TEMI E TESTI

82

"BETWEEN MECHANICS AND ARCHITECTURE"
SERIE DIRETTA DA ANTONIO BECCHI E FEDERICO FOCE

MECHANICS AND ARCHITECTURE BETWEEN *EPISTÉME* AND *TÉCHNE*

IN COMMEMORATION OF EDOARDO BENVENUTO (1940-1998)
ON THE TENTH ANNIVERSARY
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his application of the 'rules of *maximum* and *minimum*' enable him to place upper and lower limits on the structural quantities – for example, on the value of the abutment thrust.

In the same way, the structural engineer may make a safe design of Galileo's propped beam, even if it is impossible to determine its actual behaviour. Use is made of modern plastic theory in which (for this simple example) the use of analysis is rejected. Instead, equations of statics are written, and the non-unique (for a hyperstatic structure) internal stress distribution is manipulated so that the stress limits of the material are not exceeded. No reference is made to deformation or boundary conditions; the use of mechanics alone (the equilibrium equations and limiting material properties) gives a powerful method for the safe design of a large class of structures.

Bibliographic Appendix.

The historical references in this paper are well documented (apart from a discussion of Hooke's cubico-parabolical conoid, which is given in: J. Heyman, *Hooke's cubico-parabolical conoid*, «Notes Rec. R. Soc. Lond.», 52/1 (1998), pp. 39-50. Otherwise, details may be found in: E. Benvenuto, *La scienza delle costruzioni e il suo sviluppo storico,* Roma, Edizioni di Storia e Letteratura, 2006 (new edition); J. Heyman, *The masonry arch*, Chichester, Ellis Horwood, 1982; J. Heyman, *Coulomb's memoir on statics*, London, Imperial College Press, 1997; J. Heyman, *Structural analysis: a historical approach*, Cambridge, Cambridge University Press, 1998, 2007 (new edition).

Joël Sakarovitch

THE HISTORY OF CONSTRUCTION AND THE HISTORY OF SCIENCE

An asymmetric relationship.

The history of construction, which is a specific branch of the history of techniques, and the history of science maintain a complex relationship the analysis of which allows one to identify the role of the discipline that is of interest to us here in addition to opening possible research avenues[1].

When historians of science present their discipline, one's first impression is that they ignore the history of construction, possibly for very good reasons.

In order to try and understand this state of affairs, we performed a kind of test, which certainly does not aspire to give an 'objective' picture in the form of a 'representative statistical poll' but nevertheless appears to detect the symptoms of the situation. To do this, we used the book *Eléments d'histoire des Sciences* (Elements of History of Science) edited by Michel Serres and published in 1990, which contains a 'Chronology' established by Michel Autier. Of course the Encyclopaedia coordinated by René Taton[2] is a work that would have covered the history of science far more exhaustively, both in terms of the subjects approached and the periods covered. But this encyclopaedia has no chronology, and this is the essential synthetic element for the test we wish to perform. Furthermore, precisely because there is no attempt at being encyclopaedic in Serres' work, it is no doubt more representative of a certain idea of the history of science in a given epoch.

It is worth noting that as a preamble to this chronology, Michel Autier emphasises what a difficult exercise this is and explicitly cites the sources he used to establish his list. Historians of techniques are well represented in

[1] This article grew out of a paper published in French: *Histoire de la construction et histoire des sciences*, in *Edifices et artifices. Histoires constructives*, R. Carrais, A. Guillerme, V. Nègre, J. Sakarovitch eds., Paris, Picard, 2010, pp. 22-28.

[2] *Histoire générale des sciences*, edited by R. Taton, Paris, PUF, 1st ed. 1958, reed. 1995

this list and he cites in particular the works and chronologies of F. Russo, M. Daumas and B. Gille.

