# Structural Engineering - A Historical View & Challenges Ahead

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**Abstract**
History of Structural Engineering is an enchanting story of how it has served with great credit the development of the human society from the very initial stages. The early development was intuitive with no formal back up of training or education, which got initiated substantively in the 19th century. The last two centuries have seen tremendous growth in structural engineering capabilities and almost dramatic enhancement in their utilization. One primary factor enabling this growth is the electronic revolution of the twentieth century. Despite the strong platform on which Structural Engineering is placed today, new challenges are there to be addressed. These consist of the need to maintain aging infrastructure, adding huge infrastructure particularly in a developing country like India, keeping in view the important issue of sustainability, modernizing training and education of Structural Engineers to keep abreast of the new developments in technology and allied disciplines.

**Keywords:** Structures, History, Challenges

## 1 Introduction

Civil Engineering has been called the mother branch amongst disciplines in Engineering and Technology, not just because it has been serving humanity for centuries but also because almost nothing moves without Civil Infrastructure, which takes up a sizable proportion of the budget too. In the current times, whereas Civil Engineering supports other disciplines in good measure, it also draws due support from other newer disciplines. Similarly, Structural Engineering has a very substantive role in all Civil Infrastructure development and in serving allied engineering disciplines. Historically, Structural Engineering, though intuitive, can be traced back in parallel with Civil Engineering. There are numerous examples of outstanding structures, such as the monumental structures including the Taj Mahal in India, and, many Roman structures, throughout this early period of non-formal engineering. It is of interest to see how this early engineering evolved to enable the construction of the modern day bridges and buildings of imposing dimensions, such as the Burj Khalifa, Dubai, and the recently opened 1915 Çanakkale Bridge in Turkey, known as Burj Bridge. This is the world's longest suspension bridge span and would perhaps have been unthinkable even a hundred years ago. The change that has come about in the last 70-80 years can be attributed, primarily to the enormous developments in electronics (miniaturisation, computing, automation, instrumentation, robotics, etc.), materials, construction technology, besides an increasing understanding about loads and their effect.

Structural engineering today stands on a strong platform. However, new challenges are being perpetually mounted by greater demands for additional and better infrastructure, need to maintain the exiting one, besides the growing issues of environmental changes and the need to focus on the concepts for sustainability. The structural engineer of the future therefore has to equip himself with the knowledge of newly developing materials, related biological techniques, inter-disciplinarity, structural health monitoring and Forensic engineering. Despite Structural Engineering being such a vitally important discipline for the development of the societal needs, and having a great record of achievement, it is currently not a sought after area of study or practice, resulting in falling standards by and large. This is a matter of concern requiring attention from all stakeholders – the Academia, Consultants, Construction companies as well as Policy makers.

## 2 Historical

Examples of intuitive understanding of structural engineering can be seen in, a tree falling across a rivulet to be used as a bridge, the little hutments which gave way to the habitat, bridges of antiquity using primarily stones by the ancient Romans, suspension bridges using stone masonry, timber and creepers (the concept led later to the modern suspension bridges), and so on. Such early applications in India and elsewhere are a testament to the resourcefulness and ingenuity of the people who lived during that era. The history of bridges particularly highlights the progress of human civilization in the fields of engineering and infrastructure development. Likewise, animal skin served as a cover for little huts. The idea is a pre-cursor to the membrane roofs of today. These early examples were followed by the construction of numerous monuments and places of worship, mostly self-supported type and with large bases. It is interesting to note that the use of burnt bricks to construct buildings is known for over 6000 years, and mud-bricks even earlier. Twentieth century saw the use of compressed mud blocks to save on fuel required for firing the bricks. A few illustrations of early structural engineering are shown in Fig. 1.

(a) A Primitive Bridge Concept (b) An Early Non-Metallic Bridge

(c) A Stone Bridge

(d) A Little Hut

**Fig. 1.** Early Structures

A few more illustrations follow, which demonstrate a somewhat more advanced and ingenious application of the structural engineering concepts, for constructing monuments, places of religious worship, aqueducts and buildings. The Pantheon (Fig. 2), still intact after nearly 2,000 years, holds the record for the world's largest dome of unreinforced concrete (9.1 m diameter). This, was built by the Romans using *"hot mixed"* pozzolanic concrete, a spectacularly durable material of incredible strength (200 Mpa). The Romans also built many aqueducts (Fig.3) of great strength and durability, demonstrating great engineering skills. A couple of outstanding Indian examples with similar credentials are shown in Fig. 4, which is followed by a description of a few others.

