IJCS INTERNATIONAL JOURNAL OF CONSERVATION SCIENCE

ISSN: 2067-533X Volume 3, Issue 4, October-December 2012: 275-288 www.ijcs.uaic.ro

GROUTING OF MULTIPLE LEAF-MASONRY WALLS: APPLICATION ON SOME ISLAMIC HISTORICAL MONUMENTS IN CAIRO, EGYPT

Sayed HEMEDA*

Conservation Department, Faculty of Archaeology, Cairo University, Giza, Egypt

Abstract

Present study summarizes an overview on the available experimental and practical data and results from laboratory testing (ungrouted and grouted) three leaf masonry wallettes in compression and in diagonal compression. On the basis of the experimental results, (A) the structural behavior of the multiple leaf-masonry walls studied in details (b) the parameters that affect the behavior of ungrouted masonry are detected and commented upon, and (c) the behavior of grouted masonry studied in details. Particularly attention to be paid to large walls whose construction may comprise different kinds of materials. Such walls include cavity walls; rubble filled masonry walls and veneered brick walls which have poor quality core. Not only may the interior of the wall be less capable of carrying load but movement of the core material may also be a source of new stresses. As the experimental results show that the key parameter for the improvement of the mechanical properties of masonry is not the compressive strength of the injected grout, emphasis is given to ternary, as well as to hydraulic lime based grouts: those materials are expected to ensure durable interventions, they lead to a significant enhancement of the mechanical properties of masonry. On the basis of the experimental data on wallettes, as well as based on recent data from tests on grouted cylinders made of filling materials, simple formulae are drived, allowing for the strength of masonry to be calculated, and scientifically interventions processes and techniques had been applied to selected historical monuments in Cairo.

Keywords: *Islamic monuments; three leaf-masonry; grouting; ternary grout; hydraulic lime based grouts; compressive strength*

Introduction

Three or two-leaf (stone or brick) masonry constitutes a construction type that is very common in structures belonging to the built culture heritage all over the world especially in Europe and Islamic countries such as historic Cairo in Egypt: two external leaves (made of stone or brick masonry) are constructed with a void of varying thickness between them. The space between the two external leaves is filled with a loose, low strength materials made of small pieces of stones and/ or brick and mortar. This type of masonry is very vulnerable to various actions. In fact, as the bond between the external and interior leaves is deteriorated or lost with time (either due to decay of the materials due to vertical and horizontal in-and out-of-plane actions), masonry does not behave as a whole. The slenderness of the external leaves (that

* Corresponding author: hemeda@civil.auth.gr

resist the major part of any imposed action) is increased and the probability of severe damages or even collapse is enhanced, studies [1-5].

Grouting is one of the most common intervention techniques applied to improve the mechanical of the interior weak leaf mainly, as well as to re- instate the collaboration between the external and internal leaves in three leaf masonry. This technique was proven to be efficient and it is well accepted by conservators, although it is clearly a non-reversible technique. It should be noted that, although grouting is a technique applied to enhance the mechanical properties of masonry subjected to any kind of actions, the importance of both compressive and shear strength upgrading when historic structures are subjected to seismic actions can not be overemphasized.

Due to the importance of the subject, considerable research efforts was devoted to this technique during the last almost two decades. Both to design grouts adequate for injection into small voids and cracks and to measure the enhanced mechanical properties of masonry after grouting, L. Binda et al [6], R. Egermann [7].

This paper offers a survey of the practical and literature related to the mechanical properties of three- leaf masonry in compression or in diagonal compression before and after grouting.

The structural behaviour of multile- leaf-masonry walls

The behavior of any structure is influenced by three main factors: the shape and the connections of the structure, the construction materials and the actions. These factors are here examined in detail.

The structural scheme and damage

Structural behavior depends on the characteristics of the material used, the dimensions of the structure, the connections between different elements, the soil conditions, etc. The real behavior of a building is usually so complex that we are obliged to represent it with a simplified ‘structural scheme’; that is with an idealization of the building which shows, in a more or less precise way, its function in resisting the various actions. The structural scheme shows the way the building transforms actions into stresses and ensures stability.

A building may be represented by different schemes with a different complexity and different degrees of approximation to reality. The original structural scheme may change due to damage, reinforcement, or other modifications of the building. The scheme assumed for the calculations has to take into account any alterations and weakening, such as cracks, discontinuities, crushing, leanings, etc, whose effect may significantly influence the structural behavior. These alterations may be produced either by natural phenomena or by human interventions. The latter may include: the reduction of the bearing capacity due to the making of openings, niches, etc.; -the creation of unbalanced forces due to the elimination of arches, slabs, walls, etc.; the increase of the weight as a result of adding heights to the structure; the reduction of the soil capacity due to the excavations, galleries, nearby buildings, etc [8].