Other than one page devoted to High Antiquity, the Chronology (14 pages) stretches from 750 AD to 1945 and is presented in the form of three columns:

Scientific inventions - Individual and collective actors - Elements to set the scene

There are roughly 600 items in the first column, which represents the core of the history of science. In this column, the history of construction is "present" 8 times out of 600 (including descriptive geometry, so dear to us, but which some might not consider part of the history of construction):

- Vitruve's 10 books on architecture (with Vitruve in column 2)
- Hagia Sophia (with Isidore de Miletus in column 2)
- In 1430, a mechanics treatise on hydraulic mills
- Galileo and the *Dialogues Concerning Two New Sciences*, 1638
- Varignon: composition of forces in statics, 1688
- Vauban's treatise on fortifications, 1705
- Bélidor's treatise on hydraulic architecture
- The beginning of Monge's descriptive geometry in 1769[3]

In the second column, one finds a few names (other than those mentioned above) that are not foreign to the history of construction: Desargues, Claude Perrault, de La Hire, Euler, Lagrange and Coulomb. But these 'heroes' of both histories are not mentioned for their contribution to the history of construction. For example, while Philippe de La Hire is mentioned, his mechanics treatise, known to be important for the history of construction, is not. To complete the picture, we must add that the second column includes the creation of the *Ecole Polytechnique* and the *Ecole des Arts et métiers*, which are institutions 'common to both histories'.

While not totally absent from the third column, the history of construction is not well represented, to the extent that one might wonder whether it is at all part of the picture. Fifteen or so of the 1100 items listed in this column belong to the history of construction, ranging from the digging of the Samos tunnel by Eupalinos to the Eiffel Tower.

One could add to this list a few items that belong to town planning of public works (the beginning of Haussmann's major works in 1853, the Suez

[3] This date corresponds to Monge's 1st drawing course at the engineering school *Ecole du Génie de Mézières*.

Canal in 1869 or the beginning of the digging of the Panama Canal in 1880) although these are essentially noted for their economic or political value. Similarly, a number of buildings are listed, such as the Parthenon, Notre-Dame de Paris, the Shah Abbas mosque in Isbahan, 'Bernini's tabernacle in Saint Peter's' (yet there is no mention of Saint Peter's Basilica), the castle of Vaux-le-Vicomte, the Invalides by Hardouin-Mansart, etc.. However, these buildings appear more as beacons or landmarks than significant elements of the history of construction. The fact that Notre-Dame should be listed to 'represent' gothic architecture (or the gothic period) is very revealing from this point of view: should one wish to mark the beginning of gothic architecture, it would be more appropriate to mention the Saint-Denis Basilica; if the point is to illustrate the apex of gothic construction and architecture, then Beauvais is the one to choose (as did Salvadori[4]). Notre-Dame is certainly part of the 'picture', just like the re-conquering of Toledo or Dante, but not particularly for what it represents in the history of construction.

The list makes no mention of the arch, the triangular girder, reinforced concrete, I-shaped beams, preconstraint, shell-shaped constructions or light tensioned structures... There is no mention of Hooke, Young (and his elasticity model of 1809), Navier, Lamé, Clapeyron or Freyssinet (...) you do find Mariotte, but not for his work on the strength of materials.

Is this to say that the history of science is (virtually) blind to the history of construction? Not quite of course, and while the relationship between them is tenuous, we must naturally try and define the types of relationship, the field in which they occur when they do, the actors involved and the outcome.

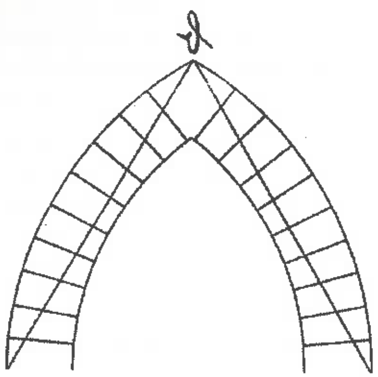
The history of construction as a branch of applied science: the modelisation of practical problems.

The first crossing points between these fields are of course mechanics (the history of which belongs to the history of science), statics, the strength of materials, the analysis of structural behaviour and the various attempts at modelising such structural behaviour.

As Benvenuto wrote, until Galileo, «geometry – rather than mechanics – appeared to be the true guardian of stability»[5]; this is illustrated by Leonardo da Vinci's first proposed modelisations of arch statics (Fig. 1).

[4] M. Salvadori, *Why Buildings Stand Up: The Strength of Architecture*, New York, Norton, 1980.