**Fig. 2.** The Pantheon, Rome

**Fig. 3.** A Roman Aqueduct

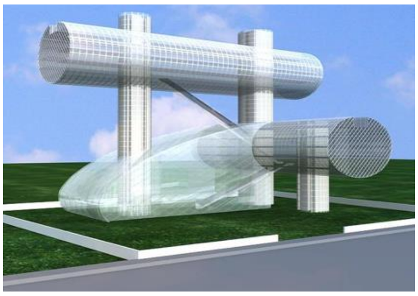
(a)Taj Mahal:17th Century 73m tall marvel (b) 560 km Long Ganges Canal Opened 1854

**Fig. 4.** A couple of Examples of Some Outstanding Early Indian Structures

There are indeed numerous other structures such as those shown in Fig.4. For example, the Hawa Mahal built in 1799, the tallest building in the world without a foundation; Sanchi Stupa, built in 3rd century BC, and declared to be a world heritage by UNESCO in 1987; Sri Ramanathaswamy Temple, Rameshwaram, built in the 17th century, with the main temple tower being 55m tall, and so on. The longevity of many of these older structures is noticeable in comparison to some of the modern constructions.

## 3 Primitive to Modern

As mentioned above too, structural engineering has taken un-believable strides forward in the last hundred years or so. A few examples may be seen in Fig.5.



(a) A Cluster of Tall Buildings (b) A Large Unusual Building

(c) Cable Truss Grid for a Roof (d) Canakkale Bridge

**Fig. 5.** Some Modern Structures

A few outstanding Indian examples of recent years are shown in Fig.6 - (a) is the tallest Shiva statue, (b) at 183 m, is the tallest statue in the world, (c) is the largest Stadium in the world which can accommodate more than a lac of spectators, (d) is the highest railway bridge in the world 359m above the river bed level.

(a) 115 m Tall Statue of Belief (b) Statue of Unity

(c) Narendra Modi Stadium (d) Chenab Bridge

**Fig. 6.** A Few Recent Outstanding Indian examples

The reasons behind this dramatic change over the last 100 years can be seen to consist of, Demand for additional civil infrastructure which has driven this growth, and, Development in materials, Appropriate choice of form, Improved understanding of loads, anaytical techniques and responses, The explosion of electronic development, Advancement in investigative facilities, Evolutions in construction technology, Advancement of allied disciplines, all of which have enabled this growth. These factors are briefly addressed in the paragraphs below:

***Demands for Additional Infrastructure***

The civil society is always demanding enhanced facilities and raising standards of life. This demand can grow further if the status of engineering and technology is seen to be advancing. The two aspects are therefore inter-twined, and, these in turn keep pushing the frontiers of structural engineering forward. That is the major basis upon which the journey of structural engineering has progressed. To have an idea of demand in the context of our country, a developing nation, there is a huge requirement for additional civil infrastructure related to transportation (a great example being the metro rail system which throws up numerous new challenges particularly for underground construction, tunnels etc.), communication, habitat, energy, recreation, to state a few aspects. As an example to demonstrate the need for additional infrastructure, a study made about 10 years ago had projected that India may need to add a *City of Chicago* each year for the coming decades. This was particularly so considering the trends in urbanisation.

***Structural Materials & Choice of Form***

The early materials were non-metallic, such as stone, creepers, timber. Cement, which is a major constituent of convential construction materials came on the scene in the Ninteenth century. Steel development also took place mainly from the Ninteenth century. This truly ushered the modern era of structural engineering. The current materials in use primarily are Concrete, Prestressed Concrete, Aluminium alloys, Steel, and, a big range of composites. Steel wires with a tensile strength of 1800 Mpa, structural steels with 800 Mpa and ultra high performance concretes with compressive strengths touching 200 Mpa (tensile strength upto 15 Mpa) and Carbon fibre based wrapping materials are arming structural engineering for greater possibilities including repair, retrofitting and rehabilitation work for existing structures. In this context, a parameter termed as the *strength-weight* ratio for a material has much influence on the choice of material, structural form, and consequently the design of structures. Given below are approximate relative values of the *strength-weight* ratio for a few materials:

| | |
|---|---|
| Mild Steel | 20 |
| Higher Strength Structural Steel | 80 |
| High Strength Wire Steel (1800 Mpa) | 240 |
| Aluminium Alloys | 60 |
| Medium Strength Concrete (30Mpa) | 04 |
| Carbon Fibre Composite (typical) | 2400 |

