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Maurizio Angelillo
Editor

Mechanics of Masonry Structures

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PREFACE

It is maybe a trivial remark saying that the vast majority of masonry structures (excluding tall towers) exhibit an extraordinary stability under the effect of age and settlements and even under the repeated action of strong winds and heavy earthquakes. Someone may be skeptical about this statement since, lately, collapses of masonry structures are not so infrequent. The point is that, almost invariably, failure is caused by some unaware but diabolic alteration of the natural and pacific equilibrium of masonry. The reason of this pacific stability stems from the so called strength by shape that is typical also of other structures carrying axial forces, such as a cord or a membrane, that is unilateral structures. If pacific-unilateral stability for masonry, does not mean plainly dumb or boring stability, this is actually due to the curved structural elements (arches, vaults and domes) that started to appear systematically in masonry Architecture since the ancient Rome. The unilateral model, which appears as the clue of structural interpretation behind the design of the great Architecture masterpieces of the past, was first rationally introduced in the scientific community by Heyman in 1966, with his mile-stone paper the stone skeleton. *Since then it has been the Italian school of Structural Mechanics to carry the torch of the old masonry tradition, with the contribution of a number of individuals dragged by the charismatic leaderships of Salvatore Di Pasquale, and of whom Lucchesi, Šilhavý and myself are, in some sense, modern followers. The fire of the unilateral model, still burning in Naples in the late seventies, was poked by the unlucky event of the Irpinia earthquake of 1980. At that time I was a young Architect working under the guidance of Giovanni Castellano (a friend and former co-worker of Di Pasquale), and I had the occasion not only to eyewitness the, sometimes turbulent, discussions on the No Tension model for masonry, but also to see the model at work in the wounded body of many masonry buildings and monuments of Naples and of its battered neighbourhoods. But how comes that the unilateral model for masonry, that has been part of the traditional scientific heritage since Mery divulgated the thrust line approach of Moseley in 1840, had to be rediscovered again (and with scant success) in the second half of the twentieth century? Indeed, though the traditional unilateral approach to masonry equilibrium has had an outstanding mentor and* *divulgator in the person of Jaques Heyman, who, after writing the mentioned paper, in 1995 published a crystalline book with the same inspiring title (a book in which the author succeeds in explaining the stone behaviour to the stones themselves by using barely a few equations), it seems that the message of the traditional masonry design has not been welcomed by the modern structural engineers. A reason for this state of affairs is given by Santiago Huerta, in his paper by the provoking title* Galileo was wrong *"... any engineer or architect with some formation in structural theory feels more comfortable within the frame of the strength approach of Galileo and the classical theory of structures. It requires an effort, and some study, to overcome our own prejudices and to accept that, for example, the medieval master masons, knowing nothing of mathematics, elastic theory and strength of materials, had a deeper understanding of masonry architecture than we engineers and architects of the twenty-first century do."*

The presentation given by Lucchesi, Šilhavý and myself in the first part of this book represents a modern update of the unilateral model for masonry and a step forward toward the goal of obtaining a useful practical tool for the analysis of masonry structures.

Though we believe that the unilateral model can be useful to practitioners and applied engineers, since it captures the essence of masonry mechanics, still the limits of such a crude model are apparent and there are aspects of masonry behaviour that need to be understood such as damage, degradation, friction, heterogeneity and particularly the role of the interface behaviour in the overall response of masonry. In order to appreciate the limits of validity of the simplified unilateral approach, it is important to study and interpret the experimental results with the "eyes" of more sophisticated models. Actually, all I have said until now refers to the phenomenological modelling of old masonry for which the assessment of the material properties in the detail required by fancy models is virtually impossible. The case of new masonries for which the nature of the blocks and of the mortar and of their arrangement is known and reliable, is a complete different story. A typical case is that of brick-works studied in the present book by Lebon, Sacco and Lourenco & Milani. In the end, these new masonry structures are nothing else than composite structures to which sophisticated techniques of homogenization can be applied. The theoretical and experimental study of these peculiar structures with this *more in depth focus, is not only useful for the closer simulation of their mechanical behaviour, but can put light on the mechanical phenomena that are behind the crude approximations of the Heyman's model, namely the unilateral and the no-sliding assumptions. Unilaterality is an extreme approximation for the brittleness of the material under tensile loads, brittleness being responsible for the softening behaviour of masonry at the macroscopic level. No-sliding is equivalent to assume infinite friction, and friction and sliding are the basic mechanisms in brick-brick, and brick-mortar-brick interactions. Understanding toughness and friction is then obviously a necessary step toward the goal of obtaining a detailed masonry description. Anyone working at some depth in material engineering knows that fracture and friction are still the most difficult challenges of modern Mechanics; the main strength of the simplified unilateral model of Heyman which assumes zero toughness and infinite friction is indeed its ability, while excluding these two tough guys, of being still able to make sound predictions on masonry behaviour.*

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Masonry behaviour and modelling

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Abstract In this Chapter we present the basic experimental facts on masonry materials and introduce simple and refined models for masonry. The simple models are essentially macroscopic and based on the assumption that the material is incapable of sustaining tensile loads (No-Tension assumption). The refined models account for the microscopic structure of masonry, modeling the interaction between the blocks and the interfaces.

1 Premise

The first basic question that any course on Masonry Structures should address is: *what we consider as masonry material?*

Masonry structures can be built with a large variety of materials, masonry blocks can be of different types and assembled in many different ways; mortar, if present, can also be of various kinds, and the way it interacts with the blocks depends on workmanship. There is old masonry, new masonry and a peculiar place is taken by brickworks.

