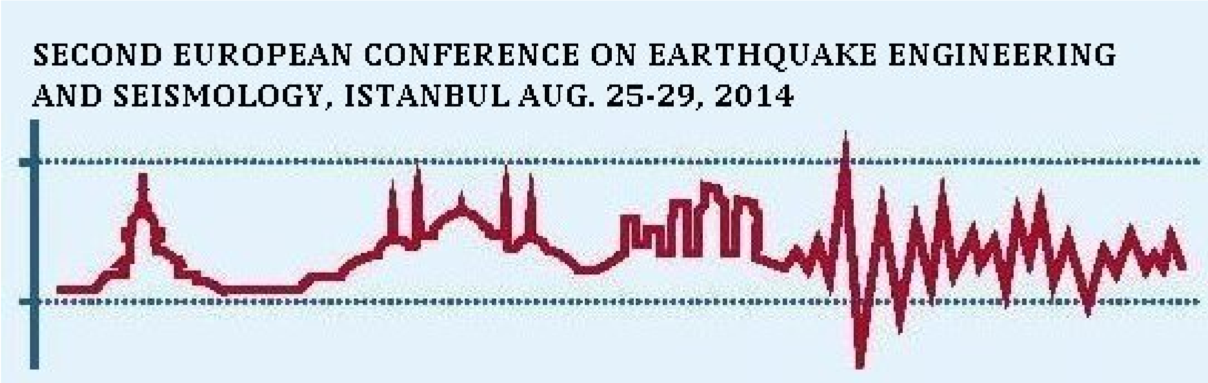

EXPERIMENTAL DATA OF FRICTION COEFFICIENT FOR SOME TYPES OF MASONRY AND ITS CORRELATION WITH AN INDEX OF QUALITY MASONRY (IQM).

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ABSTRACT

This study constitutes the results of an experimental investigation into the description of certain types of wall masonry present in traditional southern Italy buildings. The parameter applied is that of the friction coefficient between the joints of the stone blocks which constitute the masonry. The wall-to-wall friction is as important as other mechanical parameters in that it acts on the structural behaviour of masonry with regard to in plane mechanisms and mixed mechanisms (both in plane and out of plane). The friction coefficient provides a useful indication in evaluating the type of masonry and its behaviour to be used in seismic areas. Similar friction values for all types of masonry are reported in literature, while in effect these values vary according to the type of masonry and materials used. The aim of this study is not to provide certain friction values, but a range of acceptable values in relation to the type of masonry considered in the study itself. Experimental investigations which allow the estimation of the friction coefficient associated with failure through sliding, are carried out with a hydraulic jack, coherent with the Mohr-Coulomb failure criterion. Shear strength depend by compression in the wall, so it is necessary evaluate ultimate shear strength (cohesion) in the absence of normal compression. In order to obtain this result, it is necessary to carry out two tests, on two walls belonging to the same masonry type, but subject to differing values of compression. The critical interpretation of the tests provides, for each sample, the experimental values of the coefficients of friction and cohesion as well as will be shown later in this work. A further interesting aspect of this study is the verification of the existence of a correlation between experimental results, and a qualitative judgement expressed through observation of the masonry. To this end, a method well established in literature has been used for the measurement of the quality of the masonry. An index of quality masonry (IQM) is evaluated on the basis of the survey of predetermined parameters that indicate respect for the rule of the art of building (size of the stones, regularity of the texture, quality of the mortar, etc..). This methodology has been applied to the masonry samples used in the experimental investigation, in such a way as to be able to compare the results of the two procedures.

This comparison has provided encouraging results, establishing a satisfactory correlation between the qualitative evaluation of the masonry and experimental data.

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INTRODUCTION

A description of the mechanical parameters of historical buildings is not simple: this masonry parameter consists, in fact, is a heterogeneous mixture of stone blocks and mortar, whose characteristics are dissimilar to those of the individual materials, and which depend on the masonry textures and their correct application. The behaviour of a wall during seismic activity on its own plane is strongly connected with the friction resistance created along the joints between blocks where lesions appear. Friction resistance depends not only on the masonry texture and the wall cross section but also on the materials used. As has been shown in recent studies on the seismic vulnerability of traditional buildings (Neri and Marino, 2012), the precise measurement of friction resistance produced in a wall subject to mixed mechanisms (both in plane and out of plane) is necessary in reliably measuring the precise capacity of the wall. It is emphasised that mixed mechanisms can only occur in buildings with good connections between the walls. The conventional values given in literature to wall-wall friction are measured as 0.4÷0.45, for all types of walls. However, existing wall types may vary greatly, so that it is hardly reasonable to assume that a single value of friction coefficient can be universally valid. The aim of this study is, through a series of experimental measurements, to identify a range of acceptable values of friction coefficient of some wall types of traditional Sicilian buildings. Furthermore, the study aims at showing a correlation between friction coefficients identified in the experimental investigations and masonry quality as defined on the basis of specific parameters. The mechanical resistance of a wall is strongly dependent on some qualitative elements, tied to the rules of construction when followed “to the letter”. Numerous studies exist in literature providing qualitative information relating to wall masonry in quantitative parameters, with the aim of giving an indication of wall quality characteristics rather than supplying definite behavioural information. It is therefore necessary to establish correspondence between two different approaches, the first based on the qualitative analysis of building principles “to the letter”, and the other on direct physical measurements. In this way it is possible to establish a correlation between some factors relating to “to the letter” building principles, and mechanical parameters which govern the behaviour of the masonry with respect to vertical action, horizontal action in the plane of the wall, and horizontal actions out to the plane. This approach can also be extended to the description of friction which develops along the wall in the case of mixed mechanisms.