The material characteristics and decay processes

Material properties (particularly strength), which are the basic parameters for any calculation, may be reduced by decay processes because of chemical, physical or biological action. The rate of decay depends upon the properties of the materials (such as porosity), the way the structure is protected (roof overhangs, etc.). As well as its maintenance. Although decay may manifest itself on the surface, and so be immediately apparent from superficial inspections (such as efflorescence or increased porosity), there are also decay processes which an only be detected by more sophisticated tests (such a termite attack in timber) [9].

The actions on the structure and the materials

Actions are defined as any agent (force, deformations, etc.) that produce stresses and strains in the structure and any phenomenon (chemical, biological, etc.)That affects the materials, usually reducing their strength. The original actions, which occur from the beginning of the construction to completion of the building (dead loads, for example), may be modified during its life and it's often these changes which produce damage and decay. Actions have very different natures with very different effects on the structure and on the materials. Often more than one action (or perhaps unexpected modification of the original actions), will have affected the structure and this actions must clearly be identified before deciding the repair measures.

Actions may be classified as follows:

A. Mechanical actions. These, which are either static or dynamic, as described below, may be cause different kind of damage (cracks, deformations, etc.)

A.1. Static actions**.** These can be two kinds.

A.1.1. Direct actions (i.e. applied forces). These consist applied loads such as a dead load (weight of the building, etc.) and live loads (furniture, peoples, etc.) Changes in load conditions, mainly increases. Are sources of increased stresses and thus of damage in the structure. In some cases decreases in load conditions can also be source of damage to the structure.

A.1.2. Indirect actions (imposed deformations). These consist the deformations, such as soil settlements, imposed on the boundaries of the structure or produced within the body of the materials, such a thermal movements, creep in timber, shrinkage in mortar, etc. These actions, which may very continuously or cyclically, produce forces only if deformations and strains are not free to develop. The most important and often most dangerous of all indirect actions are soil settlements (produced by changes in the water table, excavations, etc.) and may create large cracks, leanings, etc.

A number of indirect actions are cyclic in nature, including temperature changes and some ground movements due to seasonal variation in ground water levels. While the effects produced may also be cyclic it is also possible for progressive deformation to be produced by such cyclic effects where each cycle produces some small but permanent change within the structure.

The temperature gradient between outer surfaces and the internal body may be the cause of differential strains in the material and therefore of stresses and micro-cracks, which further accelerate the decay.

The progressive reduction of the stiffness of the elements of and hyperstatic structure (weakening, decay processes, etc.), can also be regarded as an indirect action when this results in a redistribution of stresses.

A.2. Dynamic actions. These are produced when accelerations are transmitted to a structure. As a result of earthquakes, winds, hurricanes, vibrating machinery, etc. The most significant dynamic action is usually caused by earthquakes. The intensity of the forces produced is related to both the intensity of the acceleration and also to the natural frequencies of the structure and it is capacity to dissipate energy. The effect of an earthquake is not only a function of the forces generated but is also related to the history of previous earthquakes that may have progressively weakened the structure.

B. Physical, chemical, and biological actions. These actions are of completely different nature from those previously described. They may produce different kinds of decay and consequently change the properties of the material and so their strength.

Material properties may change over time due to natural processes characteristics of each material, such as the slow hardening of lime mortar or slow internal decay. These actions may be influenced and exacerbated by the presence of water (rain, humidity, ground water, wetting and drying cycles, organic growth, etc.) variations in temperature (expansion and contraction, frost action, etc.) and micro-climatic conditions (pollution, surface deposition, changes in wind speeds due to adjacent structures, etc.). Fire can be considered as an extreme change of temperature.

Structural Damage and Materials Decay

Structural damage occurs when the stresses produced by one or more action exceed the strength of the materials in significant zones, either as because the actions themselves have increased or because strength has been reduced by other actions like chemical and biological actions. Substantial changes in the structure, including partial demolition may also be a source of damage.

Manifestation of damage is related to the kind of actions and the construction materials, brittle materials will low deformations while ductile materials will exhibit considerable deformation before failure.

The appearance of damage, and in particular cracks, is not necessarily an indication of a risk of failure in a structure because cracks may relieve stresses that are not essential for equilibrium (as for example certain kind of cracks produced by soil settlements) and may, through changes in the structural system, allow a beneficial redistribution of stresses. However, immediate measures are required when damage produces irreversible alterations to historic buildings or when safety levels are compromised.

Damage may also occur in non-structural elements, e.g. cladding or internal partitions. As a result of stresses developed within those elements due to movement or dimensional changes within the structure.

Sometimes a structure does not consist of a single material; for example, steel or concrete frames may be infilled with brick masonry that may have an important stiffening function, masonry walls may be reinforced with metal or timber or may incorporate framed openings which act differently from the remained of the masonry and so affect the overall behavior. It is important to consider the relative behavior of these materials under load, both in the short and longer term, and their different weathering or decay characteristics.

