Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Mechanical Properties of Three-Leaf Stone Masonry

Elizabeth Vintzileou
National Technical University of Athens, Department of Structural Engineering, Athens, Greece

Androniki Miltiadou-Fezans
Directorate for Technical Research on Restoration, Hellenic Ministry of Culture, Athens, Greece

Antigoni Vrouva
National Technical University of Athens, Postgraduate Program "Protection of Monuments", Athens, Greece

Sophia Anagnostopoulou
Directorate for Technical Research on Restoration, Hellenic Ministry of Culture, Athens, Greece

ABSTRACT: In order to obtain data regarding the mechanical properties of masonry in the Katholikon of Dafni Monastery, a testing program was carried out. Six three-leaf stone masonry wallettes (scale 2:3) were constructed using materials of similar characteristics as the in-situ ones. External and internal leaves were of different thickness and construction type, whereas mosaics were constructed to cover the internal face of masonry. Mosaics were connected to masonry through three alternative substrates. The experimental results have shown a typical for three-leaf stone masonry behaviour characterized by separation between external leaves and intermediate filling material. The obtained results regarding mechanical properties both in compression and in diagonal compression are presented and commented.

1 INTRODUCTION

Dafni Monastery, situated at approximately 10km from Athens on the way to Eleusis, is one of the major Byzantine monuments in Greece (UNESCO World Heritage, 1990). The Katholikon (main church) of the monument, famous for its mosaics, has suffered severe damages during the September 1999 earthquake that affected the region of Attica (Miltiadou et al., 2003a).

Within the framework of a strategic plan undertaken by the Hellenic Ministry of Culture for the conservation of the monument (its mosaics included), a series of research programs were carried out with the aim to acquire information that is necessary both for the assessment of the monument and for the subsequent stage of interventions, such as detailed survey and study of the pathology of the monument, identification and assessment of properties of the constituent materials, etc. Within those studies, considerable effort was devoted to the identification of the construction type of masonry, since it constitutes a key parameter for the assessment of mechanical properties of masonry and by way of consequence of the monument as a whole. Furthermore, decision-making regarding intervention techniques (e.g. feasibility of grouting), design of adequate intervention materials and estimation of post-intervention mechanical properties strongly depend on the construction type of masonry.

The type of masonry being determined in-situ, an attempt was made to estimate its compressive strength using empirical formulae available in the literature. The calculated strength values were unacceptably scattered, thus making unsafe or over-conservative (and in any case highly uncertain) the selection of any of the calculated compressive strength values. Taking into account the value of the monument and, hence, the need for more accurate information to serve the design of structural interventions, the decision was made to construct wallettes following the construction type of masonry as identified in the monument and to determine basic mechanical properties by testing.

The experimental program, as well as the main experimental findings are described and commented in this paper.

In a companion paper (Miltiadou-Fezans et al., 2006), the results of testing the wallettes after the application of grouts are presented.

2 CONSTRUCTION TYPE OF MASONRY

The systematic application of radar and boroscopy allowed for sufficiently accurate identification of the in-depth geometry of stone masonry (Vintzileou et al., 2004). As anticipated, the approximately 0.60m thick masonry of the upper part of the monument is a three-leaf masonry (externally unplastered, with the interior face plastered and in large part covered with mosaics); it presents some peculiarities, namely: (a) As shown in Fig. 1, the two exterior leaves are of unequal thickness (average thickness of the external and internal leaf equal to 180mm and 240mm respectively), (b) The external leaf is made of bigger stones than the internal one, whereas solid bricks are arranged along both horizontal and vertical joints in the external masonry leaf. The percentage of bricks in the internal leaf is substantially smaller and their pattern is random, (c) The thickness of stones in both leaves is varying, both in-length and in-height of walls. Thus, the thickness of the intermediate filling material (made of small size stones, fragments of bricks and mortar) is also varying both horizontally and vertically.

It should be noted that during the extensive repair works undertaken at the end of 19th century, when some parts of the monument were rebuilt (Miltiadou-Fezans et al., 2003b), the original construction type of masonry was followed. Mosaics belonging to collapsed or heavily damaged structural elements were removed and replaced after reconstruction. The technique used for bonding the mosaics to masonry was different than that applied by the Byzantine artists; this was taken into account in the testing program, as explained further on.