1. MASONRY TYPES ANALYZED IN THIS STUDY

The subjects of this study are two different types of masonry characteristic of traditional buildings in the south of Italy: square cut blocks in soft stone, and rough cut blocks in lava stone. Ten samples were made of each type of stone, and for each sample there was:

- n.1 survey of masonry composition by removing of plaster and survey of cross section of the wall, when it was possible. Observation of masonry texture and wall section are necessary to establish compliance with the rules of construction followed “to the letter”.
- n.2 sliding tests at the point where the sample was taken and on a other wall of the same type, but subject to differing normal compression with respect to the former;
- n.2 measurement of the compression stress at the points where the cutting tests have been carried out.

Compression stress was measured through tests with flat jacks or through analysis of load. Critical interpretation of the above tests has provided, for each sample, experimental values of the coefficients of friction and of cohesion. Some examples of representative samples of each masonry type are reported below (figg. 1-2)

Figure 1–Some samples of square cut blocks in soft stone masonry analyzed in this study:(a) masonry texture in a school near Siracusa (SR); (b,c,d) masonry textures and cross section in “Concordia Theater”, Ragusa (RG); (e) masonry texture and cross section in a office building, Modica, (RG).

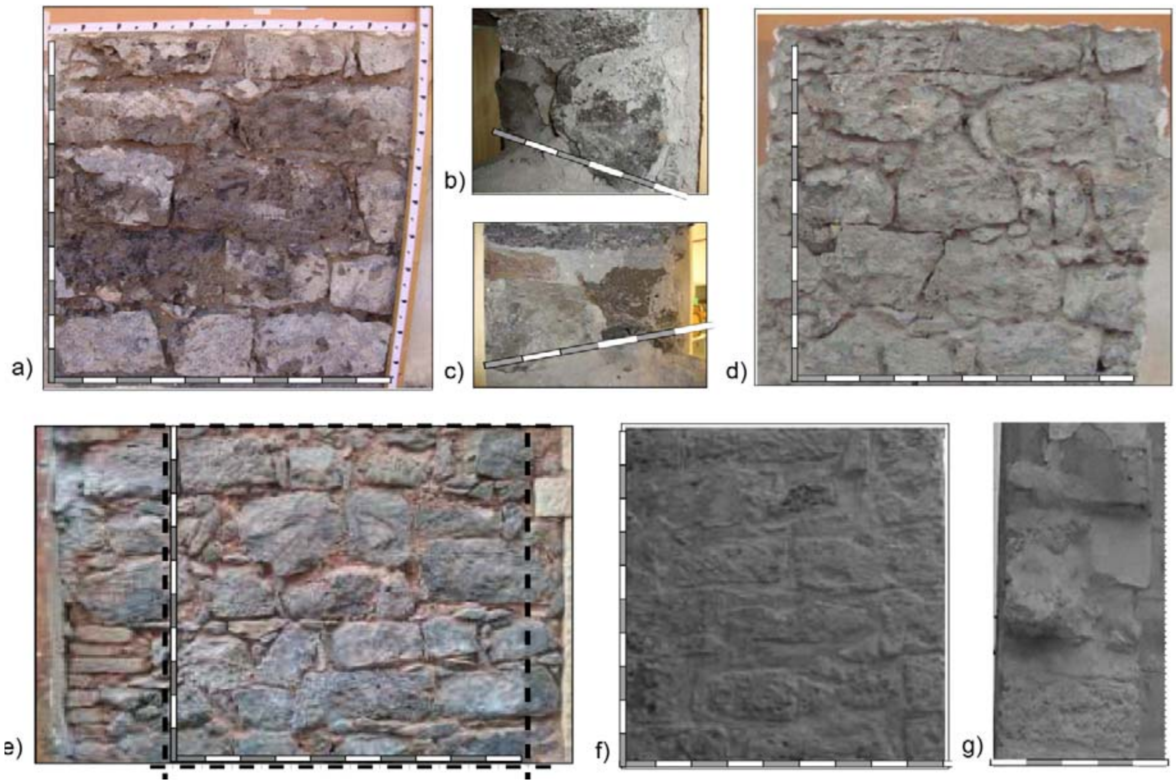


Figure 2 – Some samples of rough cut blocks in lava stone masonry analyzed in this study: (a -d) masonry textures and cross sections, in a school in Paternò (CT); e) masonry texture in an housing for undergraduate students, Catania; (f-g) masonry texture and cross section, in a municipal building, S. Gregorio, (CT).

2. EVALUATION OF MASONRY QUALITY INDEX

Rules of construction followed "to the letter" constitute the overall building measures which, if carried out during the construction of a wall, guarantee its reliability and ensure it is compact and structurally solid. This is derived from an age-old building practice, and from the direct observation of the behaviour of masonry. On observing characteristic parameters of correct and efficient masonry construction, it is possible to establish a masonry quality index for each of the possible stress directions on a wall panel. An index of wall quality is therefore obtained for vertical loads, horizontal actions out of plane and finally for horizontal actions in the plane. The degree of application of each parameter "to the letter" is evaluated through observation of the masonry, and a value is given to each according to the direction of the stress action. Building requirements which together constitute "to the letter" are listed below:

High Quality Mortar/ effective contact between elements (M.A.) This condition, which is necessary for the uniform transmission of loads and the discharge of energy on to the ground, is obtained either by direct contact between square-cut blocks or through the mortar. Besides levelling the contact between the blocks, high quality mortar ensures the wall possesses cohesive resistance.

