EXPERIMENTAL CHARACTERIZATION OF MORTAR BY TESTING ON SMALL SPECIMENS

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The experimental characterization of mortar mechanical properties in existing masonry constructions is considerably complex. Whereas bricks parameters can be assessed with a sufficient precision, the mortar properties are very difficult to obtain and the results are highly dispersed. For instance, the in-situ techniques based on the measurement of the amount of energy required to drill a small cavity provide very scattered values that should be handled cautiously. Also, the characterization of existing mortar joints by means of surface testing may be difficult, since the surface decay or even the presence of new restoration mortar may spoil the results. On the other hand, tests on small mortar cubes or double punch tests usually lead to inaccurate estimates of mechanical characteristics, since the confining effect exercised by bricks on the mortar layer is completely disregarded. Another difficulty is the extraction of undisturbed specimens from the joints of existing brickwork.
Such problems can be overcome by laboratory destructive testing on small specimens including both bricks and mortar. This activity is suitable for existing historic buildings, since it does not inflict severe damage on the structural element.
This work presents the results of a comprehensive experimental program on cores including a central mortar layer along a symmetry plane. Such specimens were easily extracted by different panels of an existing historical building using a common core drill. The cores were subjected to splitting test with a particular set-up, providing 30°, 45° or 60° inclinations of the mortar layer with respect to the loading plane. This test induces a mixed compression–shear stress state in the central mortar layer. The experimental results have been interpreted using different failure criteria in order to assess the mechanical properties of mortar.

Keywords: *Mortar Characterization, Laboratory Testing, Splitting Test.*

INTRODUCTION

The retrofit of existing buildings requires analysis approaches which are completely different from those adopted in the structural design of new buildings. This is particularly true for old monumental constructions, for which both geometrical and mechanical data are to be obtained on site with a time consuming activity based on different sources of information.
In order to carry out a reliable assessment of an historical building, the analyst has to know the old construction techniques, be aware of possible conception errors of ancient engineers, recognize the possible modifications undergone by the structure during its life and have skill

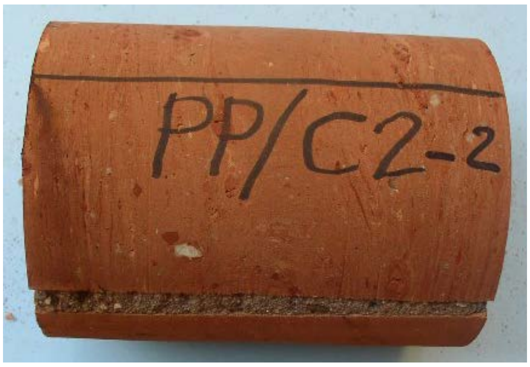
in numerical modelling techniques, such as limit analysis or finite element method (Heyman, 1962; Roca et al., 2010).

There are several critical factors which can affect the consistency of the experimental results. The mechanical properties of the masonry material do not depend only on brick and mortar properties but also to texture, degradation, presence of voids and defects. Furthermore, even if the brick properties can be mapped in the construction with a sufficient precision, the local mortar properties are very difficult to evaluate and the results are highly scattered (Gucci & Barsotti, 1995; Benedetti et al., 2008).

A suitable way to overcome the problem is based on the use of laboratory destructive testing on small specimens (Henzel & Karl, 1987). This activity can be pursued without inflicting severe damage to the construction. The simplest specimen that can be extracted is the cylindrical core. Three different cores can be extracted: the solid brick core, the core with a transversal mortar layer and the core with an axis wise longitudinal mortar layer (Figure 1).

