Preservation- Engineering Education for Masonry Construction and Structures

Paulo B. Lourenço

Is licensing for preservation engineering necessary or can anybody do it?

Introduction

The analysis of heritage masonry structures is a complex task that requires specific training. The changing materials and construction techniques, which swiftly moved away from traditional practice, and challenging technical and scientific developments, which make new possibilities available for all agents involved in the preservation of the built heritage, are key aspects in the division between the science of construction and the art of preservation. The last decades have witnessed relevant developments in the fields of experimental techniques and computer simulations of heritage buildings. These advances are a result of the growing societal concern about the need for preservation, together with the cultural and economic importance of these activities.

In the past, significant attention has been devoted to aspects of preservation trades and architectural education, with several references in the *APT Bulletin*. But only recently has more attention been given to the development of engineering curricula focused on quantitative techniques and methodologies applied to the engineering evaluation and remediation of heritage structures and to assuring that students acquire the competencies necessary to address the challenges of the market. The creation of a strong preservation-engineering community is supported by an international journal devoted to this subject, the *International Journal of Architectural Heritage: Conservation, Analysis and Restoration*, and by a series of biannual conferences on structural analysis of historical construction, which have had an average of 300 participants. Still, most engineers are rarely exposed to the specifics of preservation engineering in the course of their education. Therefore, this paper focuses on research issues, funding possibilities, and an International Master Course on Structural Analysis of Masonry and Historical Construction in Europe that successfully graduated students from more than 50 countries, all related to preservation-engineering education and with a reference to masonry construction and structures.

The Current State of Knowledge

Masonry is the oldest building material that still finds wide use in today's building industries. Innumerable variations of masonry materials, techniques, and applications occurred over the course of time. The influencing factors were mainly the local culture and wealth, the knowledge of materials and tools, the availability of material, and the shape and form of the buildings.

The most important characteristic of masonry construction is its simplicity. Laying pieces of stone or bricks on top of each other, either with or without mortar, is a simple, though adequate, technique that has been used successfully since ancient times. Other important characteristics are aesthetics, solidity, durability and low maintenance, versatility, sound absorption, and fire protection. A drawback for the modern use of masonry and for the understanding of existing masonry buildings is the education of engineers. Because design and field knowledge of masonry is absent or minimal in the curricula of most programs in civil engineering, masonry is being replaced by reinforced concrete or steel as structural materials. Another drawback is the intrinsic fragility of old masonry structures to earthquake loading, due to a combination of large masses, low tensile strength and, often, friable materials (Fig. 1).

Many advances have occurred in recent decades regarding the approach towards preservation of existing structures, nondestructive evaluation, and repair and strengthening techniques. These advances are often difficult to translate to undergraduate and graduate courses and even to engineering practice. As an example, several methods and computational tools are available for the assessment of the mechanical behavior of historic masonry structures. The methods are based on different theories or approaches, resulting in different levels of complexity (from simple graphical methods and hand calculations to complex mathematical formulations and large systems of non-linear equations), different levels of availability for the practitioner (from well-disseminated structural-analysis tools available in any consulting-engineer office to advanced structural-analysis tools available only in a few research-oriented institutions and large consulting offices), different time requirements (from a few seconds of computer time to days of processing), and, of course, different costs. The possibilities of structural analysis of historical buildings have been addressed[1], in general, and specifically for seismic assessment[2] , where it is advocated that most techniques of analysis are adequate, possibly for different applications, if combined with proper engineering analysis. Still, linear elastic analysis, which is normally used to design new buildings, can hardly be applied to unreinforced masonry structures. Figure 2 shows the collapse mechanism of a UNESCO World Heritage building during a strong earthquake using an advanced simulation technique.

Research Questions and Potential Funding

There are several issues that require additional research, many of which combine experimental and numerical techniques. One key aspect is durability and compatibility between traditional materials, such as stone, lime-based mortar or plaster, adobe, or clay brick, and new materials, such as fiber-reinforced polymers (FRP), metals, or injection grouts. Currently, using natural fibers for crack control and strengthening is becoming increasing popular as an environmentally research field. The impact of mechanical long-term effects are also relevant for further research, as creep and fatigue seem to be related to recent collapses of historic structures under sustained heavy load. Also, the distribution of stresses in multileaf walls is severely affected by long-term effects.

