Towards an ethic of construction: The *structural conception* and the influence of mathematical language in architectural design

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ABSTRACT

This paper deals with the influence of the scientific and technical knowledge on the architectonic culture, in order to underline the role they played in the design process during the centuries. The work goes over some characteristic phases of the history of constructions pointing out the so-called *ethic of construction*: the balance relationships between the various components of the building process. At the same time, the influence of the mathematical language in the process of architecture design is investigated. From the beginning, around the XVI and XVII century with the first drawings made by the renaissance architects, passing through the period of the birth of the Science of Structural Mechanics up to the present time, in which the non-linear geometry with the help of modern software leads the choices of the designers. In a period in which the architecture seems to release from the structural component of the Vitruvian triad (*firmitas*) it becomes important to make recall to the 'tectonic' tradition by taking into account all the aspects of the building practice: both those governed by the creative intuition, lying outside the structural calculus, and those related to the mathematic-mechanical models.

1. INTRODUCTION

The heritage of technological and scientific knowledge has always been integrated in different ways and meanings in architectonic cultures throughout the centuries and has contributed to the appearance of an awareness that has been capable of significantly affecting the design process. This dynamic relationship, with continuous and reciprocal repudiation and encouragement, has evolved and changed during the different historical and cultural periods.

● In architecture of the past until the Middle Ages there has not been any dichotomy between design and construction, but we can speak of only one singular action concretized in the building. There is in this case complete coherence between *structural conception,* intended as an awareness of structural design methods, and the mathematic-geometrical language, considered as language of objects. The constructive technology, common heritage of people's experience, significantly affects the realized space.

● In modern architecture a close relationship remains between geometry and structure, but the architectural design arises with the geometrical language that designates the shape of the buildings. However such design remains indissolubly related to the technological component which delimits (or exalts) and in any case affects the final result ('operative geometry', Bellini, 2004). At the same time mathematics evolves in an independent analytical context providing high-level instruments to the study of mechanical problems mostly independent from the constructional tools.

● In the industrial and post-industrial era the new constructive technologies direct towards the creation of new shapes, the applied science (mechanics) coherently develops a complex analytic system for the structural sizing. The structural conception amounts to an awareness not only of the methods but also of the models of structural design. Mathematics intended as geometry keeps being distinguished from mathematics intended as *calculus*, while the architectural design ignores the structural design and continues to lose the unitary concept of the entire architectural construction process.

● In the contemporary period the dichotomy between architectural and structural design is even more evidently translated in the dramatic separation between project and construction, also and above all as a consequence of the use of new software, capable of developing and controlling new, amazing architectonical shapes without taking into account the structural aspect, unless through diachronic phases. As opposite to what has happened until now, the technology and the building science have to chase and adapt themselves to achieve the impossible.

Differently from the visual arts and being constrained by the construction, architecture has predominantly been distinguished by the 'conformative' component, on the contrary of the 'representative' component that is related to design and geometry (De Fusco 2003). While in non-recent times Cesare Brandi asserted that "the essence of architecture is not to be revealed through communication" (Brandi 1967, p. 8), whereas today, in the electronic era, big part of the architecture has predominantly been characterized by the communicative-informative component which is strongly related to the representation.

The interest in an overall approach towards the design of 'total architecture' (Gropius 1955) should still aim though at forming a new awareness that, heading towards optimization of all resources, should become the basis of a renewed *ethic of construction.* This by repeating, in a different instrumental operative context, the material space as the fundamental result of the design process; without moralistic or Manichean behaviour but in function of a more general 'economy' principle.

The subject seems quite delicate in particular in an era of 'deconstructed', 'non linear', 'virtual' architectures, when architectural design seems to want to redeem from the need of contemplating the single parts as a whole and in particular the structural one. The intention is to understand how, in the actual electronic context and in the visual communication era, architecture can preserve a *tectonic ethic* without abandoning the communicative content of the realized work.

Is it possible to exploit the mechanical-mathematical influences (offered today by the use of software, with particular reference to the procedure of structural optimization) in order to create new shapes with a strictly meaningful role played by the structural component (with undoubted benefits in terms of building practice)? Is it possible, even in a formal and completely transformed framework, to contribute in recovering that unitary concept in the design process, intended as synthesis of all the Vitruvian components, trying to preserve one of the most important effects of the Modern Movement's reading?

