EXPERIENCES IN TEACHING ANALYSIS OF HISTORICAL MASONRY STRUCTURES

Javier LEÓN
PhD in Civil Engineering
Department of Continuum Mechanics and Structures, ETSICCP, Universidad Politécnica de Madrid
jlg@he-upm.com

Leonardo TODISCO
PhD in Civil Engineering
Department of Continuum Mechanics and Structures, ETSICCP, Universidad Politécnica de Madrid
lt@he-upm.com

ABSTRACT
Future structural engineers need to understand how existing structures are and how they work. A significant part of such constructions is made up of stone or brickwork. The complexity of such structures, as well as the difficulty to determine their mechanical properties, requires the use of alternative procedures to the traditional methods used for concrete and steel constructions. This different approach is explained on the Analysis of Historical Masonry Structures course which is taught at the Civil Engineering School of our University from the 1999-2000 academic year. Firstly this paper describes the raison d'être of a course about masonry structures, and then presents the contents of the course, including the student evaluation based on a real case study. Next, this paper points out the close connection between teaching and research. Indeed, this subject has been the source of doctoral theses, articles, and other academic works. Finally, this team’s vision in relation to the future of this discipline is also presented.

KEYWORDS: masonry, history, heritage, conservation, history, sustainability, equilibrium

1. Raison d'être of a course about masonry structures
A significant part of existing buildings and bridges, at least in Europe, is made up of stone or brickwork. Constructions of this type undergo increased loads, accumulated imposed movements (foundation settlements or rotations, tilting of walls or pillars, as well as creep of mortars, stiffness degradation, etc.), as other type of structures do. However, the fact that they are still standing, despite showing degradations, might give the impression that they do not require particular attention, since they have always been there, apparently without any engineering care. Owners and those responsible of their maintenance may be tempted to think that such constructions are out of the scope of ensuring adequate performance in terms of structural safety and durability, as applied to modern structures. It is indeed true that such buildings and bridges have proved, after centuries, to withstand external actions and time reliably, much more than ‘modern’ materials such as steel or concrete. Although such qualities are certainly true, it is often necessary to assess whether they are stable according to standards under current of future gravitational actions, potential imposed movements, seismic movements or, simply, whether they are robust enough.

The Latin aphorism *Vulnerant omnes ultima necat* (‘Every hour wounds, the last one kills’, figure 1)
may be applied to warn about the non-eternal character of such noble constructions and the need for engineering judgement and, if necessary, intervention (figure 2).

![Figure 1. Church of Saint Vincent, Urrugne, France](image1)

![Figure 2. Deformed interior flying buttress to brace the nave of Santa María Cathedral in Vitoria-Gasteiz, visited by students in 2014](image2)

![Figure 3. Skewed masonry railway bridge in Frómista. Why is the layout of ashlers also skewed?](image3)
However, the study of the configuration (figure 3), behaviour and way of construction ceased to be a part of university study plans about a century ago, when concrete and steel acquired a predominant role. Students trend to study only the part of the course that is examinable. Implicitly, they think that what is not examinable is not of any interest and, at the end, that it does not exist. It is needless to say how wrong this idea is, especially when translated into the professional field. Firstly would like to highlight the reasons for offering this module to students of our Master’s in Structures, by taking historical, cultural, and humanistic aspects into account. Secondly, the content of the School’s study plans from the 19th and 20th Centuries—which are of great educational value—shall be reviewed. Thirdly, the content of our course is presented, including the evolution of our own knowledge and practical experience. Last but not least, and specifically within the context of this Conference, this paper points out the extent to which this course has been the source of doctoral theses, articles, and other academic works. It is worth making reference to further sources, such as summer courses for professionals of different fields, but with masonry constructions remaining as the main focus. In addition to these, exhibitions of bibliographical funds, in cooperation with the Library of our Civil Engineering School, which make true the aphorism used by Newton: *If I have seen further it is by standing on ye sholders of Giants.*

2. Brief historical evolution of the courses related to masonry constructions at the Civil Engineering School (ETSICCP) of the Universidad Politécnica de Madrid