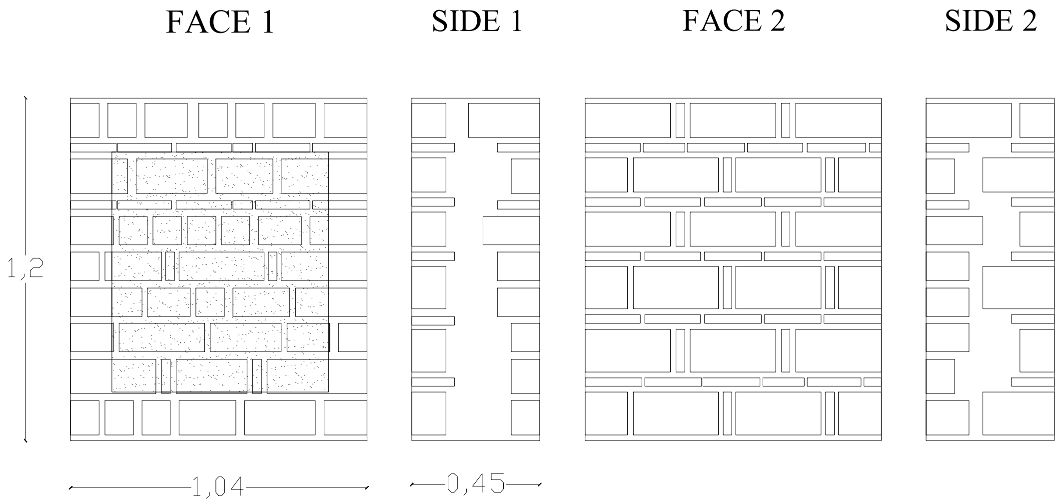


Figure 1 : Geometry of compression specimens (dimensions in [m]).

3 TESTING PROGRAM

3.1 Geometry

The geometry of the wallettes was chosen to simulate the upper and more vulnerable part of perimeter masonry in the Katholikon of the Dafni Monastery masonry. In order to avoid scale effects a scale 2:3 was selected. Six wallettes were constructed. Three of them (Wallettes No 1, 2 and 3) to be tested in compression, the remaining three (Wallettes 4, 5 and 6) to be tested in diagonal compression. The main geometrical characteristics of Wallettes 1 to 3 (Fig. 1) were as follows: Length=1.0m, height=1.2m, thickness=0.45m, external leaves thickness (average)=192mm and 135mm, internal leaf (filling material) average thickness=123mm. The respective geometrical data for Wallettes 4 to 6 (Fig. 2) were the following: Length=height=1.0m, thickness=0.45m, external leaves thickness (average)=182.5mm and 129mm, internal leaf (filling material) average thickness=138.5mm.

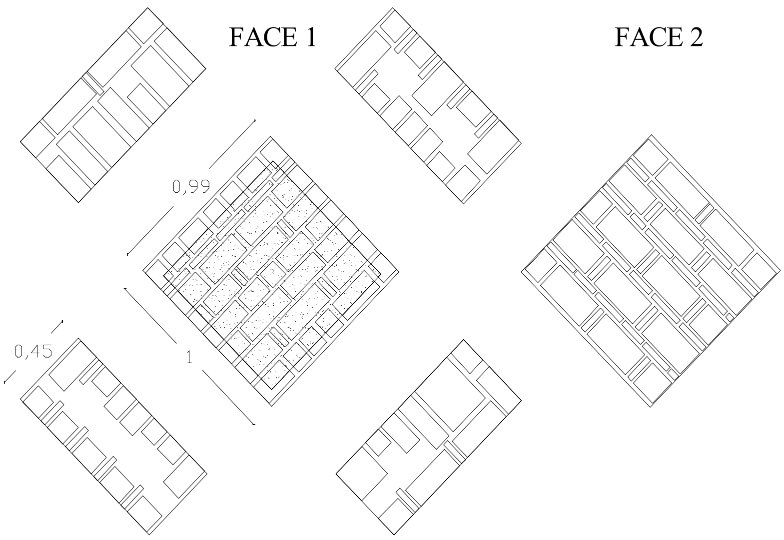


Figure 2 : Geometry of diagonal compression specimens.

