QUALIFICATION TESTS FOR MICRO- AND MACRO-MODELLING OF TUFF MASONRY STRUCTURES

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SUMMARY

Sophisticated analysis methods for masonry structures can not disregard an adequate experimental campaign which provides the necessary parameters for the calibration of analytical/numerical models. With reference to some experimental campaigns held by few researchers in the last ten years, to the enforced codes when possible and to a vast experimental campaign holding by the authors, the design and set-up of qualification tests for macro and micro modelling of tuff natural stones, are discussed.

INTRODUCTION

For masonry structures, analyzed through the macro-modelling approach, the qualification tests available in literature and in international codes so far, are quite scarce when the hypothesis of isotropy is removed or the inelastic behaviour is considered. Hitherto, the available tests allow determining only the material strength without investigating the post-peak or the straining behaviour. Furthermore, the strength along principal directions, like horizontal mortar joints, is not taken into account if the material is assumed to be isotropic. In micro-modelling, where the hypothesis of continuous and homogeneous material is removed, even less information are available. Although these models provide satisfactory results, they can not refer to the existing literature for material parameters and the related qualification tests, with the only exception of Dutch solid clay bricks. For yellow tuff stones, widespread in southern Italy, the information available are not sufficient for the use of sophisticated models, elaborated in the plasticity theory and in the hypothesis of orthotropic material. The suitability of the illustrated tests with these natural stones, on which some qualification tests are being carried out by the authors, is verified. The experiments are divided into two fundamental typologies: tests on the elements constituting masonry and tests on masonry panels.

QUALIFICATION TESTS ON CONSTITUTING ELEMENTS

The qualification tests on stone, mortar and mortar-stone interface elements are fundamental since they strongly influence the behaviour of masonry. Regarding units and mortar, compressive and tensile uni-axial tests are presented. The behaviour at the mortar-unit interface, which usually represents the weak link in the assemblage of masonry, is investigated through tensile and shear tests.

Uni-axial Compression Tests

At University Federico II of Naples some qualification tests on yellow tuff stones have been performed. The units, extracted from a pit in the surrounding of Naples had initial dimensions of 300×150×100 mm^3. The specific weight of the stones is 12.50 kN/m^3 with a standard deviation s = 0.68 and a coefficient of variation cov = 5.42%. Applying the UNI Standards for natural stones (EN 772-1, EN 1926) two series of six cubic specimens 7 cm long have been obtained. Uni-axial compressive tests have been performed (Fig. 1.a) obtaining a mean compressive strength f_{bm} = 4.13 MPa, s = 0.77, cov = 18.54%, consistently with yellow tuff stones of the Neapolitan area. In order to catch the post peak behaviour, the load has been applied via displacement control. Two LVDTs (linear variable differential transformer) were placed between the load plates.
This test allows to obtain the following information:
1. The complete stress-strain curve;
2. The peak strength;
3. The compressive fracture energy (I mode), equal to the area under the diagram of point 1.

Although from this test it is possible to derive the normal elastic modulus E and the Poisson's modulus ν also, it was preferred to use the guidelines given by the UNI Standards EN 14580 (Fig. 1.b). The following values have been deduced for six specimens: E_b = 1540 MPa, s = 99, cov = 6.43%. This value is rather low for these kind of stones.

Finally, for the pozzolana-based mortar, the procedure given by the UNI Standard EN 1015-2 and EN 1015-11 (Fig. 1.c) has been followed; a mean compressive strength f_{mm} = 7.14 MPa, s = 0.52, cov = 7.34% has been obtained. These values are quite high for this kind of mortar which mean strength is about 2.5 MPa but the tested mortar was premixed and the authors followed the prescriptions of the supplier.

