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Experimental determination of the in plane orthotropic compliance matrix of single and double leaves masonry typical of Sicilian heritage

[Laura ANANIA]

***Abstract*—In the paper the results of an experimental programme aimed both to the assessment and the comparison of the mechanical characteristics of some typologies of a one or two-leaves calcareous brick wallettes scale 1:4 size are discussed. Five Types of wallettes, built by referring to different kind of bricks assemblage have been tested in uniaxial compression, parallel and orthogonal to the mortar bed joints, and in diagonal compression. The data obtained permits us to investigate the dependence of the mechanical proprieties of the masonry from the geometrical typology, in order to better set up a retrofitting design of the damaged masonry by taking into account the real material models**

Keywords*—component, formatting, style, styling, insert *(key words)

I. Introduction

Recent earthquakes affecting Italy, such as Amatrice and l'Aquila events, have significantly damaged or destroyed the building heritage featured by masonry buildings. Those structures seem to be very vulnerable to seismic hazard and their strengthening, retrofit or seismic improvement appears to be necessary. Nowadays, the literature provide a lot of innovative reinforcement techniques based on the use of composite materials, some of which capable of guarantying a good response to the masonry structure without loss of components [1,2,3]. But, a proper post-strengthening project can not neglect the in-depth knowledge of the materials employed. Although ancient masonry buildings are the most common structural typology [4,5] found in the historical heritage of Sicily, many different typologies have been found in the ancient masonry constructions, i.e.: (i) different compound as lavic or calcareous bricks, (ii) different disposition of the bricks in all the cases of multi-leaves masonry panel.

So seismic analysis of ancient heritage is still a matter of research, since no one a single model can be universally adopted to numerical investigation of their mechanical behavior. Otherwise, simplified analysis, require accurate estimations of particular sets of material properties, for which standard testing procedure are not often available. In the case of historical masonry the experimental evaluation of their structural parameters is particularly difficult for two reasons:

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- It is not possible to take from monument building a sufficient number of samples
- The masonry typology is quite complicate and often it changes from place to place of the construction. This is especially true for masonries characterized by the presence of local stone.

In this paper a class of masonries typical of Sicilian heritage was chosen for a comparative study of the influence of geometrical assemblage on the mechanical characteristics of the masonry material.

Attention was focused on the stiffness and the ultimate resistance, disregarding at this time, to the dissipation and damage characteristics. Monotonic test were carried out on four type of masonry panels made with the same natural stone, by changing only the stone disposition. A fifth series of panels, charac-terised by an almost disordered disposition was tested of the stone bricks, was tested for compari-son. The panels was made in 1:4 size respect to the real dimension of the structure and keeping the ratio between the thickness of the mortar joints and the height of the stone blocks equal to 11, a value which is often encountered in practice..

II. Materials Employed

A. *Bricks*

White stone blocks take from a queries located in the nearby to Syracuse city were used. It is a sedimentary rock commonly known as "*Pietra di Noto*" similar to soft limestone. It colour is white grey and shows a calcimetry CaCo3 equal to 95, 1%. A deep investigation of chemical, physical and mechanical parameter is treated in [6]. The following mechanical features are obtained from tests carried out on more than 60 specimens.

Real mass for unit volume 20.08 kN/m3
Index of pororsity 24.01 %
Apparent mass for unit volume 17.51 kN/m3
Apparent imbibitions coefficient 13.92 %
Compression resistence at 50% of saturation 12.6 N/mm2
Tensile resistance 1 N/mm2
Young Modulus 675 N/mm2

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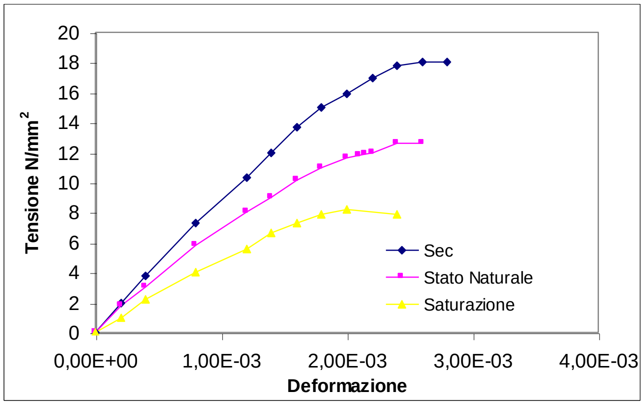

Figure 1. Calcareous sand fuse

B. *Mortar*

A cement mortar commonly known as "M4" accord-ing to the Italian code, was employed for the panel specimens realization. Its recipe is constituted by one part of Cement 325, two parts of putty lime binder and nine parts of sand. Cement was pozzolanic with compressive resistance, after 28 days of curing at room temperature , equal to 32.5 MPa; putty lime binder is a binding component mainly constituted by limestone forged in quicklime; sand was a calcareous king coming from Syracuse, with diameter smaller than 2 mm in order to consider the scaled factor of the specimens.