Material decay brought about by physical, chemical, and biological actions and may be exacerbated when these actions are modified in an unfavorable way (for example pollution, etc.). The main consequences are deterioration of surfaces, loss of material and, from the mechanical point of view, a reduction of strength [10].

Mechanical properties of masonry before and after grouting

Available Experimental Data

Despite of the importance of the subject, the experimental data available in the literature are rather limited in number. It should be noted that only experimental results obtained from testing squat specimens (thus, representative of the behavior of masonry – material and not masonry-wall) are summarized and commented upon.

Various studies [1, 2, 11-13] have tested three-leaf stone or brick masonry wallettes in compression and/or in diagonal compression, before and after grouting. The grouts cover a wide range of combinations of materials (from cement-based to pure natural hydraulic lime grouts), as well as a wide range of basic mechanical properties. In table 1, geometrical characteristics of the wallettes, as well as mechanical properties of materials used for the construction of specimens are given, along with the main experimental findings.

Table 1. Geometrical and mechanical properties of: wallettes and main experimental findings [1-3, 11, 12].

		Mechanical Properties of Ungrouted Specimen			**Mechanical Properties of grouts**		**Mechanical Properties of grouted Specimen**			
Specimens	**Dimensions (m)**	f_t Mpa)(	ε_v (%)	W_{hor} (mm)	f_c Mpa)(	$f_{t,fi}$ Mpa)(	$f_{t,f}$ Mpa)(	$\varepsilon_{v,f}$ (%)	$W_{hor,ft}$ (mm)	λ_f
SDC1	0.8x0.8x0.4	0.47	0.9	0.85	15.9	3.4	0.50	1.36	0.47	1.1
SDC2	0.8x0.8x0.4	0.38	1.2	0.71	19.5	4.5	0.68	1.17	0.05	2
SDC3	0.8x0.8x0.4	0.28	1.5	1.20	7.8	2.5	0.59	2.65	0.02	2.1
BDC1	0.8x0.8x0.4	0.44	0.8	0.50	7.8	2.5	0.60	1.56	0.17	1.4
BDC2	0.8x0.8x0.4	0.34	0.3	1.07	15.9	3.4	0.73	1.07	0.02	2.2
BDC3	0.8x0.8x0.4	0.35	0.6	0.50	19.5	4.5	0.75	1.02	0.02	2.1
9		(0.15)			30		0.64			
10		(0.15)			30		0.64			
4	1.0x1.0x0.45	0.10	2.1	5.2	4.5	2.52	0.22	1.0	0	2.2
5	1.0x1.0x0.45	0.10	1.1	0.2	8.2	2.29	0.34	0.80	0	3.4
6	1.0x1.0x0.45	0.10	1.0	1.5	4.5	2.52	0.23	1.40	0.05	2.3
1	1.0x1.0x0.50	0.10	1.2	1.6	4.7	4.23	0.22	1.50	0.02	2.2
2	1.0x1.0x0.50	0.11	1.0	0.9	7.8	2.52	0.32	1.40	0.05	2.3
3	1.0x1.0x0.50	0.11	1.1	1.9	4.7	2.20	0.25	1.10	0.02	2.6
4	1.0x1.0x0.50	0.10	1.5	3	8.7	3.10	0.29	1.05	0.05	2.2

f_t and ε_v : Tensile strength and respective vertical strain of ungrouted specimen, f_c and $f_{t,fi}$: Compressive and flexural strength of grout, $f_{t,f}$ and $\varepsilon_{v,f}$: Tensile strength and respective vertical strain of grouted specimen, w_{hor} sum of vertical crack openings on the face of the ungrouted specimen (at f_t), $w_{hor,ft}$: sum of vertical crack openings on the face of the grouted specimens (at f_t), $\lambda_f = f_{t,f}/ f_t$.

Mechanics of three-leaf masonry in compression, before and after grouting

In three-leaf masonry is subjected to compression; the applied load is resisted mainly by the external leaves. In fact, the compressive strength (as well as the modulus of elasticity) of the filling material is normally by an order of magnitude smaller than that of the external leaves, by way of consequence, as proven experimentally by R.Egermann [7], as well as by L. Binda et al [6], the external leaves carry the larger part of the applied load. Furthermore, due to the incompatibility of deformations of the leaves, (a) the bond between masonry leaves and filling material may be broken and (b) the external leaves are subjected to horizontal (out-of-plane) deformations due to the larger lateral dilatancy of the filling material.