3.2 Materials

In order to simulate the behaviour of the in-situ masonry, the materials to be used for the construction of wallettes were carefully selected. In Table1 some of the properties of the materials used within the testing program are compared with those of the in-situ materials (as assessed by means of laboratory investigation).

Table 1: Properties of stones in the monument; properties of travertine used in the wallettes

Stone type	Compr. strength (MPa)	Bulk density (g/cm^3)	Abs. water (%ΔB)
Fossiliferous marl limestone	23.0	1.97	18.0
Solid sandy marl sandstone	21.8	1.93	9.0
Travertine	25.0	2.1	5.0

Several types of stones were identified in the monument. Nevertheless, the most commonly used types were fossileferous marl limestone and solid sandy marl sandstone. A travertine having similar properties to those of the in-situ main type of stones (Table 1) was used for the construction of wallettes.

The new bricks used for the construction of wallettes had a mean compressive strength equal to 17.0 MPa (compared to approximately 15.0MPa for the in-situ bricks).

Based on the type of mortar encountered on the monument, a lime-pozzolan mortar was designed for the construction of wallettes with a mixed aggregate matrix composed of siliceous river sand and limestone gravels. More specifically: Lime putty and natural pozzolanic additive from Milos island were used as binding materials. The aggregates were siliceous river sand and coarse limestone aggregates with maximum diameter of 1.5-2.0 cm. The binder to aggregates ratio was 1/1.5. The lime to pozzolanic additive ratio was 1/1.5 as well. A water to binder ratio (w/b) of 0.65 was selected, in order to obtain mortars with a consistency of 15.5-16.0 cm. Specimens taken from the mortar during the construction of wallettes were tested at 1, 3, 6, 9, and 12 months after hardening. Since the wallettes were tested approximately three months after their construction, the tensile strength due to flexure and the compressive strength of the mortar at the same age are given here: 1.58MPa and 4.35MPa respectively.

The inner part of the wallettes was a mix of small stones (size 20 to 50 mm) and mortar (of the same mix proportions as the one used for construction of the exterior leaves) in a proportion of 2/1. This mix was poured in layers without compaction to fill the space between the external leaves. An average percentage of voids for the filling material was calculated to be approximately 40%, similar to that detected in-situ. The compressive strength of the filling material, measured on cylinders was approximately equal to 0.15 MPa at the time of testing the wallettes.

3.3 Mosaics

Following the common techniques of placing mosaics on masonry, mosaics models were prepared and placed on the face of wallettes simulating the interior leaf of the masonry, in order to check whether there is an effect of the substrate of mosaics on the after damage grouting of masonry (essential for the protection of mosaics).

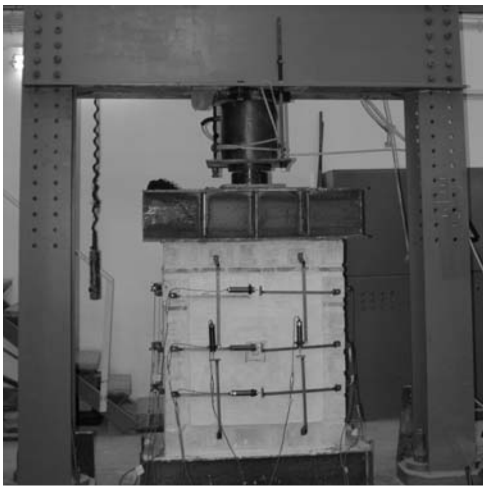
Three types of mortars were applied, namely: Byzantine (lime-straw) mortar (simulating the composition of authentic mosaics substrate-wallettes 1,4), lime-cement mortar (mid-20th century intervention-wallettes 2, 5) and natural hydraulic lime (NHL) mortar (with a binder of hydraulic nature similar to those revealed in the monument-"Novo" intervention-wallettes 3, 6).

Each substrate consists of two layers, the inner and the bedding layer, 3.5cm and 1.5cm thick respectively. The mosaics were prepared and placed on the wallettes by the Hellenic Ministry of Culture personnel, specialized in conservation of mosaics.