The analysis of the annuals kept in the Library of the Civil Engineering School (ETSICCP) of the Universidad Politécnica de Madrid made it possible to retrace the evolution of courses related to masonry constructions during the last century. From the academic year 1900-01 until 1916-17, the professor in charge of the course in ‘Foundations and Bridges’ was Luis Gaztelu Maritorena. After this period, Eugenio Ribera led the subject from 1917-18 until 1931-32. The main difference with respect to the previous phase is that Ribera introduced a new material within the syllabus of the module ‘Reinforced Concrete’. Starting from the academic year 1932-33 and until 1956-57, the course was taught by José Entrecanales Ibarra. The existing chair was divided into two different subjects: ‘Geotechnics’ and ‘Masonry Bridges’. This last one was taught by Fernández Casado until the 1968-69 academic year. Starting from the following year, the course was named ‘Bridges’ and the role of masonry started to decrease. However, Fernández Casado taught a specific course about masonry structures to PhD students (among them was the first author of this paper) until the 1981-82 academic year. From the 1999-2000 academic year, the first author of this paper started a new course titled ‘Análisis de construcciones históricas de fábrica’, which translates in English as analysis of ‘Historical masonry structures’. The following section addresses to describe the current organisation of the course.

3. The organisation of the course today

3.1. Introduction

This subject is taught to students of the Master Degree in Structures, Foundations and Materials and it has been organised to achieve the following goals:

- To place this specific topic in the general context of the analysis of existing structures.
- To present the general methodology to deal with masonry structures.
- To describe the fundamental aspects of the behaviour of the materials assembled in masonry structures, both from the standpoint of resistance and of durability.
• To understand the mechanical behaviour of masonry and its application to estimate the safety of different structural typologies: bridges, towers, and buildings.
• To train students to develop a complete analysis of a real case of study. This includes the search for information, the identification of the structural scheme, the characterization of the materials, the structural analysis and the conclusions on the structural safety.

3.2. Syllabus

A summary of the topics addressed during the theoretical lectures is outlined below:

- Topic 1. Introduction to the subject
- Topic 2. Mechanical behaviour of masonry
- Topic 3. Masonry bridges
- Topic 4. Masonry buildings
- Topic 5. Examples of strengthening interventions
- Topic 6. Management systems addressed to masonry structures

Furthermore, several experts are invited throughout the year to give lectures about related topics (e.g. deterioration mechanisms, backfills, etc.).

3.3. Evaluation and student work

In order to pass the exam, students have to carry out an individual work on a construction chosen by mutual agreement between the student and the lecturers. The minimum content of the paper is described detailed below:

1. Objectives.
2. Location: where the construction is, how it is accessed, its orientation, etc.
3. Information available: list of documents consulted about the history of the construction, the information of previous projects, interventions, press clippings, old photos, etc.
4. Brief history: succinct and brief account of the history of construction, previous constructions, subsequent avatars (accidents, collapses, reconstructions, etc.).
5. Geometry: available drawings in which all dimensions are taken into consideration (height, width, thickness, etc.), discriminating, if possible, foundations, walls, columns, backfills, vaults of all kinds, arches, abutments, flying buttresses, etc.
6. Materials: characterization of stones, bricks, mortars, backfill (if possible) that make up the construction.
7. Actions and security format: this includes self-weight, dead load, live load, snow and wind. The established security format or formats will also be considered, as well as the return periods associated with certain variables.
8. Structural analysis: to be developed, preferably, with thrust line analysis. FEM, DEM and rigid block analyses can be used for particularly specific studies.
9. Conclusions: clear conclusions on structural scheme, structural safety, recommendations for monitoring (acceptance thresholds) or auscultation.

The paper is submitted in digital format and is accompanied by a PowerPoint presentation for its subsequent public defence.
4. Research associated with the course

4.1. Introduction

As opposed to other courses, in this subject there is a strong connection between research and teaching. This subject has been the source of many academic works, and the more relevant research has been then incorporated in the syllabus of the course. The following sections briefly describe the research topics related to the contents of the course.