a) Compressive strength of the units

b) Elastic modulus of the units


c) Compressive strength of the mortar

Figure 1. Uni-axial compression tests

Uni-axial Tensile Tests

The European standards, UNI EN 1052-3 and UNI EN 13161 or UNI EN 12372, determine the bending strength respectively for the mortar-unit interface and for natural stones. Not withstanding, these tests are not adequate for the calibration of advanced analysis for

masonry, since it is not possible to deduce information on the strain behaviour, in the elastic and inelastic ranges. Therefore, direct tensile tests are necessary, being the only ones able to give the full stress-strain relationship and values of the strength meaningful of the real behaviour of the material. Making a direct tensile test on a brittle material, in displacement control, the trend is substantially linear until the peak stress and then exponentially softening. Generally, the post-peak behaviour may shows different behaviour in function of the restraint conditions. After the overtaking of the peak strength, the propagation of micro-cracks causes one macro-crack which generates a relative rotation of the two parts, with the following loss of the parallelism at the boundary faces.
Although many test methodologies have been adopted in the past for the execution of the direct tensile test (Sheffield Test, Crossed Brick Test etc.), it seems that the best methodology is by applying the load through steel plates glued to the extremities of the specimen with epoxy resin. This solution has been chosen by many authors, among which Almeida et Al. (2002). In the following, direct test for units and unit-mortar interface and indirect test for mortar are illustrated.

Direct Tensile Test on Units

The dimensions of the specimen to be tested strongly depends on the dimensions and the load capacity of the test machine, as well as the typology of the element. Generally one side has to be at least 40-50 mm and the ratio between height and base has to be around 2. In this case, prismatic trials of $50\times50\times100$ mm^3 have been used (Fig. 2.a). Once the prism is made, before it is glued (via epoxy resin) to the plates of the machine, some cuts in the middle of the element have to be made to trigger the crack in that section. In order to have a stable test, it is advisable to execute one cut bigger than the other one: in this way the crack advances always in the same verse (Fig. 2.b). At the moment these tests are ongoing. Two LVDTs have been placed for the not uniform axial strains in the crisis section.
From the tensile test the following parameters can be derived:

1. The complete stress-strain curve;
2. The uni-axial tensile strength;
3. The tensile fracture energy (mode I), equal to the area under the diagram of point 1.

Direct Tensile Test at Mortar-Unit Interface

a) Cut of the units	b) Incision of the units	c) Samples for interface test

Figure 2. Tensile test on units and interface

For this test, the samples have been obtained joining two prisms of 50×50×100 mm^3 with a mortar joint 10 mm thick (Fig. 2.a and 2.c). At present, it is waiting for the mortar curing.
Also in this test the dimensions of the specimens are function of the capacity of the machine test. According to Lourenço and Almeida et Al. (2002), the best procedure for detecting displacements is the average of four LVDTs placed at the corners of the couplet. The deductible parameters from this test are the same of the direct tensile test on units.

Indirect Tensile Test for Mortar

For determining the flexural strength of the cured mortar, the indications of the UNI Standards EN 1015-2 and EN1015-11 have been followed (Fig. 3).

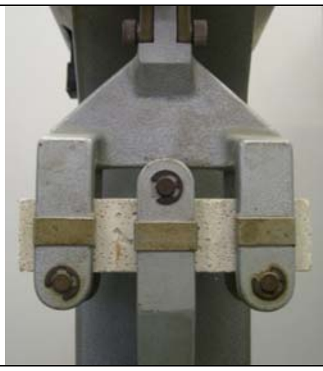
		
Sample preparation	Restraint condition	Indirect tensile test

Figure 3. Indirect tensile test for mortar

For the pozzolana based mortar, the following values of the mean tensile strength, standard deviation and coefficient of variation have been obtained: f_{mmt} = 1.43 MPa, s = 0.09; cov = 6.23%.

SHEAR TEST AT THE MORTAR-UNIT INTERFACE

The determination of the shear behaviour at the mortar-unit interface is strongly influenced by the capacity of the set-up to guarantee an uniform stress of the joint. In Fig. 4, the procedure the authors are following is shown.