This paper reviews some testing techniques, making reference to real on site investigations. The interpretation of destructive tests on cylindrical cores is presented and the relevant correlation formulas are discussed. The results of the tests are compared in order to provide some guidelines for the experimental characterization of historical mortars.

a)



c)

b)

Figure 1: View of the solid brick cores (a), cores with transversal mortar layer (b) and cores with longitudinal diametric mortar layer (c)

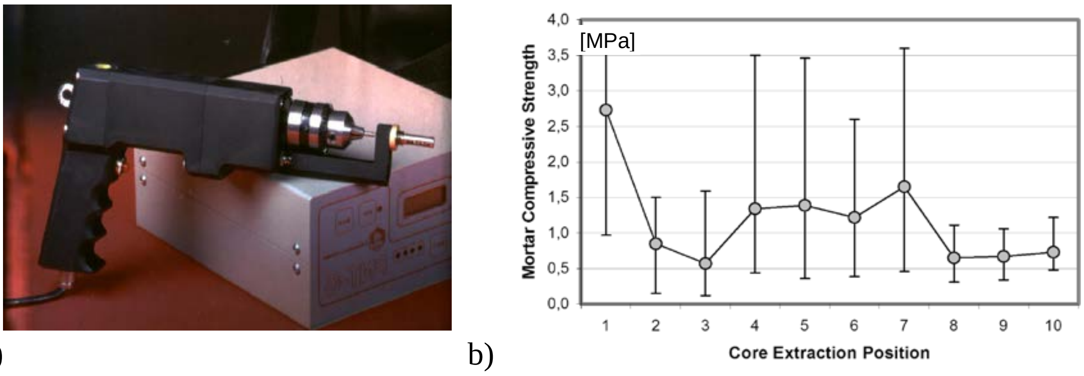
NON DESTRUCTIVE TESTING OF MASONRY

Although a comprehensive classification of NDT techniques is not possible due to large number of existing instruments (McCann & Forde, 2001), it is possible to distinguish the following methodologies:

a) tests correlated with the work dissipated in the penetration of an equipment;
b) tests correlated with the propagation of a pressure wave, or a shock;
c) tests correlated with a steady or transient vibration of the structure;
d) tests correlated with non-mechanical properties, such as thermal or electrical ones.

In general, the tests correlated with non-mechanical properties can point out the presence of voids, cavities, moisture, etc., but their capability for mechanical characterization is

questionable. On the other hand, vibration tests on the structure, or part of it, are able to detect elastic properties of the masonry material, but only on the average and for dynamic actions. Furthermore, propagation tests are valid in principle only for homogeneous elements and thus they may detect only the brick elastic properties. However, there are indications in the scientific literature for the application to masonry investigation.
Among the existing penetration equipments, the less destructive are the BRE helical rod and the PNT-G drill (Gucci & Barsotti, 1995). Both of them correlate the compressive strength of the material with the energy dissipated in creating or widening a hole (Figure 2a). The penetrometers are small and can operate on the mortar layers. Fast and multiple repetitions of the test are possible. However, the results can be considerably scattered, reaching error values up to 100% (Figure 2b). It is worth mentioning that great care has to be taken in testing the properties on the external surface of a volume. The surface tests are misleading when the mortar courses had been refilled in the past due to degradation.



a) b)

Figure 2: PNT-G penetrometer (a) and example of mortar strength measures (b)

Other important issues in masonry testing are the assessment of the anisotropic behaviour and the dependency of stress on the material properties. The ratio between the normal surface and the lateral one is high in the mortar layers. As a consequence, the confinement exerted by the neighbouring bricks on a mortar layer, can increase the elastic modulus and the compression strength predictions obtained from standard tests on cubes of side 40 mm (Hilsdorf, 1972; Vermeltfoort, 2005).

TESTING ON SMALL SPECIMENS OF MASONRY

Tests on cylindrical cores are basically of two types: length-wise compression tests and splitting tests along a longitudinal symmetry plane. The tests provide the compressive and tensile strength of the brick if the solid brick cores are analysed. The tests give information about the mortar properties if the cores with an inserted transversal or longitudinal mortar layer are used. An estimation of the masonry strength can be obtained by compressing on the bases a cylinder with a transversal mortar disk. More information can be derived from a splitting test of a cylinder with a diametric mortar layer rotated 45° from the loading plane (Benedetti et al., 2008). In this case, the mortar is subject to shear-compression and it is possible to reproduce a brick-joint interface behaviour comparable to that observed in a wall diagonal test.
The limit equilibrium of the specimen at collapse can be interpreted by using a pressure sensitive constitutive law. As usual in masonry mechanics, the Mohr–Coulomb criterion can

be considered and thus the mortar and masonry parameters can be determined by using a chain of formulas (Aprile et al., 2001).

