THE EVOLUTION OF STRUCTURAL FORMS AND ITS INFLUENCE ON BRIDGE ENGINEERING

“Looking Back to Move Forward –Scope and Challenges in Bhutan.”

Tshewang Nidup, Lecturer, College of Science and Technology

Abstract

The instinct to connect with and explore new frontier has driven mankind to engage in the art and science of bridge building since the beginning of civilization. A great many developments has occurred in the field of material science, structural engineering and construction technology through the centuries, that has had tremendous implication on way bridges were designed, built and maintained. This paper will present a historical perspective on the evolution of the various structural forms and the series of development and discoveries in other related fields that has impacted bridge engineering over the years and discuss in brief the scope and challenges of bridge engineering in Bhutan.

Introduction

“Good fences make good neighbors” a poet once said, (R. Frost) but it was good bridges that has linked people and communities, fostered trade and commerce and changed the whole notion of time and distances. Mankind has thus been building bridges since the beginning of civilization spanning over just a mere few meters (Fig 1) to over thousands of meters (Fig 2) at present. The leap from a mere few meters to such great length was not instant and easy. A great deal of development and understanding in the area of mechanics, material sciences, structural engineering and construction technology has to unfold to achieve such a feat.

Fig 1 : A makeshift bamboo bridge in Bhutan (c- C Bell, 1910)

Fig 2 : The 1991m Akashi-Kaikyo Bridge in Japan (c - Kim Rotzel, 2005)

Structural Evolution - Material Revolution

The Span and Weight Conundrum

Bridges made of timber and stones used as standard “beam for deck” have been built since civilization began but beyond a certain length, how far a bridge could span was limited by the sheer self-weight of the bridge itself because of the need for thicker/deeper sections to control deflection. The depth required to control deflection (fig 3) under its own weight varied as a function of the square of the length the bridge had to span. (J. Stanton)

$$\boldsymbol{d} = (K)\,\frac{Material\ \boldsymbol{Density}}{Material\ \boldsymbol{Capacity}}\,(\boldsymbol{l}^{2})\ eq\text{ -1}$$

k= Basic Material Constant

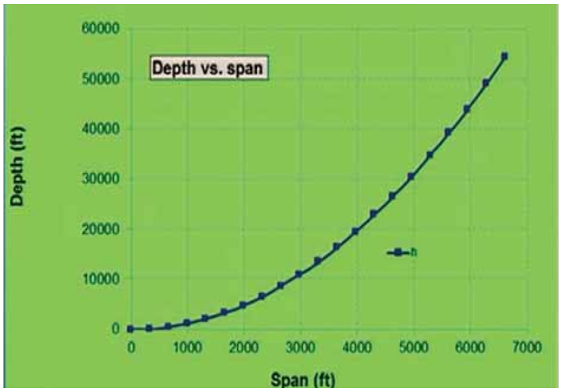


Figure 3. Span Depth Relation (c - J Stanton)

There is thus, clearly a need to use stronger material and even a much higher premium to use lighter material to be able to span longer distances (eq 1). To be strong and be light was the way to go forward. “Get Strong, Get Light”

Roman Arches : The first leap

Given this depth, span, weight and capacity relation it was not until the Romans came up with their round arches at the turn of the millennium that a bridge of any significant span could be built. The round arch and its successor, the pointed arch, by perfectly exploiting the extraordinary compressive strength of stone, has enabled the construction of a great many magnificent bridges and civil structures spanning over distances that was hitherto simply not possible (W.V Srubar). The “Pont du Gard” (fig 5) and the Mostar bridge (fig 4) in Bosnia* serve as the epitome of the efficiency and elegance of the arch systems.