[5] E. Benvenuto, *Résistance des matériaux (histoire de la)*, in *L'art de l'ingénieur*, edited by A. Picon, Paris, Le Moniteur, 1997, p.409.



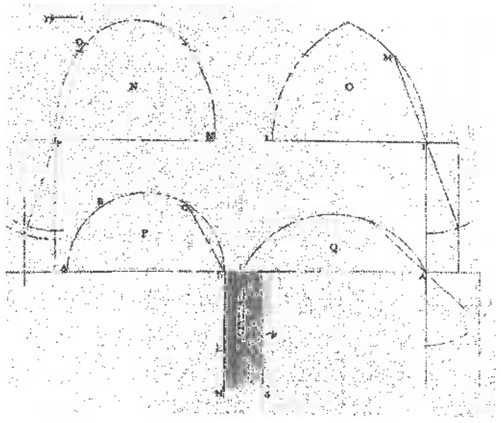


Figure 1. 'Leonardo's rule' ensures that the arch does not break if the chord of the outer arc does not touch the inner arc.

Figure 2. 'Derand's rule' gives vault sidewall dimensions that are independent of the height.

But in his stone carving treatise[6] in the middle of the 17th century, Derand still makes use of drawings probably already in use as early as the Middle Ages (Fig. 2).

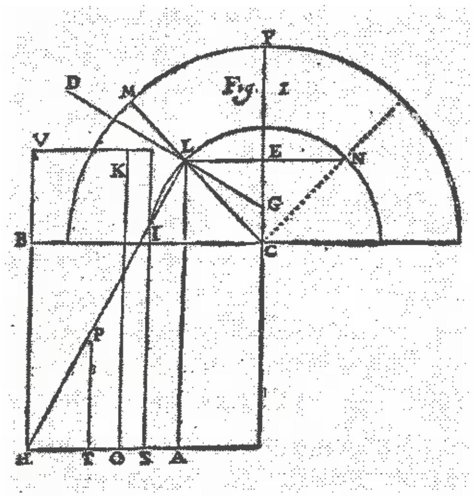
Philippe de La Hire's mechanics treatise is considered to be the first mathematical approach to the construction of arches and vaults. However, from a practical point of view, more than the 1695 treaty, it is his 1712 memoir, *Sur la construction des voûtes dans les edifices*[7] (On the construction of vaults in buildings), which was going to have the greatest impact throughout the 18th century (Fig. 3). The basic principle of the study, on determining the thickness of the sidewalls of a mortarless arch, is to subdivide the arch into three parts and to balance the momentum of the forces involved (if one ignores the forces of friction).

Taken further by Bernard F. de Belidor, Antoine Chézy or Joseph-Mathieu Sganzin, Philippe de la Hire's theory was going to be strongly criticised, particularly by Emiland-Marie Gauthey, who considered this three-partite division of the arch to be arbitrary.

But the crucial 18th century innovation in this area comes from the use of infinitesimal calculus. David Gregory gave the first demonstration of the relationship between the funicular curve (or catenary) and arch statics at the

6 F. Derand, *L'architecture des voûtes ou l'art des traits et coupe des voûtes...*, Paris 1643.

7 Presented in 1712, published in *Mémoires de l'Académie royale des Sciences*, Paris 1731, pp. 70-78.



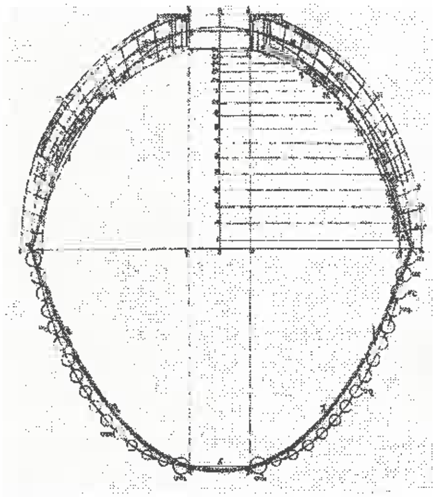


Figure 3. Ph. de La Hire. Application of the lever theory to vault sidewall sizing.