Mechanics of masonry in compression

The resistance of a masonry column with a regular bricks texture is solved by introducing the hypothesis of Hilsdorf (1972) on the transversal equilibrium. The compatibility condition of the horizontal strain is imposed and then the limit condition of the adopted constitutive law.
As usual, the indices have the following meaning: *m* – mortar, *b* – brick, *k* – masonry, *c* – compression, *t* – tension. The parameters are the elastic modulus *E*, the Poisson ratio ν, the thickness *h*, the stress σ and the strength *f*. The ratios $\rho_E=E_m/E_b$ and $\rho_h=h_m/h_b$ are defined. With reference to Aprile et al. (2001), where the analysis is discussed in detail, the horizontal compressive stress in mortar is obtained as a fraction of the vertical stress:

- $$\Phi = \frac{\sigma_{hm}}{\sigma_v} = \frac{\nu_m - \rho_E \nu_b}{1-\nu_m + (1-\nu_b)\rho_E \rho_h} \approx \frac{\nu_m}{1-\nu_m} \qquad (1)$$

Therefore, under axial load the bricks are in compression–tension stress state, while mortar is in compression–compression stress state. In case of medium strength mortars, the reduction of the brick strength induced by horizontal tension overcomes the increase in mortar strength due to confinement, so that failure is promoted by brick cracking. On the other hand, in case of stone masonry or ancient mortar, the mortar is unable to resist stresses up to the block failure, so that the tri-axial crushing of mortar is going to produce masonry collapse.
The masonry strength in case of brick cracking is defined by the Mohr-Coulomb limit condition in the tension–compression regime:

- $$f_{kc} = \frac{f_{bc} \cdot f_{bt}}{f_{bt} + \Phi \rho_h f_{bc}} \qquad (2)$$

As we can see, when the mortar thickness tends to zero, the masonry strength tends to that of the brick. A direct way to explore the effect of the mortar thickness on the compressive strength is given by the double punch test (Figure 3). This test, firstly introduced by Henzel & Karl (1987) and discussed by Drdacky et al. (2008), can highlight the dependency of the apparent strength as a function of the thickness of the layer.
Figure 3b shows the results of the double punch tests carried out on the masonry walls of the Reggio Emilia Police Hall and the St. Dominic School in Cesena, Italy. The experimental data are plotted as a function of the mortar thickness. As shown, the apparent strength is inversely proportional to the layer thickness. This effect is very important in the masonry strength prediction.
It is worth noticing that the samples of mortar layers are rarely smooth enough to ensure a correct punching test. When the extraction of regular samples is not possible, the mortar layer can be included in a regularization block (Valek & Veiga, 2005), leading to a better execution of the compression test with confinement (Figure 4a). The confinement effect has been analysed by the authors by considering compression tests on layers with different ratios between thickness and side. Exponentially decreasing strength is obtained for increasing ratios, as shown in Figure 4b. It is worth noticing that hard steel plates push directly on mortar without any brick element, thus the results of these tests should be carefully interpreted.