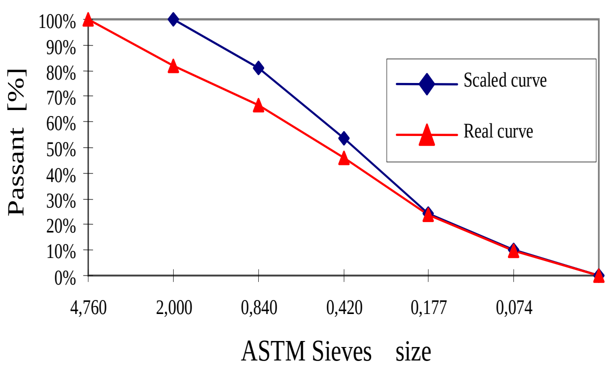

Figure 2. calcareous sand fuse

Mortar specimens were previously tested in flex-ural and compression after 28, 60 and 90 days of curing. The data reported in table below is obtained:

TABLE I. MECHANICAL PROPERTIES OF MORTAR EMPLOYED

Curing days	Flexural resistance (MPa)	Cubic Compressive Strength *(MPa)*	Cylindrical Compressive Strength *(MPa)*	*E (Mpa)*
28	0,258	0,795	0,691	675
60	0,364	1,14	0,758	740
90	0,442	1,287	0,778	1182

C. *Masonry specimens*

To this scope four groups of panels with the same geometry (55x55x7 cm3) were selected. Each series was composed by no 5 samples. Series A and B are single thickness masonry panel with different geom-etry of bricks assemblage; while series C and D are characterized by two-leaves masonry panel assem-bled with different disposition of bricks according to the disposition known in practice as "gothic".

Figure 3 shows the plan section of series C and D. Figure 4 and 5 represent the frontal view of the ge-ometry of the tested series.

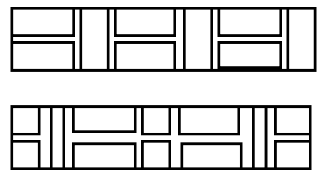

Figure 3. C-D series: plan view of gothic disposition of the bricks

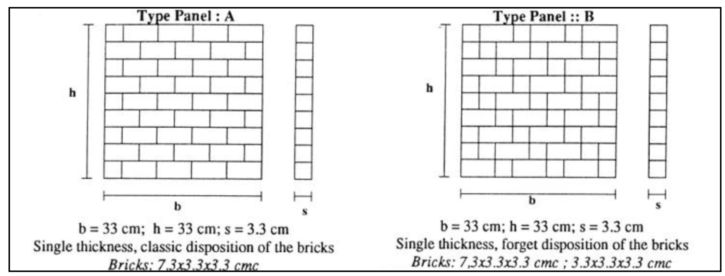

Figure 4. Series A-B geometrical features and brick assemblage

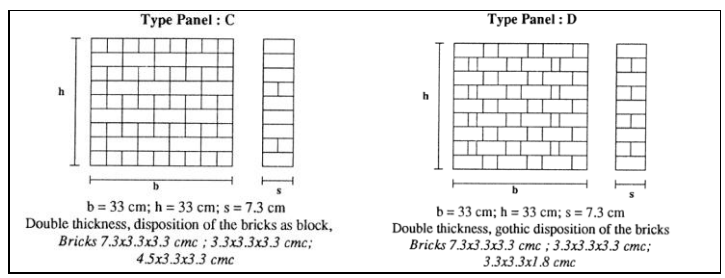

Figure 5. Series C-D geometrical features and brick assemblage

III. Experimental Programme

Three series of tests were performed for each masonry typology, namely, monotonic uniaxial compression [7-12] in direction orthogonal to the bed joints, monotonic uniaxial compression test in direction parallel to the bed joints and a conventional shear test (diagonal test) [13-14]. Each test was repeated on five samples constituting each investigated series and the results were averaged. In this way orthotropic stiffness and limit value of masonry could be determined. In the following "x" will refer to the direction of the bed joints and "y" to the direction perpendicular to the bed joints.

