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THE ROLE OF MATHEMATICS IN ARCHITECTURAL CONSERVATION



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Abstract: The paper aimed to investigate the role of mathematics in conservation and restoration of cultural heritage, with special attention to the architectural heritage. Starting from the XX cent., restoration and conservation of cultural heritage are based on scientific approaches. Brandi, the very well-known Italian theorist of restoration, states that it is possible to restore only the material of the work of art. Physics, chemistry, mechanic, geometric survey, petrography, mineralogy, wooden science/engineering, climatology, environmental sciences, economy, sociology, history, art, architecture and conservation are fields and scientific sectors involved in the process of safeguarding tangible cultural heritage and, specifically, the architectural one. All these fields are interconnected by mathematic tools, building models with which it is possible to formulate the diagnosis of the damages, offering a support to the project of conservation, to enhance the good and to plan the maintenance and the projected of new additions. The existing good is unknown until a model, capable of detecting its essence and behavior, is conceived. The model, as Piga states, "can be, for example, a tool for architectural design, for metric calculation, for the training of workers, for structural analysis: ...". The model is the way not only to represent the "shape" of an object: the construction of a mathematical model can help the synergy in the direction of the conservation. The topic is developed also from a historical perspective in order to understand how the numerical model, from the past up to now, has been able to support the understanding of goods, their restoration, conservation, enhancement and use, and their transfer to future generations.

Keywords: Heritage; Conservation; Restoration; Models; Architecture.

Introduction

The World Heritage Convention states: *“The Cultural and Natural Heritage is among the priceless and irreplaceable assets, not only of each nation, but of humanity as a whole. The loss, through deterioration or disappearance, of any of these most prized assets constitutes an impoverishment of the heritage of all the peoples of the world. Parts of that heritage, because of their exceptional qualities, can be considered to be of “outstanding universal value” and as such worthy of special protection against the dangers which increasingly threaten them”* (World Heritage Convention, 1975).

“Europe’s cultural heritage is a rich and diverse mosaic of cultural and creative expressions, an inheritance from previous generations of Europeans and a legacy for those to come. It includes natural, built and archaeological sites, museums, monuments, artworks, historic cities, literary, musical and audiovisual works, and the knowledge, practices and traditions of European citizens. Cultural Heritage enriches the individual lives of citizens, is a driving force for the cultural and creative sectors, and plays a role in creating and enhancing Europe’s social capital. It is also an important resource for economic growth, employment and social cohesion, offering the potential to revitalize urban and rural areas and promote sustainable tourism” (<https://culture.ec.europa.eu>).

The identification and the definition of Cultural Heritage (referred to as CH from this point on) constitute the main aim of the UNESCO and European policies in order to manage and drive the different approaches in the respect, the assessment and valorization of CH.

The matter relates to the methodologies and, in general, to the right actions for ensuring the transfer of CH to the future generations.

The methodologies for ensuring the conservation of CH are an issue deeply connected with the policies and with the cultural, social and economic structure of a Country. Nowadays the construction and the description of the approach and practice for ensuring the care and the preservation of CH is rightfully one of the priorities recognized all over the world, especially due to the effort of the international organization in the establishment of a fruitful intercultural dialogue.

According to the main doctrines and theories on CH (Athens Charter 1931; Venice Charter, 1964) the most important question is to pay attention to the matter of conservation, which means to preserve authentic materials as evidence of the historical and artistic values of cultural goods.

The restoration of the ancient buildings nowadays becomes a valuable field with a potential to define the identity of the new national entities, to provide a common culture to the emerging generation (as a community of universal language), to share a common idea (also from a political point of view) and a common memory.

Furthermore, the conservation of heritage is today increasingly linked to the need to preserve its trace and guarantee its usability through digitalization, to the valorization of the cultural goods, to the facilitation of their accessibility even remotely, to the management of all phases of conservation itself. Starting from the collection of information up to the restoration intervention, all steps

are managed through virtual models that guarantee a transdisciplinary and interoperable work.