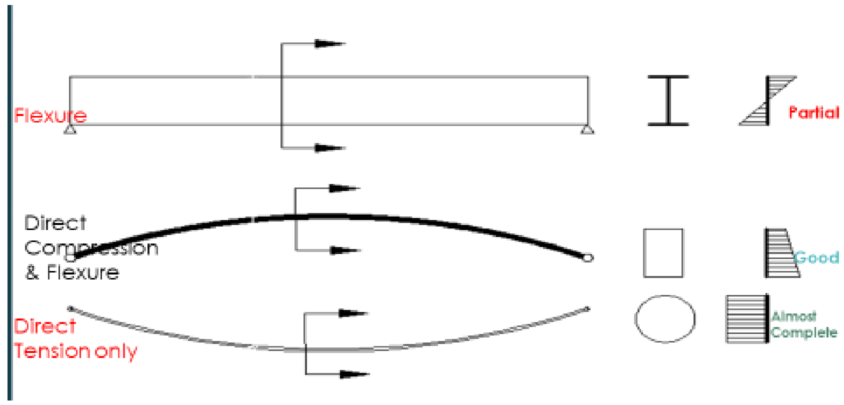



**Fig.7.** Transversely Loaded Members

The choice of geometrical form, structure type, spans and heights is irrevocably associated with the choice and availability of materials. Strucures in the earlier times used materials of low strength-weight ratios, mostly with compressive strength and weak in tension except ropes of vines and creepers, giving way to small spans or large self-supporting structures. Examples of the former are primitive suspension systems, arches and domes as shown in Figs 1-3, and those of the latter as shown in Fig.4, and, cited in continuation thereof. These applications carried loads by primarily developing compressive stresses. The advent of steel with its increasing strengths (in tension as well as compression), ultra high performance concrete and other materials such as carbon fibre composites with much higher strength-weight ratio, created a revolution of sorts for the possibility of construction of larger spans and heights, unusual geometry, as demonstrated by examples in Figures 5 and 6.

Another impertant choice involved is that of form. It is well known that axially loaded members utilise material efficiently and ties do so more effectively than struts. However, for transversely loaded members, forms which carry loads through direct compression or tension are more efficient than those in flexure. See Figure 7. It is therefore a question of combining the choice of form and material (eg concrete in compression and steel in tension) in the most efficient way. Furthermore, materials with higher strength-weight ratio make it possible to reduce dead loads and allow the possibility of taller structures, and, bigger spans. The structural forms with larger spans, primarily deploy steel, even high tensile steel. Figures 8 and 9 show the notional span limits for different bridge and roof forms.

***Improved understanding of loads, anaytical and experimental techniques***

Decades of R&D effort has resulted in better assesment of loads of various types, particularly the occasional loads due to wind and siesmicity. Methods and capabilities for analytical work have likewise made great strides. From classical methods such as the slope-deflection approach, the moment distribution method, one has moved to matrix methods, the FEM, CFD, and so on. Much of this development has taken place alongside the advent of (and because of) digital computers. There also has been a sea change in experimental techniques with significant improvement in the design of sensors led by the growth in solid state physics. As an example, today one can make dynamic pressure measurements on a model in a wind tunnel, simultaneusly over thousands of points, and, process these on a real time basis.

This has had a profound influence on the extent and speed with which structural loads and effects can be assesed.

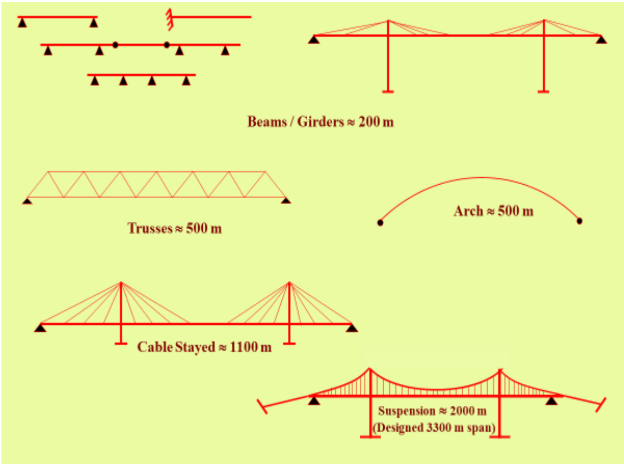



**Fig. 8.** Notional Span Ranges for Various Bridge Forms

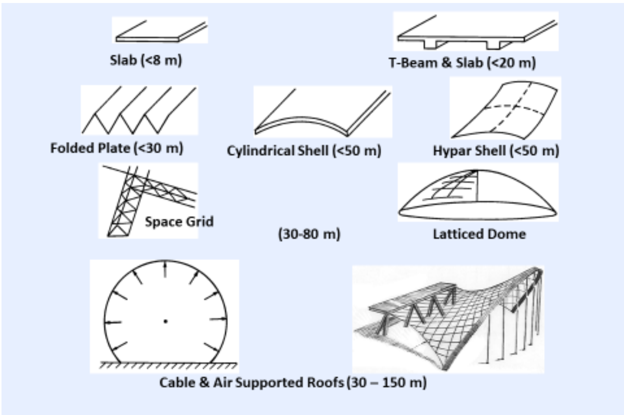



**Fig. 9.** Roof Forms with Notional Span Limits

***The Electronics Revolution***

If one were to choose one single factor that has effected most the developments in Structural Engineering, it will be the developments in electronics in the last 100 years or so. Amongst this too, it is the advent and growth of digital computers, as also mentioned earlier. This has revolutionised analytical work, design and drafting to begin with. Then there has been profound influence in construction, where automation is taking over increasingly. As an example, cutting, assembling and welding of steel elements can be mostly automatic, which is particularly a boon for larger structures, where the benefits in terms of both time-saving as well as accuracy are huge. Furthermore, developments in robotics are promising – a robot can access a location where a humans may find it difficult to reach. Items of work that had to be handled physically can now be tackled through remote sensing, such as inspection and quantity surveying through drones. In experimental work and structural health monitoring there has again been a sea change, with great sophistication in sensors.

