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THE INTERNATIONAL SUMMER SCHOOL ON HISTORIC MASONRY STRUCTURES

Maurizio Angelillo
Dipartimento di Ingegneria Civile, Università di Salerno, Italy, mangelillo@unisa.it

Gianmarco De Felice
Dipartimento di Ingegneria, Università di Roma 3, Italy, gianmarco.defelice@uniroma3.it

Santiago Huerta
ETS de Architectura, Universidad Politecnica de Madrid, Spain, santiago.huerta@upm.es

ABSTRACT

Since the beginning of the 20th Century, the progressive advent of new materials and technologies on top of old building rules has dramatically broken with the millenary history of masonry construction, leading to a progressive loss of knowledge of the traditional building techniques. In addition, the introduction of elastic analysis in the current practice of structural design and its indiscriminate use has led to a systematic erroneous assessment of safety with harmful effects on structural interventions on existing masonry buildings. There is a need to regain the knowledge of traditional construction techniques and recover the understanding of the structural behavior of historic buildings for a proper and reasonable approach to their preservation, restoration, re-use and, at the same time, design.

We witness a lack of teaching about these topics in Schools of Architecture and Engineering, and the difficulty of compensating this deficiency with specialized education. This wealth of knowledge should be re-learnt on site, through fieldwork experiences, open-air laboratories, and practical construction stages. The International Summer School on Historic Masonry Structures represents a first step in this direction.

SOMMARIO

LA SCUOLA INTERNAZIONALE SULLE STRUTTURE IN MURATURA STORICHE

Sin dall'inizio del '900, la progressiva sostituzione di nuovi materiali e tecnologie al posto dei tradizionali canoni costruttivi ha interrotto drasticamente la storia millenaria delle costruzioni in muratura, portando ad una progressiva perdita di conoscenza delle tecniche costruttive antiche. Al tempo stesso, l'introduzione dell'analisi elastica nella pratica corrente della progettazione strutturale e il suo uso indiscriminato ha comportato una sistematica sottovalutazione della sicurezza della costruzioni antiche con effetti dannosi sugli interventi strutturali sugli edifici in muratura esistenti. Appare necessario recuperare la conoscenza delle tecniche costruttive tradizionali e migliorare la comprensione del comportamento strutturale degli edifici storici per un approccio corretto e ragionevole alla conservazione, restauro, riuso delle strutture antiche e, al tempo stesso, alla progettazione di strutture in muratura moderne. La scarsità di materie di insegnamento su questi temi nelle Scuole di Architettura e Ingegneria è difficilmente compensabile con una successiva formazione specialistica. Questo patrimonio di conoscenze dovrebbe essere riappreso attraverso l'introduzione di corsi specifici teorici e pratici nei primi anni di studio, attraverso esperienze di lavoro sul campo, laboratori a cielo aperto e laboratori pratici di costruzione. La "International Summer School on Historic Masonry Structures" rappresenta un primo passo in questa direzione.

KEYWORDS | PAROLE CHIAVE

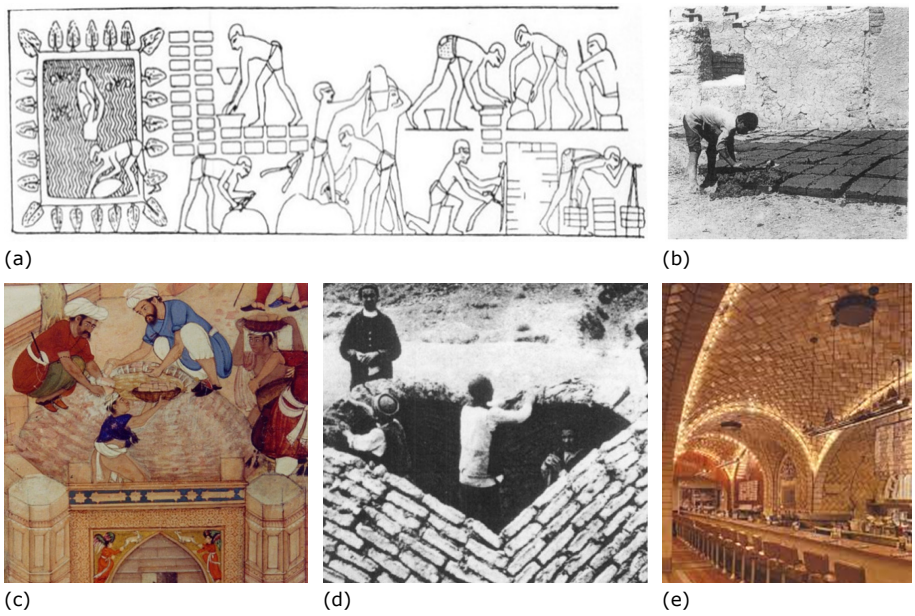
Masonry Constructions, Structural Analysis, History of Constructions, Material Models for Masonry