Digitization is based on the mathematical reading of both predictions for the future and the reading of the past. In the case of restoration of this past, also in the form of architecture, digitization has the function of helping knowledge and thus supporting the entire design process aimed at conservation. The virtualization of the past certainly facilitates the usability of the object, for the purpose both of scientific knowledge and of its accessibility, a necessary condition today, also in line with the 2030 Agenda on Sustainability.

If digitization enters the fruition process, it is essential to register and report the present physical state of the architectural and urban heritage, a necessary condition to give meaning to its enhancement process.

For what has been said, mathematics has provided, and still provides, the tools necessary for the conservation of heritage, always to be understood as an action based on acquisition of knowledge, data collection, intervention and valorization.

Restoration, Conservation, Science and Mathematic

Eugène Emmanuel Viollet-le-Duc, the “father” of restoration, defined this discipline as a stylistic reconstruction of the monument as it was, representing the chosen historic moment to show and remember the monument (CH is a locution introduced after the Second World War) in its entirety. At the same time, he was particularly improved in the research on the strength of materials and structural behaviour of buildings.



Figure 1. The restoration of Carcassonne by Viollet-le-Duc (Viollet-le-Duc, 1981, pp. 46-47 e 49)

If we consider the training and the specialization of Viollet-le-Duc, it is easy to combine the needs of restoration, that means the stylistic rebuilding of several parts of the monument, and the reinforcement of its other parts from the structural and from the material points of view (Dezzi Bardeschi, 1992). In France, where the first schools for engineers were established, the definition of the science of restoration by Viollet-Le-Duc was accepted in the mid-19th century when he wrote: *"The term Restoration and the thing itself are both modern"* (Viollet-le-Duc, 1854-1868, Kindle edition).

The emergence of the science of restoration is inseparable from the growth of chemical, physical and mechanical sciences which had greatly progressed in those same years. For example, the creation of the metric system had a strong influence on the development of physics in France in the end of the 1700s (Jacob, 1988).

Certainly, the historical and analytical disciplines in the humanistic field, such as philology and the historical method, are fundamental for restoration of ancient or old buildings, or the buildings and monuments that represent the cultural identity of a country. They provide essential tools to identify the history of monuments and to interpret monuments themselves (architectural in particular) as historical documents.

But alongside the humanistic studies, the so-called pure sciences also become a useful, if not indispensable, tool for defining the methodology of restoration.

Moreover, Viollet-le-Duc believes that restoration is a recovery of the initial image of the building. According to his theory, through a methodical stylistic analysis it is possible to reinstate the precise original shape of the building, or alternatively, a shape that had never existed but is true to the building's stylistic and structural character.

Viollet-le-Duc had utilized scientific tools to define an analysis and intervention methodology for restoration that became the basis for the current safeguarding and conservation principles. The understanding of the structure and of the construction materials, the representation of the geometry of the building, according to the descriptive geometry by Gaspard Monge, the recollection of the monument's history with a use of the heuristic research methods inspired by the positive ideology of the Enlightenment era, constitute the fundamental approach helpful to transfer the cultural heritage to the future generations.

The role of Monge was not only connected with the foundation of the "Ecole centrale des Travaux publics", after "Ecole Polytechnique" (starting from 1794), of the "Ecole Normale" and, the reorganisation of the schools in France in the Napoleonic period, but also with the plundering of the European and Italian cultural heritage (paintings, sculptures, books, musical instruments) after the Napoleonic victories in northern Europe.

The Italian arts were also appreciated and made known by the Encyclopédie by Denis Diderot and Jean-Baptiste Le Rond d'Alambert, while the sciences, through the work developed by Alessandro Volta, Ruggiero Giuseppe Boscovich and Lazzaro Spallanzani, had reached very high levels, in frequent contact also with the French colleagues. *"Finally, the Po Valley, with its well-ordered network of*

rivers and canals and with its already rationalized agriculture, provided a model of efficiency that they wanted to study and imitate". [Monge, 1993, p.25].



