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Philosophy of the design of the Eiffel tower

J. Rondal
University of Liege, Belgium

ABSTRACT: The aim of the paper is to show how engineers, more than one century ago, have been able to design and to build a tower with a height of almost two times the height of the highest building existing at that time.

1 GUSTAVE ALEXANDRE EIFFEL – THE MAN, THE ENGINEER

Gustave Alexandre EIFFEL is born on 15 December 1832, in Dijon, Burgundy, France. His family was of a Germanic origin with the name "Boenickhausen – Eiffel" but had lived in France for well over a century before his birth. His father was an officer in the armed forces of Napoléon I.

After a baccalaureate at the Lycée Royal de Lyon, he was sent to Paris by his father to prepare for l'Ecole Polytechnique but he did not succeed at the entry examination. He was accepted by l'Ecole Centrale des Arts et Manufactures where he graduated in 1855 as an average student, no more.

At the beginning of his career, EIFFEL was employed by a construction company and was soon in charge of the construction of a 500 m railway bridge in Bordeaux (France). From 1855 to 1867, EIFFEL was an engineer who worked hardly for his firm and, in 1867, he decided to launch his own company.

Between 1867 and the building of the tower in 1889, he designed and built interesting bridges and buildings in a lot of countries as, for example, Egypt, Russia, Vietnam, South and North America, Hungary, Greece, Portugal, … and France, of course. From a long list of references, one can mention for example:

- the Maria-Pia bridge over the Douro river at Porto (Portugal), built by the cantilever method, 1877;
- the Garabit Viaduct (France), with a total length of 564 m, an arch of 165 m and piles up to 82 m, 1879;
- the frame for the Statue of Liberty of Bertholdi in New York, 1881;
- the floating dome of the observatory in Nice (France), 1885.

In 1884, EIFFEL and two of his collaborators took out a patent for a high tower "N° 164364 on September 18, 1884 to Gustave EIFFEL, Emile NOUGUIER and Maurice KOECHLIN" (Fig. 1).

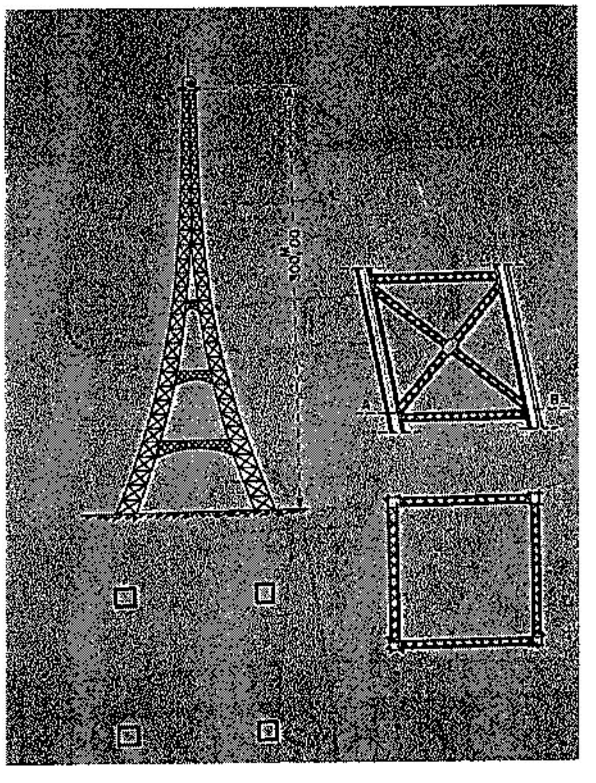

Figure 1. Patent for a high tower N° 164364 on September 18, 1884.

This invention was facilitating the construction of a tower greater than 300 m in height by taking the shear not by X bracings, as previously done, but by inclining the chords of the tower. This patent and others he had previously obtained for canal locks of great height enabled him to undertake simultaneously two major engineering works:

- "La Tour de 300 mètres", for the 1889 exposition to celebrate the 100th anniversary of the French revolution, and
- The locks for the Panama Canal.