The mechanical characterization of irregular masonry remains a true challenge; the in-plane and out-of-plane behavior of historic multileaf walls is far from being well known. Multiscale and multiphysics modeling of masonry, which involve a closer link with material science, aim at developing eco-efficient materials and at predicting deterioration.

Seismic assessment of historic structures remains a major challenge, given the fact that linear elastic analysis and push-over analysis usually fail to replicate a building's true behavior. Reliable analysis of existing structures, possibly coupled with structural-health monitoring techniques, is a way to limit overly conservative assessment and strengthening design, given the significant variability of masonry materials and the difficulties of characterizing them in situ.

In order to address these research questions, academic funding is essential. This funding is also necessary for an advanced-education program, for two reasons. First, research must provide answers to the difficulties encountered, and this research must be incorporated into engineering curricula so that it is adequately disseminated and has an impact on the market. Second, research must provide financing for grants, as, optimally, a combination of self-financed students and grants from the program is requested for a successful graduate program. Typical funding possibilities are government agencies, nongovernmental organizations, heritage authorities, and the construction industry. For European government agencies, research on cultural-heritage buildings has had funding opportunities for decades due to a societal, economic, and cultural demand. Cultural-heritage buildings have a large economic value, as the existence of a monument or a historic district is often a key attraction of a city. Tourism and leisure are a major industry in this millennium, representing about 10% of the Gross National Product in

Europe, according to the European Commission estimates, Communication COM(2010) 352. Modern societies also require heritage protection as a part of preserving their culture, history, and memory. For the U.S., if cultural-heritage buildings are not considered a priority, political lobbying is necessary to connect the importance of the past with economic value.

Several nongovernmental and international organizations are involved in culture-related issues and can provide funding for research or pilot projects. Examples are The Getty Foundation, the Aga Khan Foundation, the World Monuments Fund, UNESCO, and the World Bank. Heritage authorities tend to have limited funding, but agreements between them and universities can provide good support and experience to drive research and fund students.

Funding from industry is usually difficult to attract, as the sector is characterized by small and micro enterprises, often specializing in traditional materials and techniques. Large contractors often have difficulties complying with long execution periods, small quantities, and careful execution in cultural-heritage buildings, as their overhead costs are too high and they need industrialized production. They mostly hire subcontractors to carry out work. Large material suppliers tend to have a very diverse range of products, and preservation projects account for a very small fraction of revenue. A possible way to involve large contractors or large material suppliers is to promote the impact of heritage buildings in cultural aspects in society, allowing them to consider nonaccountable benefits. Another possibility is to promote techniques and products developed for repairing and strengthening existing construction in general for heritage preservation where the solutions are technically viable, thereby enlarging the potential market.

The University of Minho in Portugal coordinates an international program with a one-year master's course (MSc in Structural Analysis of Masonry and Historical Construction, http://www.msc-sahc.org/) and advanced independent courses with a focus on preservation engineering. The program is oriented to civil engineers having a minimum of four years of university education. It includes six regular units, one integrated project, and one dissertation (carried out in a second country). The six units address aspects such as history of construction and preservation, advanced structural-analysis techniques, dynamic analysis and seismic engineering, inspection and diagnosis, repair and strengthening, and conservation and restoration of materials. In the integrated project, the students must provide the design and detailing of an engineering case study, including drawings, technical specifications, bill of quantities, and cost estimation. In the dissertation the students develop additional scientific and/or professional competencies in the field of heritage structures. The program has been financed by the European Commission since 2007 and up to 2016. The number of students has been kept constant in the last years, with 30 students per year, with an origin from 50 countries and with larger attractiveness from the U.S., Italy, Greece, and China (Fig. 3).