Figure 2. Collection of mails by G. Monge written during his journey in Italy (Monge, 1993); Raffaello, L'estasi di Santa Cecilia, Pinacoteca di Bologna: one of the works of art transferred by Napoleon from Italy to France [<https://letteraturaartistica.blogspot.com/2014/06/gaspard-monge-dallitalia-1796-1798.html>].



Figure 3. Traité élémentaire de statique: à l'usage des écoles de la marine (3e éd.), par Gaspar ["sic"] Monge 1798; Géométrie descriptive. Leçons données aux Écoles normales, l'an 3 de la République; par Gaspard Monge, (1746-1818).

Viollet-le-Duc's approach has its origins in the French polytechnic culture which went through a period of rapid growth at the end of the eighteenth century and during the Napoleonic rule.

Till the mid-1800s, the construction of new buildings did not appeal to mathematical formulation. The structures of existing buildings were not calculated, they were built according to a proven dimensional practice that varied from region to region, from culture to culture.

The introduction of new materials, such as iron, and the development of mathematics entail the first formulations for the verification of structures.

"But if in those years the theory of resistance of materials and the theory of structures had not yet reached, if not in rare exceptions, simple formulations and usable in practice by engineers, it is true that there were not even technical standards for the structural design nor clear legal implications on the work of engineers" (Nascè, 1982, p. 11. Translation from Italian to English by the author).

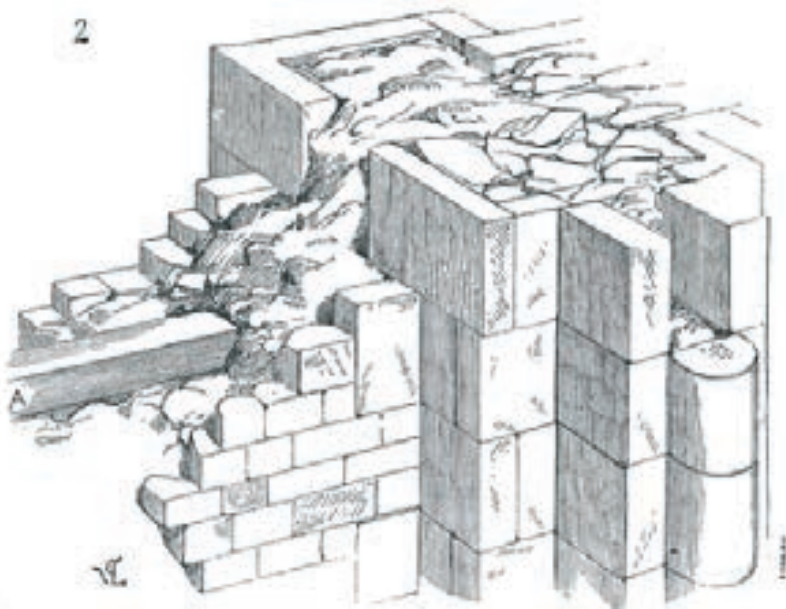


Figure 4. Viollet-le-Duc-Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle, 1854-1868, tome 4.djvu/15.

During this period mathematicians developed the studies of complex and imaginary numbers, which does not seem to find immediate application, if not in a completely marginal way, in the design of structures (Di Pasquale, 1996).

The static analysis guides the restoration intervention ensuring the improvement of the structural behaviour.

