

Developments in the architecture of earthquake resistant high-rise buildings in the period from the end of the 18th to the beginning of the 20th century

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Abstract

This paper studies the influence of building structural systems and the usage of new materials such as iron, steel and reinforced concrete on the developments in the architecture of earthquake resistant high-rise buildings in the period from the end of the 18th to the start of the 20th century. The paper chronologically analyses and presents a few selected building examples that presented a novelty from the structural or architectural point of view at that time. Special importance is given to the examples where some architects or constructors from the 19th century were able to determine the architecture based just on the principles of structural logics.

1 Introduction

Architects from all artistic periods often sought inspiration in structural logics. The purpose of the paper is to illustrate the influence of structural logics and the effect of the implementation of new building materials on the architecture of high-rise earthquake resistant buildings in the expanded period of the 19th century. At that time the separation of structural engineering and the architectural profession became evident. The structural system became a crucial parameter determining the architecture and the functionality of buildings. The beginning of the 19th century brought new (artificial) building materials such as reinforced concrete, cast and wrought iron and steel. New demands of investors and new knowledge obtained by structural engineers importantly influenced further developments in architecture which became an autonomous field of science and art, yet strongly interrelated with other fields.



Centuries have passed from the invention of the first simple structures, such as a simple beam, vault, arch or dome that allowed relatively short spans and low-rise buildings. At that time the earthquake resistance of the buildings was achieved by the tectonic building approach (e.g. masses are concentrated as low as possible, walls have significant thickness at the bottom of the building which is reduced in the higher stories, buildings are rarely higher than 4 or 5 stories, floor plan is usually regular with walls running in the two orthogonal directions). The building elements were mostly loaded in compression, due to large self-weight the axial and bending stresses were minimized. All that changed in the 19th century with the emergence of new materials, such as reinforced concrete, wrought and cast iron and steel. The new materials enabled lighter, higher and slenderer buildings and different use of building space. For such building also the earthquake loading became a much more important parameter in the building design. In general, the structural logics are much easier to control if the loading is only vertical where we can – with some experience - follow an adopted feeling for the right proportions of the elements. However, when some stronger horizontal loading (such as an earthquake) appears, the adopted feeling based on experience might soon be insufficient. Experience shows that the biggest conflicts between the structural engineer and the architect arise precisely in the case of earthquake loading. The following chapters describe the development of relations between the building structure and architecture from the end of the 18th to the beginning of the 20th century.

2 The separation of structural engineering and the architectural profession

A builder – a skilled master from antiquity and the Middle Ages – was treated as a universal builder in the renaissance period – an architect who unifies an artist and a scientist in one person (e.g. Michelangelo or Leonardo Da Vinci). At the end of the 18th century and in the 19th century the separation between the structural engineer and architect/designer became a fact and the discord between the branches that followed was inevitable. The conditions for modern architecture arose at the beginning of the 18th century. In 1747 the first engineering school *École de Ponts et Chaussées* was founded in Paris, which symbolizes the separation between engineering and architecture (Frampton [4]). The ancient Vitruvius criteria (Vitruvius..., [15]) (firmitas-strength, utilitas-serviceability, venustas-beauty) were replaced by the new ones, where the strength criterion is replaced by artism and proportional logics determined by the architect-artist (C. Perrault and A. de Cordemoy). However, in the works of A. Choisy from the end of the 18th century, we can already find a statement which says that structure is the essence of architecture and that all stylistic transformations are mainly logical consequences of technical developments. The first example of labor division can be found in 1808, when a new dome with iron ribs in Paris granary (Halle au Blé) was designed by the architect F.J. Bellange and structural engineer F. Brunet (Frampton [4]).



In the period that followed all outstanding building achievements, such as railway bridges, stations, halls, towers etc. were built by engineers who had the necessary technical knowledge of new construction types and materials. Architects in the periods of romanticism, neo-classicism, historicism and eclecticism could not follow the rivalry for the largest bridge span or the greatest building height. It seems they did not recognize the advantages of the materials and possibilities they offer. The building previously designed on the basis of experience, became the object of scientific research with the purpose of minimizing its weight and cost and maximizing its functionality and economy. The architecture of this period still neglected the inevitable influence of science on art. The architect E. Viollet le Duc stressed already at that time the need for cooperation between architecture and engineering (Viollet-Le-Duc [14]). It seemed that a new era of engineers focused on structure and science achievements only would have began. However, the artistic part of the architecture could not be achieved only by composing the scientific discoveries and new demands in architecture. The majority of architects at that time refused to cooperate in the building of these »ugly, technical and temporary« structures. Nevertheless, the new structural esthetic presented the basis for the development of modern architecture at the beginning of the 20th century (Mušič [10]).