Transversal Locking /presence of diatones(P.D.). This condition prevents the wall dividing into various sections simply positioned one next to the other, and furthermore, permits the load to be distributed along the entire width of the wall even when the load bearing is on the wall edge (e.g. a floor lying only on the internal part). This condition can be met thanks to "diatones", or rather, blocks crossing the entire width of the wall.

Form of Resistant Elements (F.E.L.). The presence of blocks with a regular shape ensures the activation of the friction force, to which a large part of a wall's ability to resist horizontal actions is due. In fact, friction is principally activated through the effect of weight from masonry lying above the sliding surface, and is maximised for horizontal sliding. It can thus be seen that this is one of the conditions necessary in obtaining efficient locking between the wall elements.

Dimension of the Elements (D.E.L.). Resistant elements of large dimensions with respect to the width of the wall, ensure a high degree of stability to the wall, as do the diatones. Furthermore, thanks to their elevated dimensions, they are extremely heavy with good locking between them.

Staggering of Vertical Joints/In Plane Locking (S.G.). This condition allows for the application of a further resistance element in the wall: wedging between resistant elements (also known as "locking effect") which, together with friction, guarantees resistance to co-plane action.

Horizontal Rows (O.R.). This condition makes for good distribution of vertical load in that regular support is obtained. However, the horizontal aspect also assumes importance during seismic activity as it allows for oscillation around horizontal cylindric hinges without damaging the masonry.

High Quality Resistant Elements (RE.EL). Stone elements must be resistant and in good condition: intrinsically weak (e.g. mud bricks used in certain areas of the world) or heavily degraded elements invalidate other "to the letter" conditions.

In order to arrive at an judgement of masonry quality, as has been said above, it is indispensable to evaluate (analytically or qualitatively) to what degree the seven parameters defining "to the letter" have been respected. Only following this preliminary step will it be possible to put the seven partial considerations together into a complete evaluation. It is often easy to recognise the two differing stances, to respect (R.) or not (N.R.) a given parameter "to the letter". Field observations on masonry in real buildings have, however, shown that middle-range stances exist as well, which neither fall into or outside the "to the letter" definition. Thus, for each parameter in question, a category of judgement defined as "partial respect" (P.R.) of the "to the letter" has been introduced. After having evaluated the degree of respect of each of the above parameters, a certain number of points can be awarded to each, described in table 1. The points reported in the table are then inserted into the formula below, therefore arriving at a total number of points for each type of stress action.

$$\text{IQM} = \text{RE.EL.} \times \left(\text{OR.} + \text{P.D.} + \text{F.EL.} + \text{S.G.} + \text{D.EL.} + \text{MA.}\right) \qquad (1)$$

This procedure, therefore, leads to three values of IQM between 0 and 10: one for each direction of stress. What defines each IQM value is the various weight attributed to the "to the letter" evaluation for the three stress charges.

Table 1. Value given to each parameter depending on degree of respect "to the letter"

Building principles "to the letter"	Vertical loads N.R	P.R	R.	Horizontal load out of plane N.R	P.R.	R.	Horizontal load in plane N.R	P.R.	R.
O.R. Horizontal Rows	0	1	2	0	1	2	0	0,5	1
P.D. Transversal Locking	0	1	1	0	1,5	3	0	1	2
F.EL. Form of Resistant Elements	0	1,5	3	0	1	2	0	1	2
S.G. In Plane Locking	0	0,5	1	0	0,5	1	0	1	2
D.EL. Dimension of the Elements	0	0,5	1	0	0,5	1	0	0,5	1
MA. High Quality Mortar/	0	0,5	2	0	0,5	1	0	1	2
RE.EL. High Quality Resistant Elements	0,3	0,7	1	0,5	0,7	1	0,3	0,7	1

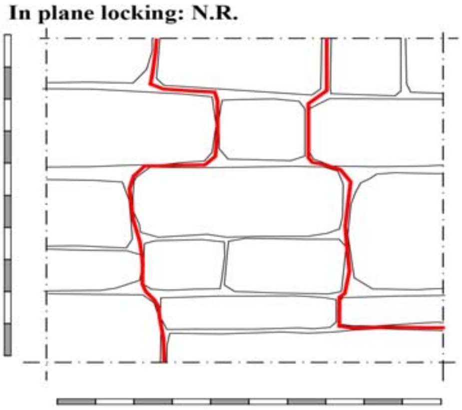
The weights attributed indicate the importance of a certain parameter for a good reaction of the wall under a certain type of stress action. The conventional aspect of the method is therefore emphasized, whose aim – evidently unrealistically– is not that of establishing a certain characterization of the mechanical behavior of a masonry wall, but that of providing a general realistic indication. The resistance of a wall on its plane is due to following characteristics: cohesion attributed to the masonry by high quality mortar; friction optimized for sliding on horizontal surfaces of elements resisting contact with each other; vertical joints staggered in order to provide adequate friction resistance. Given the above, it is implicit that the three parameters "to the letter" held to be fundamental in the development of friction resistance and in the provision of high resistance to in-plane action, are the presence of square cut blocks, staggering of vertical joints and the quality of the mortar (F.EL.,S.G. and M.A.). Greater weight has also been given to the presence of diatones (P.D.). These are important as they allow horizontal in-plane action to work over the entire thickness of the wall. Masonry of a quality index below 4 does not generally manage to develop monolithic behaviour, therefore friction resistance cannot be calculated. Some examples are reported below relating the samples analysed, and their relative IQM. (fig 3)

