The evolution of architectural form and the formulation of mechanics

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**Abstract**

From the beginning of civilization humans built structures, initially for shelter in established communities and later structures of worship. The materials available and the cumulative empirical knowledge of successive generations of masons determined the architectural form of the structures. Throughout human history there are many examples of such structures. Mathematics, initially geometry, was the next step in the ability of the architect to materialize his ideas. Later, mathematical analysis brought together the strength of materials and the geometrical distribution of mass to build greater and safer structures. Finally, in today’s immense computerized capabilities, the human imagination and new materials can only limit the architectural form.

This paper describes the side by side evolution of architectural form and the formulation of mechanics from the early days of civilization to the present day achievement of high rise towers.  
*Keywords: architectural evolution, structural mechanics, historical buildings, civil engineering.*

**1 Introduction**

The significance of the theory of relativity that Einstein announced in 1905, lied not only in the tremendous technological changes it brought in the following hundred years, but also in the audacity of man to challenge existing knowledge. ‘Time’ was no longer measured in absolute terms. And while it did not affect ordinary people, it made a world of difference in physics and space exploration in later years.

Architecture on the other hand is based on building technology, which is conservative, based on cumulative knowledge from the beginning of human life.
In an article on architecture Lawrence B. Anderson wrote in the Encarta encyclopedia: *Although design and construction have become highly sophisticated and are often computer directed, this complex apparatus rests on pre-industrial traditions inherited from millennia during which most structures were lived in by the people who erected them. The technical demands on building remain the elemental ones – to exclude enemies, to circumvent gravity, and to avoid discomforts caused by an excess of heat or cold or by the intrusion of rain, wind, or vermin. This is no trivial assignment even with the best modern technology*. [1]

The history of architecture is full of achievements in form, materials used and construction methods. But while ‘architecture is to building as literature is to the printed word’, civilization as we know it today, owes its existence to the engineers [2]. No architectural form could advance beyond the capabilities of the construction engineers, to build it. Before the latter part of the 19th century, construction know-how was mostly empirical, carried out by masons with cumulative knowledge inherited from previous generations, like cooking recipes. Masons over the centuries have learned to experiment with new ideas and accept failure as a necessary learning process [3]. Unlike science and mathematics, which are based on exact formulations, engineering is based on experience. If a structure can stand after its construction, that is proof of its worthiness. Masons through centuries built temples, cathedrals, bridges and other structures that failed, some sooner than later and some still stand today after hundreds of years. It was their way of learning through experimentation by modifying their design after each failure, something unthinkable today. Once they found a form that worked, they kept it for later generations. Any old building that survived the environmental deterioration through many years to this day is based on an unknown learning history, not only in its architectural form, but also in its construction engineering and materials used.

By the early part of the 20th century the advances in mathematics together with the understanding of strength of materials, empowered the method of engineering analysis in new construction and within less than a hundred years it replaced the empirical methods used by the masons for centuries. It was no longer necessary to waste time and money to experiment with old ideas, but instead a new design was proven with mathematical models and computer simulation. Laboratory testing of materials is still necessary and steel, used in all large structures, is now produced under strict specifications. The quality of all materials used and the certification of all technicians are now part of all building codes. Large construction companies have design books with proven engineering formulas and data that engineers use in new structures, which in many ways is similar to the building recipes of the masons. Any new formula used must be well proven before it is entered for use, especially in aircraft design. However, although construction methods are the same for buildings and aircraft, there is a basic difference: the estimation of structural fatigue. An aircraft will not be submitted to test flying unless its basic components are first tested through the fatigue spectrum. Such testing could not be carried out for large buildings and bridges. During the last few years, however, models of buildings and bridges
have been tested successfully in wind tunnels. Similar testing using scale down models of large structures on shaking platforms to prove theoretical predictions for seismic loads had only moderate success, since the results depend not only on the building structure under testing, but also on the unknown geological substructure.

The fatigue life of most concrete buildings is not known to this day for two reasons: a) because the pouring of concrete is carried out under conditions that can be specified, but not easily controlled on site and b) because of the chemical decomposition of concrete with time. The infrastructure of USA bridges, for example, that is, the ramps and approaches built in the early part of 1900 with concrete, has deteriorated so badly that by the end of the century it required 1.5 trillion dollars to repair or replace it. The same of course can be said with certain stones used in construction, when exposed to the environmental elements. The effects of pollutants and especially sulfur dioxide are known to accelerate the deterioration. Buildings under static loading, however, can only be tested under real life simulation. That is why old buildings must be studied carefully in order to find the reasons of their survival.