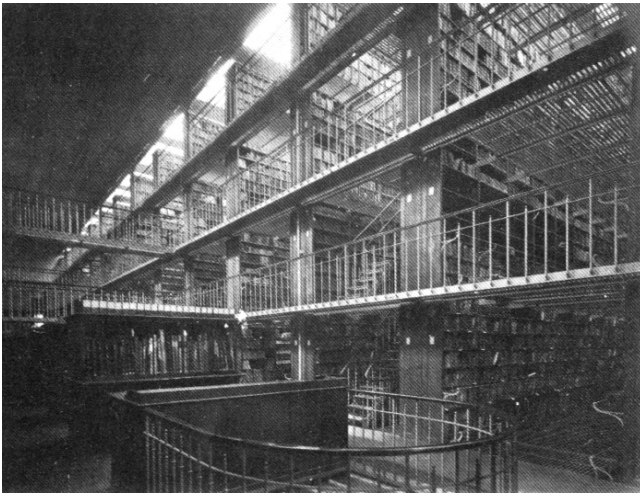


Figure 1: H. Labroust: Bibliotheque Nationale in Paris, 1860 – 68 [4].

3 The period of structural development in the 19th century

The 19th century presents a milestone in the development of building structures. Previous limits of building height and floor span disappeared with the appearance of light metal truss structures. The development begun with the usage of cast iron and wrought iron which enabled advanced structural solutions. The first buildings made of iron were libraries: Bibliotheque Ste. Genevieve

designed in 1840 and Bibliotheque Nationale designed in 1860 (Figure 1) by H. Labroust. The whole structure is made of cast and wrought iron, the architecture is adapted to the function of the building and dominated by the semi space frame structural system.

The first architects who accepted and understood the challenge of using new materials were the so called »School of Chicago« (architects Sullivan, Adler, Burnham, Root, Holabird, Roche etc.) (Hatje [7]). They designed many skyscrapers in the USA between 1880 and 1900 (Figure 2, 3). The structure is steel space frame filled and hidden by ordinary brick. The main vertical and horizontal structural lines can nevertheless be seen on the facade and form a well-known rectangular »Chicago window« (Frei [5]. Earthquake loading was not explicitly considered in the design of these buildings.

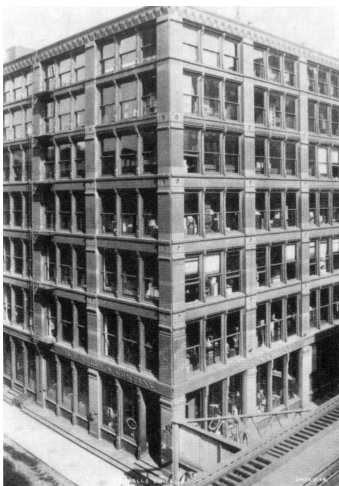


Figure 2: Jenney: First steel moment resistant space frame structure in Chicago (1885) [5].



Figure 3: Sullivan & Adler: The Guaranty space frame steel building in Buffalo, N.Y. (1895) [5].

3.1 Building structures made of iron and steel

Iron was the first artificial building material used in architectural history. Iron was used as a building material already in some cathedrals from the 13th century, in Perrault's east facade of Louvre (1667) and in Soufflot's portique St. Genevieve (1772). The first bridge made of cast iron was built in 1779 (span 30.5m) over the river Severn near Coalbrookdaleu. The system of fire resistant multi-storey frame structure was developed in the last decade of the 18th century (Frampton [4]. We can point out two buildings: a weaving factory from 1792 designed by W. Strutt in Derby and a rope spinnery in Shrewsbury designed by C. Bage in 1796. In both buildings the columns were made of cast iron and the

beams were T-shaped iron girders that carried shallow brick vaults. The horizontal resistance and overall rigidity were achieved by outer brick walls and diagonals from wrought iron.