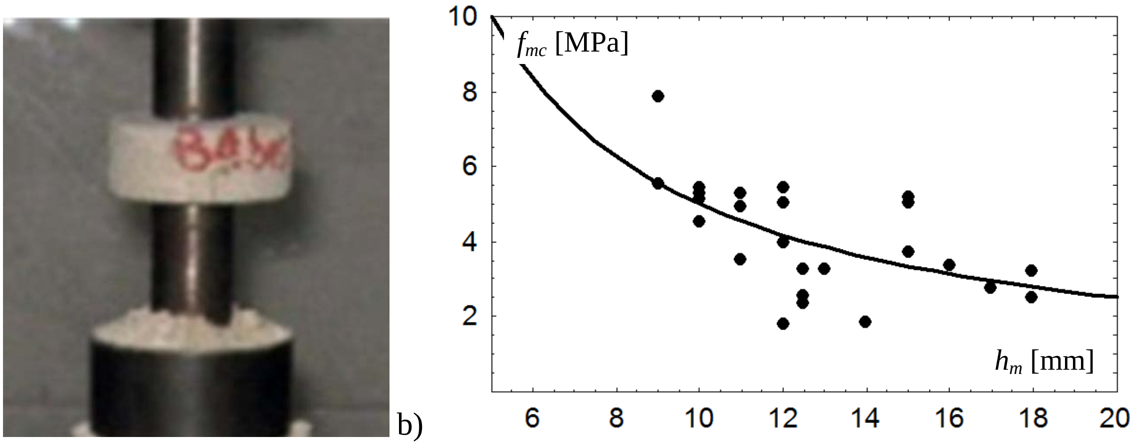


Figure 3: Double punch test setup (a) and strengths as a function of the thickness (b).

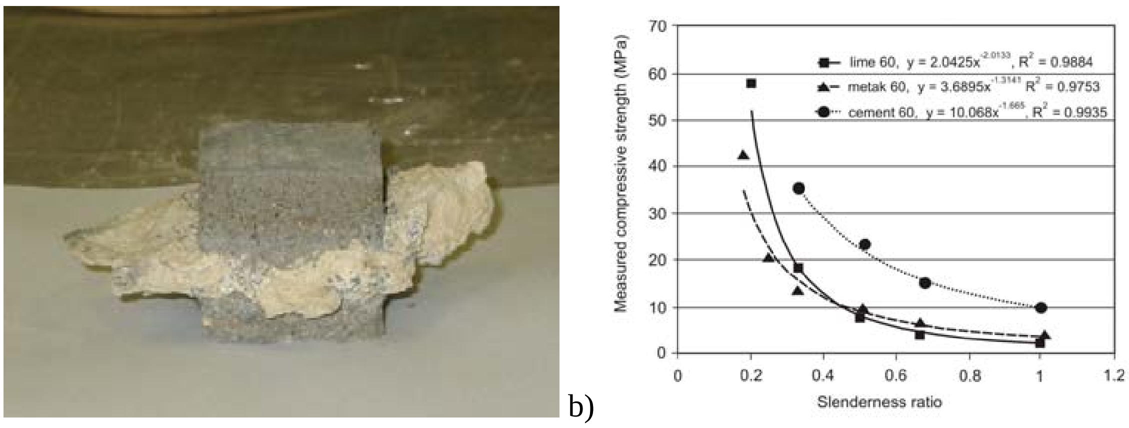


Figure 4: Irregular mortar specimen (a) and compression tests results (b).

Shear strength of masonry

The shear strength of a panel subject to compression and shear has been discussed deeply. Among the possible solutions, limit analysis is capable to draw the compression-shear limit domain for a given rectangular panel. A very simple solution is obtained by forcing the limit condition of the Mohr–Coulomb law in the centre of the panel by assuming that the principal stresses are a compression–tension combination. By virtue of a simple rearrangement of parameters, the following form is obtained:

- $$f_{vk}(\sigma_0) = \frac{\sqrt{f_k f_{mt}}\sqrt{(f_k - \sigma_0)(f_{mt} + \sigma_0)}}{f_k + f_{mt}} \qquad (3)$$

Mechanical properties of the brick

The mechanical properties of the bricks can be readily obtained by using standard compression and splitting tests on solid brick cores. As usual, a compression test on a cylinder with a height to diameter ratio equal to two can give the compressive strength. Once denoted with P the splitting load and with D and L the core diameter and length, the tensile strength of the material is obtained as:

- $$f_{bt} = \frac{2P}{\pi DL} \quad (4)$$

MECHANICAL PROPERTIES DERIVED BY THE MASONRY SPLITTING TEST

The splitting test performed on cylindrical cores with a mortar layer lying in a diametric plane can provide reliable estimations of the mechanical properties of mortar (Benedetti et al., 2008). The planes orthogonal to the mortar layer are subject to pure shear, whereas the planes parallel to the mortar layer are subject to shear-compression, see Figure 5. The test can be performed with different inclinations of the mortar layer. The tests discussed in this study consider 30°, 45° and 60° inclinations as representative of different shear to compression ratios. Denoting the average pressure with *p*, the stresses values can be expressed as a function of the mortar layer inclination, see Table 1.

