, concrete
Longest Single Span	Single Span: 854 m (2,800 feet)
Engineer(s)	Leon Moisseiff
Cost	\$6.4 million

After the German innovation just after the World War II, many cable-stayed bridges have been constructed as economical construction and recent increase of Chinese bridges is noted. The maximum bridge span length of cable-stayed bridges is becoming quite comparable to that of suspension bridges. Furthermore,

floating bridges are drawing much attention. Such is the case of Yumemai Bridge of Osaka City [13] (Figure 12). Besides, hybrid bridges made of steel and concrete are becoming more popular because of their better corrosion resistance and long life.

Presently, the importance of bridge management and maintenance is becoming widely recognized worldwide because of unavoidable long-term deteriorations. For such purposes, the asset management logistics are being utilized [14].



Figure 12. Yumemai Floating Bridge after the on-site installation. Courtesy of Osaka Construction Industry Times.

CONCLUSIONS

In this paper, the origin of iron and its early use by the mankind are described. Then, the Industrial Revolution was mentioned together with the early founders of modern iron and steel bridges. The progress of steel bridge technology was described expand the span length in the form of steel truss bridges with the improvement of the quality such as the strength, ductility, the easiness in casting structural profiles and the weldability. Then the arrival of the age of long-span suspension bridges was described particularly, in the USA primarily due to the high tensile strength of steel. Things were not so easy, however, and engineers had to face with accidents due to ignorance of fundamentals such as the aerodynamic stability and buckling. Furthermore, engineers learned that bridges in the seismic area should be protected from earthquakes from the past big earthquakes such as the Hanshin-Awaji Great Earthquakes.

Furthermore, floating bridges are drawing much attention. Such is the case of Yumemai Bridge of Osaka City. Besides, hybrid bridges made of steel and concrete are becoming more popular because of their better corrosion resistance and long life. Presently, the importance of bridge management and maintenance is becoming widely recognized worldwide because of unavoidable long-term deteriorations. For such purposes, the asset management logistics are being utilized.

Various kinds of structural steels are utilized at the present time in the fields of bridges and buildings. For example, atmospheric corrosion resistant steel or weathering steel and titanium or stainless steel linings are being developed. In the future, the cycle maintenance of existing structures is surely one of the main themes for

the structural engineering. For this purpose, the logistics such as the asset management system is becoming more and more important with the minimum life cost, LCC, under the philosophy of the preventive maintenance and under the condition of sustainable development of the earth.

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Cast iron, wrought iron and steel structures first developed in Europe spread throughout the entire world as a result of a host of technological breakthroughs accompanying the progress of iron and steel making technologies and culminated in the remarkable development of steel construction we see today.

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REFERENCES

- [1] Japanese Society of Steel Construction, Milestones in Steel Construction, Brochure in Commemoration of the 50 Years Anniversary of Kozai (Steel) Club (2001) (in Japanese)
- [2] Owence, G. W. (Chairman of Steering Committee). Steel Construction: Introduction to Design, *ESDEP* (European Steel Design Education Programme) Society, Translated Booklet with Copyright by Kozai Club (2001). (in Japanese)
- [3] Nippon Steel Company, <http://www0.nsc.co.jp/monozukuri/download/V15.pdf> (in Japanese)
- [4] http://www.pbs.org/wgbh/buildingbig/wonder/structure/iron_bridge.html
- [5] http://en.wikipedia.org/wiki/Thomas_Telford
- [6] http://en.wikipedia.org/wiki/Menai_Strait
- [7] http://www.pbs.org/wgbh/buildingbig/wonder/structure/garabit_bridge.html
- [8] http://www.pbs.org/wgbh/buildingbig/wonder/structure/brooklyn1_bridge.html
- [9] <http://www.clifton-suspension-bridge.org.uk/>
- [10] http://en.wikipedia.org/wiki/Quebec_Bridge
- [11] http://www.pbs.org/wgbh/buildingbig/wonder/structure/goldengate_bridge.html
- [12] http://www.pbs.org/wgbh/buildingbig/wonder/structure/Akashi2_bridge.html
- [13] Watanabe, E.: Floating Bridges: Past and Present, *Structural Engineering International*, **13**, No. 2, pp. 128-132 (2003).
- [14] Watanabe, E., Utsunomiya T. and Frangopol, D. (editors), *Bridge Maintenance, Safety, Management and Cost*, A.A. Balkema Publishers, Netherlands (2004).