Fig 4 : 29m stone arch Mostar Bridge (c- Yvon Fruneau)

Fig 5 : "Pont du Gard" (c- Mas de Rey)

Getting Stronger: Cast Iron and the Bessemer's Process

By the late 1770's cast iron was manufactured quite extensively and this new "modern" material, with a better strength to weight ratio than stone and which is moldable was used to build the first ever major bridge without stone or timber. The iron bridge (fig 6) as it is called, with a span of 30.63m was built in 1779 and still stands a testament to the ingenuity and strength of the Roman arch and iron. The bridge weighs approximately 380 tonnes (structurae.net) almost three - four times lighter than an equivalent one made of stone. However the use of cast iron as a structural material was limited due to its brittleness. Also because of the high amount of carbon content connecting members by welding was problematic. In 1856, Henry Bessemer invents the method to manufacture steel from pig iron (fig 7), a material that is stronger, more robust and ductile than any manufactured till date (M. Miodownik). The arch system used with the new wonder material called steel has thus facilitated the leap in bridge engineering to the next level.

Fig 6: 30.5m The Iron Bridge in Coalbrookdale (c- Wikimedia UK)

Fig 7 : A Bessemer's furnace prototype (c - britannica.com)

Getting Lighter: Shedding off useless Weight

By 1750, Euler and Bernoulli had propounded the classical beam theory and a proper understanding on the nature and distribution of stresses in horizontal members, such as a bridge deck/girder, when loaded transversely to its longitudinal axis has been gained. This knowledge on the variation of stress along the cross section of a member has made it possible for members to "lose weight" by trimming or taking off chuck of material without compromising on the section's stress capacity.

Trusses – Beams that have lost Weights

Trusses are an excellent example of the beam that has lost weight while still maintaining its original depth. A very deep beam (fig 8) with all the unnecessary materials, in the region where the stress level are minimal, taken out keeping some vertical and diagonal segment to hold the top and bottom portion in place becomes a truss (fig 9). The vertical and diagonal also help to resist shear.

Fig 8 :A Deep Beam (c- author)

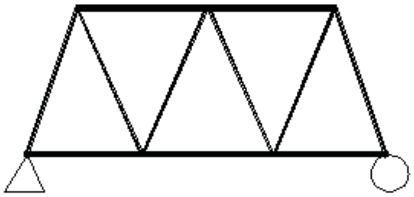


Fig 9 : "Perforated Beam" - Truss (c- author)

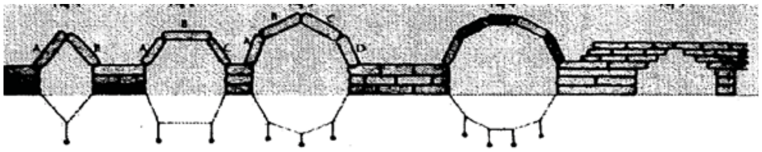
A truss is thus a very efficient beam and therefore a truss, especially one made of steel, is a very suitable system for bridges given its higher strength and comparative lightness. Methods to analyze trusses were formulated by the 1840's, which was further refined by the likes of Culman, Maxwell and Mohrs (J.J. Jenson). All this development has culminated into the design and construction of the first ever to reach 521m in a single span still in service, the cantilevered truss system Firth of Forth bridge in 1889 by John Fowler and Benjamin Baker (fig 10). The truss however becomes uneconomical for very large spans as an effect of the "span depth conundrum."

Fig 10 : The Steel Truss Cantilever Firth of Forth Bridge (c- Jochen Kratschmer

Suspended Cables – An Inverted Arch

While steel has this unique property of being equally strong in tension as well as compression, it is a dream material to be used in tension as the issue related to buckling need not have to be addressed as is the case when used as a compression member. As the Romans have mastered the art of exploiting the strengths and avoiding the weaknesses of the stone with their arches, the foundation to explore a new structural system that could capitalize on the strengths of the steel as an ideal material for tension was first laid by Robert Hooke in his attempt to determine the perfect profile of an arch in 1676 (M. Collins).

Fig 11 : Hooke's profile for Perfect Arches (c- M Collins)



As hangs a flexible cable so, inverted, stand the touching pieces of an arch."