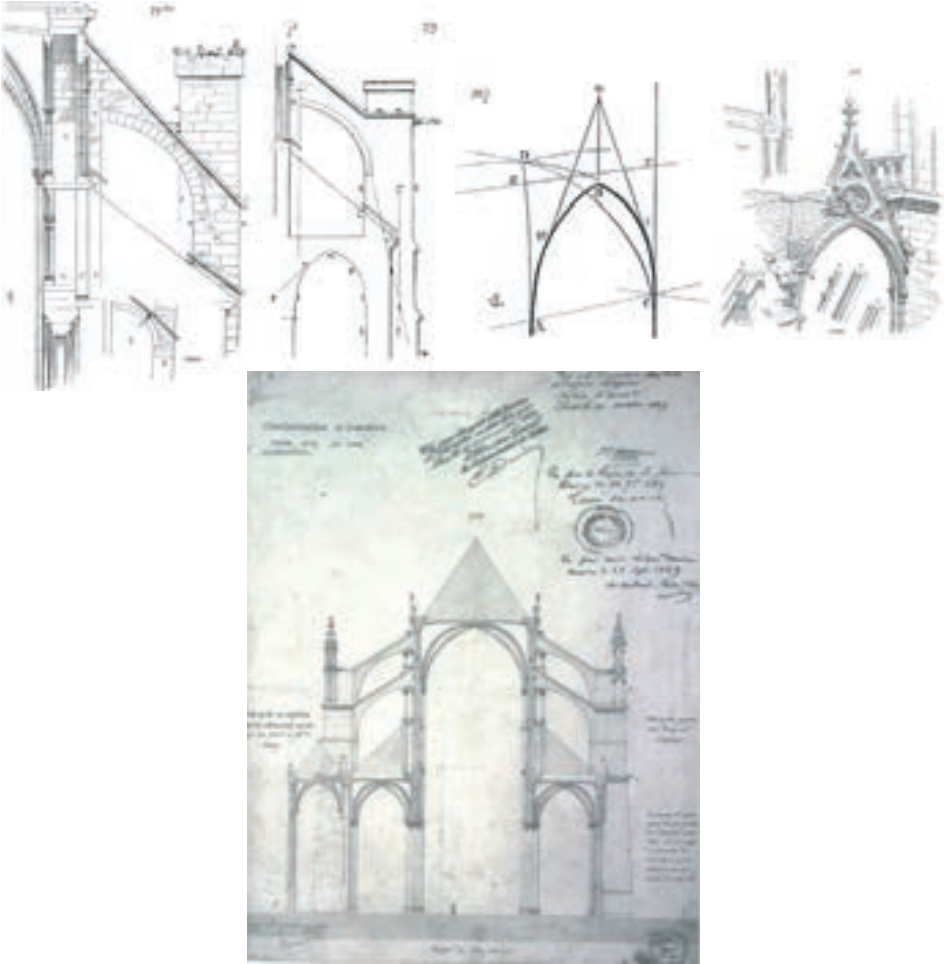


Figure 5. Viollet-le-Duc 1854-1868, tome 4.djvu/141, 142, 196, 197.

The calculation principles adopted by Viollet are those of graphic statics, through which he finds the tool to calibrate the distribution of loads and forces during the stylistic re-design of the monument.

In order to precisely accentuate the structural performance of the architectural monument, Viollet also indicates the improvement of the stones with the use of silicates and fluosilicates, materials already in use since the first half of the 19th century (Tomaselli, 2005; Dezzi Bardeschi, 2005).

“.... Towards the middle of the 18th century, a substance began to be glimpsed, spreading, for example, in civil and military technical schools. Suffice it to recall, in France, the “École des pontes et chaussées” takes shape

and substance, spreading, for example, in civil and military technical schools the teaching is based on solid scientific knowledge, thus configuring in an increasingly specific way the professional figure of the “engineer” distinct from that of the “architect” (Benvenuto, 1981, p. 416. Translation from Italian to English by the author)

“.... Perhaps the decisive element of the new organization of construction studies is represented by the creation of the “École Polytechnique”: “engineering” so clearly took over “architecture”; and at the same time, a closer relationship was established between the physical-mathematical sciences and technical applications, “democratizing” the theoretical debate, and offering increasing scientific dignity to the design intervention, especially in relation to large public works.

Around the early Nineteenth century almost all of the great French scientific culture gravitated around the “École”. The students were engaged in exercises and in chemistry and physics laboratories:.... Since its foundation, the school has also set itself a popular purpose of knowledge: the foundation of the “Journal Polytechnique” (Benvenuto, 1981, p. 417. Translation from Italian to English by the author).