Figure 4. Gregory's catenary.

very end of the 17th century (Fig. 4), Jacob Bernoulli demonstrated the properties of the catenary in 1704 and Giovanni Poleni, consulted following the alterations to Saint-Peter's dome in Rome, proposed a series of measures to stop the degradation of the building after having published a treatise on the subject in 1748, a very exhaustive assessment of the science of construction at the time[8]. This intervention no doubt reflects the first successful application and mastery of structure statics and mechanics in relation to a concrete construction problem.

From the 1770's onwards, the theory of arches and vaults gave rise to substantial literature, the most important contribution being without doubt that of Charles Augustin Coulomb[9]. Taking friction into account lead him to consider the possible sliding of voussoirs against each other as well as the possible rotation of the key voussoirs around an axis that belongs either to the intrados or the extrados of the arch (Fig. 5). Coulomb also showed that the coincidence between the pressure curve and the curve of the centres of

8 *Memorie istoriche della grande cupola del Tempio Vaticano* (Memoir on the History of the Great Dome of the Vatican Church), Padova, 1748.

9 C. A. Coulomb, *"Essai sur une application des règles de maximis et de minimis à quelques problèmes de statique, relatifs à l'architecture"* (Essay on the Applications of Rules of Maxima and Minima to a Few Problems of Statics in Relation to Architecture), in *Mémoires de mathématiques et de physique, présentés à l'Académie. royale des Sciences*, year 1773, Paris 1776, pp. 343-382.

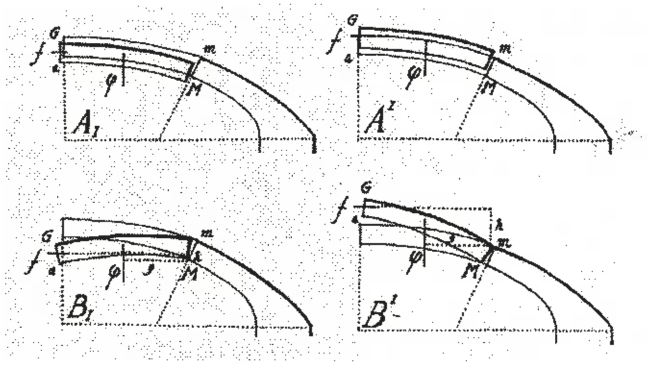


Figure 5. Coulomb: Taking friction into account.

gravity implies it will be a catenary only in the case of infinitely thin vaults. As for the stability of arches and vaults, the history of the arduous problem of elasticity in the resistance of materials lead to the meeting of works by the most famous mathematicians of the 18th century, particularly those of Bernoulli and Euler. The long list of 18th and 19th century publications on the various applications of infinitesimal calculus to such problems clearly shows the scholarly interest in the subject.

The history of these successive modelisations is of interest to historians of construction because it provides information on how the state of the art was perceived at a given point in time and also allows one to understand the possible springboards for technical innovation, based on such perception. This history in fact gave rise to numerous studies, including those of Clifford Truesdell, Jacques Heymann and Edoardo Benvenuto as well as those of Stephen Timoshenko on the history of resistance of materials.

We are making these points, which are well known, only to underscore the fact that the studies mentioned above treat the history of construction as if it were a branch of applied science. But this point of view fails to encompass the subject of the relationship between the history of science and the history of construction.

The theorisation of practical problems.

Another way of formulating the problem is indeed to reverse the question and try to find out whether there are branches of scientific theory that stem from problems identified in the history of construction. What practical construction problems might have served as a base, a source of inspiration, a driving force for the formulation of a scientific theory? Who are the actors in such theorisations? When did they act and in which institutions?

Huber Damisch has written that in order to understand the origin of perspective, one must reconstitute «the ground of pre-geometrical experience»[10] in the studio of painters at the end of the Middle-Ages. It is for us a matter of rediscovering «the ground of pre-scientific experience» that provided the rich soil in which the great tree of science might develop and give rise to a multiplicity of branches.

We have tried to show in a number of earlier studies that descriptive geometry was born from the practices and drawings of stone carvers. The objective of these studies was to show the transformation of a manual skill into an intellectual skill, which eventually provided the matrix for geometrical operations used in the drawings of master carvers before being formalised as descriptive geometry[11].