At the same time also a new building technique of suspended iron bridges was developed. In 1801 J. Finlay (USA) invented a rigid suspended bridge with a flat deck. Drawn wire was first used in 1816, when ropes were used for a pedestrian bridge designed in Pennsylvania by White and Hazard. The materials and techniques that were originally used by the railway industry were also used for building structures. Today's classic I-section was developed from the railway rail profile at the end of the 19th century. Iron and steel (after 1860) enabled substantially longer spans and greater building heights. It is important that also the floor plan disposition became much more flexible as it was before. The space frame structures and trusses transformed the wall and roof in a filling which became transparent and followed new requirements for light and air.

In 1860 the first four-storey building made completely as an iron skeleton was built. It was found at that time, that profiles could be standardized and that the iron/steel column and beams could be prefabricated. Fully glazed buildings were first designed as greenhouses, but after the abolishment of tax on glass, they came in general use. The first permanent closed spaces with big glass windows were railway stations and exhibition halls. The best example is the *Crystal Palace* (dimensions: 124 x 563 m) built in 1851 by J. Paxton for the needs of the first international exhibition to be held in London (Figure 4) (Tietz [13]). The building is an interesting example of efficient prefabrication; the building process lasted only 4 months (McKean [9]).

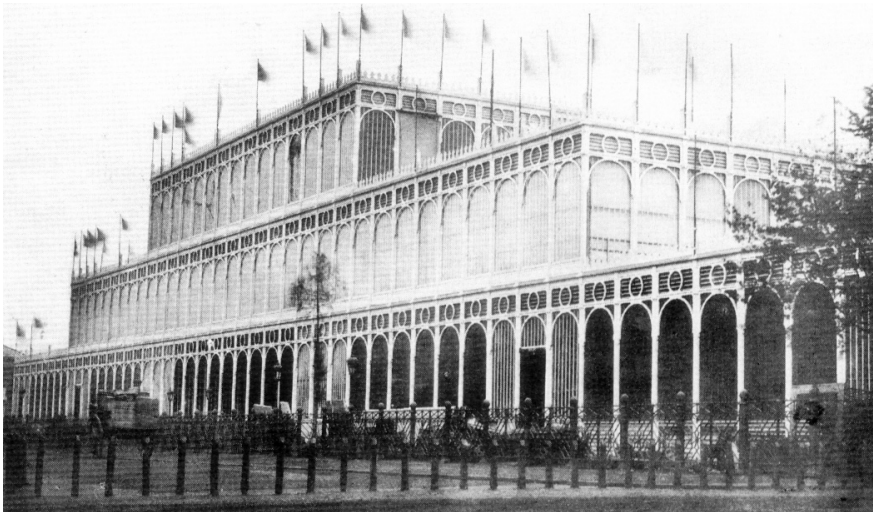


Figure 4: Crystal Palace designed by J. Paxton (1851) [9].



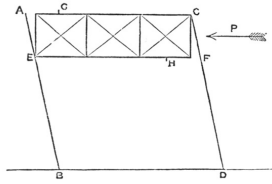


Figure 5: The effect of »soft story« was questionable already at that time [9].

It is interesting that the construction of the *Crystal Palace* presented such a novelty that many assumed the structure was unstable and might collapse under the first strong wind impact. The reason was the high centre of gravity and too slender columns on very small foundations. Today such a system is called a space moment resisting frame. From the earthquake resistance point of view it presents a ductile structure, assuming the connection details are made correctly.



Figure 6: Galerie des Machines during the construction, Eiffel tower is being built in the background [2].



Figure 7: F. Dutert: Galerie des Machines first three point arch (statically determined structure) [2].



Figure 8: G. Eiffel: a 300 meter-high tower [8].

The French response to the famous *Crystal Palace* followed in 1889, when they built the *Galerie des Machines* (dimensions: 111 x 420 m; F. Dutert and V. Contamin) and the *Eiffel tower* (G. Eiffel, Figures 6, 7, 8, 9) with the height of 300 m. The gallery was not as famous as the tower; however, it presented a very useful structure with victory over material and not a rebellion against it [Durant, 1994]. The span of the gallery was by 30% longer than the spans of all structures known before. The project was made possible by using steel as a new building material that replaced wrought iron.

For the *Galerie des Machines* the engineer Contamin used a simple statically determined structure of three-point arch founded on simple foundations. The structure seems simple, but it was very advanced at that time. The three-point arch, as a statically determined structure, has all the advantages (temperature deformation freedom, simple calculation) and disadvantages (failure of one element causes the failure of the whole structure) of such structures. We should be aware, that at that time the exact calculation of statically indetermined structures by computers was not possible.