***Evolutions in construction technology***

Developments in electronics (read computers, sensors and other monitoring devices) have impacted all aspects of civil engineering, including construction. Besides this the higher capacities of lifting equipment, advancements in construction procedures and techniques have made it possible to concieve and achieve larger construcion projects in good time.

***Growth of allied disciplines***

Notwithstanding the growth and developments in structural engineering, described in the aforesaid paragraphs, it must be said that the developments in allied disciplines in civil engineering and other branches such as Mechanical, Electrical, Metallurgical engineering and Architecture have played their due role in the outstanding achievements of structural engineering. There are other branches, such as Biotechnical engineering that are growing fast, and, are expected to effect civil and structural engineering. The future will lie in interdsciplinarity.

## 4 Challenges & Way Forward

The aforesaid sections illustrate that Structural Engineering as a concept and a formal discipline has served the society for centuries, and its various aspects stand on a firm footing. This is demonstrated by the achievements within the country as well as outside. However, there are several issues related to the future which are mounting a challenge, particularly related to a developing country like India. These are briefly mentioned below, followed by those issues requiring to be addressed:

***(i)Maintainence of the Existing Infrastructure.***

The existing civil infrastructure constructed before the 1950s has aged, and that constructed after the 1950s is also beginning to age. Considering that a developing and populous country like India requires huge infrastructure, the existing one has to be *carried to the last Rupee of investment,* by regular maintenance as well as *repair, retrofitting and rehabilitation*. In fact, if feasible and economically viable, service life should be enhanced too. It is also important for the heritage structures (though a good number of them are still in good health), which the country can ill afford to lose. This will require to strengthen considerably the capacity and procedures for *Structural Health Monitoring,* and utilise current developments in relevant technologies.

***(ii)The Huge Scale of Demand for Additional Infrastructure.***

It is well understood that India requires to add a huge quantum of infrastructure to fulfill the societal needs of transportation (both urban such as metro rail system, as well as long-distance), energy, habitat, agriculture, industrial development, recreation and, so on. Furthermore the country has been urbanising on an unprecedented scale, which is adding to the considerable pressures that already exist, related to the infrastructure needs. It is also impotant to understand that the country has to move fast towards attaining a *developed* status, in order to combat the ever changing International scenario. The speed of engineering inputs required therefore adds another dimension.

***(iii)Issues Requiring to be Addressed***

In order to deliver safe and good quality solutions in the context of the above two scenarios, at least the following issues require to be addressed on an urgent basis:

**(a)** Upgrade the education and training programmes for civil & structural engineers to create the necessary quantity as well as the quality. Curricula have to ensure that awareness is created about the new materials and technology for construction.

**(b)** For (a) above to happen, it is also imperative that the societal perceptions about civil & structural engineering have to become more favourable and the construction industry has to earnestly come on board. Industry – Institute interaction has been talked about for decades, but the time has come to *walk the talk*.

**(c)** Engineers must constantly innovate, and, imbibe the developments in conventional materials, such as various ways of cement replacement in concrete, developments in new materials such as phase change materials for special applications, and so on. They have to be equally aware of improvements in construction technologies, such as 3-D printing, developments in softwares, growth of allied disciplines such as *biotechnology, information technology, artificial intelligence, machine learning, robotics, and automation*.

**(d)** Address the highly important issue of sustainability.

**(e)** Strengthen considerably the capacity and procedures for *Structural Health Monitoring* (as said already) and *Forensic Engineering*. This is imperative to combat the embarrasment due to failures of aging, new, as well as 'under construction' infrastructure, on an increasingly regular basis.

**(f)** With large complexes of buildings and other imposing structures coming up, and the general atmosphere around becoming increasingly aggressive, *safety and security* take an important place in planning the structures.

## 5 Conclusion

The text above indicates the continuing contributions of high quality from structural engineering, covering a wide spectrum of needs for the growth of the society. However, the all- round change of scenario in engineering and technology, changes in environment, and the huge additional demands related to civil infrastructure, throw up new challenges. The future of structural engineering will therefore require continued innovation and collaboration. It is an exciting time for our profession, and with the right approach, we can create structures that will stand the test of time and serve as a testament to human ingenuity and innovation.