Table 1: Stress states in the mortar for different inclinations of the layer in the test

Angle	30°	45°	60°
Compression	$p\,\sqrt{3}/2$	$p\,/\sqrt{2}$	$p\,/2$
Shear	$p\,/2$	$p\,/\sqrt{2}$	$p\,\sqrt{3}/2$
Circle Radius	$p\,\sqrt{11/16}$	$p\,\sqrt{5/8}$	$p\,\sqrt{13/16}$

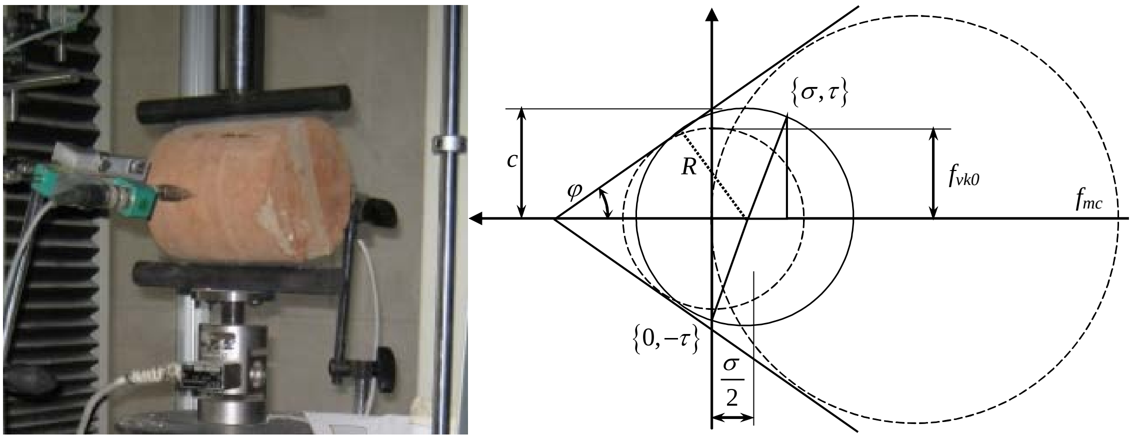


Figure 5: Rotated mortar layer splitting test and Mohr–Coulomb failure interpretation

Assuming that a sufficient number of experimental results of squeezing tests and rotated splitting tests are available, the properties of mortar can be obtained by a least squares fit of a given failure function. For the sake of simplicity, only two parameter domains are considered herein in the Mohr plane, namely the linear Coulomb and the parabolic Leon (Chen & Zhang, 1988). These functions are sufficiently accurate for the tension-shear regime but lead to some approximations for biaxial or triaxial compression states. Therefore an elliptic cap is introduced to describe the limit behaviour for the confined compressed mortar. The following limit equations are considered:

- Coulomb: $$\frac{\tau + \sigma \tan\varphi}{c} = 1 \quad (5)$$
- Leon: $$\left(\frac{\tau}{\tau_0}\right)^2 + \frac{\sigma}{\sigma_0} = 1 \quad (6)$$

- Cap: $$\left(\frac{\tau}{\tau_1}\right)^2 + \left(\frac{\sigma - \Delta\sigma}{\sigma_1}\right)^2 = 1 \quad (7)$$

A more refined failure criterion was introduced by Bresler-Pister (1958) for concrete, by formulating a generalization of the Drucker-Prager cone with a closure cap. As will be discussed in the following, the proposed limit surfaces can be used in connection with the Hilsdorf's analysis in order to predict the collapse compression of the confined mortar.
The best fit is obtained by minimising the squared sum of the distances between the circles representing the tests and the limit curves (Figure 6). The distances are the differences between the length of the normal to the curve from the circle centre and the circle radius.