3.4 Testing set up and measurements

Wallettes subjected to compression were resting on a stiff steel beam (Fig. 3). An identical steel beam was resting on top of each wallette to allow for uniform distribution of the load applied by a hydraulic jack. Wallettes subjected to diagonal compression were resting on a steel corner element (Fig. 3); the load was applied through an identical steel corner element, using the same hydraulic jack. The deformations of wallettes were measured using LVDTs, as follows: For wallettes in compression, four LVDTs (two per face) were used to measure vertical deformations, six LVDTs (three per face at three levels) were recording horizontal deformations and vertical crack openings, whereas another six LVDTs (three per side at three levels) were installed to measure transverse deformations of wallettes and separation between exterior leaves and filling material. In wallettes subjected to diagonal compression, vertical deformations were measured by two LVDTs (one per face); horizontal deformations and opening of vertical cracks were measured by six LVDTs (three per face at three levels).

Since the wallettes were to be tested, grouted and retested, they were loaded up to their maximum resistance and unloaded before disintegration occurs.



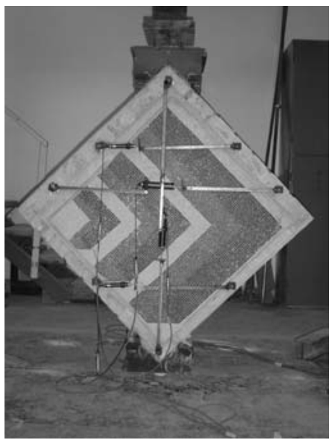


Figure 3 : Test set up for wallettes in compression and in diagonal compression.

4 EXPERIMENTAL RESULTS-WALLETTES IN COMPRESSION

4.1 Failure mode

Wallettes 1 to 3 exhibited the same failure mode, illustrated in Fig. 4: Vertical cracks opened on the two faces of wallettes, crossing mortar joints and stones. The vertical cracks were apparent on the mosaic as well (see Face 1 in Fig. 4), whereas partial debonding of mosaics from masonry occurred.

The specimens exhibited the characteristic for three-leaf masonry separation between the external leaves and the interior filling material (observe vertical transverse cracks, Sides 1 and 2, in Fig. 4). It should be noted, however, that transverse cracks appeared not only at the interface of the external to the interior leaf: In fact, there are cracks passing within the filling material; cracking of protruding stones was also observed.

It has to be mentioned that a systematic difference was observed in the degree of cracking in the two opposite faces of the wallettes. This is partly due to the inevitable eccentricity of the applied load. It is, however, believed that this behaviour is mainly due to the inherent eccentricity of wallettes that reproduces the real in-situ conditions. In fact, the two external leaves were of different construction type, of unequal average thickness and made of different in size stones.

4.2 Stress-strain and stress-crack opening curves

In Fig. 5a, vertical stress-vertical strain curves are shown for Wallettes 1 to 3. The curves reported in Fig. 5a constitute average curves obtained from the four vertical LVDTs on the two faces of wallettes. Table 2 summarizes the experimental results. It seems that the scatter of the experimental results lies within the margins expected for masonry for both the compressive strength and the initial modulus of elasticity (E_0 denotes the inclination of the initial linear part of the vertical stress-vertical strain curve).

In Fig. 5b, the curves of compressive stress-horizontal deformation at mid-height of specimens are presented. It should be noted that horizontal deformations are given in (mm), since they represent the total opening of vertical cracks that appeared on the faces of each wallette. The main characteristic of the behaviour of three-leaf masonry can be observed by comparison of curves plotted in Fig. 5b with the curves presented in Fig. 6. In fact, the total opening of vertical cracks on the faces of wallettes was at maximum equal to ~1.6mm. On the contrary, transverse deformations (i.e. opening of cracks between external leaves and filling material) reached values between 4.0 and 8.0mm. This shows clearly the primary cause of failure of this type of masonry.