Sample n°: 1		
Type of masonry: square cut blocks in soft stone		
Tests on sample	YES	NO
survey of masonry texture	x	
survey of wall section		x
sliding tests	x	
flat jacks tests	x	

Rules of construction followed "to the letter"

O.R. Horizontal Rows	0,5
P.D. Transversal Locking /presence of diatones	2
F.EL. Form of Resistant Elements	2
S.G. Staggering of Vertical Joints/In Plane Locking	0
D.EL. Dimension of the Elements	1
MA. High Quality Mortar	2
RE.EL. High Quality Resistant Elements	0,7

IQM=RE.EL.x(OR+PD+F.EL+SG+D.EL+MA)=**5,25**



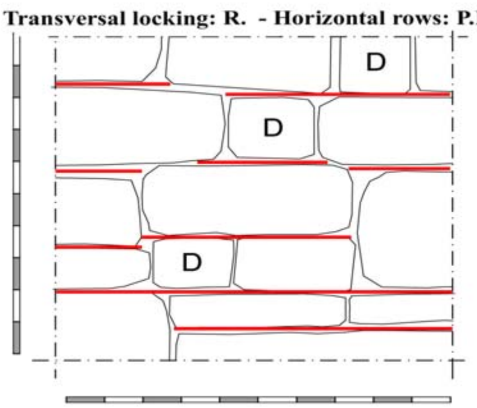


Figure 3 –Evaluation of IQM in a square cut blocks in soft stone masonry. (N.R.: not respected parameter; R.: respected parameter; P.R.: Partially respected parameter; D.: Diatones).

Sample n°: 14		
Type of masonry: rough cut blocks in lava stone		
Tests on sample	YES	NO
survey of masonry texture	x	
survey of wall section	x	
sliding tests	x	
flat jacks tests	x	

Rules of construction followed "to the letter"

O.R. Horizontal Rows	0,5
P.D. Transversal Locking /presence of diatones	2
F.EL. Form of Resistant Elements	2
S.G. Staggering of Vertical Joints/In Plane Locking	1
D.EL. Dimension of the Elements	1
MA. High Quality Mortar	2
RE.EL. High Quality Resistant Elements	1

IQM=RE.EL.x(OR+PD+F.EL+SG+D.EL+MA)=**8,5**

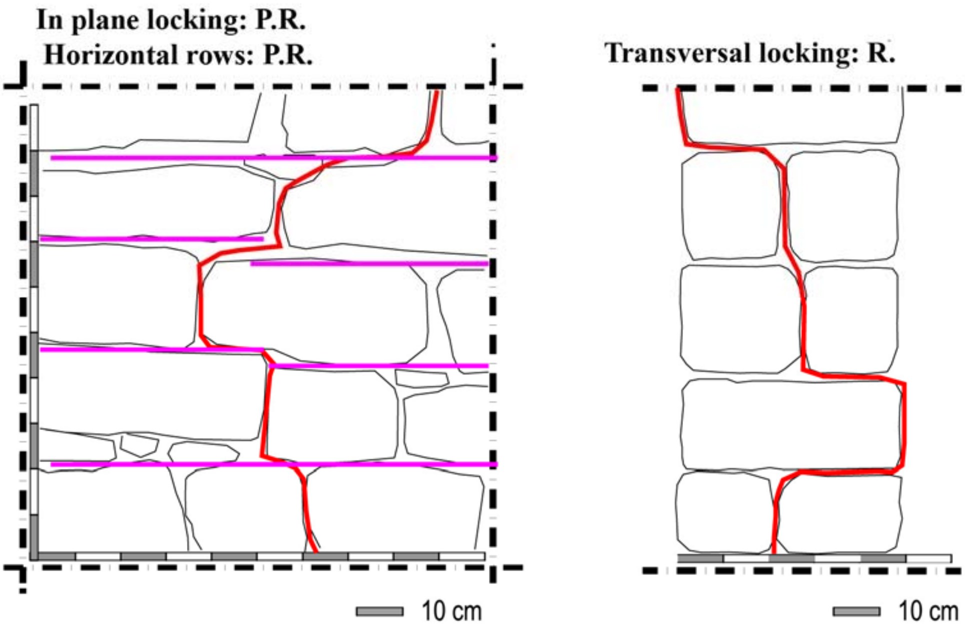
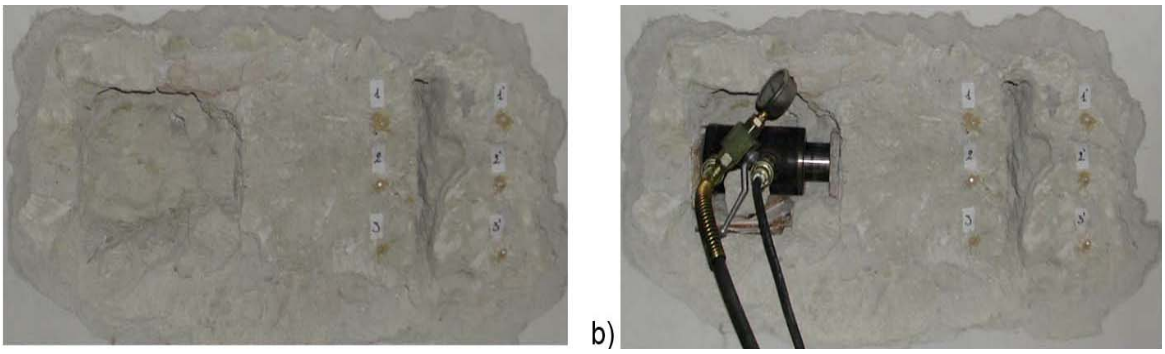


Figure 4 – Evaluation of IQM in a rough cut blocks in lava stone masonry. (R.: respected parameter; P.R.: Partially respected parameter;).