2 The empirical foundation of structural mechanics

One of the most revered surviving buildings is the Parthenon, built during the 5th century BC in Athens Greece, fig. 1. In Sicily there are many ancient Greek temples as well, built with the same ‘golden ratio’ between the sides, and otherwise the same proportions as the Parthenon, probably by the same architects and masons. The only difference was the material used, instead of marble used in Athens, they used limestone that was locally available. The deterioration of limestone over the centuries is considerably worse than that of marble. So we have the same architecture under the same bright Mediterranean sun, but with a different aesthetic value in each case. Instead of the earthy look of the temples in Italy, a brighter, ethereal white is seen in the temples in Athens. Temples like the Parthenon were built in many parts of Greece.

Figure 1: The Parthenon of Athens, Greece.
The spacing between the columns in the temples was determined by the strength of the lintels above them. The cross section of the lintels was square. Observing the surviving temples today we see that none of the lintels had cracked at the lower part of the lintel under load, a proof that tension was at a minimum. The two architects, Iktinus and Callikrattes spent eleven years to perfect the Doric temple. To ensure that the temple looked perfectly straight to the human eye, they used the geometrical technique known as entasis that permitted a slight tapering of the columns. It was a brilliant device that depended on the architect’s great mathematical judgement and on the equally great mason’s skill [4].

The columns are made of horizontal sections and are connected together at the center with iron pins, covered with led in order to prevent oxidization, but also in order to prevent breaking the marble (a brittle material) when the building experienced an earthquake. High-speed pictures taken of a column shaken by an earthquake showed that each section of the column wobbled about its center pin, eventually settling down in its original place at the end of the vibration period. In fact, all the stones of the temple depended on compression and frictional forces to stay in their place. No bending moments, as we know them to day, developed, since all the parts of the structure were free to move in small displacements without deformation, with the exception of the lintels: in other words the building consisted of discreet elements. The same kind of engineering was used in the temples in Egypt, built in earlier times with much heavier columns. It is obvious that the technology was developed over many years. In fact all these engineering principles are in use today: they are taught in engineering schools all over the world. They started as new ideas with Archimedes and Aristotle back in the third and forth centuries BC. Archimedes was a mathematician and inventor, born in Syracuse, Sicily then a Greek city and educated in Alexandria, Egypt, a city greatly influenced by the ancient Greek culture. A Roman soldier during the invasion of Sicily killed him as he was absorbed with diagrams drawn in sand. He defined the principle of the lever and is credited with inventing the compound pulley. These two devices were the main tools of masons for moving heavy stones for many centuries to this day. We had to wait for Newton and Hook for the next great contributions to mechanics in the eighteenth century.

Construction was also greatly enhanced by military engineering during the Roman times that influenced all construction. Byzantine emperors built many churches using Roman engineering know-how and the Venetians extended the building traditions to the 18th century with impressive fortifications that still stand in the Mediterranean today (Crete).

Another structural design, like the Parthenon, that was developed initially in Rome and was used later, with few modifications, in the construction of churches in Europe and Asia Minor was the Basilica. One of the earliest was St. Maria Maggiore in Rome 432-40) AD and St. Apollinare in Classe in Ravena (534-549). In the 6th century, as darkness descended in Europe, the Byzantine emperor Justinian revolutionized church building and architecture. Hagia Sophia (Divine Wisdom) in Constantinople, (532-537) was the most adventurous, fig. 2. The dome structure of Hagia Sophia was later, during Renaissance, the basis for
great cathedrals like St. Peter’s, in Rome and St’ Paul’s in London. The architects Athenius of Tralles and Isidorous of Militus were skilled mathematicians and engineers. The dome, however, collapsed 30 years after its completion. It was attributed to the speedy construction demanded by the emperor Justinian and not to the calculations of the architects. Hagia Sophia later influenced many mosques and churches. The greatest copy was that of the magnificent St. Mark’s cathedral in Venice, built in 1063-1073 [4]. By this time, however, mortar and brick was discovered and used. (Some claim that mortar and brick were used by the Babylonians back in the 18th century BC). The mortar used in Hagia Sophia was like cement with some tension capabilities. To this day they have not found the chemical formula. Since then the structure has experienced strong earthquakes without damage.

Figure 2: Hagia Sophia, inside view.

If we compare the geometrical, aesthetic and psychological effects human beings experience entering a Greek temple and the Basilica churches today, we find the differences striking. In the Greek temples the exterior was much more important than the interior, whereas in the Basilicas the importance was placed in the interior. In the Parthenon the geometry is within the human grasp of height and width, and therefore friendly and playful, with the impressive spacing of the columns welcoming you from many entrances. The vastness and darkness of Hagia Sophia on the other hand is frightening. Aesthetically and psychologically the Parthenon is cheerful and gracious, Hagia Sophia is imposing, mysterious and demands submission as you stare in awe at the dome that momentarily is like heaven with deem light entering from the windows far in the sky, unable to focus with the naked eye.
Bending moments with internal stresses and strains were at a minimum in Hagia Sophia. Of course the definition of stresses and strains was unknown at that time. The ability of the architects to build with compression forces, minimizing tensions, as an engineer would argue today, was the only way for a masonry structure to survive for so many years. Yet none of this was formulated then and only the logic and intuition of the engineer-mathematicians could have provided such a result. Yet again, it is possible that they knew more than we give them credit for. Geometry was an advance tool of architects involved in construction from the earlier times: the behavior of a structure as a whole could only be analyzed geometrically without analysis of three-dimensional stresses at a point. The method of erecting the dome was by itself a geometrical feat.