Costruzioni in muratura, analisi strutturale, storia delle costruzioni, modelli materiali per la muratura

A large part of the European built environment is represented by historic masonry structures, such as buildings, churches, bridges, which need to be preserved for the next generations. The preservation of historical constructions requires a multi-disciplinary effort with diversified competences covering historical, technical and mechanical aspects. Although masonry represents the most ancient and durable technology for housing or monumental buildings (figure 1), its mechanical behavior is still a matter of debate and is currently subjected to in-deep investigation within the scientific community.

The intrinsic mechanical difficulty resides in modelling the unilateral response as masonry can resist only feeble tensile stresses. Old master builders adopted specific construction techniques to overcome this limitation turning this weakness into its strength, which allowed them to build complex and impressive structures such as the Roman vaults and aqueducts, the Gothic cathedrals and the Baroque domes.

Historic buildings have survived for centuries or millennia, and this is an indisputable proof that they were well designed and built. These buildings are robust, durable and they were maintained with the same materials and methods along history, at least up to the 20th century.



(a) (b) (c) (d) (e)

1. Masonry construction know-how had a sort of genetical evolution that lasted through several millennia until it eventually disappeared in modern times. Appearance of the adobe brick technology in ancient Mesopotamia (2500 bc)**(a)**; similar technique still used (1960's) in North Africa **(b)** (from [1]). Self-supporting vault technology in India **(c)** in late XV Century and in Marocco **(d)** in mid XX Century. Modern self-supporting vaulting: Guastavino's tile vault in New York (from [2])**(e)**.

However, today, historic buildings, particularly masonry buildings, are viewed with great mistrust. The progressive fading of the old masonry building tradition based on the use of the arch and the vault, is one of the reasons for this mistrust [3].

The increasing attention paid to new materials (such as steel and concrete) has pushed the development of models and numerical methods describing their behavior as conventional *continuous media* that can resist both compression and tension. Conversely, the essential nature of masonry, an orderly stacking of stones or bricks, is essentially discontinuous and heterogeneous and does not resist tension [4], [5].

The masonry building shows cracks and deformations in a way that we do not understand and that seems dangerous to us because it is in contrast with the practice of assessing modern reinforced concrete or steel structures, where the crack is the warning sign of a malfunction.

Knowledge

Another direct consequence of the loss of interest in masonry studies is that they are no longer central to the educational background of new engineers and architects. The consequence is that traditional building rules of construction have been almost forgotten from both, a theoretical, and technical point of view. We have become ignorant since we have lost the ability to understand or appreciate the essential robustness of these marvelous constructions. Ignorance breeds fear. Fear clouds judgement and leads to wrong decisions. Moreover, fear often leads to an aggressive, defensive, reaction.

Many interventions that are carried out today – often with the best of intentions – are actually harmful to the building itself. The architect or engineer unconsciously assimilates historical structures to monolithic structures and works to prevent the natural cracking and movement of the masonry, to transform the whole construction into a monolithic body. He then inserts steel bars to bind one part to the other and applies externally bonded reinforcement to absorb tensile stresses (figure 2) [6].

These modern interventions seek this transformation in vain, and historic buildings see their essential nature violated by massive applications of reinforced concrete, steel, carbon fibers, resins, et cetera.



(a) (b)

2. The monster. A recent (2019) retrofitting with a concrete cap reinforced with a double net of steel bars on top of the first floor vaults of a convent in L'Aquila: before **(a)**, and during retrofitting **(b)**.