2. ANTIQUITY AND MIDDLE AGES - *THE MATERIAL IMPOSES THE SHAPE*

The stone walls of the Greek and Roman temples were perfectly congruent with the space for praying rituals and recollection during which a particular illumination was required. The solidity of the walls and the difficulty of making openings in it gave the temples the right character based on the optimal mixture among structure, form and function. The perimetric main walls could in fact not easily be holed due to the static function they accomplished, a function that much more than the other ones in the Antiquity has contributed in determining the image of the buildings. The need for stable building has then imposed the use of heavy materials as well as the realization of small holes in order not to weaken the resistance of the wall. Furthermore the need to use solid walls in which the relationship between bulks and voids was extremely advantageous for the first, was in perfect line with the climatic demands.

The discovery and, more appropriately, the diffusion of the arch systems meant a significant technological step forwards. The overcoming of the simple trilite, columns with architrave, has led to the realisation of wider openings without weakening the walls, thanks to the vertical loads carried by the piers. The public buildings of Ancient Rome, from the thermal baths to the places of worship and entertainment, were built with the new technology that perfectly matched with the permeability demands of the buildings in question. The big openings assured the transit of a large number of persons walking through contemporaneously without crowding or danger.

The technological invention of Roman concrete (*opus caementicium*) favoured the development of arch, vault and dome systems, enabling the creation of spaces of superior quality and dimension for buildings of major importance. The structural language, although only instinctively and experimentally understood, became predominant: maybe for the first time the *structural conception* was expressed with celebrative aim, although still in service of the functional demands.

In civil constructions instead, the brick formed the basic construction component. No longer the stone blocks, but the terracotta bricks we still use today. The *domus* for example, a completely introverted construction, developed towards the *compluvium,* the internal space on which all the rooms of the house converged and looked out, did not require particular structural arrangements. The ordinary buildings in general followed traditional constructive schemes and shapes in order to maintain an harmonious correspondence with the functions (*opus incertum*, *opus reticulatum*, *emplecton,* etc., Vitruvius, VIII).

In the Middle Ages the specialization of the constructive technique together with a significant technological evolution in the cutting of stones, has led to a distinction between carrier and carried structures. The ribs in the vaults clearly showed which parts of the wall were mostly stressed. All the stresses came together in the columns, the walls partially lost the carrier function and sometimes tended to disappear as they were substituted by enormous stained glass windows. The structural frame showed the system of thrust and counterthrust towards the ending in the climbing arches.

Whereas the *firmitas* completely informed the construction, the mathematical language still was a part of the constructive process as geometrical support. The module, related to the stone block size, and the brick were the basic dimensional elements of architectonic buildings. The former made it possible to control the final shape of the building on the basis of simple aggregative principles, whereas the latter became the object that, multiplied on demand, became the essence of the volume built. The discovery of concrete revolutionized this linear relationship between basic element and realized shape, as the material does not have a default configuration but takes on the formation obtained in function of the final use.

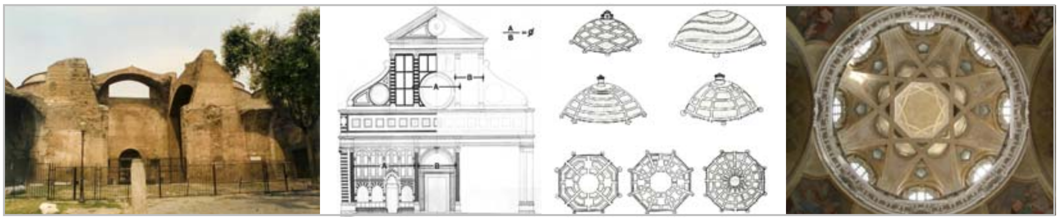
Then, independently from the adopted constructive technology, the architectonic work of the past has been the result of a more or less successful synthesis of the components of the Vitruvian triad (*utilitas, venustas, firmitas*).