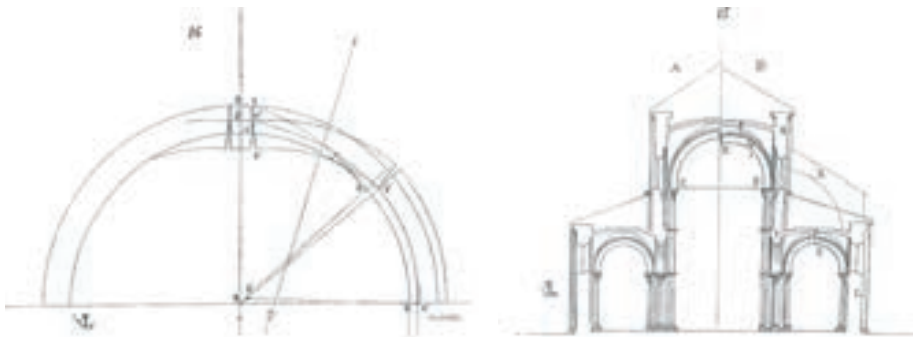


Figure 6. Viollet-le-Duc 1854-1868, tome 4.djvu/29 and 30

As Stephan Timoshenko states, at the end of the 18th Century and the first half of the 19th Century the research on the elasticity and of the strength of structures was improved. The different studies and experiments, applied on the wooden elements, were devoted to determining the safe dimensions of timber beams, with the aim to define a more rational method for the structural analyses (Timoshenko, 1983; Galilei, 1638; Mariotte, 1686; Benvenuto, 1981, Lombardini, 2007).

The mechanics of rigid and deformation-free bodies, together with the study of friction, are the basis of the structural calculations adopted in the verification of existing structures and in the design, by Viollet, of the stylistically mimetic added parts.

Structural checks became, in those years, a fundamental tool for the study of the history of architecture and contributed to the deepening of the construction concept of the ancients.

The introduction of vector calculation allows the preliminary check of the added parts considering the differences in the building materials and their processing.

“There are two aspects.... Of the significant shift of interests promoted by engineers and scientists of polytechnic schools in the early nineteenth century, compared to the old [science of engineers]: the first is to focus attention on the mechanical properties of materials in their response to stress. New “characters” truly become protagonists; in particular, the tension and the deformation, to which safety limits must be imposed. The much longer period of the previous science of building was instead marked by other pre-eminent concerns: for example, that of guaranteeing a composition of elements – think of the ashlar of a wall structure, an arch or a dome – capable of excluding the onset of kinematics. For this reason, the geometric shape of the building was, in the past, the protagonist of the structural intervention; the compositional invention and static compatibility were two inseparable moments of the same design process.... While in the conception of the ancients..., the elements of the building, the arch, the wall, were made guests of some “simple machines”, such as the lever or the wedge, now the whole building is captured in its load-bearing skeleton that conveys and resolves stresses; new “characters” work in it such as the continuous beam on several supports or the frame” (Benvenuto, 1981, pp. 395-396. Translation from Italian to English by the author).

In this sense, Rondelet in his *Theoretical and Practical Treatise on the Art of Building* gives an excellent example of analysis of ancient structures through the geometrical proportions.

This is an equilibrium calculation that does not take into account the resistance of the material or the degradation that the material may undergo. The method of calculating the resistant sections of vertical wall structures, proposed by Rondelet, starts from a fundamental premise: the “rule of art” (it means of the building practice) during the construction of the masonry wall pursues the internal “cohesion” of the masonry itself. The composition of the forces acting on the structure, through the geometric composition of the forces in place, i.e. the external ones, combined with those resisting within the structure, and due to the geometry of constructions and their specific weight, allows us to offer an analysis of the equilibrium of the structure. (Lombardini, 2013; Rondelet, 1802-1817).