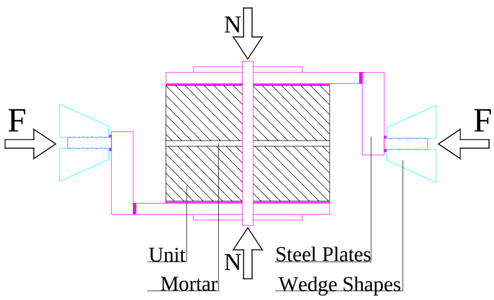
		
Samples	Test preparation	Load condition

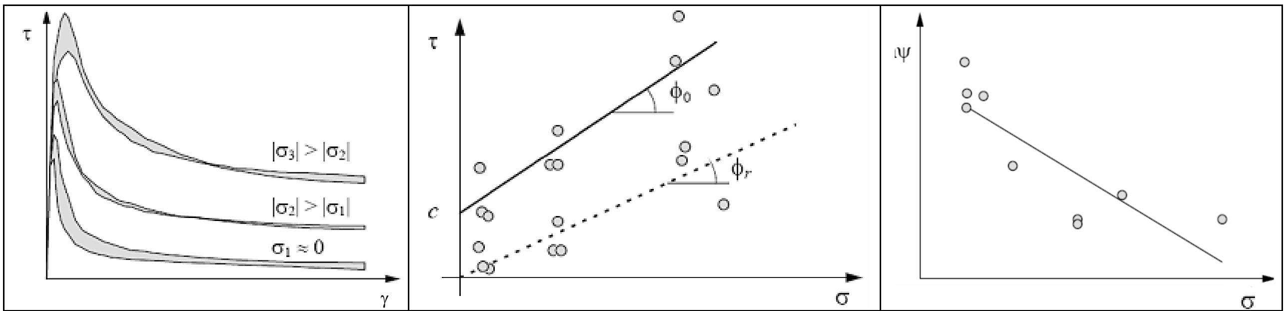
Figure 4. Shear test at the interface

Different configurations have been proposed by many researchers to minimize the non-uniformity distribution of the sample. Generally, there are two test typologies: the couplet test (two units and one mortar joint) and the triplet test (three units and two mortar joints) according to UNI EN1052-3. In any case, the test set-up has to allow a uniform normal stress to the samples, since the behaviour of the sliding interface surface is strictly dependent from the acting normal stress. Although the bigger complexity of the couplet test, its results are more reliable than the triplet test, since the bending moment acting on the section is zero. Exhaustive experimental campaigns on solid clay bricks have been conducted by Van Der Pluijm (1999) and Oliveira (2003).

For the displacement investigations, two vertical and one horizontal LVTDs have to be placed at least for the measurement of the relative displacement and the shear force. Naturally, to characterize the behaviour at the mortar-unit interface, it is necessary to test the samples with different values of the axial load.

The following parameters can be derived:

1. The complete shear stress – strain curve for each value of the axial load. The diagram (Fig. 5.a) is linear until the peak strength and then exponentially softening. The shear peak stress corresponding to a zero normal stress is the cohesion (c) (Fig. 5.b).
2. The peak shear stress – normal confinement stress curve. Once the interpolation straight line is obtained (Coulomb friction law), it is possible to detect the inclination which is the initial internal friction angle ϕ_o (Fig. 5.b).
3. The residual shear stress – normal confinement stress curve. The linear interpolation gives a straight line which angle is the residual internal friction angle ϕ_r (Fig. 5.b).
4. The dilatation angle ψ, which is the uplift of a stone relative to another one due to the shear action. It is the arctangent of the vertical displacement-sliding ratio and inversely proportional both to the normal confinement stress (Fig. 5.c) and to sliding. This effect can be neglected since ψ is about zero for low values of the confinement normal stress.
5. The shear fracture energy (mode II) G_f^{II}, corresponding to the diagram area at point 1. Since the area increases when the normal stress is increased, the fracture energy is function of the normal stress. It is possible to connect the fracture energy and the confinement normal stress through a linear regression of the experimental data.