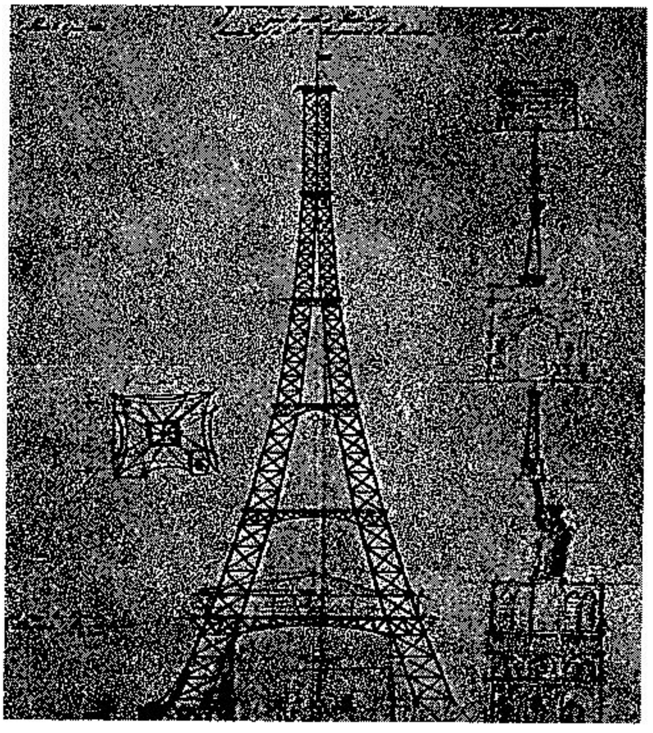

Figure 2. First project by Emile NOUGIER and Maurice KOECHLIN (1884).

2 THE FIRST PROJECTS

The decade 1880–1890 may be considered as one of the most successful in the story of steel structures. In addition to the various accomplishments by EIFFEL himself, one must mention the Brooklyn bridge (1883) and the Firth of Forth bridge (1890).

Some years ago, in 1874, at the occasion of an exposition in Philadelphia, a project for a tower of one thousand feet was proposed by two American engineers, CLARKE and REEVES, but without any success.

In 1884, a project for a tower of 300 m for the celebration of the 100th anniversary of the French revolution was presented to EIFFEL by two of his main collaborators; Emile NOUGUIER and Maurice KOECHLIN, an engineer graduated from the Polytechnic of Zürich after studies with Professor CULMANN (Fig. 2).

This project was considered too "structural" by EIFFEL and modified by the Architect SAUVESTRE, another collaborator of EIFFEL. A synthesis of the two projects led finally to the well-known version of the tower (Fig. 3).

With a height of almost two times the height of the highest monument existing at that time – the granite obelisk in Washington, 169 m – the tower redeemed the French from the stigma of the capitulation to the Germans in 1870.

The project was criticized by numerous artists but was built without any fatalities, not withstanding the site conditions at that time (Figs. 4 and 5), completed on time and attracted 2.000.000 visitors in its first year.

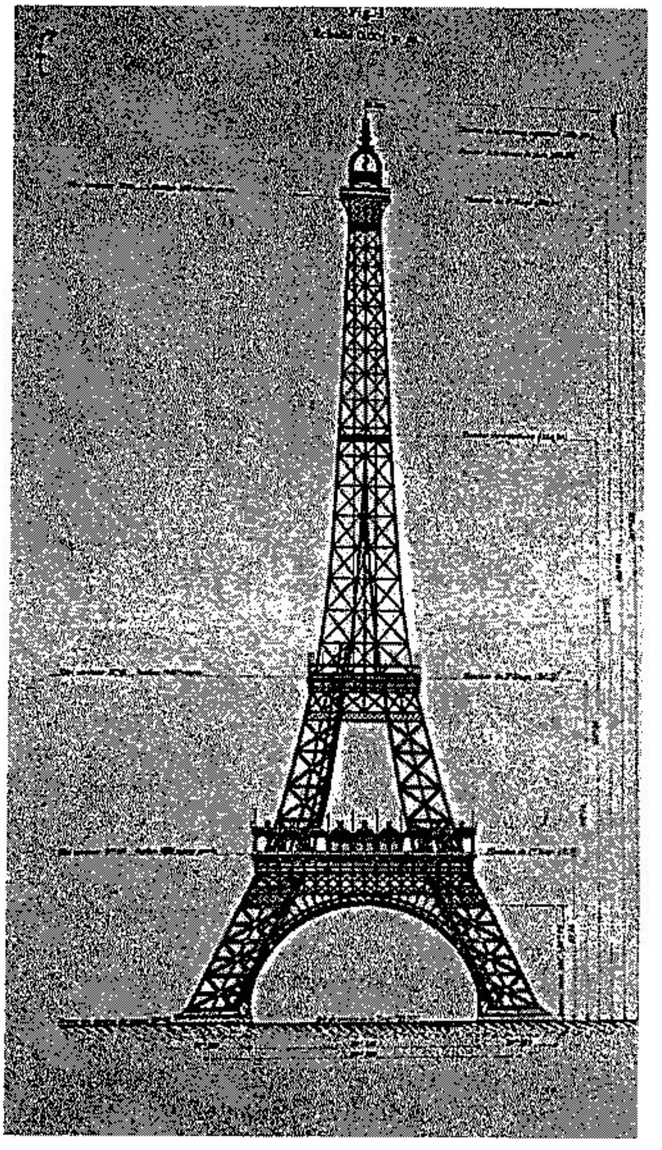

Figure 3. Final project.