But the application of mathematical and physical formulations to the mechanics of structures not only serves, in the context of restoration, the reconstruction or completion of existing buildings, aimed at the construction of the image of the new post-Napoleonic nations, but also leads to understanding that some parts must be preserved and must be transmitted to the future not in a mimetic way.

The juxtaposition of John Ruskin's theory (Ruskin, 1849) with that of Viollet implies that the conservation theories that seek to avoid the mimetic reconstruction of the monument began to increase in popularity.

For this reason, the study of the building is aimed precisely at attributing all its historical and material importance to the existing building.

The defense of arts and crafts, carried out by John Ruskin also in support of William Morris's Society for the Protection of Ancient Buildings (SPAB, <https://www.spab.org.uk/>), attributes to the material of the artefact and its processing an importance that not only assumes a social but also historical significance. In this historical defense of material and its signs, Victor Hugo also stands and again in France (Hugo, 1832).

The material and its degradation take on a meaning that goes beyond an aesthetic vision of decadence.

The material, the original so to speak, is the manifestation of a building's culture, of a society it represents. The material, with its implementation, its processing, its deterioration, is the first document, almost in an archaeological sense, to reconstruct the history of the building.

The importance of preserving the material in place, rather than replacing it, leads to its conservation and to the study of materials suitable for this purpose.

The restorations of the marbles of the basilica of San Marco in Venice, in the second half of the 19th Cent., are set in this direction.

The voice of protest promoted by Ruskin to avoid their replacement, leading to the great monograph edited and published by Ferdinando Ongania in collaboration with Camillo Boito (the so called "father" of Italian restoration) (*La basilica di San Marco*, 1881-1887) testify how important it is to preserve ancient material and how important it is to pass it on to the future.

This Italian need for the conservation of the existing material on site stimulates the study of the characteristics of the materials themselves, of their degradation patterns, with the implementation of diagnostic tools and practices that bring into play mathematical algorithms useful both for the interpretation of the data collected and for the correlation of the different data between them.



Figure 7. E. Pedon, eliografia, J.R. Istituto geografico militare in Vienna, Tav. II2 e Tav. II4, in La basilica di San Marco 1886.

The survey of the building in all its geometrical detail and the knowledge of the materials are crucial for understanding the causes of degradation and researching remedies.



Figure 8. N. Girotto dip., Giesecke & Devrient, chromolithographies in La basilica di San Marco 1886; Rondelet, Jean-Baptiste 1802-1817, tome 1, p. 244.

The studies of Giovanni Battista Milani and Gustavo Giovannoni (Milani, 1920-1923; Giovannoni, 1925; Goodyear, 1907), also, moved in the direction of philological and scientific attention to the constructions of the past. Specifically, Giovannoni was a well-known theorist of restoration (able to introduce attention to the safeguarding of a portion of old historic centres) and an architectural historian capable of making use of the science of construction (that is, of graphic statics) to understand better and interpret the buildings of the past (in particular of the Roman period).

Today, it is possible to proceed with the construction of a mathematical and not just a physical model capable of representing the behaviour of the structures and of the material both for determining its state of conservation and for predicting the trend of deterioration in the future, analyzing its trend in the past.

In addition, mathematical evaluations are now conducted to interpret and predict the use of certain materials that consolidate the surfaces of the structures, such as the marbles of the basilica of San Marco (La Basilica di San Marco, 1887).

About the structures, for a long time the use of graphical statics prevailed in structural verification.

The introduction of electronic computers, in more recent times, has allowed a further study of existing buildings, placing the need to deepen the knowledge of the mechanical characteristics of materials and structures. The impossibility of transposing the knowledge of the “new” material with the knowledge of the material in place which always represents a “great unknown” that requires a design of a scientifically and critically interpretative model.