A. *Uniaxial compression test*

The test was carried out on uniaxial testing machine by rotating the sample so as to apply the load in x or y direction respectively (fig. 6). The loading surface of the sample were levelled by putty and smoothed, then the sample was placed between two steel plates of 30 mm thick. A Teflon layer was interposed between sample and steel plates in order to avoid load concentration. A ball joint was placed between the screw jack and the panel in order to avoid misalignements..

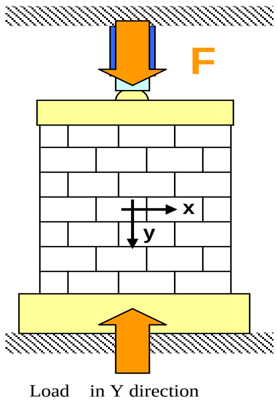

Figure 6. Compression test scheme in x and y direction

The load was measured by a pressure transducer. Both vertical and horizontal deformations on the sample were measured by means of LVDT and Ω transducers glued on both sides of the specimen. The instruments were applied as shown in figure 7. Furthermore, the strains evaluated along greatest longitudinal dimension of the sample, measured by means of transducers placed across the first and the lowest course of bricks, were compared to the those evaluated on the short dimension (chosen equal to three bricks). Significant difference were found.

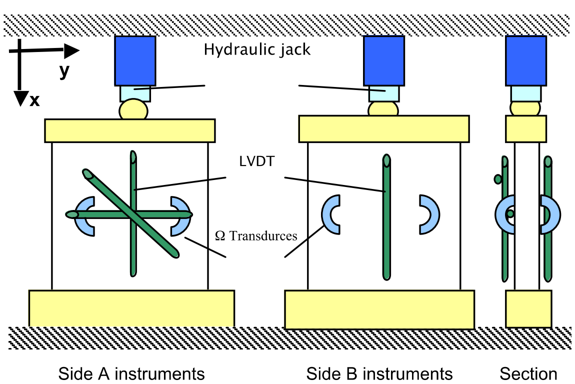

Figure 7. Scheme of the instruments position on the sample

The following quantities were measured :

Compressive strength "σ" as the ratio between the collapse load and the loading surface "A" on the top of the panels.

Longitudinal elastic modulus E as the ratio of the compressive stress σ_R and the longitudinal strain ε_v the latter given by the average of the strains measured on both faces of the sample.

Transversal elastic modulus E0 as the ratio between compressive strength and transversal strain ε0 given by the average of the strains measured on both faces.

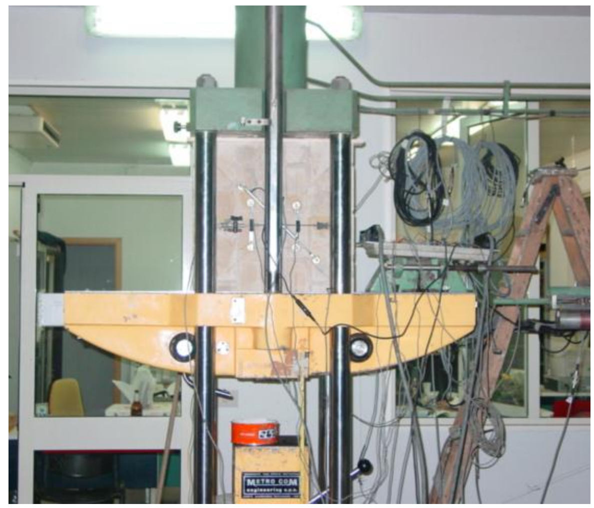

Figure 8. Sample in testing machine

Poisson modulus as the ratio between ε_{0m} and ε_{vm}. The longitudinal strain is that one measured in the direction of the applied load, while transversal strain refers to the direction orthogonal to the load. Due to the non linear behavior elastic moduli were not constant with the stress level different moduli were evaluated:The *initial tangent moduli*, *secant modulus* at a load level equal to 40% of the ultimate load, (commonly very close to the limit of the quasi linear trend behavior of the material), the tangent stiffness modulus at the load level equal to 40% of the ultimate load. Each deformation was evaluated as following:

$\varepsilon_{VA} = \dfrac{\Delta l_{VA}}{l_{VA}}$; $\varepsilon_{VB} = \dfrac{\Delta l_{VB}}{l_{VB}}$	Longitudinal deformation of the side A and B
$\varepsilon_{Vm} = \dfrac{\varepsilon_{VA} + \varepsilon_{VB}}{2}$	Averaged longitudinal deformation
$\varepsilon_{OA} = \dfrac{\Delta l_{OA}}{l_{OA}}$; $\varepsilon_{OB} = \dfrac{\Delta l_{OB}}{l_{OB}}$	Transversal deformation of the side A and B
$\varepsilon_{Om} = \dfrac{\varepsilon_{OA} + \varepsilon_{OB}}{2}$	Averaged tranversal deformation

B. *Diagonal compression tests*

Shear strength parameters of ancient masonry buildings is actually a very relevant parameter for the evaluation of seismic behaviour of masonry buildings. To its evaluation, the diagonal compression tests are required [15,16]. The test was performed according to the American standard ASTM E519.

It is an indirect shear test in which the square-shaped masonry specimens are subjected to an uniaxial load applied on 45° with respect to the mortar beds joints and cyclically increasing up to the failure. In order to have samples in a vertical position in the test machine, each specimen was clamped between two angular "L" shaped steel profile 130 mm wide specially designed. A quick-setting plaster mortar was used in order to make uniform the application of the load. The load was applied by means of a screw jack allowing you to run the test in displacement control.

To prevent the load eccentricity on the top of the specimen a ball joint was placed between screw jack and the sample.

Figure 9. Screw jack

Figure 10. Load cell ball joint

Figure 11 shows a scheme of the test. Deformations along diagonal were evaluated on both sides of the sample; figure 12 shows the testing set up.

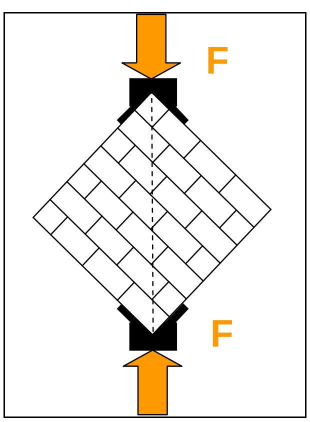

Figure 11. Diagonal test scheme

The load was applied by means of a screw jack, has been measured by a load cell from 25kN Figure 12; the action was increased cyclically up to the collapse value N_r. The omega transducers disposed on the diagonals of the specimen, have been placed on both the sides of the sample

The diagonal compression test, performed according to the ASTM E519 standard, provides us, through the following formulas, a conventional measure of the shear strength τ_r under zero compression:

$$\tau_r = \frac{\sqrt{2}}{2}\frac{N_r}{A_n} \quad (1)$$

Where A_n is the net area of the specimen's cross-section calculated according to eq. 2

$$A_n = \frac{l+h}{2}t \quad (2)$$

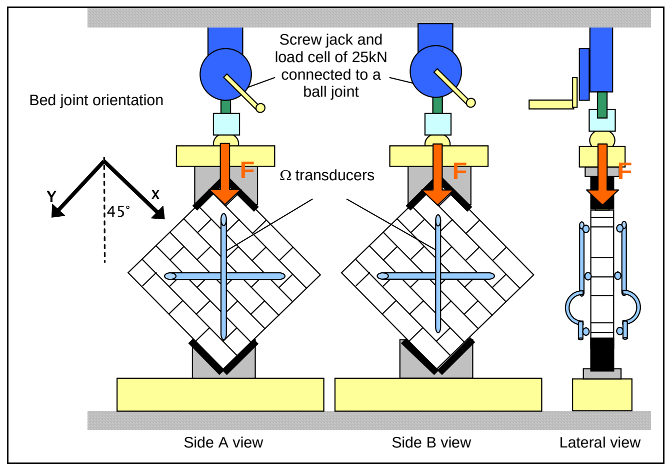

Figure 12. Instruments scheme on the sample for diagonal test

Where l= length, h= height and t is the thickness of the tested sample.

