Proceedings
of the
International
Symposium

STUDIES on HISTORICAL HERITAGE

Antalya, Turkey
September 17-21, 2007

Organized by
YILDIZ TECHNICAL UNIVERSITY
RESEARCH CENTER for PRESERVATION for
HISTORICAL HERITAGE

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INTERNATIONAL SYMPOSIUM
STUDIES on HISTORICAL HERITAGE
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ON SITE AND LABORATORY DETECTION OF THE QUALITY OF MASONRY IN HISTORIC BUILDINGS

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ABSTRACT
Following a long experience on the study of historic masonry characteristics by on site and laboratory tests in seismic areas the authors to are proposing a methodology for the definition of the masonry quality This procedure can be useful for professionals designing appropriate repair and conservation intervention on historic buildings. The methodology is proposed together with some considerations on the use of the test results.

1. INTRODUCTION

The influence of the masonry characteristics on the physical and structural behaviour of load-bearing walls is fundamental. Masonry, especially in historic buildings is often a complex composite material not only due to the variation in origin and properties of its components (brick, stone, mortar), but also to the multiple technique of construction of the wall. In the case of old stone masonry the walls are frequently built with the multiple leaf system, the stones are irregularly cut and the irregularities of the courses are filled with thick mortar joints, while the leaves can be badly connected along the depth of the section. The behaviour of these walls is influencing the safety of the building not only under the vertical actions, but especially under the horizontal actions during seismic events. In the last case the effect of this behaviour can bring to the separation of the leaves and the overturning of the wall under out of plane actions (Figure 1).

Therefore both for repair and prevention purposes, a good knowledge of the masonry characteristics is needed.

Figure 1. Separation of masonry leaves and collapse under out of plane actions

The possibility of gaining this knowledge is given by tests which can be carried out on site and in laboratory; the tests on site should be non destructive or slightly destructive, while the laboratory tests are carried out on specimens sampled directly from the walls; sampling has to respect the existing wall as much as possible, therefore the quantity of the sampled material has to be minimal. This last recommendation obviously excludes sampling of masonry prisms to be tested in laboratory.

Nevertheless the quality of the masonry wall can be detected first of all by knowing its morphology (prospect and section), the physical, chemical and mechanical properties of its components and the properties of the masonry as a composite material. It is easy to describe how to tests the material in laboratory, but the on site testing has to be based on non destructive or minor destructive techniques (NDTs, MDTs). Among the proposed techniques the most effective are without any doubt the sonic and flat jack tests.

A methodology for on site and laboratory investigation is proposed by the authors following an extensive research carried out after the Umbria earthquake in 1997 and experienced in different sites. Some considerations on the evaluation of the results of the proposed testing procedure are also made in the last section.

2. A METHODOLOGY FOR THE DETECTION OF THE QUALITY OF MASONRY

When dealing with the design for conservation, it is important to know the geometrical, morphological, physical and mechanical characteristics of the masonry walls. It is well-known that these characteristics cannot be deduced by the ones of the components, nor using existing standards for new masonry, nor through laboratory tests on materials sampled from the walls. Sampling of masonry specimens is highly destructive and also impossible in the cases as in Fig.1. So only on site testing on masonry are possible and they have to be non destructive. Up to now the only test which can characterize the state of stress and the stress-strain behaviour of a masonry is the flat-jack test (single and double), [1],[2],[3] which is a carried out locally , helped by sonic pulse velocity tests to determine the density and homogeneity of the material [4]. Of coarse perhaps more reliable, but also much more destructive tests are available as shear strength diagonal tests and compression- shear tests carried out on site [5].

Following the proposal made by the 2003 Italian Seismic Code produced by the Civil Protection Department [6] to adopt three different levels of knowledge, the authors have tried to propose a methodology] after the long experience of on site testing they have developed in Umbria after the 1997 earthquake, Liguria and Lombardia after the 2004 earthquake [7].