The latter is, on the contrary, under the beneficial confinement offered by the external leaves, thus improving somehow its poor mechanical properties. This behavior leads to the failure mode that was observed in all specimens subjected to compression: As the load on masonry increases, cracking is initiated both on the faces on the wallettes and on their sides. Vertical cracks on faces of the specimens pass through mortar joints or they cross also stones and bricks, depending on the relative strength of the materials. On the other hand, transverse (vertical) cracks appear along the interface between the external and internal leaves mainly, whereas in a number of cases, cracks open within the filling material as well. The mechanism leading to the failure of masonry can be detected if one observes the development on the vertical cracks in masonry.

In fact, as shown in table 1, the opening of transverse cracks is substantial larger than the opening of those appearing on the faces of masonry. This shows clearly that once transverse cracks are formed, each leaf behaves almost independently from the others. As the slenderness of each leaf is substantially larger than that of the whole element, out-of-plane deformation of the external leaves becomes apparent, as the compression load increases. The phenomenon is accentuated by the horizontal deformations imposed by the filling materials.

When masonry is grouted (using a high injectability grout) all voids and cracks are filled down to a size of some tenths of millimeter. The major part of the injected material improves the behavior of the filling material, as well as that of the interfaces, whereas, secondarily, the properties of the external leaves are also enhanced. Thus, masonry is more or less homogenized. As a result, (a) the contribution of the filling materials to the resistance against the compression loads is increased. Thus, the stresses on the external leaves are reduced. On the other hand, (b) the grout contributes to the enhancement of the bond along the interfaces between the consecutive leaves. As a result, the opening of (critical) transverse cracks is delayed and the compressive strength of masonry is enhanced, the delay in the appearance of transverse cracks is observed in experimental results. In fact, as shown in table1, although before grouting, transverse crack openings (W_{transe}) of the order of millimeters were measured at the moment of attainment of the compressive strength of ungrouted masonry ($f,_{wc.0}$), of the same value of compressive stress, the opening of transverse cracks in the grouted wallettes ($W_{transe},_{fwc0}$) is practically equal to zero. Nevertheless, when the resistance of (grouted) interfaces is reached, separation between leaves takes place and the final mechanism of failure is similar to that occurring in masonry before grouting or in thick single-leaf masonry.

Mechanical properties of ungrouted masonry in compression

On the basis of the experimental summarized in table 1, the following comments can be made:

(a) The compressive strength of masonry units is not a decisive parameter for the compressive strength of ungrouted masonry: compare, for example, the value of compressive strength of masonry measured by E.Ventzileou et al [2, 11] on wallettes made of stones having compressive strength equal to 100 N/mm^2, with those obtained by E.E.Toumbakari [12] (for compressive strength of stone equal to 55 N/mm^2) on the contrary.

(b) It seems that the compressive strength of the mortars and that of the filling material affect more the compressive strength of masonry. In fact, the wallettes tested by E. E. Toumbakari [12] reached, in general, higher compressive strengths than the wallettes tested by E.Ventzileou and T.P. Tassios [11] thanks to the higher compressive strength of both filling material and mortar.

(c) The values of compressive strength of masonry, measured on identical wallettes, present a difference of approximately 30% between the minimum and the maximum value. This fact is taken into account in section4, when the estimation of the compressive strength of masonry is attempted.

(d) The ratio of modulus of elasticity (measured at a stress level approximately equal to 0.3 $f_{wc,0}$) to compressive strength of ungrouted masonry seems to be very scattered (Fig. 1). However, as it is the case for modern masonries as well, most of the values of this ratio lie between 500 and 1500.

(e) The values of vertical strain corresponding to the compressive strength of masonry before grouting are very scattered, Figure 1b.

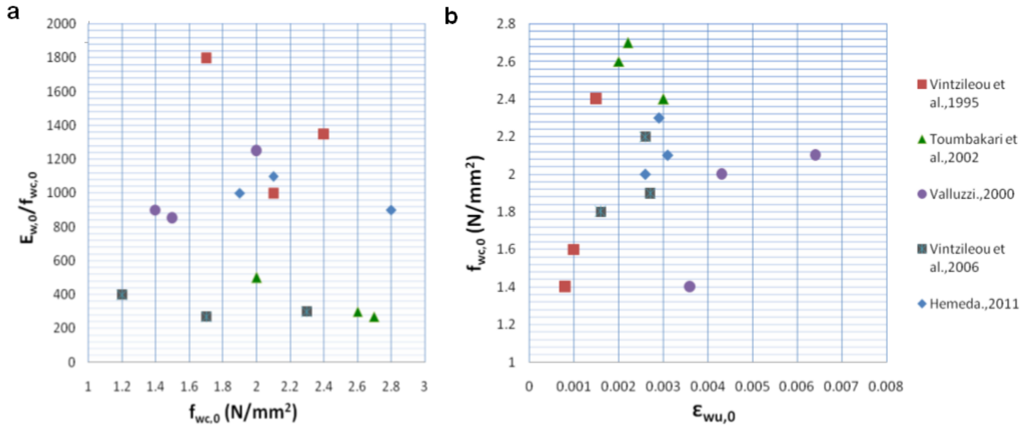

Fig. 1. Modulus of elasticity of ungrouted masonry, normalized to the compressive strength of masonry v.s compressive strength of ungrouted masonry(a) and relationship between the compressive strength of ungrouted masonry and the corresponding strain (b) [1, 2]