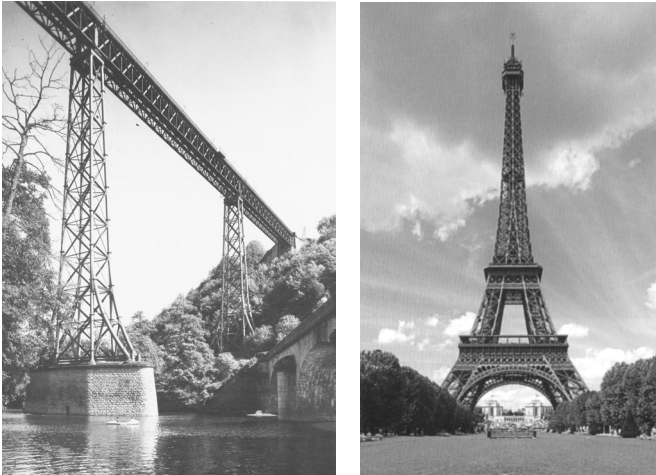


Figure 9: Comparison of the supporting column of a railway bridge and the construction of the Eiffel tower [8]

The arch of the Gallery of Machines is shaped in the gothic form and thus formed outside the ideal parabolic shape. At the point where the greatest tensional stresses occur, its static height is greatly increased.

For the same exhibition also another structure was built: the Eiffel tower in Paris. The tower was designed by G. Eiffel in cooperation with the engineers Nougier and Koechlinom and with the architect S. Sauvestre (Lemoine [8]). The Eiffel tower triggered numerous thoughts about the new structural esthetic. It is basically a 300 meter-high column shaped in a parabolic form due to wind or earthquake loading. Its center of gravity is relatively low; Eiffel developed the column shape during his construction of railway bridges (Figure 9).

Steel became a rapidly and widely used building material. The first steel skyscraper was built in 1883-85 by William Le Baron Jenney in Chicago (Figure 2). From the outside, the building is still an ordinary brick building; however, a steel skeleton is hidden inside. After the world fair in Chicago, the period of the so called »School of Chicago« and the time of big business buildings ended. The use of steel as a building material ended the period of strict height limitation that was valid in many centuries before (Hatje [7]; Frei [5]).

3.2 Reinforced concrete

Concrete as a material was known already back in history, however, all knowledge was lost during the Middle Ages. The first tests with cement and concrete mixtures were made in 1792 by Loudon. The first use of reinforced concrete might be considered in the year of 1861, when French F. Coignet developed a technique of reinforcing the concrete with steel mesh. The concrete developed very fast between 1870 and 1900. The first architect who built using reinforced concrete was A. Baudet. One of the first reinforced concrete skeleton structures was his church Saint-Jean de Montmartre in Paris. The first RC frame structure connection (Figure 10) was patented by F. Hennebique.

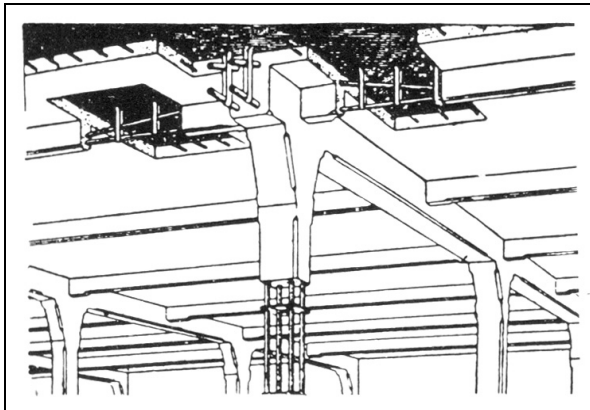


Figure 10: F. Hennebique, monolithic RC joint, patented in 1892 [4].

The first engineering code for RC concrete was issued in France in 1906. The first decades of the 20th century were the period of fast development of all sorts of reinforced concrete structures, including large flat roofs without beams, reinforced concrete skeletons, domes, ribbed slabs etc (Frampton [4]). French E. Freyssinet patented the first prestressed RC structures in 1939 (Figure 12).