The Code asks for information on: (i) the evolution of the building through archive documents, (ii) the building geometry and the details on connections between walls and walls and floors and roof, (iii) the crack pattern and damage survey. Furthermore a knowledge is required on the *quality* of the masonry. What the request means about "quality" can be easily clarified. The knowledge should be extended to: (i) the masonry morphology, (ii) the technique of construction (single, multi-leaf), (iii) the component properties, (iv) the mechanical properties of the masonry under horizontal and vertical actions.

The requested knowledge can be reached first of all by surveying the masonry not only superficially through the prospect, but by "looking inside" in order to detect how the masonry section is made. The section geometry is a parameter for the structural analysis and it is also important for the choice of the type of intervention when necessary.

For the choice of an appropriate analytical model the constitutive laws of the materials are needed; therefore the highest number of mechanical parameters is known the most reliable can be the chosen model.

Even if very few parameters can be driven from on site and laboratory tests, nevertheless the experience of the authors has shown that two type of tests can be useful on site: the sonic pulse velocity test and the single and double flat-jack test [8]. The first one is a qualitative procedure which can be useful, when carried out by *transparency,* to find though the distribution of the calculated velocities (Figure 2) the differences in density across the wall. When low velocities are detected (area A in Figure 2b) the masonry might have voids and defect inside, when velocity high peaks are found there might be a connection between the masonry leaves along the section (area B in Figure 2b). Of coarse the results do not give the morphology of the masonry section, which has to be found in other ways. The test can be useful to locate the position of the flat-jack test. The single flat-jack test allows to calculate the state of stress (Figure 2a) in a compressed masonry (by dead loads) and the double flat-jack test allows to find the stress-strain behaviour of the masonry (Figure 2a).

What is needed more in order to qualify the masonry is the section morphology and the properties of the components which can be found by small dismantling of the section and by sampling from the inside mortar, brick and stones. IF all the mentioned information can be referred to the same area of the masonry, then the quality of it can be completely studied.

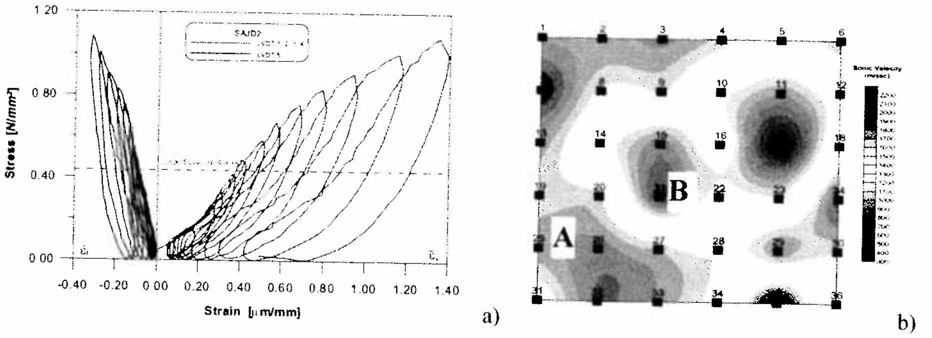

Figure 2. a) Result of flat jack-tests, b) Sonic velocity distribution

It is very important for the chosen area to be representative of the masonry under investigation; the problem on how to find a representative area arises in the case of ancient or old buildings especially in seismic areas which where several times modified or partially reconstructed in the past and in which different types of masonries can be found even in the same wall.

2.1. Description of the methodology

The proposed investigation is carried out according to the following steps: (i) choice of the strategic points on all the types of loadbearing masonries in the building (e.g. choice of a point for each masonry texture observed through the prospect, at the lowest most loaded part of the wall), (ii) survey of the masonry texture of the chosen area in prospect, (iii) sonic pulse velocity test by transparency on a grid of 1mx1m including the area chosen for the flat-jack test; the velocity peaks as said above will indicate a higher density of the material, perhaps the presence of a continue stone or a course of stones crossing the whole section, (iv) single flat-jack test to define the state of stress of the masontry in the chosen area, (v) double flat-jack test with the collection of data, appropriate drawing of the stress-strain curve and calculation of Young modulus and Poisson's ratio; on the diagram also the calculated value of the stress (by single flat-jack) should be reported in order to see the residual load-carrying capacity of the masonry in the elastic state (Figure 2). The sonic velocity distribution should also be represented (Figure 3a,b), (vi) small dismantling of one or two stones through the section up to ¾ of its thickness, possibly made in correspondance of the sonic velocity peak (Figure 4), (vii) graphic representation of the prospect and section of the wall, (viii) sampling opf a stone and of mortar from the internal part of the masonry in order to be sure that they are the original ones, (ix) chemical, petrographic analyses on mortars, physical and mechanical tests on mortars and stones in order to define their composition and origin in view of a future intervention, (x) repair of the small damge caused to the masonry by sampling.