Mechanical properties of grouted masonry in compression

a. The data of table 1 prove that, as in the case of compressive strength of masonry before grouting, a difference of the order of 30% is observed between the minimum and the maximum compressive strength after grouting within each individual series of testing. This affects the degree of accuracy that should be sought for, when estimating the compressive strength of grouted masonry through any model (be in empirical or analytical).

b. Figure 2a, shows the relationship between the compressive strength of the grout and the respective compressive strength of grouted masonry. One may observe that there is a clear tendency of the compressive strength of grouted masonry to increase (almost linearly) with increasing compressive strength of grout, $f_{gr,c}$, when the latter does not exceed 10 N/mm^2 are ternary grouts with reduced cement content (less than 50%wt) or hydraulic based grouts, whereas cement based grouts exhibit compressive strengths between 15 N/mm^2 and 30 N/mm^2 .This important observation insinuates that the key property governing the mechanical properties of grouted masonry is not the compressive strength of the grout.

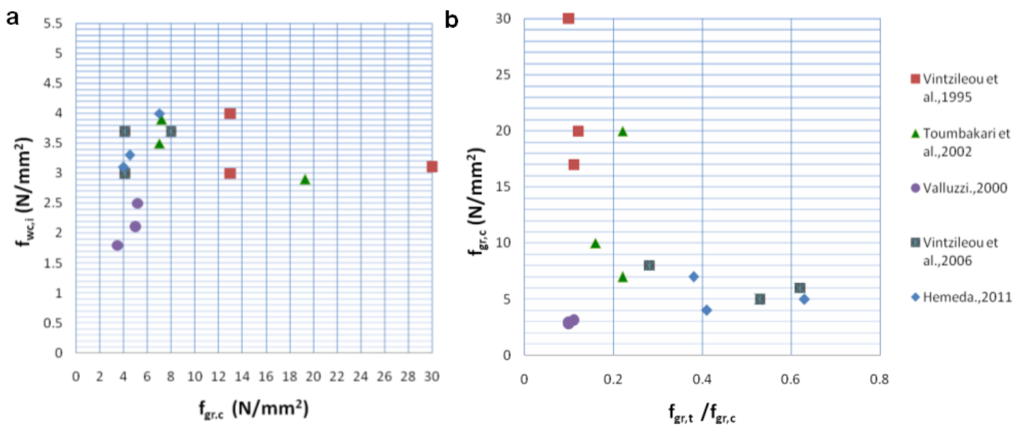

Fig. 2. Relationship between the compressive strength of the grout and the obtained compressive strength of grouted masonry (a) and ratio of tensile to compressive strength of grout as a function of compressive strength of the grout (b) [1, 2]

c. E.E. Toumbakari [12] made the works hypothesis that the key parameter for the improvement of the mechanical properties of three-leaf masonry is the bond properties of the interfaces between grout and in-situ materials, as improved bonding properties along the external leaves to filing material interfaces contribute to delayed opening of transverse cracks that lead to failure of masonry. In fact, shear tests on such interfaces, E.E. Toumbakari [12] have proven that the maximum bond resistance obtained by (lower compressive strength) ternary grouts was equal or even higher than the bond resistance by (higher compressive strength) cements grout to in-situ materials interfaces. This result was fully confirmed by a systematic experimental investigation conducted by C.E. Adami and E. Vitzeleou [1-3].

As bond properties depend on the tensile strength of the binding materials, one may expect a better correlation between the compressive strength of the grouted masonry and the tensile strength of the grout. A first positive sign for the validity of this assumption is the fact that, as shown in figure.2b, the ratio between compressive and tensile strength of grout is not constant. On the contrary, there is a clear tendency of the $f_{gr,t}$/ $f_{gr,c}$ ratio to increase for decreasing compressive strength of the grout. It should be noted that, as shown in the same figure 6, for compressive strength of grout varying between 3.0 and 10.0 N/mm^2 (corresponding to ternary and to hydraulic lime based grouts), the values of the $f_{gr,t}$/ $f_{gr,c}$ ratio, on the base of the available test data.

d. Furthermore, in figure 3a, the experimental compressive strength values are plotted against the tensile strength of the respective grout. Taking into account the differences from one series of tests to the others (in geometry, quality of materials used, construction details, etc), the quite linear correlation between $f_{wc,f}$ and $f_{gr,t}$ may be considered as satisfactory. This result (a) explains the fact that high compressive strength grouts are not as efficient as it might be expected from the mechanical point of view and, more important, (b) it proves that ternary and hydraulic lime based grouts, that are expected to satisfy durability requirements, may also enhance the mechanical properties of three-leaf masonry to a level that complies with the bearing capacity requirements set for historic structures.