3. EXPERIMENTAL METHOD FOR FRICTION EVALUATION.

The methodology for the identification of the experimental friction coefficient uses semi-destructive tests which have been the subject of recent studies. The mechanisms of failure of a masonry wall stressed by in plane action are associated with either the sliding of the stone along the mortar joints, or with a break in the normal direction of isostatic traction, which usually coincides with the diagonal line of the wall panel. A semi-destructive test procedure will be illustrated which allows the evaluation of the friction coefficient associated with failure through sliding, along mortar joints. The test is carried out with a hydraulic jack, coherent with the Mohr-Coulomb failure criterion. A block of masonry is isolated through the removal of mortar on one side and the adjacent block on the other. The block is kept up through its upper, lower and posterior sides, and is therefore subject to the normal compression acting on the wall. A hydraulic jack is inserted into the empty cavity of the removed block (fig.5). The test consists in applying horizontal pressure on the previously isolated block, which is increased at a steady rate, resulting in the contemporary movement of the block, until the block begins to slide. The horizontal movement of the block is measured with a suitable means, rigidly attached to the wall at an initial distance of about 200 mm, so that the axis of the bases is directly next to the jack inserted into the masonry. The measurement of the bases, or rather the position relative to the centres of the disks can be obtained through electronic transductors of millimetric accuracy; the pressure is measured through digital meters of 0.1 bar. The measurement of the weight applied to the block is estimated from the pressure in the hydraulic circuit connected to the jack, and correlates with the deformation of the block itself until sliding occurs.



a) b)

Figura 5. Semi-destructive test carried out with a hydraulic jack: (a) removal of a masonry block; (b) insertion of hydraulic jack in the empty cavity.

It is reasonable to assume that sliding occurs along the horizontal mortar joints, subject to normal compression (fig. 6), whose value can be obtained on the basis of load, or rather on the basis of the results of a test with a single flat jack; normal compression along the back of the block is inexistent. Given a simplified hypothesis of elastic material, which is perfectly plastic, isotropic and homogeneous, and in general suitable to calculation models, the plastic phase equilibrium of the block is expressed as:

$$F_u = A_s(\tau_0 + \mu \cdot \sigma) + A_v \tau_0 \quad (2)$$

A_s Total area of horizontal mortar joints along which sliding occurs;
A_v Area of vertical posterior sliding surface;
τ_0 Ultimate shear strength in the absence of normal compression (cohesion);
μ Friction coefficient;
σ normal compression stress;

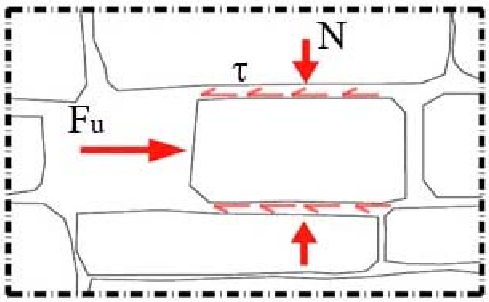


Figure 6: stress state on the stone subject to sliding.

In most investigations carried out, it has been noted that the posterior side of the block had no mortar, and therefore its relative contribution to sliding was negligible. Equation 2 has two unknown factors: the ultimate strength in the absence of normal compression, and the angle of friction. Shear strength depend by compression in the wall, so it is necessary evaluate ultimate shear strength (cohesion) in the absence of normal compression. In order to obtain this result and to calculate a single experimental value of friction coefficient it is therefore necessary to carry out two tests, on two walls belonging to the same masonry type, but subject to differing values of compression; the two walls may be on different floors of the building in case of same masonry type on two different levels, or there may be a central wall and a side wall in t case of differing masonry types on different levels (fig. 7).