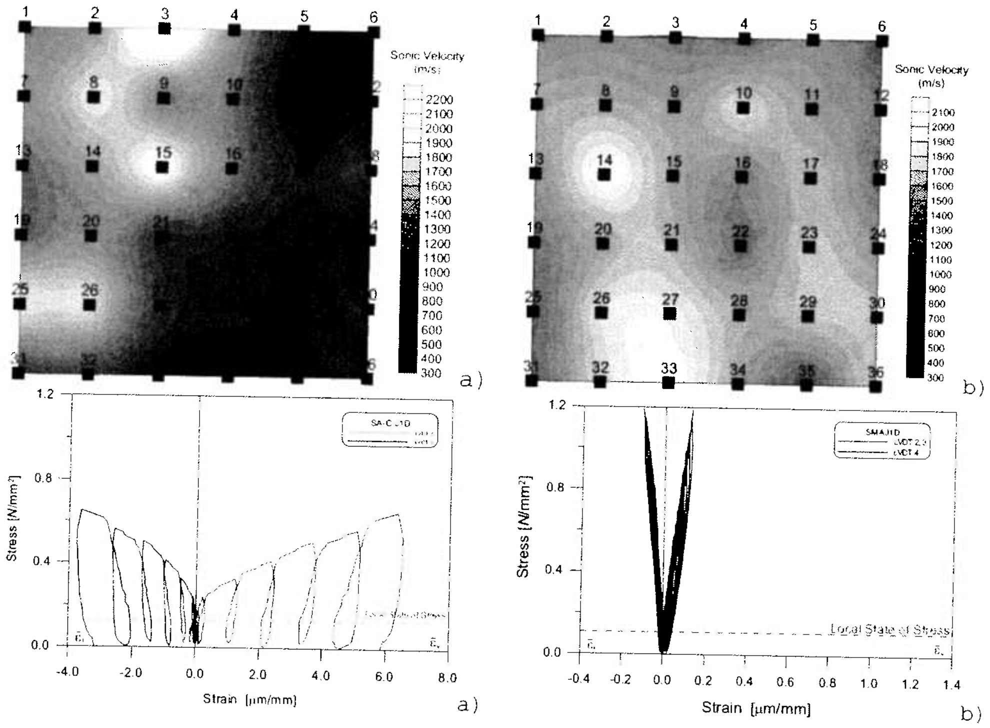

Figure 3 a,b, Results of sonic and flat-jack tests on the masonry of two churches in Lombardia [10].