A conventional shear modulus G is obtained as the ratio between shear stress and conventional slip $\gamma = \varepsilon_{Vm} - \varepsilon_{Om}$ estimated by eq. (3) and (4) respectevely for the Conventional shear stress at 10% of the ultimate load and for the Conventional shear stress at 50% of the ultimate load:

$$G_{10\%} = \frac{\Delta\tau}{\Delta\gamma} \quad (3)$$

$$G_{50\%} = \frac{\tau_{50\%}}{\gamma_{50\%}} \quad (4)$$

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IV. Analysis of the results

Table 4-5 show the results obtained as the average of five samples for each series for the ultimate stress and the stiffness moduli, evaluated as specified before. The investigated series behaves different in terms of deformation characteristics and in failure patterns. Under compression all the samples tested, have shown vertical cracks extended to the entire height of the specimen. In many cases they are equally spaced. They start form the mortar joint on the top of the specimen and cross the brick in the middle (fig.13-14). This collapse mode is due to the tensile stress occuring either in the mortar joint, with conseguent detachment between mortar and brick, or in the brick.

Figure 13. Cracks after compression test x direction

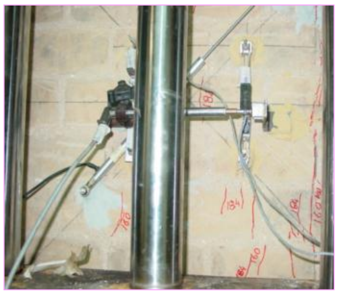

Figure 14. Cracks after compression test y direction

The collapse, under diagonal compression, occurs by the formation of a crack along the diagonal which, develops in a zig-zag to the entire panel, up to the panel breaks down into two distinct parts (fig. 15).

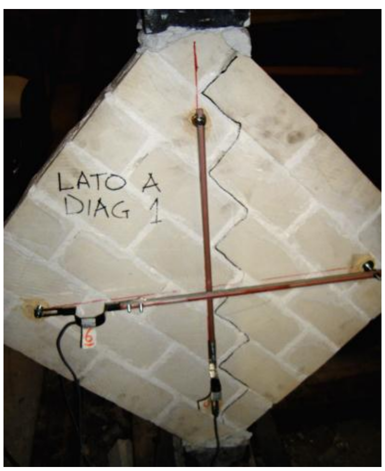

Figure 15. Cracks after diagonal test

Figure 16. Resulting pieces after diagonal test

TABLE II. UNIAXIAL COMPRESSION IN X DIRECTION

Series Type	A	B	C	D
σ_r (MPa)	7.72	5.10	5.58	5.59
$E_{tg\,(0,5)}$ (MPa)	5102	3880	5329	2775
$E_{sec\,40\%}$(MPa)	4554	3660	4550	2560
$E_{tg\,40\%}$(MPa)	4038	3240	4300	1680
$E_{0tg\,(0.5)}$(MPa)	-4663	-2352	-3058	-3791
$E_{sec\,40\%}$(MPa)	-2960	-2168	-1668	-1357
σ_0 (Mpa)	2.04	1.64	1.28	1.22

TABLE III. UNIAXIAL COMPRESSION IN Y DIRECTION

Series Type	A	B	C	D
σ_r (MPa)	9.04	8.7	7.98	6.12
$E_{tg\,(0,5)}$ (MPa)	4224	4300	6500	4855
$E_{sec\,40\%}$(MPa)	4224	-	-	-
$E_{tg\,40\%}$(MPa)	4224	-	5750	-
$E_{0tg\,(0.5)}$(MPa)	-16016	-11093	-4200	-6060
$E_{sec\,40\%}$(MPa)	-16016	-	-	-
σ_0 (Mpa)	4.2	3.62	4	3.66
σ_0/σ_r (Mpa)	46%	42%	53%	60%

For the uniaxial compression test in x direction, the structural responce was generally non linear; departing from linearity was more evident in transverse deformation, that shows an yielding at very low level of the load (denoted as s0 in the table 2) Failure occurs in a brittle way and it is anticipated by the formation of fracture lines along the mortar bed joints (parallel to the load). Therefore the panel turns into a series of prisms.

There is evidence that this phenomena begins for very low level of the stresses, indeed Poisson ratio, initially smaller than 1, grows up continuously with the stress.

C series type samples show an anomalous behaviour since the departure from linearity is caused by the formation of a crack line between the two leaves of the sample. This phenomena does not occur in D samples due to a better interlock between the leaves.

The response to uniaxial compression test in y direction is quite linear for low level of stress, then a departure from the linearity occurs due to the first crack formation in direction parallel to the applied load. For *C* and *D* series the collapse occur for cracks developed between the two leaves.

Table 4 reports the data obtained from the diagonal tests. In this case the response is non linear with a continuous loss of stiffness up to the fracture formation corresponding to the sharp yield in the stress strain curve.