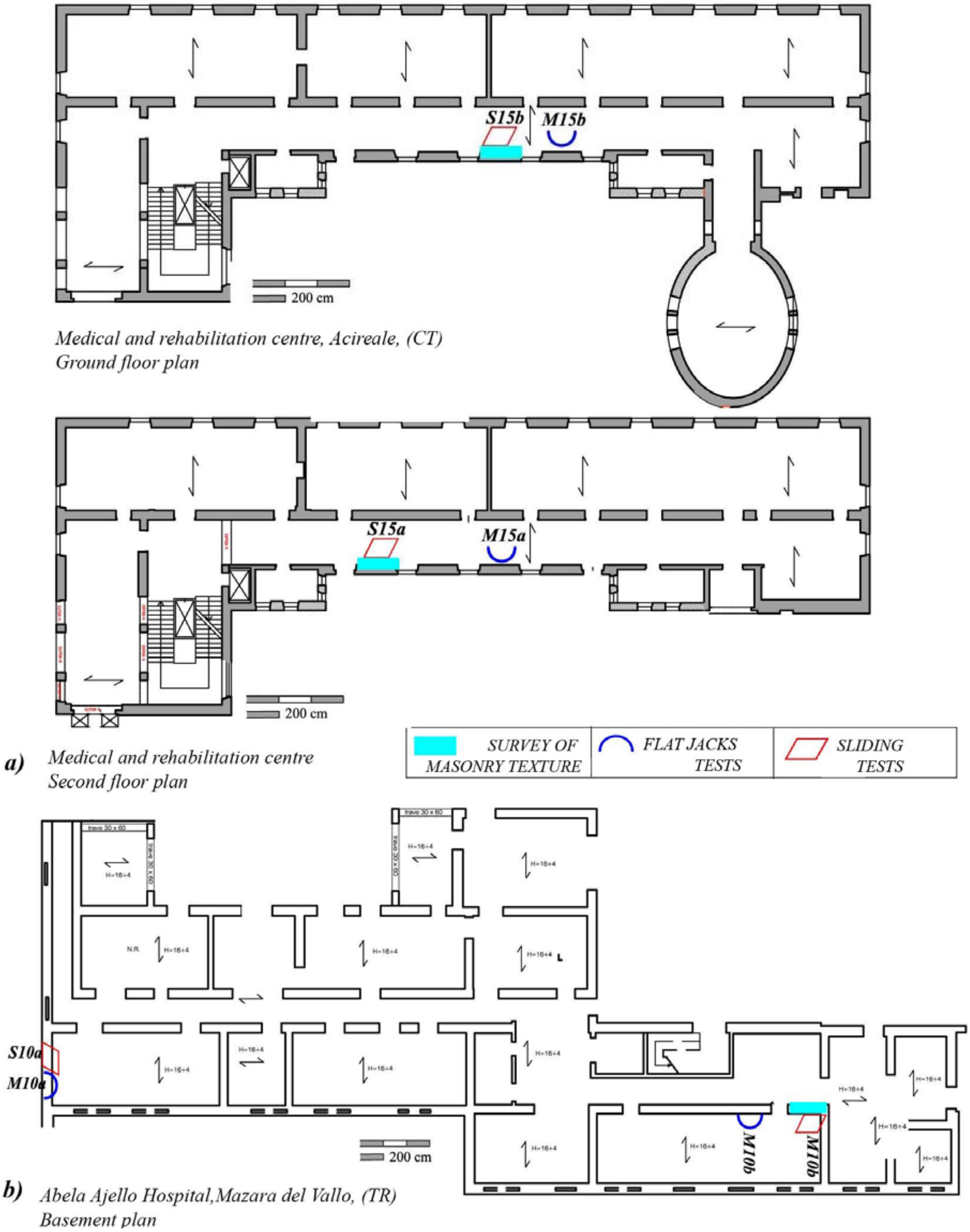


Figure 7. Example of location of on-site tests. The samples may be on different floors of the building in the case of the same masonry type on two different levels (a), or alternatively there may be a central wall and a side wall in the case of differing masonry types on different levels (b). Slide tests are indicated with code SiA and SiB; flat jacks tests with code MiA and MiB, where -i is the number of sample.

Every pair of values obtained in the tests is recorded on a diagram, having values of the shear stress and values of compression stress. In this way two points and a straight line are unequivocally obtained: the slant of the line indicates the angle of friction, while the interception with the vertical axis indicates cohesion. Values of shear stress and of compression stress obtained from sample n. 2 are summarised in table 2, where the letter S indicating the horizontal sliding tests, and the letter M indicating the jack tests for the calculation of the compression load. The diagrams of the tests carried out on wall sample n. 2 and their correlation are illustrated in figure 8.

Table 2- Experimental values obtained from tests on sample n.2.

sample	compression stressσ [MPa]	tangenzial stress τu [MPa]	attrito μ	Coesione τ_0 [MPa]
S2A	–	0,30	0,67	0,13
M2A	0,25	–		
S2B	–	0,24		
M2B	0,16	–		

