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Toward Structural Mechanics Through Wooden Bridges in France (1716–1841)

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To Luca, Pietro, Benedetta and Matteo

Preface

La filosofia è scritta in questo grandissimo libro
che continuamente
ci sta aperto innanzi gli occhi (io dico l'universo),
ma non si può intendere se prima non s'impara
intender la lingua,
e conoscer i caratteri, ne' quali è scritto. Egli
è scritto in lingua matematica
e i caratteri son triangoli, cerchi ed altre figure
geometriche,
senza i quali mezi è impossibile a intenderne
umanamente parola;
senza questi è un aggirarsi vanamente per un oscuro
laberinto.

G. Galilei, *Il Saggiatore*, 1623

Understanding the structural design of construction works built between the eighteenth and the nineteenth centuries is a particularly delicate issue; in fact in this period, due to the advancing and progressive diffusion of the scientific method by Galilei, heuristic criteria based on tradition and experience were gradually converted into scientific ones, based on mathematical analysis.

This work aims at examining the effects that the rationalization of empirical knowledge had in building practice, analyzing in particular the evolution in the design of wooden bridges between the second half of the eighteenth century and the first half of the nineteenth century. A new design mentality, very different from the previous one, arises.

Furthermore, this work observes the effects that structural mechanics theory had on building practice, focusing in particular on the bending problem.

In a context strongly influenced by the Aristotelian tradition, Galilei introduced a new kind of knowledge based on experimentation.

In this innovation, based on the works by Galileo, mathematics is adopted to describe physical phenomena, great importance is given to the relationship between theory and experimental tests, and a slow outmoding of the supposedly "correct" structural forms in favor of element dimensioning based on the strength of materials, initially proposed by Galilei himself, is underway.

The progress in wooden bridge design which occurred between mid eighteenth and mid nineteenth centuries is extremely significant, both in terms of structural typology and for the material, wood.

A bridge is, in fact, a particularly challenging structural typology, and wood has a good behavior both in bending and in tension; the same cannot be said of stone, which has only a good compressive performance.

The *Grand Tour*, the traditional journey throughout Europe undertaken by upper class European young men, and the *Encyclopédie* played an important role in disseminating knowledge: the *Grand Tour* contributed significantly to increase wooden bridges documentation: precious information about bridge elements dimensions can be found in drawings and sketches, while the *Encyclopédie* by Diderot and D'Alembert contributed to disseminate knowledge to a wide audience and in creating a common technical language.

A primary role in civil engineering is played by the *École des Ponts et Chaussées*, the most famous School of Engineering of the time. The *Académie d'Architecture*, the *Académie des Sciences* and, later, the *École Polytechnique* had preeminent importance in students' training and were characterized by a lively scientific and cultural debate. Based on the model of these Schools, similar academies were founded throughout Europe: in 1751 the *Wiener Neustadt Academie* in Wien, in 1787 the *Reale Accademia Militaredi Napoli* and in 1824 the *Cadetti Matematici Pionieri di Modena*.

Architecture and engineering treatises were mainly conceived and developed within these cultural institutions that played a key role in understanding the mentality change and in disseminating the new concepts in building design.

Due to their strong rational mentality, French scholars were able to recognize the innovative nature of challenging solutions. A network of cultural exchanges and interactions extended as far as the United States of America through the nineteenth century.

With reference to such cultural network, this research tries to outline and discuss the emerging of the scientific approach to the design of wooden bridges between 1716 and 1841. In 1716, the *Traité des ponts* by Henri Gautier was published; it is the first French treatise devoted only to bridges. This text is among the first books where the need for rules based on scientific criteria is expressed. In the 1841 issue of the *Annales des Ponts et Chaussées* is documented the first application of the bending theory by Navier to a specific bridge. It concerns a test related to the bending strength of a wooden bridge truss built in France according to the structural layout patented in the United States by Ithiel Town. In the United States indeed, in 1829 a table based on the Navier's bending theory was published by Stephan Harriman Long in order to make the application of this theory, easier.

This work is developed into three steps. The state of heuristic knowledge inherited from the past and based on handed down experience is documented in the first step through the analysis of wooden bridges built in the Alps and in France in the period that preceded the knowledge transformation process.