Essential Competencies

In the process of educating preservation engineers specializing in masonry structures, several subjects must be addressed. A first subject is construction technology and structural components, including traditional materials (stone, brick, adobe, or mortar), their mechanical properties, and the function and role of structural elements (walls, foundations, columns and pillars, arches, and vaults). Walls, for example, have several functional and structural roles, namely to form an envelope to provide shelter from view, wind, rain, and temperature; to support the weight of floor and roof systems; and to provide in-plane strength and thus contribute to resist lateral forces (e.g., wind, earthquake). Historic masonry walls are often multileaf, with an inner leaf of rubble masonry. Foundations have the role of distributing the bearing stresses to acceptable levels by expanding the base of the structure in contact with soil. The role of the foundations in the overall stability of structures is critical and well known. Modern engineering defines the soil-bearing capacity as the maximum bearing pressure that can be developed under a foundation without causing movements that could damage the structure. However, modern criteria must be carefully applied to ancient and historic buildings: due to the durable construction processes and the nature of masonry itself, ancient structures were able to accommodate large settlements or deformations with little or no damage; damage due to soil settlement was (or is) easily repairable in many cases; settlement and the resulting damage may have stabilized centuries or decades ago; the soil might be well consolidated under the foundation.

A second relevant aspect is the overall structural arrangement, which originally started as lintel (or post-and-lintel) construction and then rapidly moved to different vaulting construction styles (Roman, Byzantine, Romanesque, and Gothic), also incorporating major technical achievements in domes. Lintel construction is confined to small spans, due to the need to limit the bending forces experienced by the stone. The tensile strength of stone can easily deteriorate due to a variety of actions (earthquake, thermal variations, settlements, chemical attack, erosion, etc.); if it were not for the possibility of lintels to work as jack-arches (and the supporting structure being robust enough as to counteract the resulting horizontal thrusts), almost all post-and-lintel ancient structures would have collapsed. Lintel construction was used in many countries, in some cases in the not-so-distant past (Fig. 4). Vaulting construction allowed significant material saving, structural slenderness, and openness in Gothic construction (compared with other architectural approaches). Gothic structures consist of a skeleton of piers, buttresses, arches, and ribbed vaulting. The walls enclose, but do not support, the structure, and they consist mainly of glazed windows. These members form a pure skeletal structure, where forces are adequately balanced and neatly channeled towards the buttresses and foundation with close to minimum material.

A third relevant aspect is the need for understanding structural analysis methods for masonry. To acquire the necessary knowledge, a review of ancient rules (based on geometry) and classical approaches (graphic statics and limit analysis mechanisms) is required. Also modern advanced methods, particularly based on finite-element modeling, must be addressed. Masonry is usually described as a material exhibiting distinct directional properties due to the mortar joints, which act as planes of weakness. A different description can be given at structural level, as the approach towards the numerical representation of masonry can address the micro modeling of the individual components or units and mortar, or the macro modeling of masonry as a composite[4]. The simplest approach related to the modeling of masonry buildings is given by the application of different structural elements, with truss, beam, panel, plate, or shell elements representing columns, piers, arches, and vaults and the assumption of homogeneous (macro) material behavior. This approach allows the assessment of the system behavior in more detail. In particular, it is possible to determine the sequential formation of local failure mechanisms and overall collapse, both statically and dynamically.

The finite-element model seems to be the most appropriate tool for the application of continuum macro models in which structural elements are represented in detail and local failure can be clearly captured. Difficulties of conceiving and implementing macro models for the analysis of masonry structures arise especially due to the intrinsic complexity of formulating anisotropic inelastic behavior.

A final relevant aspect is the safety validation of structural elements and design of strengthening. This must include the design of structural elements subjected to, for example, vertical loading, combined in-plane loading, out-of-plane loading, and concentrated loads. It must also include the design of masonry buildings as a whole and a discussion of the use of linear elastic methods, the influence of rigid and flexible diaphragms, and the use of push-over analysis for buildings with box behavior and collapse mechanism analysis for buildings without box behavior. In this respect, preservation-engineering education also needs to include information related to code requirements for structures, including ramifications with buildings services and comfort, particularly taking into consideration the new energy-conservation demands. These issues can affect behavior and detailing of masonry assemblies.