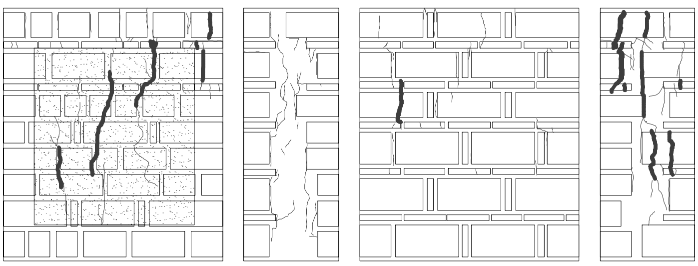


Figure 4 : Typical failure mode of wallettes in compression; Wallette 3

Table 2 : Summary of results of compression tests

Wallette	σ_{max} (MPa)	ε_v ($^0/_{00}$)	E_0 (GPa)	E_0/σ_{max}
1	1.82	*	1.0	594.45
2	1.74	-1.6	1.44	827.59
3	2.26	-2.25	1.5	663.72

(*) Unreliable measurements of some of the LVDTs

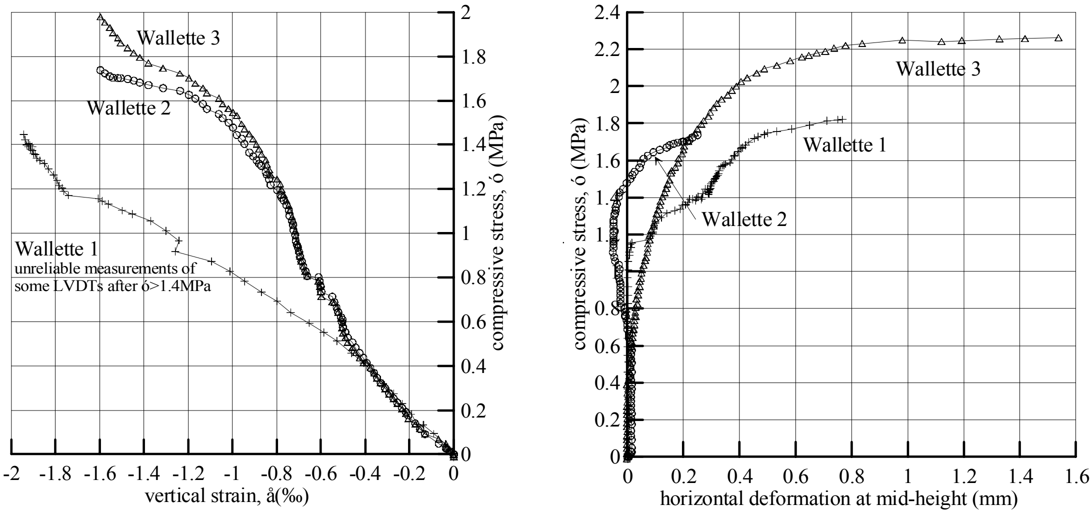


Figure 5 : Wallettes 1 to 3, (a) Vertical stress-vertical strain curves, (b) Vertical stress-horizontal deformations at mid-height of the specimens

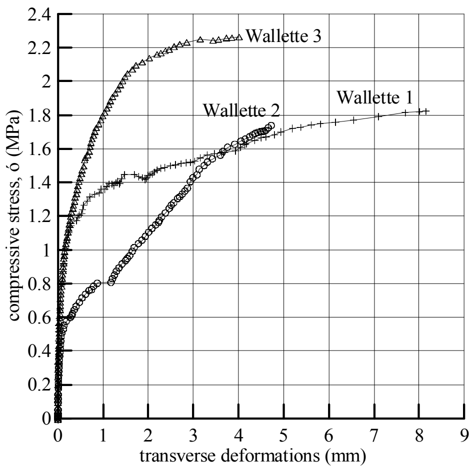


Figure 6 : Transverse deformations of Wallettes 1 to 3, subjected to compression

5 EXPERIMENTAL RESULTS-WALLETTES IN DIAGONAL COMPRESSION

5.1 Failure mode

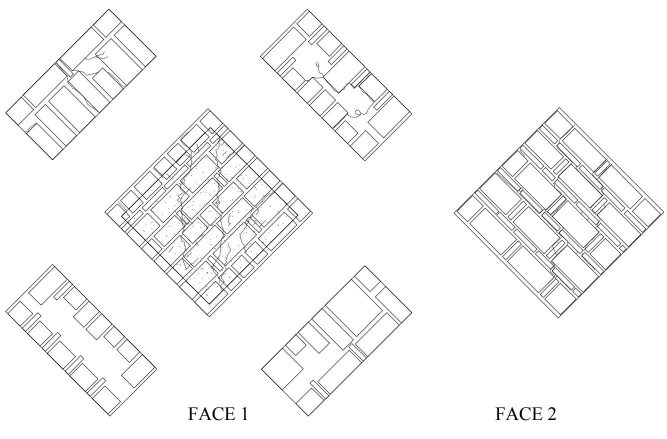


Figure 7 : Typical failure mode of specimens subjected to diagonal compression: Wallette 4.