In general, the first half of the eighteenth century is characterized by a strong need for renewal in the scientific field and the desire to adopt rational criteria. In the *Fonds Ancienof theÉcole des Ponts et Chaussées* a few isolated attempts to dimension wooden bridge elements are reported; the most significant ones were selected and have been discussed in this work.

In the second phase, the early decades of the nineteenth century, structural mechanics theory developed considerably; design criteria of structural elements began to be rationally based. The study of this period makes reference to the architecture and engineering treatises, that are the main means in disseminating the theory of structures. In these treatises both mathematical studies and results of experimental tests are reported, both of them are equally important to prove the new theory.

The first effects of the theory of structural mechanics on building practice are documented in the third phase. The new capabilities offered by the computational approach are applied to test construction works built according to heuristic criteria. It is the beginning of a new way to building, which rationalizes and thus revitalizes the old traditional practice.

Milan, May 2013 Chiara Tardini

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Unit of Measure

Unit of length	mm	cm	m
Line	2.2558	0.2256	
French inch	27.07	2.707	
Tesa		194.9	1.949
French foot		32.48	0.3248
Vicenza foot		35.7	
Bavarian foot		29.859	
English foot		30.48	
American foot		30.48	

Unit of surface	mm^2
Square line	5.08876

Unit of weight	g
French Lbs	489.5
French Ounce	30.59

Contents

Chapter 1
Tradition and Innovation: The Case of the Eighteenth and Nineteenth Century Wooden Bridges

E ancora che la natura cominci dalla ragione e termini nella sperienza, a noi bisogna seguire il contrario, cioè cominciando [...] dalla sperienza, e con quella investicare la ragione.
Leonardo, Ms 55 recto

Abstract A synopsis of the wooden bridges carried out in the second part of the eighteenth century would be hard to construct, as it would necessarily result much fragmented and incomplete. In that period, a sign of the need for renewing the criteria and rules of design may be perceived in the *Traité des ponts* by Henri Gautier. The state of knowledge at that time is well testified by the *Encyclopédie* of Diderot and D'Alembert, which had a primary role in characterizing the culture at that time. An extended research at the *Fonds Ancien* of the *École des Ponts et Chaussées* has led to identify a particularly significant manuscript, dated 1793, in which the beginning of a new approach to design is clearly evident. The very meaningful story of the *Concours de pont* within the *Concours d'architecture* at the *École des Ponts et Chaussées* is thus addressed. The cultural institutions of the period played a key role in generating and disseminating knowledge in a variety of forms. The *Académie Royale des Sciences*, intrigued by the accomplishments of the wooden bridges designed by the Grubenmann brothers created the opportunity to obtain a copy of the drawings and drew up a report of the bridge of Schaffhausen. Finally, some works by Karl Friedrick von Wiebeking are presented in this chapter.

Keywords Heuristic design criteria · Rational approach · Wooden bridge · Ecole des Ponts et Chauusées

1.1 The Beginning of a New Path

In the first half of the eighteenth century an ever increasing need to formalize knowledge is felt. Empirical rules traditionally employed in design were perceived as insufficient. Additionally, the new design rules that were awaited were also

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expected to derive from experimentation, in a continual comparison with physical reality. Following Galileo's teaching, the sizes of structural elements should be computed according to the load they will bear. According to him, the load bearing capacity of the structural elements is obtained by multiplying the width of a cross section by the square value of the depth divided by length.

These new instances are demonstrated in the treatises by Gautier and Bélidor within the debate of the period.

1.1.1 The Need for a Rational Criterion

The *Traité des Ponts* by Henri Gautier (1660–1737) published in 1716 [1] is the first French treatise on bridges. After Roman and medieval bridges, Palladio's bridges are described in the treatise. According to Gautier the bridges must be *dressés*, perpendicular to the river, *commodes*, with an access not too steep, *durables,* constructed according to the art of building, with good quality materials, and finally, *bien ornés,* made according to the rules of fine Architecture. Dimensioning rules are contained in the architecture treatises by Leon Battista Alberti [2] and Sebastiano Serlio [3]. The traditional approach to the sizing of structural elements of bridges is clearly based on geometric principles. Referring to the work of François Blondel [4], Gautier says that the best architects have left written instructions on sizing based on proportions, but the rational demonstration of these rules has still not been provided.[1] This statement is extremely important because it is one of the first signs of a newly developed need for rationally based rules, rather than rules handed down from predecessors, the reliability and effectiveness of which could not be demonstrated. Moreover, according to Gautier, even the best architects disagree not only on the proportions to be assigned to elements, but also on decoration: indeed, Arts and Sciences are still incomplete.