4.2. PhD Theses

The first investigations relating to masonry constructions are associated with two PhD Thesis developed during the same period. The first one, by Martín-Caro [1], focused on the structural analysis of masonry bridges and related criteria to assess their safety, while the second one, by Martínez [2], investigated the theoretical and experimental determination of interaction diagrams in masonry structures and their application to existing structures. A few years later, Bauder [3] studied the analogy between a masonry bridge and a person, from a metaphoric point of view. Through a cognitive and terminological study, this work allowed to fill a gap in the linguistic analysis of masonry bridges. More recently, Ramos [4–7] focused on the essential role of the backfill at the extrados of masonry vaults and domes which has been ignored or misunderstood in the technical literature. This work contributed to overcome such a lacuna, and pointed out the crucial importance of backfill, not only for the stability of vaults or domes, but also for the equilibrium of walls, pillars and buttresses. Furthermore, it is worth mentioning other theses which have focused on the more general topic of existing structures. The first, by Pamies [8], analysed the evolution of knowledge of reinforced concrete structures until 1973. The second one, by Díaz-Pavón [9], investigated the cause of the collapse of the 4th compartment of the 3rd Reservoir of Canal de Isabel II in Madrid, designed by Eugenio Ribera. This accident happened in 1905 and 30 people died. The thesis identified the causes that could have provoked the initial failure and those that could have led to the global collapse. It presents a good example of lack of robustness, studied in the past in relation to the case of flat masonry bridges [1].

4.3. Master’s Theses

Together with PhD Theses, several Master’s Theses have been carried out at the last few years. Espejo [10] focused on the experimental behaviour of two masonry bridges until collapse; while Rojo [11,12] studied the graphical methods adopted by Luis Moya Blanco for the design of the Church of Nuestra Señora de la Araucana in Madrid (figure 4) by using the original author’s working-drawings. Lázaro [13] focused on the structural behaviour of the plane dome located in the “Casa de Mina de Limpia” of Pontón de la Oliva, which cannot be analysed through the classical approaches of masonry analysis. Stocks [14,15] studied the high potential of masonry as a primary load-bearing material when combined with post-tensioning. Specifically, this research illustrated the introduction of external loads by internal post-tensioning to favourably increase the axial forces in a masonry arch, consequently improving its structural behaviour.
4.4. Exhibitions and summer courses

The Civil Engineering School at the Universidad Politécnica de Madrid holds an extraordinary heritage in terms of books and drawings. This school was the only Civil Engineering School to exist in Spain until 1966, and therefore it was the national centre for collecting all the relevant treatises on the subject.

In April 2016, an exhibition about masonry bridges was organized in the Civil Engineering School of the Universidad Politécnica de Madrid. The exhibition was based on a selection of bibliographic collections that for over two hundred years supported the training of engineers. These essays were written by renowned European engineers of that period: Jean-Rodolphe Perronet (1708-1794), Carl Friedrich von Wiebeking (1762-1842), Romain Bricheteau de la Morandière (1809-1875), Paul Séjourné (1851-1939) and Luis Gaztelu Maritorena (1858-1927). Figure 5 shows two drawings of these treatises.

Taking advantage of this exhibition, a summer course about masonry bridges was organized by the Juanelo Turriano Foundation and the Civil Engineering School at the Universidad Politécnica de Madrid. The invitation to the summer course explained that despite the great variety of form and materials of modern bridges, the experience of people who inspect them teaches that masonry bridges are those that have shown better behaviour, lower costs of maintenance and, ultimately, are the most sustainable. The proceedings of this course have been recently published in a book [16].
Figure 5. Examples of drawings shown during the exhibition held at the Civil Engineering School of the Universidad Politécnica de Madrid (Wiebeking and Perronet)

4.5. Other publications

In the last few years, several journal papers [17] [18] and guidelines have been published on this topic. It is worth mentioning the books on intervention criteria on masonry bridges [19] and masonry foundation of bridges [20] published by ATC (the Technical Road Association) and a book about inspection and diagnosis of railway bridges [21] published by ADIF, the Spanish state owned company that manages most of Spain's railway infrastructure.
The authors believe that ‘pure rational’ way of teaching is not enough. In our view, it is indispensable to show enthusiasm, even passion, when transmitting the experiences we have lived, to pass on romanticism, that is, love, the motor for good actions. It does not imply that everything is done for love of the art. It is indeed a fascinating topic, but the result of deep and responsible engineering work, which is not paid well enough.

It is also worthy to note how important it is to achieve practical experiences, to deepen into the causes of the problems, to analyse the risks that threaten the construction under study. That is why we prepare practical exercises for students so that they are faced with real situations.

We consider that the engineering approach to masonry constructions we propose may not be merely retrospective to the already existing ones. On the contrary, this vision enables us to suggest new and interesting possibilities for the development of new stone or brick structures.

The authors believe that their experiences can contribute greatly to the dissemination of this old and new knowledge across the universities of such countries which, like Spain and many other European countries, possess a very rich form in the brick and stone constructions.

6. References