a) Shear stress-strain curve	b) Coulomb friction law	c) Dilatancy - axial load law

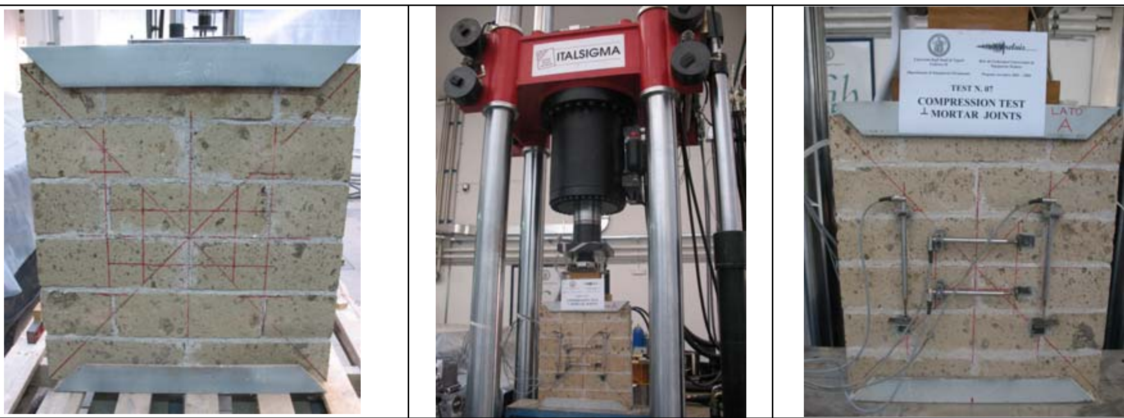
Figure 5. Relationships derivable from the shear test (Lourenço, 1998)

QUALIFICATION TESTS ON MASONRY SPECIMENS

The experimental tests on masonry elements can be divided in uni-axial tests, conducted in compression and tension on both the principal directions, and biaxial tests.

Uni-axial Compression Test in the Direction Orthogonal to the Mortar Joints

For long time the compression strength of masonry along the orthogonal direction of the mortar joints has been considered as the only relevant feature of the material. The definition of advanced models for masonry structures requires knowledge of compression behaviour along both the principal axes, not only in terms of strength. An outstanding aspect when these tests are conducted, is that the specimen behaviour is strongly influenced by the size effect and restraint conditions due to the strain localization. Larger is the element, larger the area subjected to the crack opening which dissipate energy. Therefore, if the volume subjected to the opening of cracks is larger, then the value calculated for the fracture energy is larger. The uni-axial compression test is ruled by the UNI Standard EN 1052-1, which indications have been followed for the tests at the moment in progress (Fig. 6.a and 6.b).
For the displacement measurements, the UNI Standard cited considers the layout of the transducers only in the vertical direction; it is opinion of the authors that the displacements have to be recorded also in the horizontal direction. It has to be recalled that the test has to be conducted in displacement control.
It is well known that in uni-axial compression the mortar expands laterally more than the unit due to the larger value of the transversal dilation coefficient. The continuity between mortar and units, ensured by cohesion and friction, produces a confinement phenomenon in the mortar included between two units. A tri-axial compression state in the mortar and a vertical compression-bilateral tension state in the units form. Due to this phenomenon, the crisis in the units occurs for cracks parallel to the load direction until the splitting phenomenon, characterized by the separation of the element in two vertical parts (Fig. 6.c).