There are essentially two ways of approaching the modelling of masonry: the first one is rather ambitious and aims at the modelling of large classes of masonry buildings (e.g. old masonry structures). The second one is more pragmatic and restricts to the mechanical description of very specific types of masonry (masonry structures of regularly arranged blocks, e.g. brickworks of known geometry). Here Silhavi, Lucchesi and myself adopt the first approach and Sacco, Lebon, and Lourenco & Milani propose the second one (also if Sacco has had experiences and papers where the first approach was considered).

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It is evident that with the second approach the models adopted can be very sophisticated and more *close to reality*, whilst the first approach asks for very crude material assumptions and produces predictions on real constructions that are affected by large approximations. The point is that, often, the real geometry and material behaviour of the building is not known in the detail required by the second approach, the definition of even the most primitive material parameters, such as strength and stiffness, being generally difficult and affected by an elevated randomness and uncertainty.

The most basic assumption that can be made, in view of the small and often erratic value of the tensile strength of masonry materials, is that the material behaves unilaterally, that is only compressive stresses can be transmitted (No-Tension assumption). It is generally recognized (since the pioneering work of Heyman (1966)) that such an assumption is the first clue for the interpretation of masonry behaviour; on adopting and applying it, we acquire the *eyes* to appreciate and interpret the fracture patterns, that is the masonry most peculiar manifestation, representing, in a sense, its *breath* (that is the way in which the masonry buildings relieve and can survive also to radical and, sometimes, dramatic changes of the environment).

We call the models based on the No-Tension assumption *simple models* and the models accounting for more sophisticate stress-strain laws (i.e. exhibiting damage, softening, brittleness) or based on the micro/meso-scopic structure of the material, *refined models*. The book is divided into two interconnected but separate parts: Part I, where the simplified models are studied, Part II where the refined models are described.

In the present Chapter we discuss the basic experimental facts on masonry materials justifying the introduction of the simple and refined models for masonry.

2 Basic behaviour of masonry and simplified unilateral models

M. Angelillo

2.1 Local failure modes

There are basically three failure modes that are visible locally in masonry structures.

1. The first one is the one associated to the brittleness of the material and that manifests itself with *detachment* fractures, such as those reported in Figure 1. Such fractures consist in cracks that usually separate neatly two parts of seemingly intact material and are usually

the "good" ones, that is those contributing to the accommodation and release of stress.

Figure 1. Fracture of detachment in brick walls at different scales

2. The second one is a kind of mixed mode in which fractures of detachment alternate to lines of sliding, such as those appearing in the examples of in-plane shear shown in Figure 2. This mode of failure presents usually itself in walls subjected to high compressive loads and shears.

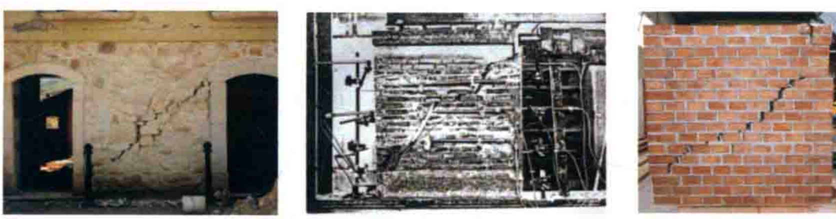

Figure 2. Detachment and sliding due to combined compression and shear.

3. The third failure mode is the so–called crushing of the material (Figure 3) and occurs essentially under compression. By looking closely to this failure mode one can see again that it consists of finer detachment fractures, close together and separated by damaged material, having sometimes the consistence of powder.

The first type of fractures is the most frequent and usually irrelevant. The second and third modes often occur when the load is critical or close to become a collapse load. The third one is the most dangerous since failure under compression is usually sudden.

2.2 Structural failure mechanisms

Besides crushing of compressed members, such as those shown in Figure 3, there are basically other two structural failure mechanisms through

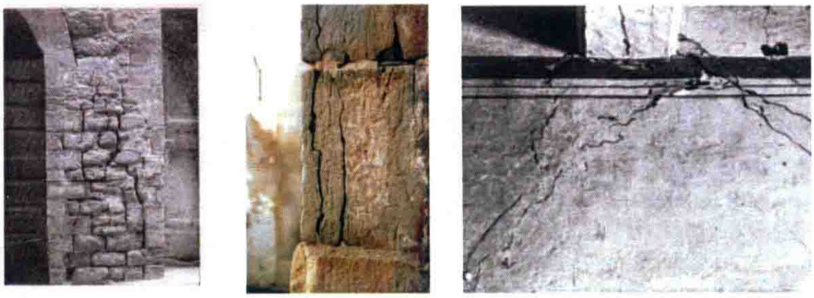

Figure 3. Crushing due to compression.

which a masonry structure (or a part of it) may collapse. The most frequent one, under seismic loads, is out of plane rocking as shown in Figure 4. Such a mechanism can be due to the effect of the self load solely, or can be favoured by the pushing of the roof, or the hammering of a heavy floor or ceiling.

Figure 4. Out of plane rocking.

Both crushing failure and out of plane rocking are usually the result of a poor design, or of unwise modifications of the original construction. To avoid out of plane rocking many regulations prescribe the maximum distance between two consecutive transverse walls. The demolition of such transverse walls is one of the most common examples of risky modifications.

The third failure mechanism, that is in-plane shear, is the one proper of well designed buildings, that is structures sustaining the horizontal actions through the harmonized cooperation of the shear resistant structures (Figure 5), i.e. with local failure modes of their masonry units in their own planes, of the type shown in Figure 2.