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ASSESSMENT OF PHYSICAL AND MECHANICAL PROPERTIES OF HISTORICAL AND TRADITIONAL MASONRY BUILDINGS: A CASE STUDY

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Abstract

Historical buildings demand a full characterization of the materials used for their construction, before any rehabilitation action. The assessment of the mechanical characteristics of the masonry materials is based on visual observation, sampling of the construction materials and laboratory testing of the samples. The work described is concerned with the rehabilitation of a traditional masonry house in Athens which over the years suffered damage due to various causes. The paper describes the early preliminary stages of the rehabilitation work concerned with the description of the structural system, the mapping of damage and the documentation of the materials used.

Keywords: *Building materials; Cracking; Damage; Deterioration; Structural assessment; Traditional masonry building.*

Introduction

It has become customary to classify as traditional buildings all buildings constructed without a formal design process. Their form, plan and method of construction simply follow a tradition developed with time at the place of their construction [1]. Masonry is a non-homogeneous material comprising blocks, natural (stones) or manufactured (bricks), and a series of mortar joints arranged either irregularly (in stone masonry) or regularly (in brickwork) [2-4].

Traditional ways of building have evolved, one person learning from another. Changing circumstances have led to changing solutions and along the line influences from other cultures have gradually been blended in. At any given point in time, there have been shared values, shared customs, local materials and local ways to use them and the learning process has always been to build on the past [5]. Historic traditional buildings are constructed from old materials that are rarely used in the majority of buildings constructed today.

The main distinction between historic and contemporary buildings results from the fact that labour was comparatively cheap in the past and the transportation of materials difficult and expensive when compared with current costs. Past building practices are now regarded as

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craftsmanship, and this difference between traditional and modern construction practice increases the value of our historic buildings, as the latter are part of our cultural heritage, and, thus an irreplaceable resource. All historic buildings, large or small, complex or simple, make a contribution to the quality of our life by informing us of our past, the lives and achievements of our predecessors.

There are significant variations in construction methods, materials and structural elements connections. In general, the historic traditional houses in Athens have slightly square or rectangular in-plan geometry, with two or three floors at most. Their first floor elevation is usually the highest, with that of the third floor, if existing, being the shortest (see Fig. 1). Most of these building are constructed with rubble ashlars masonry stones which may have polished, droved or broached finish [6].

Fig. 1. Typical two and three floor houses in Athens with different floor elevation heights

Their load-bearing walls are one of two types, single-leaf type or three-leaf type (with two discrete external leafs and an infill material with a large void ratio), with thicknesses less or more than approx. 700mm, respectively [6].

The building that forms the subject of the case study presented herein is located at the intersection of Aktaiou and Lykomidon streets and will be referred to as 'Aktaiou' building, thereafter. It was built in the early 1900's and it is considered to represent the structural and architectural trends prevailing in Athens this period. Over the years, this house (see Fig. 2) has suffered significant damage due to various causes, such as seismic excitation, lack of maintenance, construction defects, etc.; now it is in the process of being rehabilitated and converted into a cultural centre.

Fig. 2. The main facade on the Aktaiou Street

Structure

General description

The Aktaiou building is a two-storey masonry building with basement; the bearing walls forming part of its structural system are shown in figure 3, which also shows the wall names

adopted for the work. The facade of the building lies in Aktaiou Street (wall 1) and has a length of 18.40m (Fig. 4); its left-hand side face (wall 2), which lies in Lykomidon street, has a length of 18.00m, whereas its right-hand side face (wall 3) sees in an internal open space and has a length of 17.00m. Wall 4 is essentially forms the fence separating the building from the adjacent property.

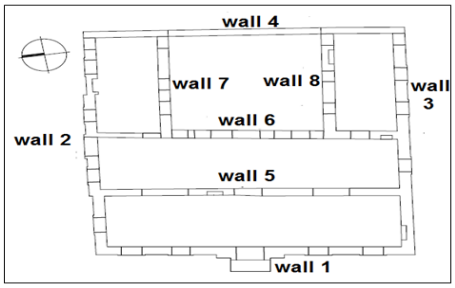

Fig. 3. Bearing masonry wall system

Fig. 4. Building façade: a - wall 1, b – wall 2 (Northern face)

The basement extends within the part of the plan enclosed by walls 1, 5 and parts of walls 2 and 3. The in-plan geometry of the building has a U shape with a central part (CB) extending between walls 1, 6, 2, and 3 and two wings extending between walls 6, 4, 2, and 7 (W1) and walls 8, 3, 6, and 4 (W2), respectively. An open space forms between walls 7, 8, 6 and 4.