Figure 7 shows the typical failure mode of wallettes subjected to diagonal compression. It is interesting to observe the difference in cracking pattern between the two faces of the specimens: On face 1 (simulating the interior leaf of the wall made of rather small stones) the cracks parallel to the loading axis appear as more or less continuous lines; on face 2-made with larger stones-the cracks follow the path of horizontal and perpendicular mortar joints. Some minor cracks appeared also between the external leaves and the filling material.

5.2 Stress-strain and stress-crack opening curves

In order to calculate the tensile strength of masonry (from the load applied diagonally to the specimens), the well known formula $\sigma=2P/\pi A_w$ was applied (P denotes the vertical load and A_w is the vertical area of the specimen). As shown in Fig. 8, Wallettes 4 to 6 reached almost equal tensile strengths (~0.10MPa), under vertical strains comparable to those recorded in the case of Wallettes 1 to 3. On the contrary, the value of vertical cracks opening at maximum stress seems to be quite scattered.

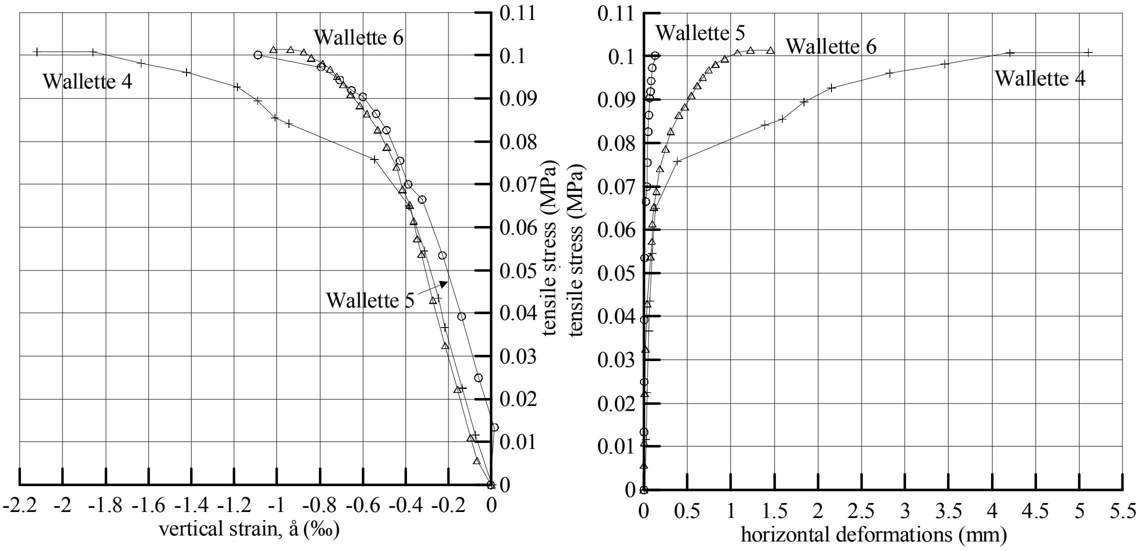


Figure 8 : Wallettes subjected to diagonal compression, (a) tensile strength-vertical strain curves, (b) tensile stress-horizontal deformation at mid-height of specimens

6 COMPARISON WITH DATA FROM LITERATURE-CONCLUDING REMARKS

Table 3 summarizes the main results of tests on three-leaf stone masonry walls available in the literature. The results of the present work are also included. It may be observed that, although the mechanical properties of constituent materials (especially of the stones) used in various researches vary substantially, the compressive strength of masonry does not vary considerably. This might be attributed to the fact that the separation between external leaves and infill material is the governing mechanism. This mechanism depends on the strength of the infill material, as well as on the bond between infill material and masonry, rather than on the strength of stones. Regarding the behaviour of masonry in compression, the results of this work seem to be in accordance with those available in the literature. There is, however, a substantial difference with the results by Toumbakari (2002) regarding the tensile strength as measured on wallettes subjected to diagonal compression. This difference can be explained by the substantial difference in mechanical properties of the inner filling material between the two series of tests (1.0 and 0.15MPa respectively).