3. RENAISSANCE AND MODERN ERA - *DESIGN AS PARADIGM OF CONSTRUCTION*

The awareness of possessing this technological knowledge and the codification of the rules of good construction also permeated the humanistic and renaissance culture. In his treatise Leon Battista Alberti tackled the problems of constructions by exploiting the rules of the *divina proportione*, providing detailed indications about the realization of the different works and adapting the static considerations to the particular aesthetic demands. For Alberti the concept of structure had a broad meaning and implied an internal principle of organization on which the reason of the figurativity was founded: "[…] the way of construction consists in obtaining from the different materials, put in a certain order together with art, a compact and - within the limits of possibilities - intact and unitarian structure. The whole can be called integer and unitary when the parts are not separated from the other ones or out of place, and when over the whole the lines show coherence and necessity" (Alberti 1450, III, I). The tectonic aspect (Frampton 1995), in the sense of art of constructing, was subordinate to the geometric design which from then on has become the paradigm of the architectonic project.

The architectural design has specialized more and more in the restrictive geometric approach until becoming a sort of conceptual exposition of the building itself: a clear demonstration of the shared internal space related to the need of peremptoriness of the image representing the building status. The warning signs of decoupling between form and structure were shown in the concept of 'ideal act of design': the geometrical design on which the concrete architectural operations are depending. The direct consequence has been selecting simple static devices independent from the shape or even effecting static interpretations depending on formal choices. Alberti (1450, III, XIII) for instance judged (erroneously) that the shape for semicircular arches was safer than the other ones. In some cases it came to a real detachment between architectonic composition and structural devices.

From then on the world of the represented shapes has started to contrast the world of the constructed shapes: "the geometrical design is indeed a paradigm of the constructed that the construction itself is not capable of reaching, because the ideality in it is antonymic in comparison with the reality" (Purini 2003, p. 92).



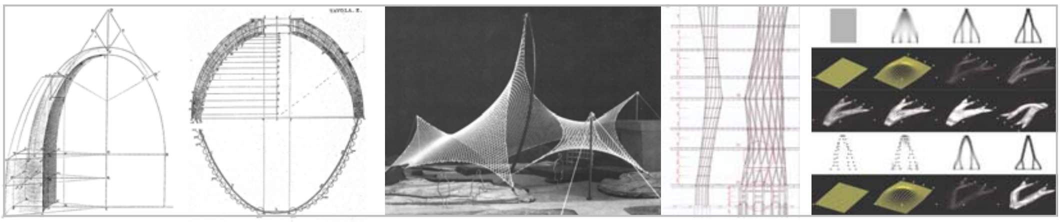
In the meanwhile mathematics, still intended as geometry, offered instruments for deepening the mechanical knowledge of the structural behaviour. For example, through the genial intuition of Leonardo regarding the resistance and the stability of materials, the statics of arches, the composition of forces. Probably for the first time, it was intuitively perceived that it was possible to use the geometric principles and rules in order to study mechanical problems related to constructions. Such a possibility was going to be extensively exploited by subsequent architects and constructors. Preliminary examples were the studies by Leonardo and Francesco di Giorgio concerning the static of the lantern of the Milan cathedral (Pedretti 1995, pp. 32-51, Benvenuto 1981, pp. 46-50, 324-325).

The geometry adopted, using Bellini's happy definition (Bellini 2004, pp. 21-32) 'operative geometry', was traditionally linked to construction problems, that consisted in finding a way to realize a given geometric shape with the exclusive use of a ruler, set square and compass. The knowledge of geometry and the use of intimate rules, often in contrast with the static ones, have proved to be fundamental sources of inspiration for those architects-constructors of past times that were instead interested in overcoming the antonymy between designing and 'making' architecture. In Baroque Rome for example there were numerous centres for scientific studies (Accademia dei Lincei, Collegio Romano dei Gesuiti, etc.), where teaching was specifically aimed at the application of geometry to architecture and to figurative arts. The architect and military engineer Muzio Oddi from Milan declared about an architect like Borromini, for whose education the mathematics lessons have played a significant role, that some of his designs were applications of 'practical mathematics'. The big constructors moreover, were often exponents of the mathematics world (Guarini, Wren) that still used the language of the classic geometry. Moreover, it so happened that, seen the mainly 'conformative' instead of 'representative' vocation of the architects of that time, the contemporary studies on projective geometry by Desargues were largely ignored (Cache 2003).