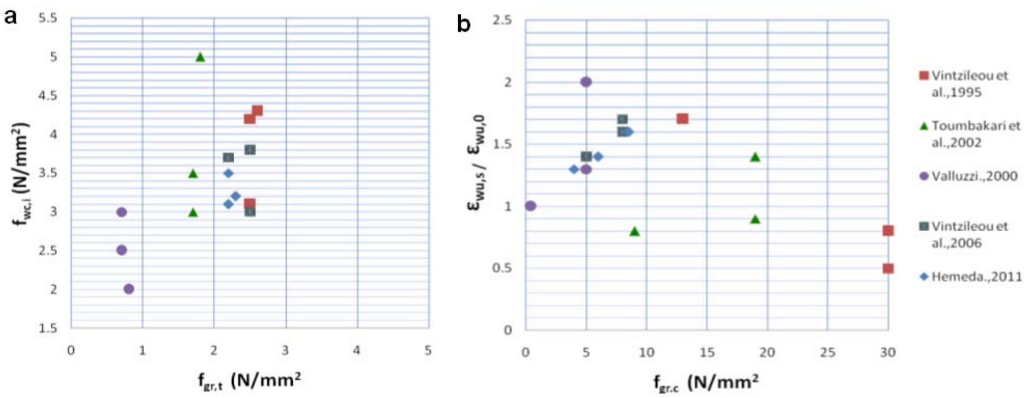

Fig. 3. Relationship between the tensile strength of grout and the obtained compressive strength of grouted masonry (a) and relationship between the compressive strength of grout and the strain at strength of grouted masonry normalized to the respective strain of ungrouted masonry (b) [1,2]

e. The experimental results show that, in general, the stiffness of the grouted masonry (expressed by means of the modulus of elasticity) is higher than the stiffness of the grouted wallettes, although the experimental results are quite scattered in this respect, the vast majority of $E_{wc,s}/E_{wc,0}$ values do not exceed 1.60. Furthermore, the data of table 2 show that strength enhancement is higher than stiffness enhancement. Thus, the ratio between the modulus of elasticity and the compressive strength of masonry after grouting is as a rule, smaller than the respective ratio before grouting.

f. Another important finding is illustrated in figure 3b: when a medium to low strength grout is used, i.e. a grout with reduced cement content or hydraulic lime based grout; the strain corresponding to the compressive strength of the grouted masonry is larger than that of the ungrouted masonry. The opposite occurs of case of cement based grouts. It seems, therefore, that grouting with cement based mixes leads to ore brittle behavior of masonry, whereas ternary and hydraulic lime based grouts allow masonry to sustain larger compressive strains before its maximum resistance is reached. This is another sign in favour of the use of low to medium strength grouts.

Mechanical properties of grouted masonry in diagonal tension or in shear

The effecting of grouting on the shear strength of three leaf masonry was measured either by testing walls under vertical loads and horizontal forces, M. Tomazevic et al, [14, 15] or by testing wallettes in diagonal compression. As shown in table 2, although the available results are rather limited in numbed, it is evident that grouting leads to substantial strength enhancement, in this case as well, it may be observed that the strength increase of the stress at failure obtained with medium to low strength grouts suggests that, in this case too, the decisive parameter is the bond between grout and in-situ materials.

M. Tomazevic and P. Sheppard [14] reached similar results through testing of walls in shear (under simultaneous vertical loads) the masonry was constructed in various ways to simulate those of historic structures in Slovenia. The walls were grouted with a cement grout. The authors found in most cases an increase of shear resistance varying between 110% and 250%, associate with a rather slight decrease of horizontal displacement at maximum shear resistance (between 10% and 30%). It should ne noted that, the walls, subjected to cyclic horizontal forces exhibited a quite stable behavior, without significant force response degradation for imposed angular distortions up to 1%.

It has to be noted that, the available experimental results regarding the shear behavior of ungrouted and grouted masonry or walls are rather scarce and they do not allow for reliable prediction of the efficiency of grouting to be made.

Prediction of compressive strength of three-leaf masonry before and after grouting

Analytical modeling of three-leaf masonry walls using finite element methods was attempted by several researchers, L. Binda et al [6-9], in several cases the researchers were able to reproduce experimental stress-strain curves quite accurately. Nevertheless, such valuable works, although they contribute to the understanding of the behavior of three-leaf masonry, did not yet yield sound engineering models that could be used in the design of interventions to historic masonries by means of grouts. Thus, there is still a need for simple physical models that would allow for the compressive strength of three-leaf masonry before and after grouting to be predicted. Although in case of major monuments it may possible or advisable to conduct tests, in order to determine the mechanical properties of masonry in reliable way, in the general case of interventions either to less important historic structures or to buildings belonging to urban nuclei, neither the time or the fund are available for such an experimental campaign. Therefore, the availability of simply (but physically sound) formulae is of great importance.