There are a number of internal walls which, as discussed later, are classified as bearing or partition walls depending on the wall width. The timber floors are supported by wooden beams simply-supported at the opposite walls, whereas the roof is supported by a simply-supported truss system (Fig. 5 and 6).

Fig. 5. Building's roof: a – central roof 1, b – wing roof

Fig. 6. The truss: a – central roof 1, b – wing roof

Structural walls

The structural walls have a width that varies from 0.5 m up to approximately 0.7 m. They were built with inert semi-chiseled stones, bound together with mortar, in two interlocking layers. More specifically, the materials used for building the masonry walls were as follows:

- **Limestone**(**LS**) – semi-chiseled or chiseled stones used as corner stone's or for strengthening the sides of wall openings (doors or windows)
- **Marble**(**MS**) – of irregular shape and varying sizes being one of the constituents of the parts of the masonry between wall openings and wall corners,
- **Volcanic stone**(**VS**) – encountered in the walls of the 1st floor in between limestone and marble stones , and
- **Mortar** (binding material) – containing a large quantity of sand and a significantly smaller quantity of lime

The connection between the main bearing walls was effected not only through the use of large pieces of limestone (corner stone's), but also through the use of steel connectors (short anchor elements) which improve the connection of walls orthogonal to each other.

Floors

Both the ground level and the 1st storey floors were made of 17cm high x 11cm wide timber beams arranged in parallel at distances of 50cm, covered with 21cm wide x 2.5cm thick planks. The beams are simply supported within recesses formed in opposite walls (Figs 7, 8, 9 and 19).

Fig. 7. Typical galleries looking in the internal open space with temporary prop

Fig. 8. Typical damage of main bearing walls from left to right and top to bottom – Cracking of wall 3 (ground floor); Lintel cracking of wall 1 (1st floor); Vertical crack of wall 6 near wall connection (1st floor); Cracking of wall 2 at top of building

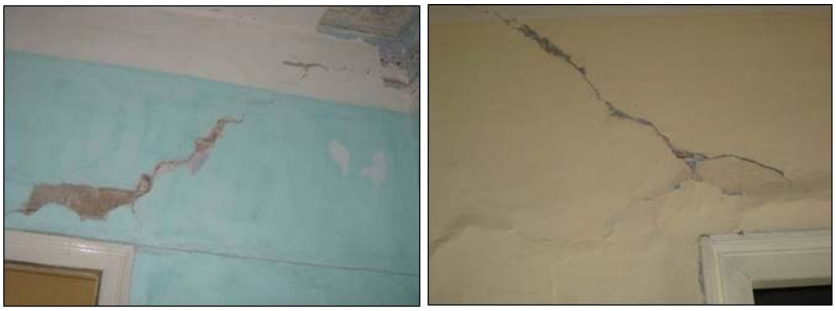

Fig. 9. Typical diagonal cracking of secondary walls

Fig. 10. Excessive truss deflection and typical failure of truss member

Roof

The roof of the central part of the building (CB) is two-way supported and comprises single and double slope trusses, whereas the roof of the wing parts (W1 and W2) of the building are one-way supported and comprise double slope trusses. The latter comprise one vertical and two inclined struts, a horizontal tie and two diagonal struts as indicated in figure 6. The inclined struts of the trusses support 2 cm thick purlins extending in parallel to the supporting walls, with the purlins being covered by planking which underlies the byzantine tiles. The trusses of the wing roofs comprise inclined struts and horizontal tie only. Although carpenter connections were formed for the truss members, steel connectors were also used in certain cases.

The stair steps of the main entrance to the building are made of marble stones, whereas the internal staircase is made of timber. The balconies on the faces on the Aktaiou and Lykomidon streets are made of marble plates supported on marble cantilevers. The galleries looking in the open space forming between the building's central and wing parts essentially form extensions of the 1st floor and roof beams, and they are currently in a state of collapse (Fig. 7).

Damage identification and mapping

From visual observation, it has been established that the building did not suffer any significant structural damage in the perimeter masonry walls, such as crushing or sliding, swelling, out-of-plane displacements, loss of mass, deep cracking, collapse of corner wall connections, etc. The damage suffered as a result of aging, construction faults, lack of maintenance, seismic and environmental actions may be broadly described as follows (see Figs. 8 to 10):

- Inclined and vertical cracking with a relatively small width not extending throughout the wall thickness
- Fragmentation of masonry mortar
- Extensive detachment and loss of wall plaster
- Failure in localized regions and large deflections of the bearing members of the roof structure
- Collapse of timber balconies

Documentation

Sampling

The main materials used for the building construction are limestone, marble and volcanic stones and mortar. The sampling included all types of stones. It was effected either by carefully removing relatively small stones through the use of chisel or by drilling cores out of larger stones.