It is the case of L'Aquila, where most of the historic churches were retrofitted in the Seventies by substituting the original wooden roof with concrete slabs provided with a reinforced concrete ring-beam on the top of the walls. This choice was driven from the intention to provide the construction with a box behavior, but resulted in a wrong solution, not only for conservation purposes, but also for their future seismic response. In fact, most of the churches that were retrofitted experienced heavier damages in recent earthquakes (figure 3) due to the increase in weight and stiffness of the concrete additions [7].



3. The damage of two small churches that were previously retrofitted with a top ring beam after the 2009 earthquake in L'Aquila.

At present time, more than ten years after the earthquake of April 2009, L'Aquila is not yet alive. A huge amount of money was spent on the restoration of the monumental buildings facing the main road axes, but the urban tissue of the city is still damaged and evacuated as it was ten years ago. Many people decided to leave. The city will probably never recover the population that was resident before 2009 and the texture of memory, tradition and culture that was brought by the original population through the centuries. The loss in resilience caused by the earthquake is impressive, especially when compared with the traditional high resilience of historic masonry buildings, which are generally able to cope with the damages and changes in their use. The few current buildings undergoing restoration were demolished and reconstructed in a similar shape with loss in their historical assets, authenticity and charm.

Fear

We cannot preserve what we do not understand; we cannot understand and respect what we fear. The cracking of masonry structures is generally considered as proof of a dangerous state, as evidence of a pathology that needs to be treated (figure 4). Whereas most of the time, cracking is merely the natural response of the structure to changing boundary conditions and denotes its ability to accommodate a subsidence or adapt to external actions without any detriment to its safety.

Today we see all too often the consequences of this vicious circle of ignorance and fear, which leads to an aggressive response.

Moreover, there is desire for profit and money. Aggressive interventions, besides damaging the monuments, are expensive and lead to profits for those who participate in them. The engineer who, according to the principle of minimum intervention, seeks the possibility to reduce any intervention, at the same time takes on more responsibility and earns less. We should reverse this vicious circle and reward those who are able to do less.

This cocktail of ignorance, fear and greed is destroying our monuments, turning them into a sort of Frankenstein's monsters. One wonders what will be left of them in 100 years' time. Will any building survive these strange grafts that violate their very nature?

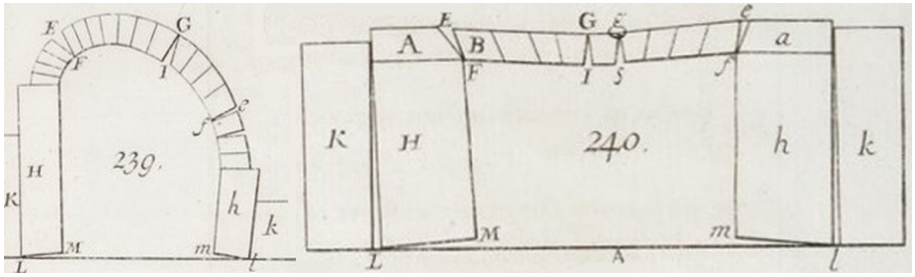
The only way to reverse, or at least slow down and eventually stop, this process is knowledge. Knowledge eliminates fear, or at least keeps it within tolerable limits.



4. The cracks in the basilica of Aquileia are simply plastered underneath, without concealing the effects of the earthquake or taking care to restore the continuity of the masonry.

Modern tools for structural assessment

In daily practice, professionals are often called upon to deal with the assessment of old masonry buildings in order to maintain, restore, preserve and renew them. Despite the availability of a rigorous and adequate theoretical framework for the structural behavior of masonry buildings, current practice too often makes use of numerical methods conceived for other materials and not suitable for masonry structures. The essential ingredients of masonry behavior are condensed into the material restrictions first foreseen by some old pioneers such as Coulomb, Couplet and Mascheroni and later on formulated as a modern theory by Jacques Heyman in the seminal paper [8] and in its well-known book [9].