Conclusions

Preservation engineering is necessary for understanding the behavior of and damage to historic masonry buildings in order to safeguard this heritage. While a successful program by the University of Minho in Portugal addressing heritage structures was briefly introduced, several topics lend themselves to the addition of new modules to existing courses in civil-engineering programs. Examples are construction technologies and structural components or overall structural arrangement, which can be added to existing courses on introduction to civil engineering, ancient rules and classical approaches, statics, or strength of materials. These additions can be made at the undergraduate level, so that students develop interest in the field. At the graduate level, a module on pushover analysis of masonry can be added to existing courses on masonry structures. It is noted that in most universities, a course on masonry structures is not offered, and this module requires that the students had previously completed a course on structural dynamics. Another alternative is to create a module in a course on structural dynamics, but this module requires that the students completed a course on masonry structures. Finally, a course on advanced structural analysis and repair of existing structures should be created in most universities, providing also some focus on heritage and significance.

Ideally, a preservation engineer should then have the knowledge necessary to adopt a decision-making process that includes understanding the history of the building, diagnosis (often involving nondestructive or minor-destructive techniques), safety assessment (often using advanced analysis tools), definition and execution of remedial measures (if necessary), and control of the execution.

Paulo Lourenço is experienced in non-destructive testing, advanced experimental and numerical techniques, strengthening and earthquake engineering. Dr. Lourenço worked on more than fifty monuments in several countries, authored over 800 publications and received the 2010 John B. Scalzi Award from The Masonry Society.

Notes

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Captions

Fig. 1. L’Aquila earthquake, Italy, 2009. Photo by Lourenço, P.B.

Fig. 2. Simulation of the failure of the Monastery of Jerónimos, Lisbon, subjected to an earthquake load. Image by Roque, J.[4]

Fig. 3. Origin of the students for the International Master Course on Structural Analysis of Masonry and Historical Construction. Image by Lourenço, P.B.

Fig. 4. Fatehpur Sikrit, India, built in the sixteenth century as post-and-lintel construction, obviously inspired by timber construction arrangement and details. Photo by Lourenço, P.B.

Figure 1. L’Aquila earthquake, Italy (2009)