a) Specimen to be tested	b) Test machine	c) Instrumented sample

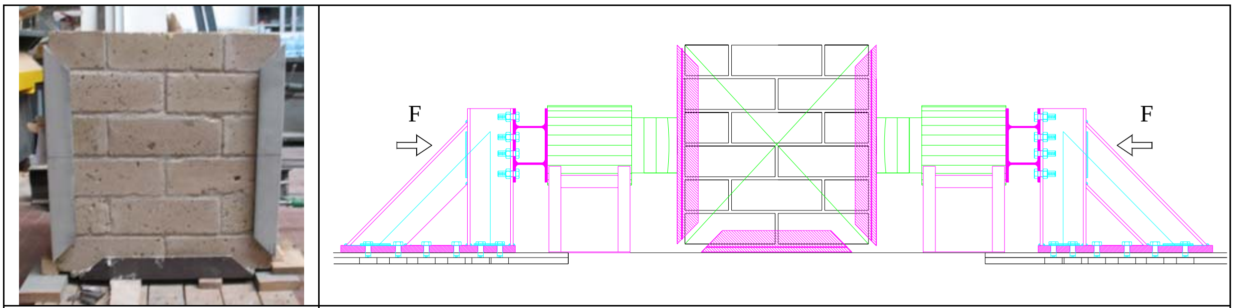
Figure 6. Uni-axial compression test orthogonally to the mortar joints

From this test the following information can be deduced:
1. The complete stress-strain curve;
2. The peak strain;
3. The elastic modulus;
4. The Poisson’s modulus;
5. The compression fracture energy (mode II), from the area at point 1.

Uni-axial Compression Test in the Direction Parallel to the Mortar Joints

The masonry characterization in compression along the direction of the mortar joints has not been under attention by researchers until now. However, since masonry is an orthotropic

material, the compression strength also along this direction can be a fundamental parameter in the determination of the bearing capacity of a masonry structure. In Fig. 7 the test set-up for the ongoing test is illustrated.



Sample to be tested	Experimental set-up

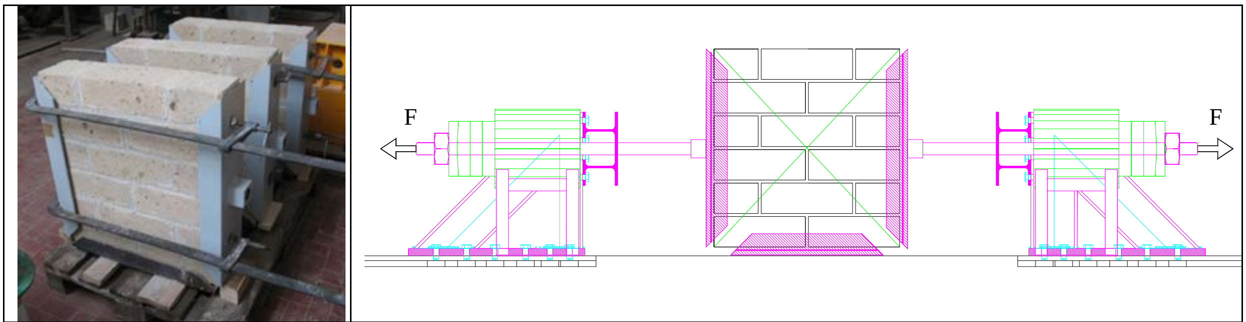
Figure 7. Uni-axial compression test in the parallel direction to the mortar joint

Uni-axial Tension Test in Direction Orthogonal to the Mortar Joints

It is possible to avoid this kind of tests on big elements and assume the minor mechanical characteristics derived by tests on units and units-mortar interface.

Uni-axial Tension Test in Direction Parallel to the Mortar Joints

The tensile behaviour of masonry along the direction parallel to the mortar joints is a fundamental aspect for a correct modelling of masonry. In fact, when an adequate evaluation of the elastic and inelastic parameters lack, the numerical analysis could not be reliable. The authors have scheduled the execution of this test as indicated in Fig. 8.



Specimens to be tested	Experimental set-up of test n. 9

Figure 8. Uni-axial tension test in direction parallel to the mortar joints

Depending on the relative strength in the joints between mortar and units, two different crisis mechanisms may occur:

- Collapse with formation of a zig-zag crack which develops along the horizontal and vertical joints with unbroken elements. The typical stress-strain relationship has a plateau with hardening. The post peak behaviour is driven by the mode I fracture energy (in tension) of the vertical joints, and mode II (in shear) of the horizontal joints.