On the basis of the work presented in this paper, it may be concluded that although the mechanism of developing compressive and tensile strength of three-leaf masonry is known, further experimental work is needed, in order to assess the effect of major parameters (such as bond between constituent materials). For the case of monuments and historic buildings in earthquake prone areas, the shear behaviour of three-leaf stone masonry should also be studied. Last but not least, there is an urgent need for developing physical models describing the behaviour of this vulnerable type of masonry under various types of actions. This is a subject of paramount importance for a rational assessment of the state of old masonries, as well as for their rational design after strengthening, especially by grouting.

Table 3 : Comparison of main test results with available literature

	Strength of materials S/M/I (MPa)	Thickness of leaves E/I/E (mm)	Compressive strength (MPa)	Modulus of elasticity (MPa)	Tensile strength (MPa)
Valluzzi	160/1.6/?	180/140/180	1.70/1.94	2210/1506	
Toumbakari	55/3.4/1.0	130/140/130	2.02/2.09/ 2.65/2.71	720/1139/ 1375/1443	0.47/0.34/ 0.28
Vintzileou-Tassios	100/1.7/0.15	130/140/130	1.60/1.70/1.35	4402/5670/5625	
This work	25/4.35/0.15	192/123/135	1.82/1.74/2.26	1000/1440/1500	0.10

S/M/I: Stone/Mortar/Infill, E/I/E: External leaf/Infill/External leaf

ACKNOWLEDGMENTS

The continuous support of Prof.T.P.Tassios, as well as the contribution of N. Delinikolas, N. Minos, D. Chrissopoulos E. Anamaterou and F. Georganis, E. Zarogianni, V. Sideraki, A. Kordoulas (Hellenic Ministry of Culture) and A. Zagotsis (NTUA) is gratefully acknowledged.
The project was included in the Operational Program "CULTURE". It is funded by European Regional Development Fund (ERDF-75%) and by National Funds (25%).

REFERENCES

Miltiadou-Fezans A., Tassios T.P., Delinikolas N., Chorafa E., Zarogianni E., Chandrinos I. 2003. Earthquake structural problems and urgent measures undertaken to support the Katholikon of Dafni Monastery in Athens, Greece. *Proceedings of the 8th International Conference STREMAH 2003: Structural studies, Repairs and Maintenance of Heritage Architecture,* Halkidiki, Greece.

Miltiadou-Fezans A., Delinikolas N., Chorafa E., Zaroyianni E. (2003b). Study on restoration of the Katholikon of Dafni Monastery, Phase A - Structural Survey, Analysis and remedial measures, Ministry of Culture (in Greek)

Miltiadou-Fezans A., Vintzileou E., Papadopoulou E., Kalagri A. 2006. Mechanical properties of three-leaf stone masonry after grouting. Submitted to the *5th International Seminar on Structural Analysis of Historical Constructions.* New Delhi, India

Toumbakari E.-E. 2002. Lime-pozzolan-cement grouts and their structural effects on composite masonry walls. Doctor Thesis, Katholieke Universiteit Leuven,

Unesco, World Heritage Centre, 1990. Year of inscription of Dafni Monastery: List of monuments, see http://whc.unesco.org/en/list/537,

Valluzzi M.-R. 2000. Comportamento meccanico di murature storiche consolidate con materiali e tecniche a base di calce. Doctor Thesis, University of Trieste.

Vintzileou E., Tassios T.P. 1995. Three leaf stone masonry strengthened by injecting cement grouts. *Journal of Structural Engineering, ASCE,* Vol. 121, No 5, pp. 848-856.

Vintzileou E., Miltiadou-Fezans A., Palieraki V., Delinikolas N. 2004. The use of radar techniques and endoscopy in investigating old masonry: the case of Dafni Monastery. *Proceedings of the 4th International Seminar on Structural Analysis of Historical Constructions.* Modena C., Lourenco P.B., Roca P. (ed.), Rotterdam, Balkema, Vol. 2, pp. 351-360