However, for this example to be totally convincing, one must also show that descriptive geometry fully belongs to academic geometry. Now this point of view is certainly a matter for debate; Gaspard Monge himself began the presentation of his descriptive geometry course at the Ecole Normale in year III of the Revolutionary calendar with these words: «The aim of this art is two-fold...». And in a letter to his son-in-law, he wrote: «For [descriptive geometry] to be useful and fulfil its true purpose, it must go down to earth. It is a field fertiliser not to be cast on trees; it is the geometry of workmen and artists; it is the foundation of the national industry and not an object of meditation for philosophers»[12]. In spite of the explicit declarations by its founder and without trying to place it between art and science, we believe, as did Michel Chasles and many others after him, that descriptive geometry fully belongs to the history of science and can therefore provide an example of the path leading from practice to theory.

The history of graphic statics seems to parallel that of descriptive geometry: after spending time in America from 1849 to 1850 to study wooden bridges, Karl Culmann wrote a report in 1851 comprising a graphic theory of lattice beams. He then developed graphic statics for his teaching course at the Zurich Polytechnicum, as a counterpoint to mathematical physics, taught by mathematicians who «idolise abstraction and generalisation, and find reality horrifying»[13]. As in the case of descriptive geometry, we see a theoretical

[10] H. Damisch, *L'origine de la perspective*, Paris, Flammarion, 1987.

[11] Cf. J. Sakarovitch, *Epures d'architecture. De la coupe des pierres à la géométrie descriptive, XVIe-XIXe siècles*, Basel, Birkhäuser, 1998.

[12] Unpublished letter from Monge to Nicolas Joseph Marey, dated 27 Pluviose, year V (15th February 1797).

[13] Henri Bouasse, cited by B. Lemoine, *L'architecture du fer*, Seyssel, Champ Vallon, 1986, p. 40.

field arising and developing from construction problems, for the purpose of an engineering course and with the same idea, underlying Monge's undertaking and more explicitly formulated by some of his disciples, which is that «drawing is the engineer's language». Both in the case of graphic statics and descriptive geometry, one therefore has a 'practice-teaching-theory' triptych of great creative force.

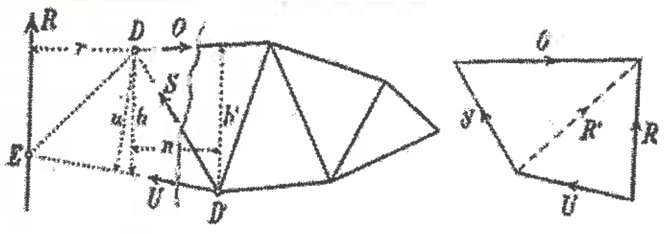


Figure 6. K. Culmann's graphic statics.

Another example is to be found in one of Monge's memoirs (still in the field of geometry but totally unrelated to descriptive geometry), the *Mémoire sur la théorie des déblais et remblais* (Memoir on the theory of excavations and embankments)[14]. Very elegantly theorising a practical problem encountered by engineering corps officers, i.e. minimising the displacement of earth when building embankments, Monge was led to initiate a study that eventually contributed to his theory of ruled surfaces. But this memoir can also be seen as the first piece of operational research, a branch of mathematics that was going to show great development after the Second World War.

Many other situations remain to be studied, such as the period preceding Galileo's *Dialogue Concerning the Two New Sciences*; what exactly happens between the intuitions of a Leonardo da Vinci and the concepts that eventually emerge?

Still in the same vein, objects of study that we consider most fertile are practical problems acting as intellectual stimuli though they may not necessarily give rise to a full or new scientific theory. The case of chemistry seems to be a case in point. Why does cement solidify? How can one explain the setting phenomena for the various mortars and the solidity of the resulting constructions? This question and the study of 'Roman

[14] Hist. Ac Sc., 1781, pp. 666-704. The results date from 1776 and were first presented on 27th January and 7th February 1776, with a Bossut and Vandermonde report; Monge reworked the memoir and presented it on 28th March 1781; it was published in 1784.

cement' in particular, fascinated European scholars in the 18th century and Lavoisier first and foremost. But the complexity behind the phenomenon of cement setting (with the carbonation principle described in 1813 and the micro-crystallisation principle described in 1884 by Le Chatelier) resisted the understanding of chemists until the end of the 19th century. Though not directly the source of a new chemical theory, this question acted as a driving force in chemical research and this role would be worth exploring further.