- Robert Hooke 1676

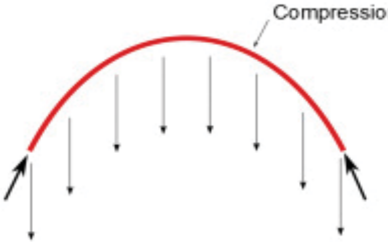


Fig 12 : Arch under compression

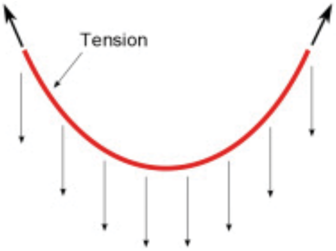


Fig 13 : Flipped Arch - Suspension under tension

Flip an arch over and it becomes a "suspension" with all the thrust reversed from compression to tension (*Funicular form*). The suspension system combined with the higher-grade steel has underpinned most of the major advances in long span bridge design and construction.

Fig 14 : 177m The Menia Strait bridge (c- Kev)

Fig 15 : 1280m The Golden Gate Bridge (c- D.R Logan)

The 177m long Menia strait suspension bridge (fig 14) designed by Thomas Telford is the first ever to cover such a distance in a single span. Iron bars chains were used as suspension cables. The 1280m long golden gate bridge considered as the Mona Lisa of the bridges, uses 27, 572 high tensile strength wires of 5mm diameter in each of the two 0.924m diameter cables. One problem with suspension bridges is the need for hard and strong subsoil to anchor the cables.

Stayed Cables – Self Standing Bridge

At sites where ground conditions are poor, the cable-stayed system becomes an ideal alternative for long span bridges. The central towers known as the pylons supports the cables suspended to the bridge deck and the under compression pylons transfers the load to the foundation eliminating the need for anchorages at the ends.

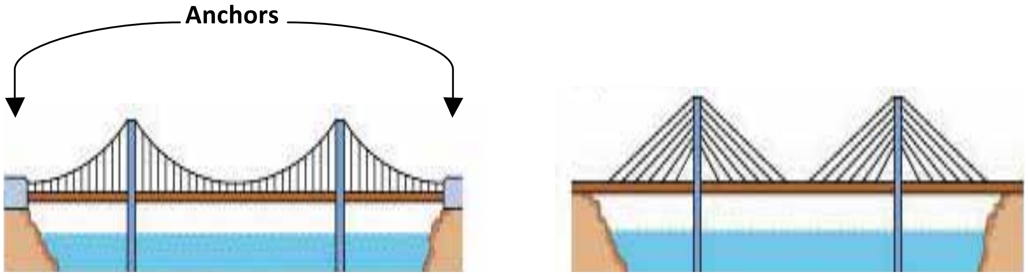


Fig 16 : Schematic representation of Suspension and Cable Stayed (c- Britannica.Inc) Bateman)

The 2460m long cable stayed Millau Viaduct (fig 17) across river Tarn in southern France designed by Sir Norman Foster and Dr. Michel Virlogeux is considered to be among the greatest engineering achievements of all times. It is also the tallest bridge in the world with a mast of the pylon at 343m above ground. (Foster and partners)

Fig 17 : The Millau Viaduct (c- Ian Bateman)

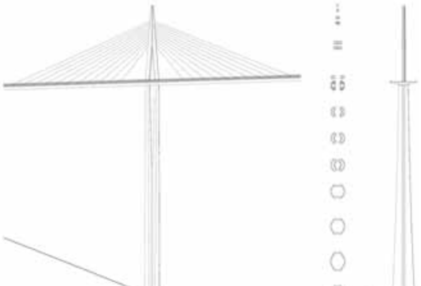


Fig 18 : The sectional view of a Pylon of the Millau Viaduct (c- foster and partners)

Reinforced Concrete – The New wonder material

An alternative to steel as a structural material was being discovered by the middle of the nineteenth century. Joseph Aspdin invented the method for producing and obtained the patent for the "Portland cement" in 1824 (O. Bowles) and by the mid 19th century, concrete, a material that yielded excellent mechanical and durability properties when cement is mixed with sand, aggregate and water was widely used in the construction of numerous civil infrastructures(JJ Jenson). Techniques to improve the concrete's inherent weakness in tension have also been discovered by embedding reinforcing steel bar in plain concrete members in 1867 by one Joseph Monier, a gardener by profession The 13.8m bridge at the Castle of Chazelet in France designed by Monier in 1875 is the first ever reinforced concrete bridge (structurae.net).