- Collapse with formation of a vertical crack from one side to the other one through the units. The typical diagram is characterized by progressive softening till the complete loss of strength. The post peak behaviour is ruled by the mode I fracture energy of vertical joints and units.

From this test, conducted in displacement control, it can be derived:

1. The complete stress-strain curve;
2. The tensile strength;
3. Tensile fracture energy (mode I) from the area at point 1.

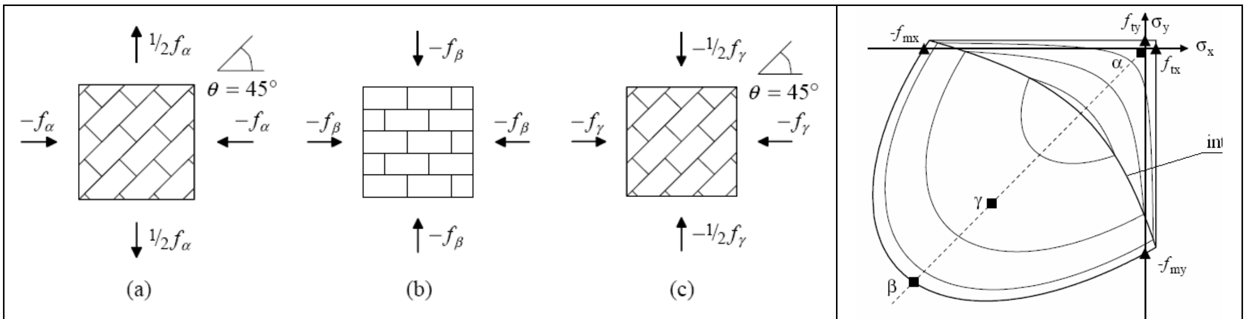
Biaxial Tests

The definition of a complete constitutive model for masonry can not be founded exclusively on the knowledge of the uni-axial behaviour. The coupling of stresses acting along different directions has to be investigated also. Biaxial tests were firstly conducted by Page (1981, 1983) who noted that two orthogonal compressive stresses applied contemporarily give a greater strength compared to a uni-axial force. On the contrary, if tension is orthogonally coupled to compression, the strength material decreases. Therefore, it is evident that plane strength domains need to be determined.

In the following, the limit surface of the Rankine (in tension) and Hill (in compression) continuum orthotropic model which is reported. It need to be defined:

1. Uni-axial compressive and tensile strength, along each principal axis of the material;
2. α coefficient which considers the influence of the tangential stress in the tensile crisis;
3. β coefficient which takes into account the normal stress along the two axes σ_x and σ_y;
4. γ coefficient for the influence of the shear stress in the compressive crisis.

For their calibration, Lourenço (1996) advises to carry out the biaxial tests reported in Fig. 9.