Estimation of compressive strength of three-leaf masonry before and grouting

Simple available formulae allowing for the estimation of compressive strength of grouted leaf masonry require the compressive strength of ungrouted masonry to be estimated as well. For this purpose, M.R. Valluzzi [16], suggests that the compressive strength of the external leaves can be measured in-situ, applying the flat jacks techniques. The compressive strength of the filling materials can be measured in the laboratory, on cores taken in-situ. Subsequently, am engineering model is needed, in order to calculate the compressive strength of three-leaf masonry.

The simple model, proposed by R. Egermann [7], could be used for this purpose. Nevertheless, according to this model, two parameters need to be estimated, in order to take into account the interaction between external leaves and filling materials, as described in figure 3. As stated by Egermann himself, however, the actual state of knowledge does not allow for accurate estimation of those two parameters.

T.P. Tassios, [18] derived closed formulae for the estimation of compressive strength of ungrouted masonry, based on model by R. Egermann [7] and taking into account the available experimental data. Formulae by Tassios proved to predict rather satisfactorily the compressive strengths measured by M.R. Valluzzi [16], E.E. Toumbakari [12] and E. Vintizileuo and T.P. Tassios [11].

Intervention techniques of multiple leaf masonry walls

On the basis of the experimental data on wallettes, as well as based on recent data from tests on grouted cylinders made of filling materials, simple formulae are drived, allowing for the strength of masonry to be calculated, and scientifically interventions processes and techniques had been applied to selected historical monuments in Cairo, Gonblat mosque and Rabaa, Kuttab and Sabeel Al-Qazzlar, Figures. 4-9.

Repointing of the existing structure:

- Injection of the existing double faced walls with hydraulic lime based grouts
- Reinforcing the wall with vertical, longitudinal or transverse reinforcement.
- Removal and replacement of decay material
- Dismantling and rebuilding, either partially or completely.

Fig. 4. Gonblat Mosque, Kutab and Sabeel in Cairo before restoration

Fig. 5. Gonblat Mosque,Kutab and Sabeel in Cairo. Grouting and injection processes.

Fig. 6. Gonblat Mosque, Kutab and Sabeel in Cairo. After restoration and intervention processes.

Fig. 7. Rabaa,Kutab and Sabeel Al-Qazzlar in Cairo. Before restoration and intervention processes

Fig. 8. Rabaa, Kutab and Sabeel Al-Qazzlar in Cairo. During restoration and intervention processes

Fig. 9. Rabaa, Kutab and Sabeel Al-Qazzlar after restoration processes

While interventions to address problems of both extensive cracking decay are often carried out by the appropriate fluid lime mortar to consolidate the structure (grouting). The selection of these (lime, cement, resins, special products, etc.) depends on the characteristics of the structure. Particular attention has to be given to the compatibility between original and new materials.

The use of cement-containing mortars should be avoided in the restoration of historic buildings. In walls built with gypsum- containing mortars, the reaction between gypsum and cement –minerals results in the formation of salts that sooner or later will lead to destruction. In other cases there may be a problem of leaching of soluble salts from the mortar resulting in efflorescence on the surface of brickwork, (particularly dangerous when there are historic plasters or frescoes) or there may be changes in the path of moisture through the wall.

A part from the consolidation of the material itself (by grouting when possible or by repointing) the most efficient measures to counter both the effect of vertical loads and internal pressures in rubble core walls are the use of ties made of appropriate materials.

Finally it has to be noticed that introducing other materials into the structure may locally modify its stiffness; and the possible significance of this alteration has to be taken into account. As a rule the use of reinforced concrete to strengthen historic buildings should be avoided.

Conclusions

The survey of literature presented in this paper allows for the following conclusions to be drawn:

- three-leaf masonry subjected to compression exhibited in all cases the same behavior and the same failure mode. Although there is a significant inherent scatter of the experimental data, the effect of parameters, such as mechanical properties of constituent materials, strength of filling materials, etc., on the compressive strength of ungrouted masonry was detected and explained.