3 THE DESIGN OF THE TOWER

The design of the tower, with all the calculations and drawings, is given in a wonderful two-volumes in-folio book published in 1900 (Eiffel, 1900).

The design is based, of course, on the linear elasticity and the structural theory used to calculate forces in the members is based on the simple statics of statically determinate systems and graphical methods. Most of the bars were box bars made by four angles connected by small trusses composed of angles or flats. They were thus riveted built-up members with a total of 1.050.846 rivets.

The book doesn't give results of tensile tests of the material used which was rolled iron but one can consider that the ultimate stress was about 300 MPa.

Figure 4. On site conditions.

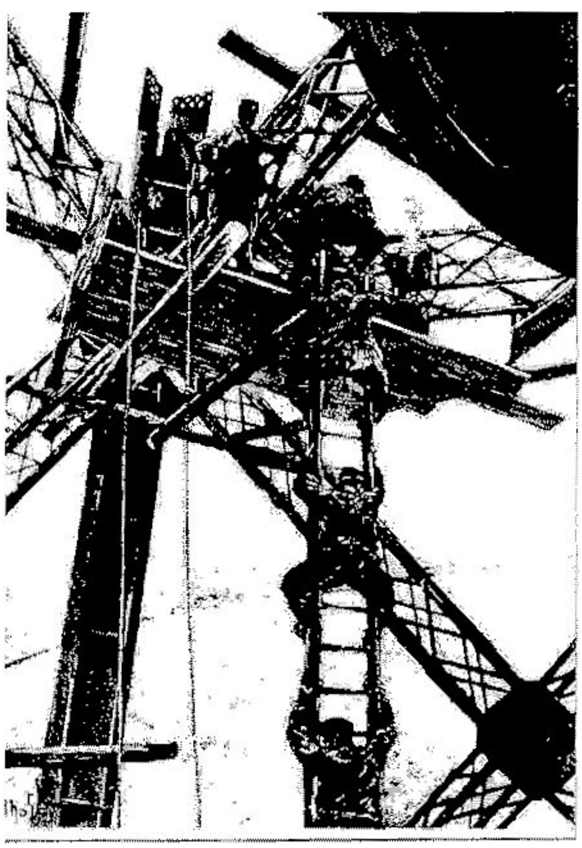

Figure 5. On site conditions.

A safety coefficient of at least 2.5 on the ultimate tensile strength has been used by EIFFEL but without any justification.

The loads that are considered for the design are the dead weight, the wind and temperature variations. It is assumed that the dead weight can be combined either to the wind effects or to the temperature variations. The wind effects were evaluated on base of two hypotheses:

- A wind pressure of 2.000 N/m^2 constant till the 2nd floor and than varying linearly to 4.000 N/m^2 at the top;
- A wind pressure of 1.000 N/m^2 at the basement varying linearly to 3.000 N/m^2 at the top.

For the temperature, EIFFEL was considering the range $-30°C/+30°C$ uniform throughout the tower.

All the structural elements are compact sections with a slenderness less than 45 for the chords and 40 for the bracing members. For these reasons, all the bars were designed by using the simple formula $R = N/A$ in tension and compression with an allowable stress of 110 MPa in the material (rolled iron).

With regards to modern recommendations on buckling, this hypothesis leads to an overestimation of the strength of 10% approximately.

4 CONCLUSIONS

It is hard to conclude a paper on a so exceptional work without some indications on the general characteristics of the tower:

- The exact height of the last platform is of 300,51 m (at present time, the height up to the T.V. antenna is of 320,76 m);
- The total weight of the iron parts is of 8.564.816 kg;
- The tower has been built between January 28, 1887 and May 6, 1889 with a total of 114,558 work days;
- And, finally, the total coast of the tower including lifts was, exactly, of 7.393.304.97 French francs which corresponds approximately to 15 millions of actual US dollars.

And, what if the Eiffel tower would be designed today? Probably two or three times lighter, using high strength steel. Regarding the duration of the construction, I am not sure that it would be faster today because of the high degree of prefabrication units used by Eiffel. But it is not possible to give a clear answer to this question because the imagination of modern architects is endless and the design tools are now so sophisticated that practically all is close to be possible.

REFERENCES

Eiffel, G., 1900. La tour de trois cent mètres, Lemercier, Vol. 1 and 2, In folio, Paris.