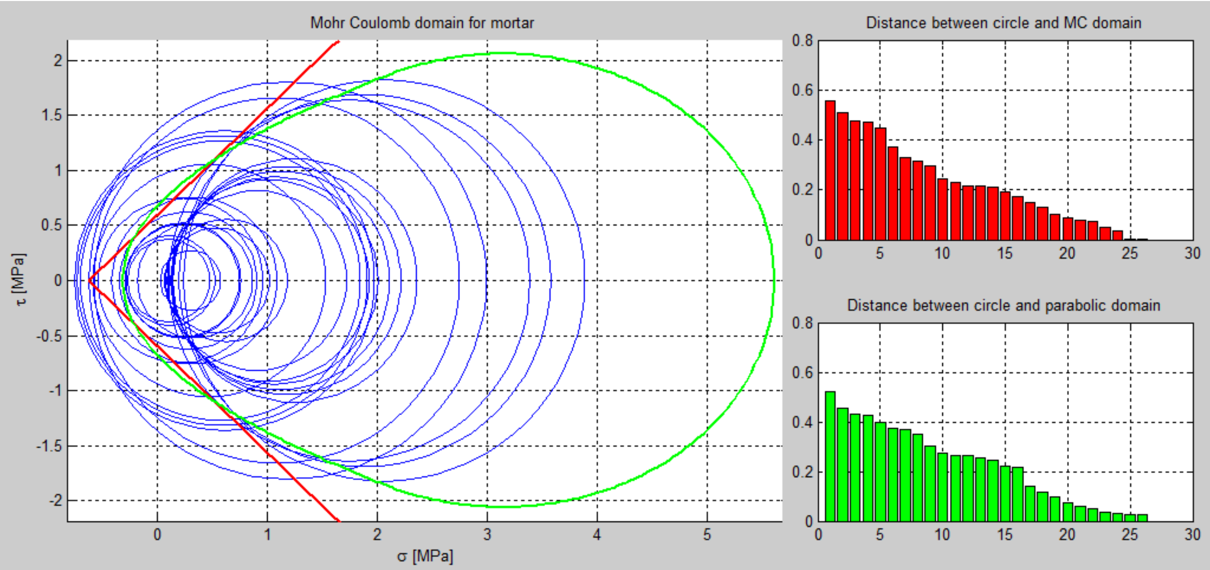


Figure 6: Best-fit and error minimization procedure.

Once the best fit limit curves have been identified, the strengths of mortar for the different stress combinations can be calculated. When the Coulomb cone is considered, the mechanical properties of the material derive from the Coulomb parameters as follows:

- $$f_{mc} = \frac{2c \cdot \cos\varphi}{1 - \sin\varphi}, \quad f_{mt} = \frac{2c \cdot \cos\varphi}{1 + \sin\varphi}, \quad (8)$$

Alternatively, if the Leon domain is considered:

- $$f_{mc} = \frac{\tau_0^2}{\sigma_0} + 2\tau_0, \quad f_{mt} = \sigma_0, \quad (9)$$

In any case, the biaxial strength has to be defined experimentally or as an amplification of the uniaxial compression strength.
Mortar is a dilatant material, which increases its Poisson's ratio during plastic straining. The Coulomb representation does not describe this variation during confined compression, since it considers a constant friction angle. In fact, we can assume that the dilatancy is linked to the

apparent friction angle. Assuming that the latter is the tangent inclination at a given point, the Poisson's ratio can be expressed as:

- $$\nu = \frac{1 - \sin\varphi(\sigma)}{1 + \sin\varphi(\sigma)} \qquad (10)$$

The confined strength of the mortar can be estimated by the ratio of the minimum to the maximum stress when a Mohr circle is tangent to the limit curve. By solving the geometrical problem in the Mohr-Leon domain with cap, the evolution of the compressive strength with the confining pressure is obtained, see Figure 7.