The XVII century has also been the century of the big progress of mathematics and mechanical sciences. With the famous *Discours de la méthode*…(1637), containing a preface on geometry, Descartes established the birth of modern analytic geometry. In this way it became possible to represent the curves and figures with algebraic expressions by means of a system of coordinates. The basis of a strong instrumentation of mathematical analysis was set which further on was going to be developed by Newton and Leibnitz.

The XVII century has also been the century of mechanicistic naturalism and the beginning of the "New Science". With Galileo (*Discorsi e dimostazioni matematiche intorno a due nuove scienze*…, 1638) the traditional language of objects in mechanics was substituted by the first structural model, the cantilever, accounting for the constitutive mechanical properties of the matter. At the same time the rules of the *divina proportione*, based on the concept of similarity, were abandoned favouring those principles that are based on a more rational, even if still geometrical, structural sizing. The basis of the future science of constructing started to form the tracks for subsequent speculations on the subject of deformative behaviour of structures.

Subsequently the enormous potentialities offered by the new powerful language of differential calculus (*calculus*) were exploited for the first time in order to study issues of architectonic design. Known is the debate of the 18th century about the *velaria curves* and the *laminae elasticae* by Jakob Bernouilli and about the studies on the 'best figure' of the vaults by Pierre Bouguer and Charles Bossut (Benvenuto 1981, pp. 339-355). These were the earlier speculations on *structural optimization*, subsequently reassumed by Frei Otto, Sergio Musmeci and others, on which the recent research on architectural optimal shapes is actually based (Sasaky 2005). On the other hand, also the mathematicians who started to be asked for expressing static opinions on constructional difficulties, exploited the analytic results obtained until then. A paradigmatic example was the study on the stability of the Vatican dome using the 'catenaria' solution detected by Bernoulli in 1697 (Poleni 1748).



Nevertheless, the dichotomy between mathematics, now intended as *calculus* and not any more as geometry, and the art of constructing kept existing. The mathematical models adopted for the study of mechanical problems of structures were in fact based on the complex formal apparatus of the infinitesimal calculus and the issues to be solved by means of simplified analysis instruments were still completely unknown.

In the XVIII century mechanics was by now completely formalized in the mathematical language. The mechanical models were ready to develop all applicative potentiality. The "New Science" still had to go through the whole century, that was entirely dedicated to abstraction, before it started to have significant influence on the culture of constructors.

4. INDUSTRIAL AND POST-INDUSTRIAL ERA - *THE STRUCTURAL FORM*

The technological evolution boosted by the industrial revolution and the general renewal of the production process provoked a radical transformation of the consolidated construction techniques, earlier through the introduction of steel and later through reinforced concrete. Different spaces were needed because of the growing new social functions in the public and private sector (train station, factories, residential complexes) and this imposed the creation of typologies unknown until then. The speed of execution, prerogative of the new technologies, headed decisively towards formal solutions which were inspired on simplicity and based on regular and reticular mesh or framework schemes. The decorative apparatus tended to be minimized until disappearance, although with difficulty because of the traditional construction concepts that continued to exist and that were inherited by the technology of the carrier brickwork.

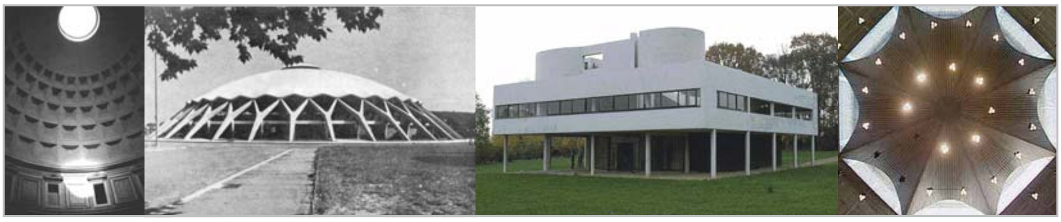
Subsequent to the changes, the urgent need arose to define a specialistic discipline on constructions suitable to meet the demands of the rising society. Both the technological progress and the development of the private initiative, as well as the establishing relationship between contractors and professionals, stimulated the research in this direction. These components were the origin of such transformations that gave birth to the figure of the *structural engineer,* a professional figure that until today bases his knowledge on the theoretic background of analytic mathematics and rational mechanics that he applies to the solution of structural problems.