5. Danyzy's Experiments demonstrating Couplet's theory, from [10]

Heyman's 1995 book [9] contains a synthetic, yet deep and sophisticated treatment of what is the essence of masonry behavior. The flood of multi-parameter constitutive assumptions that have been lately proposed to model masonry materials, including elastic deformation, brittleness, friction, damage and degradation, resulted with few exceptions, in failing to catch its very essence: masonry behavior is ruled primarily by mass, geometry and unilateral behavior. The model proposed by Heyman put forward in 1966 in [8], simple as it may seem, penetrates the very idea behind old masonry design, and incorporates those assumptions that were the goals of any master builder: to give the construction a geometry and the stones an arrangement such that the structure could remain, with limited cracks and little movement, comfortably compressed, whatever external actions might affect it. The material restrictions discovered/invented by Heyman are the essential ingredients for the theorems of Limit

Analysis to be valid, and both the static and kinematic theorems can be successfully adopted for assessing the stability of the structure.

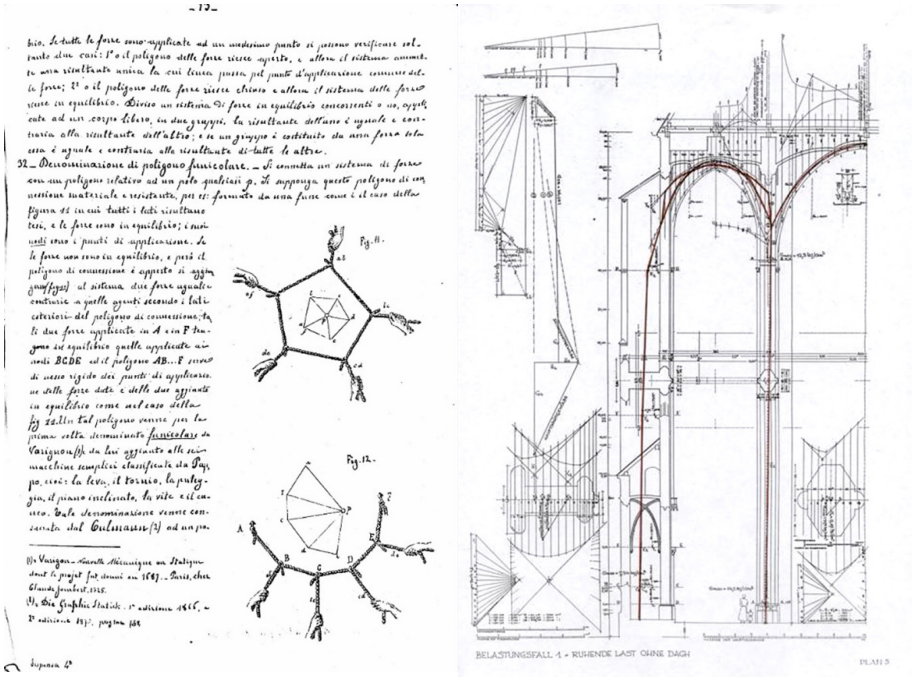
The adoption of this model naturally enables to use Graphic Statics to assess the equilibrium of structures, allowing to retrieve the traditional scientific methods of assessments of arched and vaulted structures and, at the same time, opening up a new frontier to Computer Graphic studies (see figures 6,7).

Construction History

Heyman theory provides a general framework for the safety assessment of masonry structures which is a powerful tool that must, however, be supported by a check on the construction quality. There is the need to assess the fulfilment of rule of the art, i.e. the set of rules, methods and details that were commonly used at the time of the construction but which today no longer constitute common knowledge.

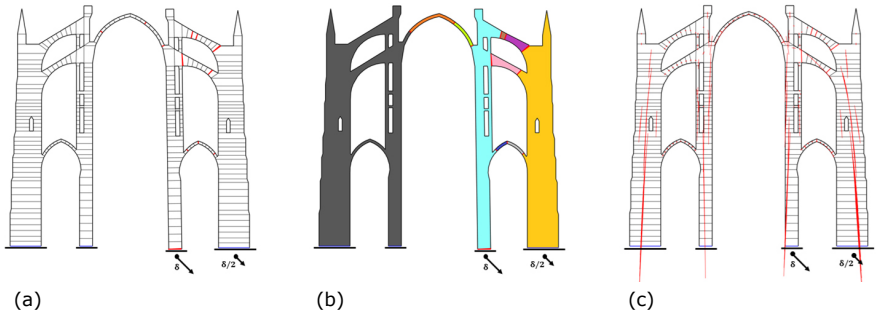
How can we be able to assess a historical building without knowing the construction rules used at that time. In situ investigations can be of help. But claiming to make up for a lack of knowledge of construction history by means of a systematic set of investigations, would be like judging a patient's health on the basis of a set of specialist test reports, without the knowledge of human anatomy. How can we analyze, for example, a Gothic church if we do not know how it was built, what geometric rules were used in the design, how it was founded, how its vaults were erected, how the stones were chosen and the mortars manufactured?