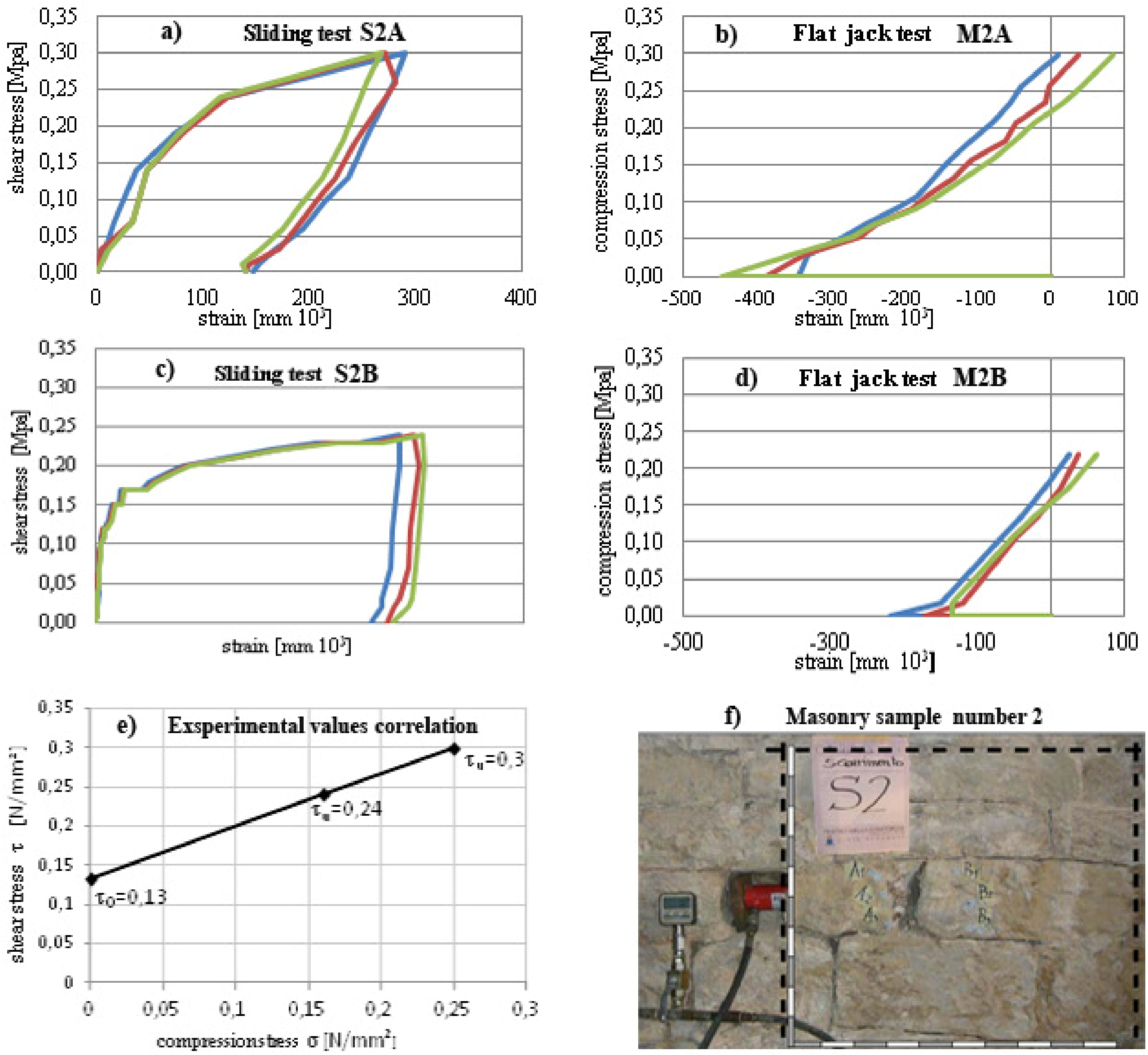


Figure 8. Diagrams obtained from tests carried on sample n.2: (a) sliding test S2A; (b) flat jack test M2A; (c) sliding test S2B; (d) jack test M2A; (e) correlation of values obtained by tests; (f) sample S2A.

Once you have two pairs of values for compression stress and for ultimate shear strength, the friction coefficient μ is calculated as following:

$$\mu = \frac{(\tau_{uSiA} - \tau_{uSiB})}{(\sigma_{iA} - \sigma_{iB})} \tag{3}$$

τ_{uSiA}, σ_{iA} values of ultimate shear strength and respective compression stress obtained from sliding tests S*iA* and flat jack test *MiA*, where -*i* is the number of the sample;

τ_{uSiB}, σ_{iB} values of ultimate shear strength and respective compression stress obtained from sliding tests S*iB* and flat jack test *MiB* where *i* is the number of the sample;

4. TEST RESULTS AND CORRELATION BETWEEN IQM AND EXPERIMENTAL FRICTION

Results of the investigation are reported in the Tables 3. The values of the experimental friction and the values of the index of masonry quality on the plane have been obtained for each type of stone block:

Table 3 – Results of experimental tests.

n° sample	masonry typology	τ_{uSiA}	τ_{uSiB}	σ_{iA}	σ_{iB}	μ	IQM
1	Square cut blocks in soft stone	0,27	0,21	0,18	0,08	0,60	5,25
2	Square cut blocks in soft stone	0,30	0,24	0,25	0,16	0,67	6,3
3	Square cut blocks in soft stone	0,30	0,23	0,29	0,20	0,78	7,0
4	Square cut blocks in soft stone	0,27	0,24	0,23	0,18	0,60	5,6
5	Square cut blocks in soft stone	0,32	0,28	0,23	0,153	0,52	5,6
6	Square cut blocks in soft stone	0,25	0,21	0,19	0,13	0,67	5,6
7	Square cut blocks in soft stone	0,15	0,11	0,22	0,156	0,63	4,9
8	Square cut blocks in soft stone	0,16	0,13	0,28	0,22	0,54	4,9
9	Square cut blocks in soft stone	0,23	0,32	0,18	0,36	0,50	4,9
10	Square cut blocks in soft stone	0,24	0,15	0,287	0,15	0,65	6,3
11	Rough cut blocks in lava stone	0,22	0,11	0,20	0,07	0,88	8,0
12	Rough cut blocks in lava stone	0,20	0,13	0,19	0,10	0,81	7,0
13	Rough cut blocks in lava stone	0,427	0,29	0,27	0,12	0,89	8,0
14	Rough cut blocks in lava stone	0,52	0,39	0,24	0,10	0,92	8,5
15	Rough cut blocks in lava stone	0,44	0,37	0,39	0,29	0,70	7,5
16	Rough cut blocks in lava stone	0,87	0,63	0,72	0,46	0,94	10,0
17	Rough cut blocks in lava stone	1,30	1,14	0,322	0,18	1,10	10,0
18	Rough cut blocks in lava stone	0,66	0,58	0,36	0,26	0,76	8,0
19	Rough cut blocks in lava stone	0,71	0,60	0,44	0,29	0,75	7,5
20	Rough cut blocks in lava stone	0,65	0,61	0,23	0,17	0,67	7,0

Early interpretation of the results confirms the assumptions made during the initial phase of the study, which are that friction coefficient values in literature cannot be assumed for all types of masonry. In fact, they are decidedly underestimated for the type of masonry walls examined with respect to the experimental data. Collected data has been used to identify interval values of the friction coefficient regarding the type of masonry structure in the object of this study. The aim is not to identify a certain unequivocal parameter, but to give information regarding the behaviour of masonry. The acceptable range of the friction coefficient values has been calculated for each type of wall masonry, eliminating the highest and lowest values, subtracting and adding standard deviation to the average of these values.

$$\Delta_x = \bar{x} \pm \sqrt{\frac{(\bar{x} - x_i)^2}{n-1}} \tag{4}$$

where:

$\bar{x}$	average value of experimental tests.
x_i	value obtained from each test
n	number of tests.