Structural design became sensitive towards formal arrangements and the art of construction released from the empiric dimension, distinguishing itself as 'science of the art of construction' (Di Pasquale, 1996, pp. 470-489), at least in relation to adopting new technologies and new materials. This led to the progressive establishing of the field of the applied sciences, prerogative of the emerging bourgeois, at the expense of the mathematical sciences. Such process of "democratization of sciences" caused the division of knowledge that even today dramatically keeps existing. If, on one side, a new happy combination of mechanics and mathematics was growing aiming at the rationalization of the design process, of which Navier (1827) was the first to become aware, on the other side, a progressive confinement of the architectonic design was noticed in the field of representation. Then, on one end there was the *mechanics applied to constructions,* perceived as an autonomous discipline, taught at the engineering schools, which was structured from a linguistic-mathematic point of view and was able to deliver useful operative tools for the structural designer. On the other end, there was the *architecture*, taught in the Academies, mainly orientated towards the formalistic aspects supported by the recent developments of the descriptive geometry, neglected in the previous centuries in favour of the ‘operative geometry’ and recently reintroduced by Monge (1794).

The effect of the rationalization of the structural design has been though the proliferation of the models and methods which, due to the extreme laboriousness of the calculation, have caused the lost of view of the unitary of the design process impoverishing the creative process from the start. This is what especial structural architects like Torroja and Nervi, which more than others tried to overcome the gap between the mathematic-deductive and the artistic-intuitive mentality, often complained about. On the other hand the designs developed in the schools of architecture led the creative invention towards the virtual act of representation, neglecting the constructive aspects which, where necessary, were subsequently delegated to the insiders. This inevitably led again to the dichotomy between design and realization.

It was within the Modern Movement, following above the lesson of Gropius, but also of Mies and Le Corbusier, that the need to regain an unitarian conception of architecture arose, accounting for all the Vitruvian components and finalizing the project operation at the constructive act. Besides this, such an act ought to have had the power to engrave on an auspicious transformation of society.

The Modern Movement proclaimed the *sincerity* of architecture: the form-structure which follows the function. The building had to show on the outside its internal dynamics, its own structural shape, that was also in clear contrast with the previous era of the Baroque or of the Eclectism. Periods in which the structure, made of carrier brickwork or steel, was indifferently superimposed by the style preferred by architects or building owners, or that anyhow was considered necessary or useful in some occasion, as in the thought of Gottfried Semper (1851). The contrast was so intense that it led to behaviour comparable with a sort of religious integralism. Thus the constructive technique entered straight in the design process creating the fundamental linguistic background, both in the sincerely evident shape of the works of Mies and Aalto and in the perfectly integrated way, with respect to the other Vitruvian components, of the works of Le Corbusier and Kahn, as well as of many architectures of the past.



With Le Corbusier the ‘structural’ relationship between architecture and mathematics has been defined in a philosophical and not tectonic way, as Alberti had already singled out. By stating that “the meaning of mathematics is not the mathematics itself, [with other words] it is not about calculating or forcing freely imagined elements, but about admitting the presence of a reality, a law of infinite resonance, consonance and order”, he admitted that all existing things express or require a rule revealing *strictness*, *exactness* of the solution, the reason of the *harmony*, or the creation of the desired 'ineffable space' (Le Corbusier, 1959).

In accordance with the thoughts of Quaroni (1977) and Frampton (1995), from that moment there is a broad interest concerning the influence of the structural-constructive language, definitively connected to the mathematical framework, in the conception of the architectural work ‘tout court’. In line with a ‘global’ conception of cultural processes, potentialities should be explored, that are offered to architecture by contemporary numeric mathematics in ways of a wide range of software products.