Sisto Mastrodicasa writes: *“The study of crumbling walls constitutes an interesting and arduous chapter of the construction technique: interesting, for the novelty of the matter; arduous because of the difficulties it involves. Unfortunately, the silence of the technicians on the cases entrusted to their examination, resolute, not always happily, painful effort in the light of an intuition lacking the indispensable theoretical foundations, even if full of genius, and the understandable predilection of the builders to build the new rather than to patch up what has already been done, they have been decisive in delivering these problems to the most forbidden and dangerous empiricism. And it is no wonder if, especially in the past, the good sources that the technician could draw on the subject were scarce and fragmentary and if the most abundant ones arose from superficial considerations that misled the novice professional, and not himself alone, from the right understanding. of the various phenomena. Fortunately, for several years the need to raise the problems of crumbling walls to technical and scientific dignity has been affirming almost everywhere, promoting the study and coordination of this vast and fascinating discipline in an organic complex of notions, capable of reconciling the results of practice with those of science. But the study of material is difficult due to the inapplicability of rigorous research procedures in non-homogeneous or isotropic masonry works, with the most varied shapes and the reactions of the most uncertain constraints, which oblige the scholar to set up his investigations on intuitive hypotheses of which he must limit himself to checking, from time to time, the reliability by means of experimental tests”* (Mastrodicasa, 1987, p. 731. Translation from Italian to English by the author).

The restoration is no longer intended as an intervention on a single building. It is no longer tied to the idea of actively creating a national culture.

The development of methods and technologies has increased the demand for knowledge of the cultural good. The need to respect the existing materials and structures obliges to gain knowledge without (or reducing to a conscientious minimum) destruction or withdrawal of materials.

The material, as a witness of the history of the cultural good (as in archeology), represents the authenticity of the good itself.

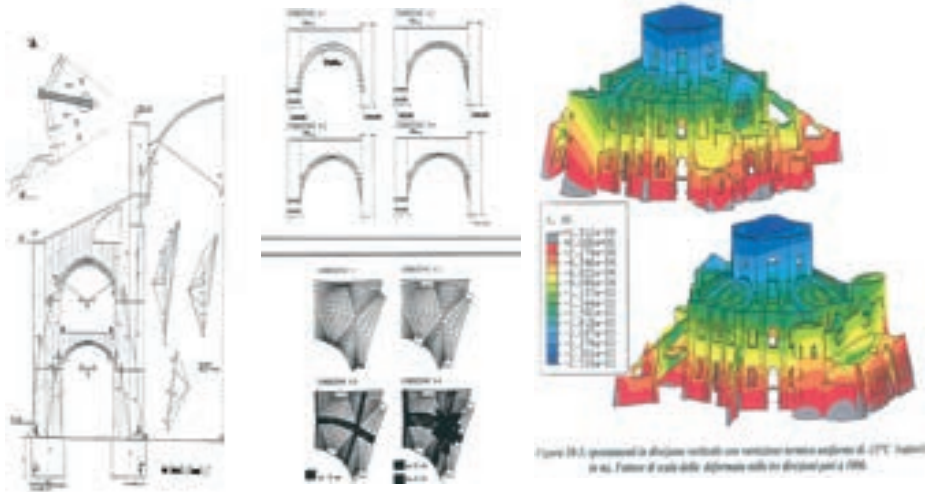


Figure 9. Structural Studies of the basilica of St Vitale in Ravenna (VI Cent.) Lombardini, 1989-1997, Brugnara, 1997, Pasta, 2003/2004

Furthermore, experience and knowledge have highlighted multiple interactions with the surrounding physicochemical and biological environment.

These interactions require complex algorithms that today can be related thanks to the identification of the right ones (and electronic calculators).

Mauro Matteini states *"The modern reality of restoration requires a strategic approach, which envisages operating in a logical, programmatic way and on the basis of a profound knowledge of the context of the problem to be faced"* (Magni, <https://it.pearson.com/aree-disciplinari/scienze-matematica/articoli/matematica-servizio-arte.html>. Translation from Italian to English by the author).

"The conservation of monuments, or more generally of cultural heritage, is a complex problem, which is deeply and intrinsically interdisciplinary. For instance, damage of monumental stones is a process in which the characteristics of the materials in combination with the environmental parameters are the main factors responsible for the decay of the artefacts" (Bonetti et alii, 2021, Preface, Kindle edition).