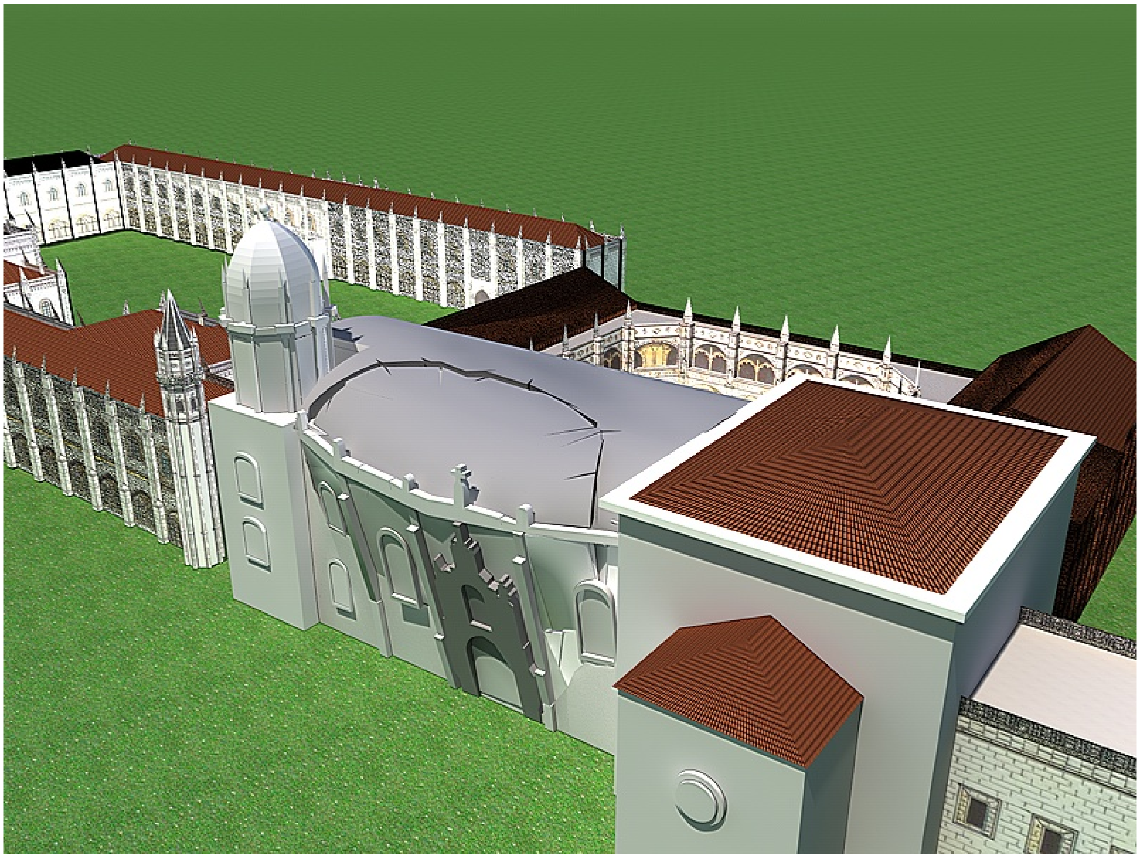

Figure 2. Simulation of the failure of the Monastery of Jerónimos, Lisbon, subjected to an earthquake load.

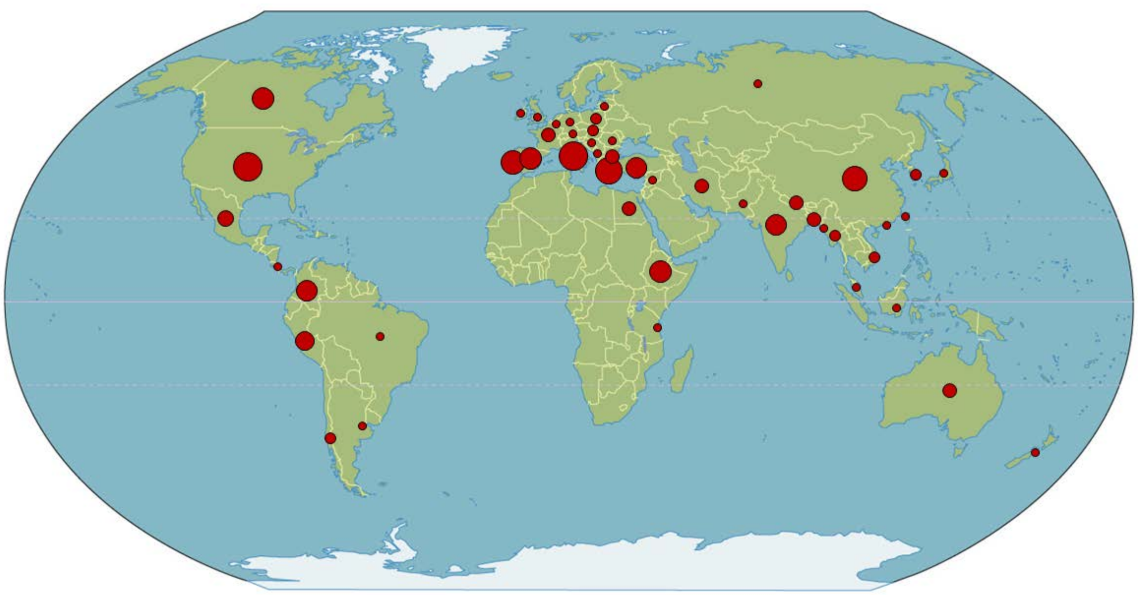

Figure 3. Origin of the students for the International Master Course on Structural Analysis of Masonry and Historical Construction.

Figure 4. Fatehpur Sikrit, India, built in 16th century as post-and-lintel construction, obviously inspired by timber construction arrangement and details.