5. THE CONTEMPORARY ERA - *A NEW ETHIC OF THE CONSTRUCTED FORM*

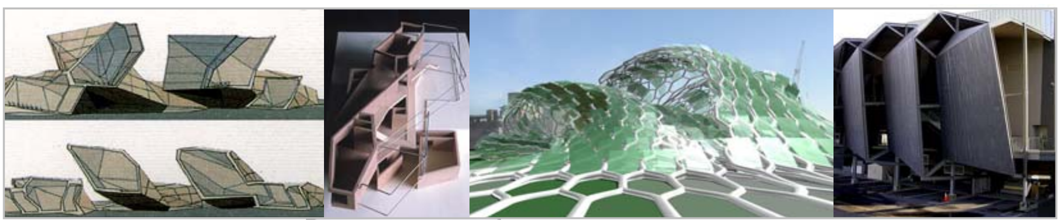
Together with the enormous and abnormal technological and scientific development, or maybe as a consequence of this, and because of the clear difficulty to control a continuously growing number of variables in the field of design, the unitary of the architectural design, that once covered all aspects of the constructive building design, has progressively gone disrupted. Furthermore it appears still today that, together with the fragmentation of the knowledge and the specialization of competences, the designer has no interest in the anyhow resolvable technical aspects.

The evolution of numeric mathematics has led to both the formulation of calculation codes (*F EM,* etc), suitable for the mechanical study of structures of any kind, and the development of sophisticated algorithms, used for the representation and graphic invention of any shape (*NURBS, genetic algorithms, ESO*, etc.). Now the digital design offers a lot of new possibilities for designers that are not necessarily qualified or selected and “the result is casual [that is] subjectiveness, anecdotal, dilettantism, ‘libertinism’” (Boulez 1979, p. 14). This puts us in front of a crucial query: how to manage and control this consistent technological heritage in order to dominate and make best use of it, maintaining respect of the tradition of 'making' architecture which is mandatory for improving the living quality?

When Heidegger (1953) asked his contemporaries about modern technique, he wanted the people to reach the conditions that were necessary not only for dominating the technique, from the instrumental point of view, but also for putting it in the “service of the spirit”. As a consequence of this, the instrumental definition, □έ□□η was linked to the broader meaning, έ□□□□ή□η that, from Plato on, always defers directly to the essence “there is nothing demonical in technique, there is however the mystery of its essence”. The essence of the technique was identified in the field of ‘im-position’, that led to the need of saving one selves by ‘unveiling’ it, by quoting Hölderlin: “Wo aber Gefahr ist, wächst/ Das Rettende auch (Heidegger 1953, p. 22).

More pragmatically in the specific case of contemporary architecture, the essence of the technique unveils itself in the recognition of a regulating principle, according to the meaning given to it by Alberti first, Le Corbusier and also Quaroni after, that “architecture is above all made to leave in order […] and less to express emotions or personal moods […]. This in the conviction, still shared with Quaroni, that the “‘real’ constructed architecture (static and fixed as it is, ordered as it is) has [anyhow] the possibility […] of ‘expressing’ all of human emotions” (Quaroni 1977, p. 155). It is not the codification of the rules or the recognition of a coherent structure that makes it impossible to make architecture today. It is rather the direct influence of who is incapable of inventing autonomously formal systems or elaborating autonomously the instruments and the basic rules: “the composition is both a science and an art, that only the Imagination is able to merge, and the result will always go beyond the applied rules” (Boulez 1979, p. 146).

Furthermore, to the compositional aim it is not necessary to renounce the ‘demon' of the technique, nowadays the computer instruments, but, paraphrasing the words of Quaroni pronounced in unsuspected times, it is enough to avoid mixing up the *geometric tool* of design (here *CAD* software) with the *geometric aim* of the design process (virtual architecture). This can be obtained by being careful not to become slaves of the deeply charming geometry, that remains a completely different thing from architecture: here instead we must be “careful to keep every creative conscience awake that tends to be overwhelmed by the newly discovered miracles and that is possibly trapped by the narcissistic mirrors it invents by itself” (Boulez 1979, p. 15). Although it is often ignored, if not even searched for, the effect of detachment and delusion felt when the effective reality imposes on the virtual one is in fact familiar to everybody.



In a renewed ‘conformative’ prospective, we find of great interest the research, set off by pairs of engineers and architects or groups of avant-garde architects (Sasaki/Ito, Sasaki/Isozaki, Kokkugia, etc.), on the possibilities arising with the software of structural optimization applied to architectural design. This software combines the purposes *form* and *structure* and can offer innovative geometric solutions with intrinsic characteristics of resistant mechanical forms (Sasaki 2005). In any case, particular attention must be paid to the inspiring principles and rules by considering that “a complicated design does not mean making more evoluted, advanced or modern architecture (Quaroni 1977, p. 153).

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