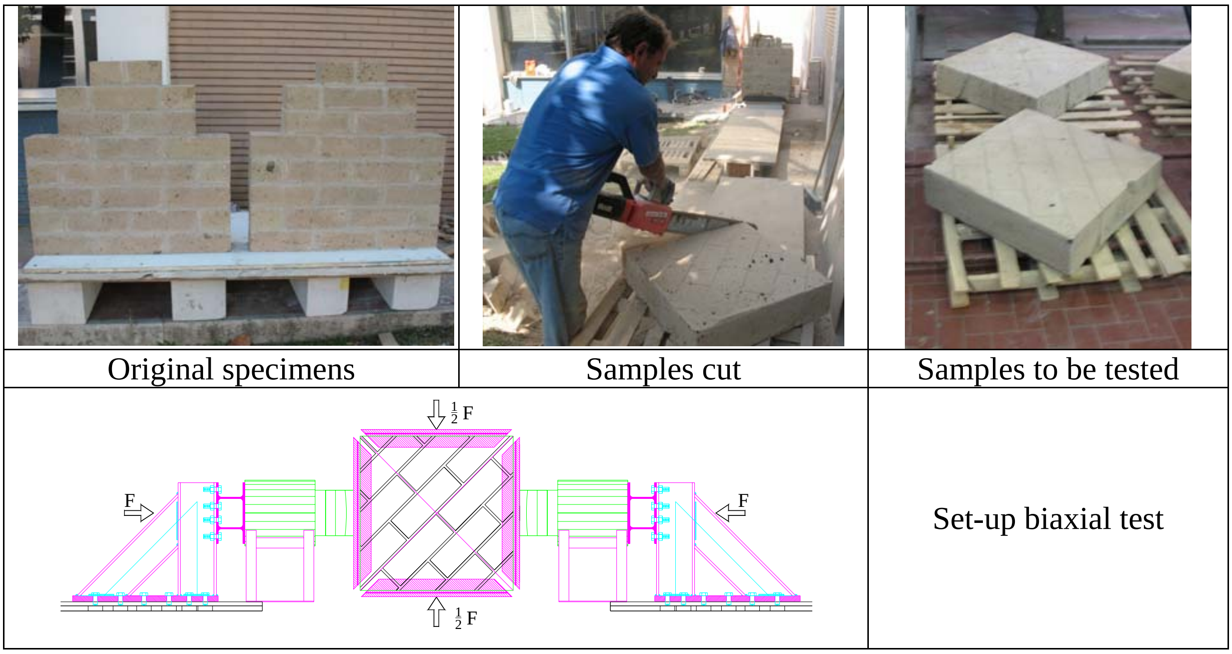
Biaxial tests proposed by Lourenço (1996)	Rankine-Hill model

Figure 9. Schemes of biaxial tests for the calibration of the orthotropic continuum model.

The advantage of these tests is that the crisis stress values are far from the regions of intersection of compressive-tensile domains namely *corner regimes*.

The variation of parameters at point 1 implies only an expansion or a contraction of the limit surface according to an homothetic transformation. On the other hand, the parameters at point 2, 3 and 4 are able to change the shape of the limit surface being related to the behaviour of the material for combined actions along different directions. Acting on both typologies of parameters, it is possible to obtain a limit surface along the experimental strength of the material.

Experimental biaxial tests on masonry have been conducted by Vermeltfoort (2005) on solid clay bricks. The authors are instead working on tuff stones (Fig. 10).



Original specimens	Samples cut	Samples to be tested
		Set-up biaxial test

Figure 10. Biaxial tests

CONCLUSIONS

Through the experimental program illustrated in this paper it is possible to execute the calibration of advanced models for masonry structures in the field of micro and macro modelling.
Micro-modelling, if from one side represents a method very burdensome in terms of structural schematization and computational efforts, from the other side is founded on experimental tests relatively simple and cheap for its calibration. This kind of modelling needs the mechanical characteristics of units and the mortar-unit interface. Uni-axial compression and tension tests are necessary to define the stone properties. For the characterization of mortar-unit interface the direct tensile test and shear test at mortar-unit interface are mandatory. Finally, the compressive behaviour of masonry is defined by the uni-axial compression test in the orthogonal direction of the mortar joints.
The opposite occurs for macro-modelling which, while demanding a reduced computation effort, requires much more complex experimental calibration. Elastic properties can be defined through the uni-axial compression test in the orthogonal and in the parallel direction of the mortar joints. Inelastic properties may be specified through direct tensile test at mortar-unit interface, uni-axial tension test in direction parallel to the mortar joints, uni-axial compression test in the parallel and orthogonal direction of the mortar joints and biaxial tests.

ACKNOWLEDGMENTS

This research has been supported by ReLUIS “Rete di Laboratori Universitari Ingegneria Sismica” in the context of the activities of “Linea 1 – Valutazione e Riduzione della Vulnerabilita’ di Edifici in Muratura”. The authors would like to thank MAPEI for the mortar supply, Eng. Giuseppe Campanella and Mr. Giovanni Belfiore and for their help during the experimental campaign.

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