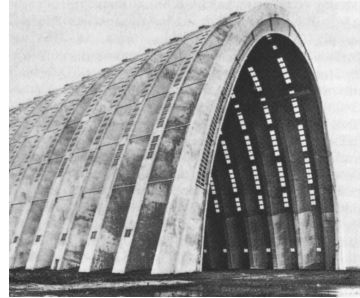
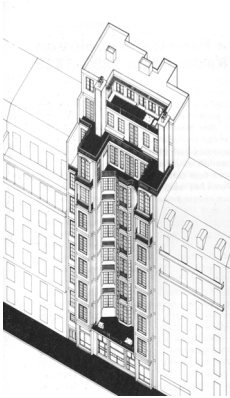


Figure 11: A. Perret, apartment house in Paris (1903) [3]

Figure 12: Freyssinet: RC prefabricated arch structure hangar, Orly 1921-24 [7].

Reinforced concrete offers numerous possibilities of shapes and forms. Frame type structures do not need walls, the facade remains merely an architectural element that can be removed. The floor plan disposition becomes more flexible, the new structural esthetic is formed on the basis of logic of constructional relations. One of the first of such »modern« buildings was A. Perret's apartment building in Paris (1903, Figure 11). Similar simple structural logics were also used by Le Corbusier (1914, Figure 13). Columns and flat slabs without any beams play a dominant role as a major element of architectural expression (Boesiger and Girsberger [1]). Such a structure proved to withstand the vertical loading well, it is however much more vulnerable to horizontal loading.

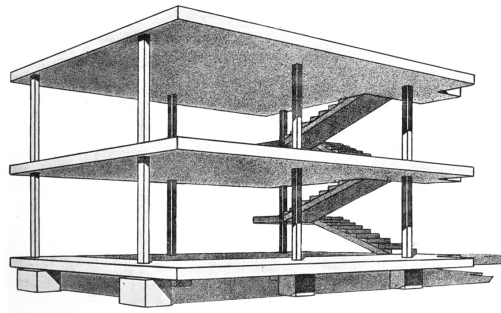


Figure 13: Le Corbusier, simple RC structural system (1914) often considered today as a »soft storey« [1].

4 The beginning of the 20th century

At the beginning of the 20th century the design of structures returned to the hands of architects. The period of *Art Nouveau* presented a classical approach to architecture, but already by using new materials. The structural system was often hidden by rich decoration. The changes in architecture were announced by a known architectural theorist E. Viollet-Le-Duc, who significantly influenced many important architects from that time (Gaudi, Hort, Berlage, Sullivan, Perret...). Very special architecture from that time can be seen in the works of A. Gaudi.

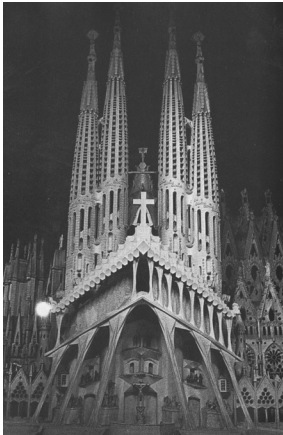


Figure 14: A. Gaudi: model of the church Sagrada Familia [6].

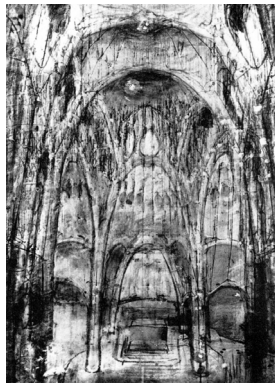


Figure 15: Structure sketch of the church - interior (compare with figure 15).



Figure 16: Chain shaped model of the church structure [6,7].

Gaudi used a complete 3D approach when designing his structures, which can rarely be seen even today. For his arches and vaults he used a specially curved shape that minimized the bending and shear stresses. To determine the best shape of the structure he used smaller testing models (Figures 15 and 16). The tectonics of these structures works firmly, the so called organic approach is based on the imitation of principles from the living world (Guell [6]). His structures sometimes resemble the skeletons of living creatures. His understanding of load paths is three-dimensional and guaranties excellent behavior under vertical as well as horizontal loading.

5 Conclusions

It can be seen that in the 19th century, structural developments were very rapid and architects were not able to follow the new trends. At that time structural engineers took the lead in designing new architectural and structural achievements. Earthquake resistance in that period was not yet systematically addressed; however, the intuitive measures were applied to design buildings with at least minimal earthquake resistance. The period of *Art Nouveau* was followed by the period of modernism. Once again the architectural and art principles changed completely. A resistance against all historical is characteristic of this period, however, the structure is again used as a means of expressing the architectural language. This period is planned to be covered in a separate paper.

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