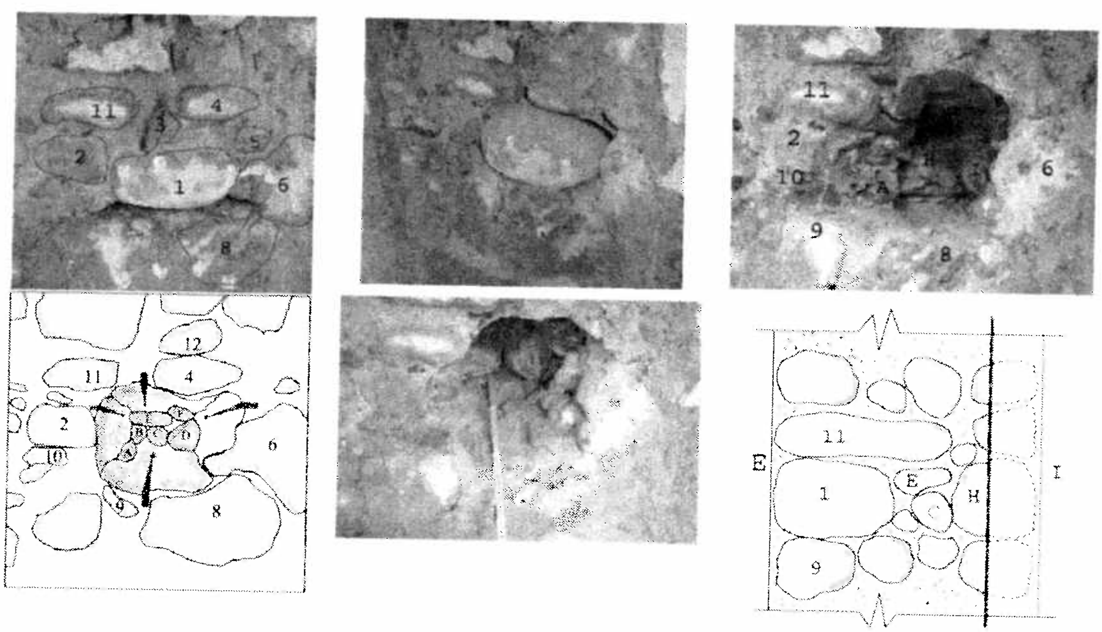

Figure 4. Study of the morphology of the masonry section. Drawing of the masonry texture in the section

It is possible to see from Figure 3 that the highest sonic velocities (Figure 3b) also correspond the the higest elastic modulus (Figure 3b); hence their is a way to define the best quality of the masonry that one which has high sonic velocity and high modulus of elasticity. The description of the masonry quality is completed by the section morphology (Figure 4) and of coarse also by the results of the laboratory investigation on mortars and stones.

3. SOME REMARKS ON THE APPLICATION OF THE METHODOLOGY

Even if ASTM proposes a methodology in the elastic modulus computation, conceptual uncertainties concern the detection of the linear behaviour of the masonry. In fact, due to the masonry peculiar behaviour , the elastic phase is often difficult to estimate. In many cases, locking in the initial phase occurs due to large deformation of the masonry in the first steps of the compression test. Furthermore, since it is impossible on site to reach the ultimate state of the masonry, changes in the curve slope can also be interpreted with great difficulty. On the experience base, the definition of the elastic modulus can be made with different types of computation, but in many cases it cannot be univocally defined. Thus it can create subjective interpretation according to the operator expertise bringing to possible different values.

According to ASTM proposal the value of E can be calculated as:

$$E_t = \frac{\delta\sigma_{mi}}{\delta\varepsilon_{mi}} \qquad \text{tangent modulus} \qquad (1)$$

where $\delta\sigma_{mi}$ and $\delta\varepsilon_{mi}$ are respectively the increment of σ and ε at each step of loading.

$$E_{si} = \frac{\sigma_{mi}}{\varepsilon_{mi}} \qquad \text{secant modulus} \qquad (2)$$

where σ_{mi} and ε_{mi} are respectively the value of stress and strain reached at step i.

While the values given by eq. (1) follow the variation of E along the envelope of the loading curve, it is more difficult to calculate E with eq. (2) particularly when a locking phase is present. Frequently the elastic modulus is calculated as secant modulus in the linear part of the σ-ε diagram. In this way the choice of the secant modulus depends much more on the operator decision. Another possibility can be to calculate the secant modulus during the unloading phase, which represent the elastic response of the masonry during unloading. In Figure 5a,b the two ways of calculation of the modulus are represented. Further elaborations are ongoing in order to better understand the differences. The possibility of a quantitative estimation of the physical- mechanic property of masonries, by the use of sonic tests, were proposed within a research carried out in 1993 in laboratory tests and on site on brick masonry of the Veneto Region [9]. Sonic tests in transparency have been carried out on several buildings in order to obtain an average sonic velocity associated to every studied typology. By single and double flat jacks the state of stress and the elastic modulus of each wall were also evaluated. Figure 6a,b shows similar correlation between elastic modulus and the sonic pulse velocity for (a) stonework (regular and irregular) and b) brickwork. It can be clearly remarked that the stonework gives much higher scattering in the results.