According to the author, each architect has different opinions both on the structural part and on the aesthetic aspect. If designers were asked the reason of an arch thickness, or of the width of the abutments built according to the geometric rules based on the teachings of the past, they would have no reasons for justifying the sizing of the elements. The dimensioning criteria in use, according to Gautier, cannot give ground to the choices they made; at the same time, these criteria appear reliable enough to be used in building practice.[2] The opposite vision

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[1] "C'est-là tout ce que les plus habiles Architectes nous ont donné par écrit de la proportion des Ponts; mais pour nous donner des raisons démonstratives, personne ne l'a fait encore" [1].

[2] "On le voit par rapport à tout ce que j'ai rapporté ci-devant d'eux; ils ne nous donnent aucune raison porquoi ils sont les piles, les culées, les arches, and c. d'une telle largeur, ou d'une telle épaisseur, and ceux qui travaillent aujourd'hui sur les exemples des Anciens, ne sçavent pas non plus pour quelle raison ces Auteurs ont travaillé ainsi. On se conduit seulement par des idées qu'on ne peut pas démontrer, mais qui paroissent assez vrai semblables pour pouvoir être suivies, à l'exemple de tant d'autres qui ont reussi ailleurs, and l'on dit que l'ouvrage est beau and solide, parce que les proportions entre les parties qui le composent, y sont observées" [1].

equally holds, architects seem to judge a work beautiful and durable only if the elements are geometrically proportioned.

Gautier submits these questions to scientists of his time, intending that when the *Traité* is completed, everyone will be able to access the proper solution based on scientific criteria, to be published in the *Journal des Savants*[3] on August 1715. Finally, Gautier is not completely convinced of the manner in which Philippe De la Hire has dealt with these issues in his *L'art de charpenterie* [5]. Those not familiar with algebra, according to Gautier, cannot comprehend the results of his work because they are expressed in the terms of a theoretical language which they do not understand and will not be able to apply in practice.

Chapter 10 is dedicated to the use of wood. A premise states that the art of carpentry has undergone continuous improvements with time: unlike previous periods, wood employed is usually squared and the connections are made with mortise and tenon joints instead of holes and pins. All these advances, according to Gautier, are due to the contributions made by Mechanics, with which the right size, thickness and length of the elements can be assigned. Gautier believes that it is harmful to oversize as well as to undersize elements, in the former case because the load is unnecessarily increased, in the latter for obvious reasons of insufficient strength. It is only practice, in Gautier's somewhat contradictory opinion, that can indicate the correct procedure[4]: thus he proposes the table in Fig. 1.1 indicating the proper dimension of length, depth and width for structural wood elements. This table is reproduced from a similar table by Pierre Bullet [6] and De la Hire represented in Fig. 1.2, in which the relationship between length, width and depth

Fig. 1.1 Henri Gautier. Table

Longueur.	Largeur.	Hauteur.
12 pieds.	10 Pouces.	12 Pouces.
15	11	13
18	12	15
21	13	16
24	13 $\frac{1}{2}$	18
27	15	19
30	16	21
33	17	22
36	18	23
39	19	24
42	20	25

[3] Journal de Savans is the first scientific journal published in Europe since 1665.

[4] "Il n'y a que la pratique qui nous enseigne la bonne manière de la faire" [1].

Fig. 1.2 Pierre Bullet. Table

Longueur des poutres. Une poutre de 12 pieds aura	leur largeur 10 pouces sur	leur hauteur. 12 pouces.
15 pieds.	11	13
18 p.	12	15
21 p.	13	16
24 p.	13 ½	18
27 p.	15	19
30 p.	16	21
33 p.	17	22
36 p.	18	23
39 p.	19	24
42 p.	20	25

of eleven beams, from 12 ft[5] in length, up to 42 ft, by multiples of 3 ft was indicated.

Unfortunately, no further steps are suggested by Gautier: the problem of element sizing does not yet have a rationally based solution.