Unfortunately such capabilities are hard to find to day. Computers have replaced ingenuity and practical utility considerations have re-directed the emotional drive for achievement.

3 The formulation of mechanics

The now famous astronomer Gallileo made a contribution to the study of the strength of materials late in his life, when he could not longer practice astronomy. He contributed his findings to two French priests who helped to found the Academy of Science during the 17th century. It is noted that none of these people were involved in construction. It was at that time that the behavior of materials and structures under loads was called the ‘science of elasticity’. The question was initially philosophical: how is it that any inanimate solid, such as steel or stone or timber or plastic, is able to resist a mechanical force at all’. [3].

Robert Hook who lived during the same period was the first to understand this problem. He answered the simple question: ‘why we do not fall through the floor’, with a simple answer, ‘because the floor pushes back with an equal and opposite force’. It is Hook’s thinking that permits us to day to draw a free-body diagram in classes of mechanics, substituting all the supports with equal and opposite forces. He saw clearly that ‘every kind of solid changes its shape- by stretching or contracting- when a mechanical force is applied to it and that ‘it is the change of shape that enables the solid to do the pushing back’ [3]. Of course Newton said it in a more eloquent way: ‘if a body is in equilibrium, the sum of the forces is equal to zero’. The science of elasticity was stuck for a long time because the scientists that study it dealt with forces and deflections by considering the whole body, as Hooke did. Leonhard Euler and Thomas Young worked through the 18th century and well into the 19th trying to show the forces and extensions at a given point. The concept of the elastic conditions at a specified point inside a material is the concept of stress and strain. Finally Augustin Cauchy put forward a generalized form of these ideas to the French Academy in 1822. This paper was perhaps the most important event in the theory of elasticity since Hook (1676). It was a practical tool for engineers rather than a happy hunting ground for a few somewhat eccentric philosophers [3].
During the first half of the 19th century most of the theoretical elasticians were Frenchmen. The work was abstract with difficult mathematics that was not accepted by engineers until 1850. *This was especially the case in England and America, where practical men were regarded as greatly superior to ‘mere theoreticians’* [3]. About the same time, 1857, Cayley wrote his memoir on the Theory of Matrices in the Philosophical Transactions of the Royal Society of London [5]. It was an organized method for solving systems of linear differential equations. At the time it was almost useless, but when the computers appeared the following century, it became the most useful piece of mathematics for solving engineering problems. As mathematicians like D’Alebert, LaGrange and Hamilton were developing their theories, engineering schools were transferring the mathematical methods to engineering solutions. It is the same relationship that the architect-engineers of the Parthenon and Hagia Sophia had with mathematics. The result was an explosion in construction, fig. 3.

![New York City](image)

**Figure 3: New York City.**

### 4 Concluding remarks

History has shown that human ingenuity has a natural way of adapting new ideas, for utilitarian, artistic and religious purpose [6]. In New York City, for example, the need for space has created a boom for high rise steel construction,
in the second half of the 20th century, surpassing the older buildings of cathedrals, buildings with individually dictated architecture, libraries and museums that were built during the first half. The earlier buildings were erected without the participation of the public at large. However, after the destruction of the twin towers in September 11, 2001, the design that was selected for the new building to replace them was the result of public participation. There was a demand that the new high structure appeals to the public character of New York. In midtown Manhattan today some new buildings have a loud artistic exterior, by comparison with the box-like buildings that sit next to them. The magnificent Time-Warner building in Columbus Circle on the hand, that opened two years ago has spacious, richly decorated areas that reduces the useful area, but increases the friendly and pleasant effect of the building.

Behind all these new ventures in architecture we find not s much the use of new materials, but better engineering know-how and daring in artistic value for their construction. A unique example is the work of Santiago Calatrava, the Spanish architect, artist and engineer that has combined his engineering knowledge with his architectural taste in some impressive projects around the world, including the Olympic stadium in Athens Greece, constructed for the 2004 Olympics, fig. 4. Tubular curved beams are used extensively in his designs, in contrast to the straight steel beams that characterized older similar structures. After the arches and domes of Roman and Byzantine times, Calatrava’s curved profiles add a new dimension. The engineering analyses of such structures could NOT have been done with a slide-rule or a table calculator. Computers, matrices, simulated models and easily accessible evaluations made such projects possible.

We can conclude that the computer technology is an extension of the human brain, doing things that a human brain does not have the capability to do. Is this bad? Is the human creativity disappearing, or atrophied by the technological progress? Only time will tell. So far we see the expansion of human knowledge.

Figure 4: From the Calatrava Olympic Stadium in Athens, Greece.
References