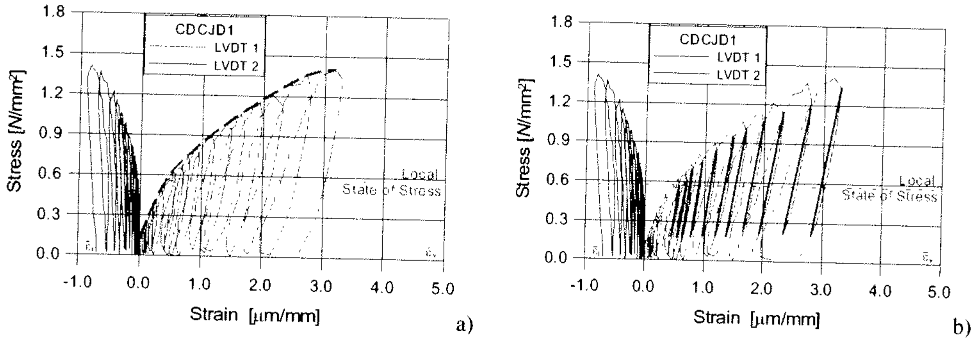

Figure 5. Calculation method of: a) the tangent E modulus according to eq. (1) and b) of the unloading secant E modulus.

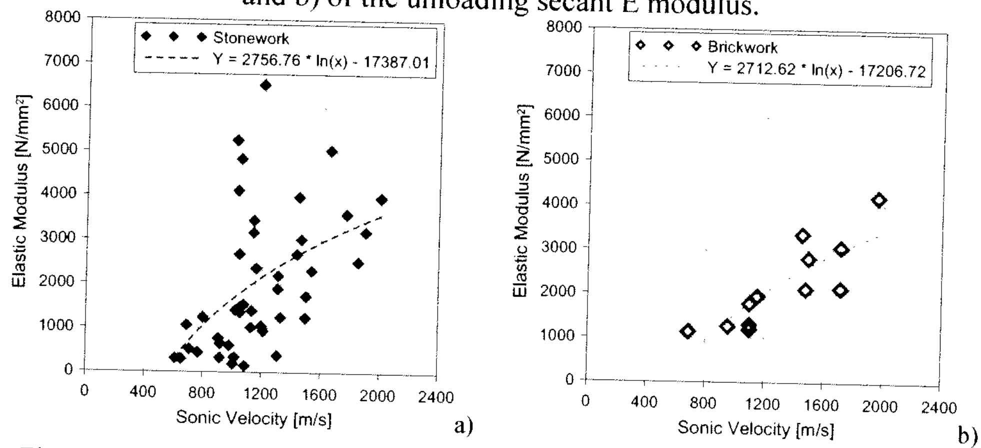

Figure 6. Comparison between elastic modulus obtained from the double flat jack tests and values of pulse sonic velocity measured in transparency in the same area, in case of a) stonework and b) brickwork

4. CONCLUSIONS

The proposed methodology is based on a long term experience of on site and laboratory investigation. The experience with single and double flat jack on masonries, allow to draw the following conclusions: the test with jacks is a valid method for the evaluation of the local conditions of the masonry, since it supplies the value of the state of stress and the stress-strain behaviour. Data can be used with success in the diagnosis of masonry structures and also in the calibration of mathematical models, taking into account that they give only local values. The test can be applied with success to regular brick masonries and stone with thin or thick joints of mortar and on irregular masonries, after a careful analysis of the data. From the elaboration of all the collected data some correlations have been found between the modulus of elasticity and the sonic pulse velocity and the modulus of elasticity can be used to characterize masonry classes.Sonic tests are useful to qualify the masonry density, find the presence of voids and even transversal connections in the section. The other steps of the proposed methodology, survey of prospects and sections, sampling and laboratory tests complete the desired qualification.

5. ACKNOWLEDGEMENT

The authors wish to thank M. Antico, M. Cucchi and M. Iscandri for their precious contribution to the experimental part of the research. The research was supported by MIUR (COFIN) and Project RELUIS 2005-2008, Linea 1 "Valutazione e riduzione della vulnerabilità di edifici in muratura".

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