TABLE IV. DIAGONAL COMPRESSION TEST

Series Type	A	B	C	D
τ_R (MPa)	0.439	0.521	0.415	0.2135
$G_{sec\,40\%}$(MPa)	2531	2910	1320	1660
$G_{tg\,40\%}$(MPa)	2106	2487	1397	665
$G_{tg\,(0.5)}$(MPa)	3788	2799	1700	2053
τ_y (MPa)	0.411	0.489	0.415	0.220
τ_y/τ_x (Mpa)	93%	94%	100%	93%

A. *Limit properties of masonry*

The results obtained show an anisotropic behavior of the masonry, with greater resistance in y direction than in x

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direction. The limit shear stress ranges from 4 to 6 % of the limit stress in y direction. The adoption of no tension model for any masonry typologies appears therefore a reasonable approximation. In those cases in which it is desired to taking into account for some tensile resistance a Coulomb type criterion can be adopted according to eq. 5 formulation:

$$\frac{\sigma_1}{\sigma^+} + \frac{\sigma_2}{\sigma^-} \leq 1 \qquad (5)$$

where σ_1 and σ_2 = eigenstresses, and σ^+ and σ^-; = limit compressive and tensile resistances. The formula is valid in isotropic case, generalization to anisotropic case is given in literature.

The diagonal compression test is identified with pure shear test (which is not) from previous formula a range for limit tensile stress can be determined, by taking $\sigma_1 = -\sigma_2 = \tau_r$ the value in x direction or in y direction. The two value are very close, as is seen from table no. 4

TABLE V. RANGE OF THE LIMIT TENSILE STRESS OF MASONRY PANEL

Series Type	A	B	C	D
σ^+ (MPa)	0.461-0.465	0.554-0.580	0.439-0.448	0.244-0.245

V. Conclusions

The paper reports the results derived from a quite wide experimental investigation carried out on single leaf or two leaves masonry specimens aimed to the determination of the in plane orthotropic compliance matrix with little approximation for the shear modulus. Panel specimens represents different disposition of the bricks.

Generic in plane orthoptropic compliance matrix can be represented as following:

$$\begin{bmatrix} \frac{1}{E_x} & -\frac{\upsilon_{xy}}{E_y} & 0 \\ -\frac{\upsilon_{yx}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix}$$

In the previous matrix the off diagonal terms correspond to the inverse of the transversal moduli listed in tables 1-3. However the values of $E_{t\sigma}^{0.5}$ taken from the tests in direction x and y are not equal so that the compliance matrix appears to be non symmetric. This is due to the fact that loading the sample in x direction causes fractures along the bed joints, which appears even at very low level of the load, so that the response of the sample is not elastic This conjecture is proved by the fact that, assuming for both off-diagonal terms in E-1 the value of $E_{t\sigma}^{0.5}$ measured from the test in x direction, the compliance matrix fails to be positive definite. It is therefore very dangerous to consider the masonry elastic when vertical loads are small. The off diagonal terms were taken equal to $E_{t\sigma}^{0.5}$ measured from the test in y direction and, in this way, the stiffness matrix could be obtained by inversion. The results for the stiffness matrix are listed below , where initial elastic moduli were used.

$$k_A = \begin{bmatrix} 5570 & 1470 & 0 \\ 1470 & 4600 & 0 \\ 0 & 0 & 3790 \end{bmatrix}$$

$$k_B = \begin{bmatrix} 4490 & 1740 & 0 \\ 1740 & 4970 & 0 \\ 0 & 0 & 2800 \end{bmatrix}$$

$$k_c = \begin{bmatrix} 9280 & 6700 & 0 \\ 6700 & 11340 & 0 \\ 0 & 0 & 1700 \end{bmatrix}$$

$$k_A = \begin{bmatrix} 3200 & 1530 & 0 \\ 1530 & 5590 & 0 \\ 0 & 0 & 2050 \end{bmatrix}$$

Generally the stiffness in y direction is greater than in x direction except for series A.

For the structural assessment of old buildings with load bearing masonry walls and for the eventual design of strengthening solutions it is required an accurate simulation of its structural behaviour.

With this work we aim to contribute to fill the void due to the lack of experimental data regarding the mechanical behaviour of the single and double leaf masonry, typically in the Eastern Sicily.

The results are useful in all cases in which a seismic assessment, strengthening or retrofitting of the structure is required.

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