The problem of 'problematisation' is often a case of encountering specific actors whose creative imagination is clearly stimulated by the study of very concrete problems (indeed not necessarily in the field of construction). This is the case for Desargues, Wren, de La Hire and Monge among others.

But beyond the role of isolated individuals, the role of institutions can be fundamental in this process: that of academies (such as the Accademia della Vecchia in Florence in the 17th century[15]) or that of engineering schools, which have already been extensively studied[16]. But in spite of these studies, much remains to be done along those lines.

'Background' elements common to the history of construction and the history of science.

Much has been written about 'the scientific experimental method' on the one hand, and the experiments conducted on certain work sites (particularly around the Paris' Panthéon) on the other. But 'the scientific experimental method' did not impose itself in one fell swoop with Galileo. Indeed, little is known about what the adoption of the scientific experimental method owes to experiments conducted in other fields, including our particular field of interest.

The history of the relationship between the history of science and the history of construction is also that of the contempt of theorisers for practical problems and of the scepticism of practical workers with respect to theories.

[15] in *Practice and Science in Early Modern Italian Building*, edited by H. Schlimme, Milano, Electa, 2006.

[16] For example, one can cite R. Taton, *L'Ecole royale du génie de Mézières*, in *Enseignement et diffusion des sciences en France au XVIIIe siècle*, edited by R. Taton, Paris, Hermann, 1986², p. 559-613; A. Picon, *L'invention de l'ingénieur moderne. L'Ecole des Ponts et Chaussées, 1747-1851*, Paris, Presses des Ponts et chaussées, 1992; B. Belhoste, *La formation d'une technocratie. L'Ecole polytechnique et ses élèves de la Révolution au Second Empire*, Paris, Belin, 2003.

Following Poleni's study, cited above, some declared that "if one was able to conceive, plan and execute Saint Peter's dome without mathematicians and without mechanics, which people are so enthused about these days, one can surely restore it as well without having recourse to mathematicians in the first place or mathematics"[17]. Tredgold's aphorism according to which «the stability of a building is inversely proportional to the science of the builder»[18], or Charles-François Viel's memoir entitled *De l'impuissance des mathématiques pour assurer la solidité des batimens* (Of the powerlessness of mathematics to ensure the sturdiness of buildings), are rather revealing about the way in which the first mathematical essays on statics and mechanics were received. Benvenuto has a very beautiful turn of phrase to describe this state of mind: «before the first theories, we only had solutions to build vaults, after that we just had problems». A large part of this particular history remains to be written.

The recent book, *La colonne. Nouvelle histoire de la construction*, edited by Roberto Gargiani, offers a good example of a research avenue hitherto under-explored. An essay with a polymorphic approach to the supporting element *par excellence*, it proposes a criss-cross approach to the subject. But to keep to the point of interest here, it not only presents the attempts made at modelling column buckling, but also discusses the influence of modelisation on architectural style, towards bare baseless columns, for instance. This type of study, where a dialogue is created between the theorisation of construction problems and the feedback of this theorisation on architecture itself, remains an exception.

Conclusion.

The fact that encounters between the history of science and the history of construction are rather rare makes them all the richer. And by encouraging new starts from points of friction between these related disciplines, such encounters offer a means of revisiting both of them. For example, some of d'Alembert's statics or dynamics memoirs would gain from being perused by strength of materials specialists because the attention of historians of science often focuses on the foundations of mechanics or the relationship between mathematics and mechanics but mathematics historians themselves have little to say about possible concrete applications. And even if these

[17] Cited by F. Klemm, in *Histoire des techniques*, Paris, Payot, 1966.

[18] T. Tredgold, *Practical Essay on the Strength of Cast Iron and other Metals*, 1822.

aspects were not d'Alembert's first preoccupation, they are no less interesting for understanding his writings.

In other words, rather than looking at the history of modelisation or the history of the theorisation of construction problems, it is probably more in the duality 'modelisation-theorisation', going back and forth between both poles, that the wealth of the field of research at the intersection between the history of science and the history of construction can be most successfully revealed.