- the positive effect of grouting on the compressive strength of three-leaf masonry, as well as on its overall behavior was proven by the totality of experimental results, furthermore,
- the preponderance of ternary and hydraulic lime based grout was demonstrated, as they offer significant enhancement of compressive strength, associated with substantial increase of the strain at strength. On the contrary, cement based grouts (of equal injectability and significantly higher compressive strength) do not contribute to further increase of the compressive strength of masonry, whereas they lead to a rather brittle behaviour.
- the advantages of ternary and hydraulic lime based grouts (due to their improved bond properties with the in-situ materials) become more important due to the durability ensured by the use of materials that are compatible with the existing ones from the physical-chemical point of view.
- simple empirical formulae, based, however, on the mechanics of three-leaf masonry were proven adequate for the prediction of the compressive strength of grouted masonry, it should be noted.

References

[1] E.N. Vintzeleou, *Grouting of three-leaf masonry: experimental evidence on compressive and shear strength enhancement,* **Proceedings of the 7th International Conference on Earthquake Geotechnical Engineering,** June 25-28, Thessaloniki, Greece, 2007, pp 477-488.

[2] E. Vintzileou, *Three-leaf Masonry in Compression, before and after Grouting: A Review of Literature*, **International Journal of Architectural Heritage**, 5, 2011, pp. 513–538.

[3] C.E. Adami, E.N. Vintzileou, *Interventions to historic masonries: Investigation of the bond mechanisms between stones or bricks and grouts,* **Materials and Structures,** RILEM**,** 2007.

[4] L. Binda., A. Saisi., R. De Benedictis., S. Tringali, *Exp. Study on the Damaged Pillars of the Noto Cathedral*, **Proceedings of the 8th International Conference STREMAH,** Halkidiki, Greece, 2003.

[5] L. Binda., A. Anzani., J. Pina-Henriques., R. Tongini Folli, *Sperimentazione su provini in muratura a tre paramenti,* **Workshop: Danneggiamento, conservazione e manutenzione di strutture murarie e lignee,** DIS–Politecnico di Milano, Italy, 2003.

[6] L, Binda., J. Pina-Henriques., A. Anzani., A. Fontana, *A contribution for the understanding of load transfer mechanisms in multiple leaf masonry walls: Testing and modeling,* **Engineering Structure, 28,** 2006, pp. 1132-1147.

[7] R. Egermann, *Investigation on the load bearing behavior of multiple leaf masonry.* **Proceeding IABSE Symposium "Structural Preservation of the Architectural Heritage",** Rome, 1993, pp. 305-312.

[8] L. Binda, A. Fontana, L. Anti, *Load transfer in Multiple leaf masonry walls* **Proceedings of the 9th International Brick Block Masonry Conference***,* Berlin, 1991, pp. 1488-1497.

[9] L. Binda., A. Fontana, G. Mirabella, *Mechanical behavior and stress distribution in multiple-leaf walls*, **Proceedings of the 10th International Brick Block Masonry Conference,** Caglary*,* 1994, pp. 51-59.

[10] L. Binda., A. Anzani., A. Fontana, *Mechanical behavior of multiple-leaf stone masonry: experimental research*, **Proceedings of the International Conference on Structural Faults & Repair,** London, 2003.
[11] E. Vintzeleou , T.P. Tassios, *Three leaf stone masonry strengthened by injecting cement grouts,* **Journal of Structural Engineering, 121**(5), 1995, pp. 848-856.
[12] E.E. Toumbakari., *Lime-Pozzolan-cement grouts and their structural effects on composite masonry walls*, **PhD Thesis,** Katholieke Universiteit Leuven, 2002.
[13] M.R. Valluzi, *Comportamento meccanico di murature storiche consolidate con materiali e tecniche a base di calce*, **PhD Thesis**, University of Trieste, 2002.
[14] M. Tomazivec, P. Sheppard, *The strengthening of stone masonry buildings for revitalization in seismic regions,* **Proceedings of the 7th European Conference on Earthquake Engineering,** Athens, Vol. 5, pp. 275-282, 1982.
[15] M. Tomazivec., V. Apih, *The strengthening of stone masonry walls by injecting the masonry friendly grouts,* **European Earthquake Engineering,, 1,** 1993, pp 10-20.
[16] M.R. Valluzi, **Consolidamento di murature in Pietra. Ineizioni di calce idraulica natural,** Collana Scientifica REFICERE, Gruppo Editoriale Faenza Editrice S.p.a., 2004, 128 p.
[17] T.P. Tassios, *Rehabilitation of three leaf masonry,* **Evoluzione nella sperimentazione per le costruzioni, Seminario internazionale, 26 sep-30 oct,** CENTRO Internationale di Aggiornamento Sperimentale- Scientifico (CIAS), 2004.
[18] M.R. Valluzi., F. da Porto., C. Modena, *Behaviour of multiple leaf stone masonry walls strengthened by different intervention techniques*. **Proceedings of the 3th International Seminar on Structural Analysis of Historical Constructions** (Editors P.B. Lourenco, P. Roca)**,** 2001, pp. 1023-1032.

Received: July, 27, 2012
Accepted: September, 10, 2012