1.1.2 The Quest for a Proper Ratio

La Science des ingénieurs dans la conduite des travaux d'architecture et de fortification was published by Bernard Forest de Bélidor (1698–1761) in 1729 [7]. In 1757, the treatise was translated and published in German. The numerous translations and reprints of *La Science des ingénieurs* confirm its editorial success; the 1813 edition was enriched with the "notes of Mr. Navier"; in 1832 Gaspare Truffi published the first Italian edition.

The treatise is divided into six books: the first provides guidance for fortifications cladding, the second treats the mechanics of the vaults and the size of piers; the third book deals with building materials, their properties and their use; the fourth is devoted to the construction of military and civil buildings, the fifth to the decoration of buildings and the explanation of some terms of the architectural orders. Finally, the sixth is about the economical estimation of fortifications and civil works. For the wide dissemination of this text that was reprinted several times for about a century, some observations contained in the second chapter of the fourth book have to be pointed out: the "general principles of the strength of wood" and the relevant notes affixed by Navier. The approach of Bélidor in dealing with the subject is mainly practical. The example of a beam supported at

[5] See table of measuring unit.

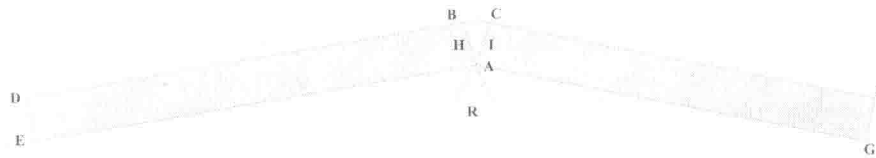

Fig. 1.3 Deformation of a beam loaded at the ends

midspan and loaded at the ends with two forces pointing down, shown in Fig. 1.3 is presented: this is the starting point for his observations. The elongation of the upper fibres, says Bélidor, will be directly proportional to the distance from the support.

After observing the phenomenon, Bélidor states that the trend of the deformation of the fibres at midspan is linear, decreasing gradually to zero at the bottom edge (point A). This refers to the formula proposed by Galileo in which the mathematical demonstrations are based on geometric similarity.

Subsequently, the resistance of wooden beams is related to an experimental test of a simply supported beam loaded at midspan. The deformation of the specimen, before failure occurs, can be detected by the shortening of upper fibres and the elongation of the lower ones, according to a linear law of variation depending on the distance from the upper edge EF as shown in Fig. 1.4.

According to Bélidor the resistance of a beam decreases if its length is increased, as the "lever arm" increases. To prevent this reduction, the cross-section may be increased; conversely, if the length of the beam is doubled, half of the force previously needed to break the specimen will be sufficient. According to Bélidor the force is directly proportional to the resistance, while the length of the beam is inversely proportional to it. Finally, to evaluate the resistance of two beams having different lengths and cross-sections as shown in Fig. 1.5, "in order

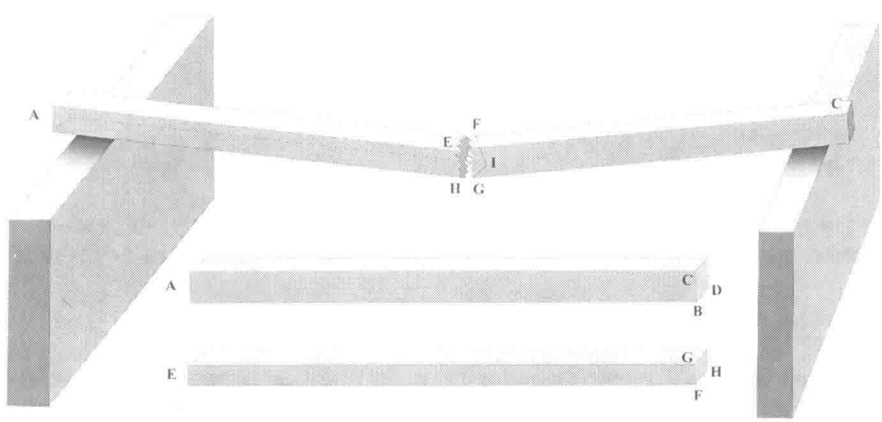

Fig. 1.4 Strength test of a simply supported beam