This new material with its improved tensile property soon became the mostly widely used material of the 21st century given its durability and resistance to corrosion unlike steel and the flexibility with which it could be molded into any shape and size in site. Of all the bridges built with this new material at the turn of the 20th century, the ones built by the Swiss Engineer Robert Malliart (fig 19) are the most impressive and widely referred to as a testimony to the suitability of reinforced concrete in bridge building.

Fig 19: The 90m Three Hinged Arch Reinforced concrete Salginatobel Bridge (c-Hanspeter Valer/Fotolia)

Prestressed Concrete: Reversely stressed from birth

For the tensile steel bars to kick into action in the reinforced concrete members the concrete in the tension region has to undergo significant cracking, which could project a rather disturbing image and also engender the deterioration of the section in the long run. Eugene Freyssinet in 1936 with his techniques of embedding pre-tensioned high strength wire in the concrete prior to the member being subjected to the external loading has revolutionized the use and application of concrete as material for structural purpose.

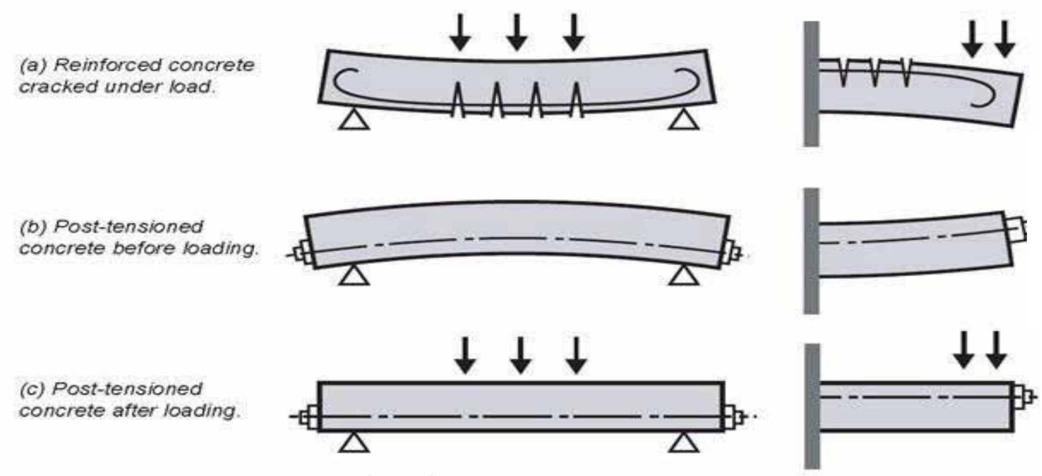


Fig 20: Effect of Prestressing Concrete Beams

As a consequence of pretensioning the steel wires/tendons, the concrete section gets induced to a significant level of internal compressive stresses, that the effects of the external loads (live load/vehicular) have to first overcome this already inbuilt internal compressive stress to cause any tensile stresses in the section, thereby, drastically enhancing the sections capacity take load and withstand deformation without any increase in its sizes. Prestressing concrete thus has made it possible for concrete decks and girders to span longer lengths with thinner and elegant members.

Bridges in Bhutan: Then, Now and Hereafter

Given the natural landscape, bridges were a necessity in Bhutan and a lot of remarkable bridges were built in the past. The still in service "suspended iron chains Chazams" believed to be built by the great artisan "drupthop Chagzopa" and the "Cantilevered wooden girder Bazams" being among the most notable ones.