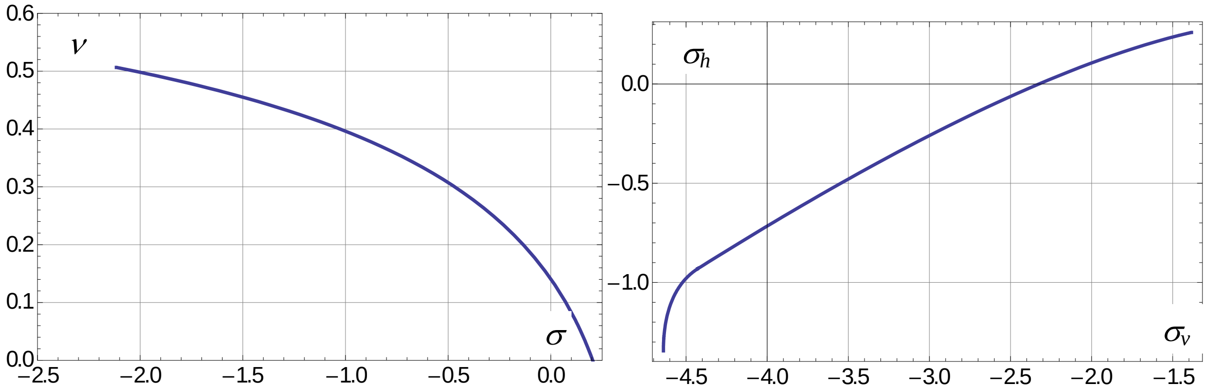


Figure 7: Poisson's ratio and confinement dependent strength in Leon function

A more effective 3D representation of the mortar behaviour can be based on the well-known Bresler-Pister criterion for concrete (1958). The limit surface can be expressed in the Haig-Westergaard space in terms of stress invariants. If the first hydrostatic invariant is denoted by I_1 and the second deviatoric invariant by J_2, the limit surface is expressed as:

- $$\sqrt{J_2} = A + B \cdot I_1 + C \cdot I_1^2 \qquad (11)$$

The three coefficients depend on three parameters which encompass the uniaxial tensile, the uniaxial compressive and the biaxial compressive strengths:

- $$A = \frac{f_b f_c f_t (8 f_b - 3 f_c + f_t)}{\sqrt{3}(2 f_b - f_c)(2 f_b + f_t)(f_c + f_t)} \qquad (12a)$$
- $$B = \frac{(f_c - f_t)(4 f_b^2 + f_c f_t - f_b f_c - f_b f_t)}{\sqrt{3}(2 f_b - f_c)(2 f_b + f_t)(f_c + f_t)} \qquad (12b)$$
- $$C = \frac{f_b (f_c - 3 f_t) + 2 f_c f_t}{\sqrt{3}(2 f_b - f_c)(2 f_b + f_t)(f_c + f_t)} \qquad (12c)$$

A very interesting analysis can be carried out by assuming that the horizontal confining stresses are expressed as a fraction of the vertical one. Given the following hypotheses:

- $\sigma_{11} = \hat{\sigma}, \quad \sigma_{22} = \rho\hat{\sigma}, \quad \sigma_{33} = \frac{1}{2}\rho\hat{\sigma},$ (13)

the failure stress $\hat{\sigma}$ can be plot as a function of the confining ratio ρ. The different predictions for Leon–Cap curve, Bresler-Pister 2D and 3D are depicted in Figure 8.

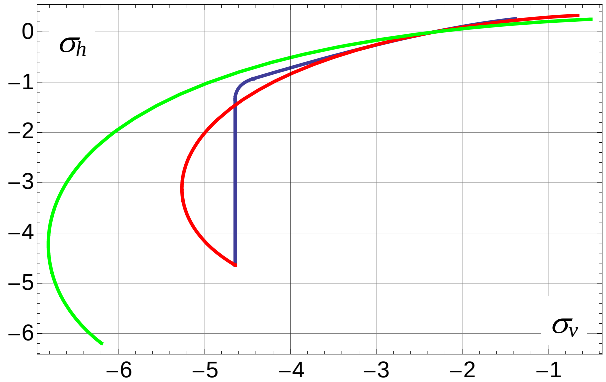


Figure 8: Leon (blue), Bresler-Pister 2D (red) and 3D (green) confined strength plots