Architectural history books abound, but they say little, if anything, about how buildings were constructed. The history of building construction and technology is an essential ingredient to complete our vision of historical architecture and to be able to make progress in recovering the knowledge lost in the during the 20th century.



(a) (b)

6. In **(a)**, classical Graphic Statics: the funicular polygon and the associated force network. In **(b)**, the funicular polygon applied to assess the equilibrium of the transverse section of San Martin in Landshut (Zorn 1933).



(a) (b) (c)

7. The PRD method applied to the analysis of the effect of settlements to the transverse section of the Amiens Cathedral (from [11]). In **(a)**, Settlement scheme; in **(b)**, corresponding partition of the section into blocks. In **(c)** flow of forces.

Summer School on Historic Masonry Structures

Understanding both the construction techniques and the structural behavior of historical constructions are essential ingredients for their preservation, restoration, reuse and, at the same time, for design purposes. Beyond the risk of losing any past knowledge on the old construction rules, masonry structures suffer from degradation phenomena and need maintenance and sometimes relevant restoration works. Our European built environment's rehabilitation and conservation costs are a big part of the "construction market". Thus, the combination of correct modelling of masonry mechanical behavior with the knowledge of old construction techniques and rules of practice would allow a proper screening of the damage level of our built heritage and consequently an adequate allocation of these resources at different scales.

A key element to spread this knowledge at the academic level among both researchers, construction firms and construction workers is the *Summer School on Historic Masonry Structures* [12], founded in Rome by a group of masonry scholars in 2017[1], and among which the authors of this article play a leading role. The experience of the "*Summer School on Historic Masonry Structures*" has begun in 2018 at intervals of one year.



8. In **(a)**, Booklet front page of the 2018 edition in Subiaco, In **(b)** Poster of the 2022 edition in Anagni.

1 The first time in which the Summer School idea materialized was in June 2017 in the office of Gianmarco de Felice at Roma Tre University , in a Meeting with the participation of Maurizio Angelillo, Gianmarco de Felice, Antonello De Luca, Santiago Huerta, John Ochsendorf. In later years also Philippe Block, Matthew DeJong and Giulio Zuccaro took part in the organization at different levels.

The Summer School aims at overcoming the practice of engineers that apply to cultural heritage the same format as for contemporary buildings, without taking care of their specificities and their historical value, and to develop assessment tools resulting from the effective comprehension of the mechanics of historic buildings. The path followed for the assessment of historic buildings Starts from the pioneeristic studies of Jacques Heyman in the sixties [8], that provided a framework for the mechanics of masonry structures [9], which was recalled and applied to different geometries and real case studies [13] and further enhanced in the framework of continuum mechanics [14]. The extension to the dynamic behavior is not trivial [15] and deserves refined analysis tools that are taught in the school, but historic knowledge remains the starting point for a reliable structural analysis. The aim is to foster the link between historians, conservators, and structural engineers to get an effective comprehension of ancient construction rules, as the starting point towards preservation, and historical continuity of cultural heritage.

The students are typically PhD students involved in masonry research at different levels. The learning program, lasting two weeks, is based on various didactic approaches, including lectures, research presentations by students, fieldwork and on-site inspections. The main idea is that the Summer School should take place in a venue where there could be easy access to outstanding monuments located in the historical city center.

The School venues were in Italy: Subiaco in 2018, Anagni in 2019, Lipari in 2020 and again Anagni in 2021 and 2022. The next editions of the summer school will include other venues such as Segovia and Santiago de Compostela in Spain, to expand the Summer School in other countries. The idea is also to extend the activity of the school integrating it with practical construction work, conducted by students with the help of construction workers skilled in old construction techniques, in an open-air construction laboratory to be in an architectural archaeological site. These laboratories would be the perfect place to integrate practical and theoretical competencies through on-field interaction.



9. Teachers and students of the Summer School during the visits in Rome (2018) and L'Aquila (2019).

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