Below is a summary table of the values of friction coefficient μ_r thus identified (tab. 4).

Table 4. Acceptable values of the friction coefficient μ_r for the types of masonry in object.

Types of masonry	μ_r average	Standard deviation	μ_r acceptable values	
Cut soft stone	0,61	0,06	max min	0,65 0,55
Rough-cut lava stone	0,83	0,09	max min	0,90 0,70

The experimental test results have been used to calculate a correlation curve with identifying values of the wall quality. To this end, the values of experimental friction have been reported in a diagram together with the relative value of IQM on the plane. For each sample, an x-axis represents the IQM value and y-axis represents the friction coefficient value measured in the test. On the diagram the correlation is represented by the curve where the distance between the points representing the wall samples is shortest. The correlation thus established is shown in the exponential curve of the equation:

$$y = 0{,}303 \cdot e^{0{,}124\,x} \qquad (5)$$

The correlation curve has been obtained using all data available, therefore on the basis of a series made up of 20 values, an satisfying curve (fig.9) is observed. The correlation curve allows for the friction value to be identified, starting with the quality index on the plane. For example, having given an IQM value equal to 8 to a specific masonry wall, and then applying this value to the curve, a friction value of 0.83 will be obtained.

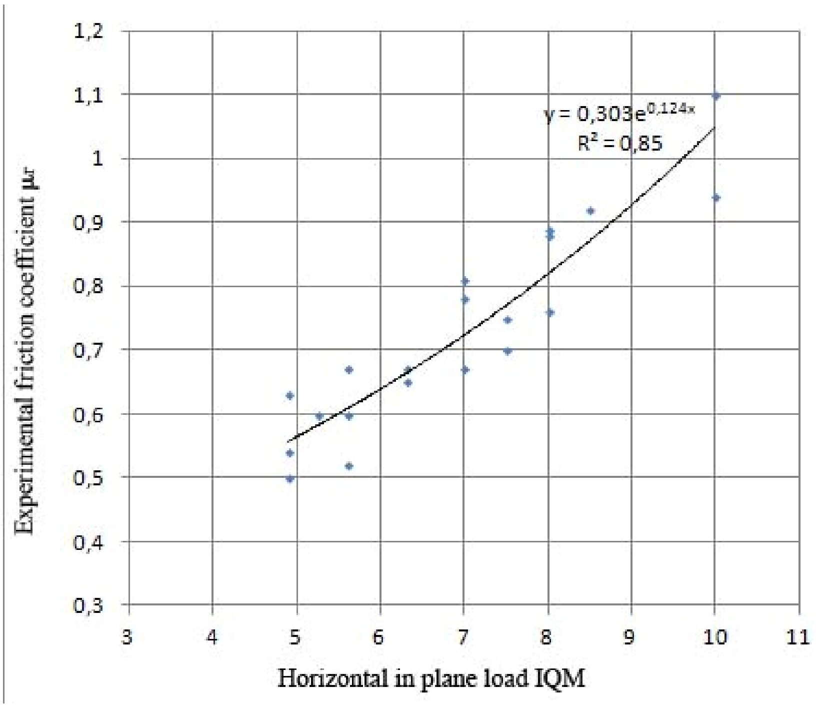


Figure 9. correlation curve between friction coefficient, obtained from experimental data, and IQM for horizontal in plane action stress.

The R^2 indicator (the maximum value assumed equal to 1) represents the measurement as far as the curve approximates the point values. It is calculated as follow:

$$R^2 = 1 - \frac{SSE}{SST}; \tag{6}$$

$$SSE = \sum (Y_i - Y_{Pi})^2 \tag{7}$$

$$SST = \sum (X^2{}_i) - \frac{\left(\sum X_i\right)^2}{n} \tag{8}$$

Yi: value of experimental friction for the i-st sample;
Ypi: value of friction foreseen in the correlation curve
Xi: value of IQM for the i-st sample;
n number of values available.

Conclusion

The contribution this study makes is that of providing a concrete indication for the evaluation of friction resistance relative to some characteristic Sicilian masonry types, in that, as has been shown, the values used in literature for the friction coefficient are usually underestimated. Experimental measurements have provided minimum and maximum intervals of values relative to the friction coefficients assumed by the type of objects being studied. Thus the study provides not a certain parameter but rather a behavior indicator, coherent with the approach of present-day technical norms on existing masonry. Furthermore, the aim is to demonstrate a correspondence between two different approaches which have until recently been seen as distinct: that based on qualitative analysis of wall masonry, and that of direct physical experimentation through mechanical tests. It has been shown how the correlation between the experimental friction coefficient and an evaluation regarding the quality of wall masonry is able to quite accurately predict experimental results on existing wall panels. Further experimental tests will be carried out to confirm the early results and to extend them to other wall types.

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