For the experimental program considered (Reggio Emilia Police Hall and St. Dominic School in Cesena, Italy), the compressive and tensile strengths of the brick resulted 16 MPa and 2.0 MPa. A value 0.33 was assumed for Φ factor. The properties of the masonry material result as follows (Marastoni, 2012):

a) Mortar– Coulomb Cone:	f_{mc} = 3.25 MPa,	f_{mt} = 0.36 MPa,
b) Mortar – Leon Parabola:	f_{mc} = 2.34 MPa,	f_{mt} = 0.32 MPa,
confined strength:	ρ = 0.33	f_{cb} = 4.20 MPa,
c) Mortar – BreslerPister:	f_{mc} = 2.34 MPa,	f_{mt} = 0.32 MPa,
2D confined strength:	ρ = 0.33	f_{cb} = 4.71 MPa,
3D confined strength:	ρ = 0.33	f_{cb} = 6.04 MPa,
d) Brick - cracking stress:	Φ ρ_h= 0.1	f_k = 8.55 MPa.

Therefore, the masonry material is going to collapse under mortar crushing even if the bricks can arrive very near to transversal cracking. However, if perfect bonding between mortar and bricks can be assumed, the wall strength can be increased more than twice the uniaxial mortar compression strength.

CONCLUSIONS

This paper presents the description and the analytical interpretation of laboratory destructive tests on small specimens including both bricks and mortar. The cores extracted from existing historical buildings were subjected to splitting tests with 30°, 45° or 60° inclinations of the mortar layer with respect to the loading plane. The experimental data have been interpreted using different failure criteria in order to obtain the mechanical properties of mortar and bricks.

REFERENCES

Aprile A., Benedetti A., Grassucci F. “Assessment of Cracking and Collapse for Old Brick Masonry Columns”, Journal of Structural Engineering, 127, 12, 2001, pp 1427–1435.

Benedetti A., Pelà L., Aprile A. "Masonry Property Determination via Splitting Tests on Cores with a Rotated Mortar Layer", ISSM 08, Istanbul, Turkey, 2008, pp 647-655.

Bresler B., Pister K.S. "Strength of concrete under combined stresses" ACI Journal, 30, 3, 1958, pp 321-345.

Chen W.F., Zhang H. Structural Plasticity, Theory, Problems, and Software. Springer Verlag, New York, 1988.

Drdácký M., Mašín D., Mekonone M.D., Slížková Z. "Compression tests on non-standard historic mortar specimens", HMC08 – 1st Historical Mortars Conference, Lisbon, 2008.

Gucci N., Barsotti R. "A non-destructive technique for the determination of mortar load capacity in situ", Materials and Structures, 28, 179, 1995, pp 276 - 283.

Henzel J., Karl S. "Determination of strength of mortar in the joints of masonry by compression tests on small specimens", Darmstadt Concrete, 2, 1987, pp 123-136.

Heyman, J. The stone skeleton. Cambridge Univ. Press, Cambridge, UK, 1962.

Hilsdorf, H. K. "Masonry materials and their physical properties", Proc. of the International conference on planning and design of tall buildings, Lehigh University, Bethlehem, Pennsylvania, III, 1972, pp 981-1000.

Marastoni D. Mechanical data of mortars estimated through non-destructive testing of different mortar samples (in Italian). Graduation Thesis, University of Bologna, 2012.

MC Cann D. M., Forde M. C. "Review of NDT methods in the assessment of concrete and masonry structures", NDT & E international, 34, 2, 2001, pp 71-84.

Roca P., Cervera M., Gariup G., Pelà L. "Structural Analysis of Masonry Historical Constructions.Classical and Advanced Approaches", Archives of Computational Methods in Engineering, 17, 2010, pp 299–325.

Valek J., Veiga R. "Characterisation of mechanical properties of historic mortars – testing of irregular samples", Structural Studies, Repairs and Maintenance of Heritage Architecture IX, WIT Press, 2005, pp 365-374.

Vermeltfoort AT. Brick–mortar interaction in masonry under pressure. PhD thesis, Eindhoven University of Technology, The Netherlands, 2005.