To improve not only conservation procedures but also to plan and manage the conservation and the maintenance of the restoration process over time, the numerical model is important: the prediction of both what could happen in specific environmental conditions and what could be adopted as restoration is a compulsory procedure in modern days. The parameterization of the data that characterize the material (the one of the cultural good, the one used for the restoration) the environment that surrounds it and the ways in which the materials interact with each other and with the environment, implies cognitive efforts extremely advanced, also guided by algorithms mathematicians. The knowledge and the interpretation of the cultural good, for instance architecture, nowadays is a combination of experience, practice, theoretical approach and scientific experimentation. The collection and connection of the parameters and data must be defined by scientific modelling, that means “the generation of a physical, conceptual, or mathematical representation of a real phenomenon that is difficult to observe directly” (Britannica, *ad vocem*).

Conclusion

Architectural restoration is part of the professionalism of the architect, who, today more than in the past, is called upon to intervene on existing buildings, whether they are monuments or not.

To guarantee a well-done intervention for the conservation of the authenticity of a cultural good, and its materials, it is necessary to make a “project of knowledge”.

The science of restoration and of conservation was defined by Viollet-Le-Duc and Ruskin, around the middle of the 19th Century, coinciding with the birth of the mechanics of structures which began to be used both to give an interpretation of existing structures (with a theoretical model) and to solve restoration problems.

The evolution of mathematics, parallel to the evolution of the principles of conservation of cultural heritage, of which international regulations underline the importance of handing down its authenticity to posterity, involves the development of predictive numerical models (Piga, 1996), with which we try to keep under control the material knowledge of the cultural asset, the evolution of its degradation (in relation to the environment) and the ways of intervening on the degradation itself.

It is, therefore, possible to argue that the science of restoration develops almost parallel to the conceptualization and interpretation of the physical object through a mathematical model that allows to obtain the comprehensive knowledge of it.

Mathematical models enter the process of architectural design as early as the search for optimal geometric proportions starts, and later it is still a mathematical model that takes over in a way that allows to assemble data and useful knowledge for interpretation of its physical behaviour, becoming a necessary tool to facilitate

the conservation intervention aimed at preserving the cultural heritage for the future.

After the Second World War the science dedicated exclusively to the safeguarding of ancient buildings had a great leap of growth, particularly in the areas devoted to conservation of the materials. The studies aimed at understanding of the causes of damages, decays and alterations were developed, with the aim to prevent further deterioration without the need to substitute the existing materials and structures, thus stimulating the research of new technologies and methodologies for intervention on historic buildings.

A necessary condition of science is the measurement and collection of data and since the existing building is an integral part of the environment in which we operate, this building too, like any unknown yet existing element, must be surveyed in order to be understood. In case of cultural heritage, knowledge can go to a great level of detail, but at the same time it requires measurable qualities that are difficult to quantify and for the determination of which great experience is needed. For this reason, the numerical model becomes a precious and fundamental asset, also useful for making shareable the critical interpretation and results.

Today, the BIM process (Building Information Modeling) applied to the study of the existing building state and to the conservation project, constitutes an extraordinarily effective tool.

The creation of the BIM model is a part of an interpretative process aimed at the precise definition of the model's properties, capable of guaranteeing the necessary interoperability between the different stakeholders and, at the same time, constituting an effective interpretative tool of the constructive reality it represents (Achilles et al, 2016; Lombardini et al, 2017; Lombardini et al, 2021).

“The human eye, however, trained and attentive, registers only a part of the observed phenomena, while the metric properties of things and the processes described by them escape our sight: to see, comprehend and measure all the minuscule, the enormous, the complex, the incomprehensible, the inaccessible and so on, we need the tools of science and the science of tools”. (Torsello, 1988, p. 116. Translation from Italian to English by the author).



Figure 10. The BIM model meets the archaeological heritage, containing drawings, ad-hoc conservation sheets, structural analyses, photos, material analyses, walls' stratification, and more.

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