Fig 21:A propped cantilever bridge over Wangchu (c- C Bell)

Fig 22: A Suspension over Phochu (c- Author)

Fig 23: A Wooden Cantilever bridge "Bazam" over Pachu (c- Author)

Presently, the CDCL is at the forefront of modern bridge building initiatives pushing the limits of bridge engineering in the country in terms of both the physical and technological scale. There is a huge need and scope for bridges and bridge engineering in Bhutan given our mountainous terrain and the numerous deep and wide streams and rivers crisscrossing the landscape. While the initial cost and the technological challenges may appear to be daunting, there is tremendous benefit to reap in the long run. A case in point is a hypothetical bridge over the Mandgechu along the Thimphu-Trongsa highway depicted in the picture (fig 24). It is one among the numerous ideal sites for a mid-span cable stayed or a suspension bridge. Imagine the impact such a bridge will have on the economy, the society and the very idea of how we perceive time and distances.

Fig 24: One of the many Ideal Sites for a Long Span Bridge(c- Author)

Where from Here – How further can we span

Fig 25: The envisioned 80km long intercontinental peace bridge (c- Aberdeen Group)

With the shedding of weight complemented by the invention of new materials and the formulation of techniques that improved the weaknesses inherent in these materials, bridges are built at locations and over spans that were once deemed impossible. The record for a single span at the moment is the 1991m Akashi-Kaikyo Bridge in Japan. A grand plan to connect the two land masses of North America and Europe (fig 25) and thus virtually the whole of the world through land has been envisioned by the likes of Joseph Strauss and Professor T.Y Lin by building a 80km long bridge over the Bering straits connecting Alaska and Siberia (Aberdeen group). Proposed during the peak of the cold war, a bridge such as this was expected to foster commerce and understanding between the people of the United States and the Soviet Union. In the words of professor Lin "this bridge will demonstrate that human energy and technical capabilities can be devoted to constructive rather than destructive measures to the benefit of all mankind" and he dubbed it the "intercontinental peace bridge"(UC Berkeley News).

How further the bridges can go is only limited by our ability to lose more weight and innovate /discover newer material and techniques for even higher capacity and performance. Concrete strength up to 100Mpa (28day strength), steel wires of tensile strength 2000Mpa and bars of 1000Mpa are now quite common (N K Raju). Recent advances in research in alternative material have discovered a possibility of a bamboo fiber based composite material that could be much stronger than steel while only weighing about a quarter of the weight of steel (D.E Hebel): a perfect material for bridge building *"Strong yet Light."*

Fig 26 : Tensile Strength Test of Bamboo
Image Courtesy : D.E Hebel - ETH

Concluding Remarks

For as long as mankind endures the need and search for ways to lose more weight and the curiosity to discover lighter, stronger and better material and techniques shall continue. A wall, no matter how big and grand, could detach and hinder, while a simple small bridge will attach and facilitate progress. Good fences may or may not make good neighbors, but good bridges certainly make great neighborhoods.

References

1. Aberdeen Group, Intercontinental peace bridge could join East and West, 1988
2. D.E.Hebel, Green Steel: Constructing alternatives out of bamboo,2015
3. European Portland Cement, Joseph Aspdin Portland Cement, From Rock Quarrying to Cement manufacturing - Oliver Bowles, 1918
4. H. Petroski: Engineering and Civilization: Bridges and Infrastructure- the sources of success and failures
5. J. Stanton :Spanning the Gap : Lessons in Bridge Engineering J.J Henson, A History of Bridges- A Philately Review
6. M.P Collins, In search for Elegance, 2003
7. M. Miodownik, Introduction to Steel, Tenaris University
8. Nat Geo : The world's Longest Suspension bridge
9. N. K Raju, Prestressed Concrete - Theory and Practice
10. R. Frost, Mending Wall, 1914
11. UC BerkeleyNew , Press Release, 18th November 2003
12. W.B Srubar III, Standing on the Shoulders of Giants - A Evolutionary history of Architectural Structural systems

Author's Profile

Tshewang Nidup is a lecturer in the Department of Civil Engineering and Architecture at the College of Science and Technology, Phuentsholing.