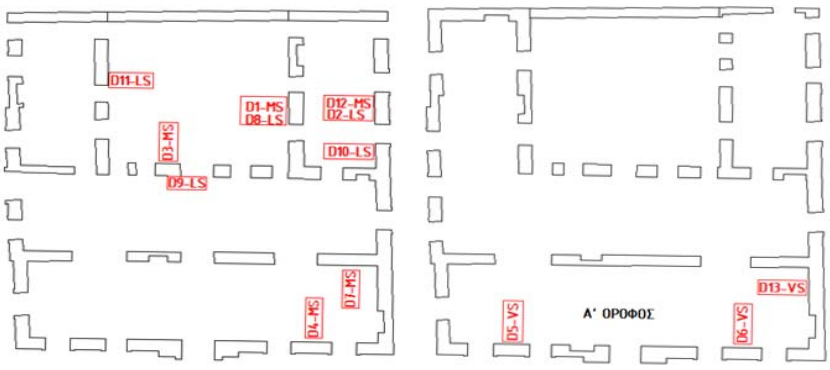

Fig. 11. Location of sampling at the ground floor and at the 1st floor

The material and specimen types are provided in Table 1 and the locations of sampling in figure 11.The precise locations of materials sampling (stones and mortar) are shown in figure 12. It must be noted that from the in-situ examination the mortar was found weak and friable (Fig. 12c) and, as a result, it has not been possible to obtain any samples.

a b c

Fig. 12. Precise locations of sampling specimens D7-MS (a) and D10-LS (b), and physical state of mortar sample (c).

Table 1. Type of samples and location of sampling

Specimen name	Material type	Specimen type	Sampling location
D1-MS, D3-MS , D3-MS, D4-MS, D7-MS	Marble	Cube	Ground floor
D8-LS, D2-LS , D9-LS, D10-LS, D11-LS	Limestone	Cylinder	Ground floor
D12-MS	Marble	Cylinder	Ground floor
D5-VS, D6-VS, D13-VS	Volcanic stone	Cube	1st floor

Testing

Chemical and mineralogical characterization

From the three types of masonry materials (LS, MS, and VS) chiseled out at the locations shown in figure 11, samples were taken and appropriately prepared for the chemical and mineralogical characterization. The chemical composition of the natural stones was established through X-ray Fluorescence (XRF) analysis, while mineralogical characteristics were determined by XRD analysis, using a Siemens D-5000 X-Ray Diffractometer (XRD), with nickel-filtered Cu Kα1 radiation (λ = 1.5405Å, 40kV and 30mA). The results of the chemical analysis of the natural stones are presented in Table 2.

Table 2. Results of chemical analysis (% w.w) of the stones samples

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	L.O.I
VS	65,87	12,86	0,93	2,21	0,13	2,90	1,27	0,41	13,19
LS	0,83	0,14	0,10	30,50	21,12	-	0,11	-	46,61
MS	0,62	0,21	0,20	55,21	-	0,52	0,10	-	42,60

XRD patterns of the stones samples examined are presented in figure 13 According to XRF and XRD analyses, sample of type **VS** is a stone of volcanic origin, while samples of types **LS** and **MS**, derived from carbonate rocks (crystalline to microcrystalline limestone). In sample **VS**, a large proportion of amorphous phase is recorded by the XRD analysis, while the main detected mineralogical phases were quartz, alunite, dolomite, and calcite. **MS** derived from metamorphic carbonate rocks, microcrystalline and grainy. The main mineral phase is that of calcite. Other recorded phases are those of quartz, muscovite, clinochlore, and anorthite, but it is estimated that they exist at a low quantity level. **LS** is a limestone mineral with the main mineralogical phase of dolomite and secondary of calcite. As far as the masonry mortar is concerned, XRD and optical microscopy were used in order to mineralogical characterize the sample and to assume whether or not a lime-pozzolan mortar was used for the masonry

construction. The segregation of the mixed aggregates was achieved using ambient grinding and sieving in a 0.63mm sieve. XRD analysis was made to the passing fraction of the mortar and calcite, quartz, muscovite, and clinochlore were the main detected mineralogical phases (Fig. 14).

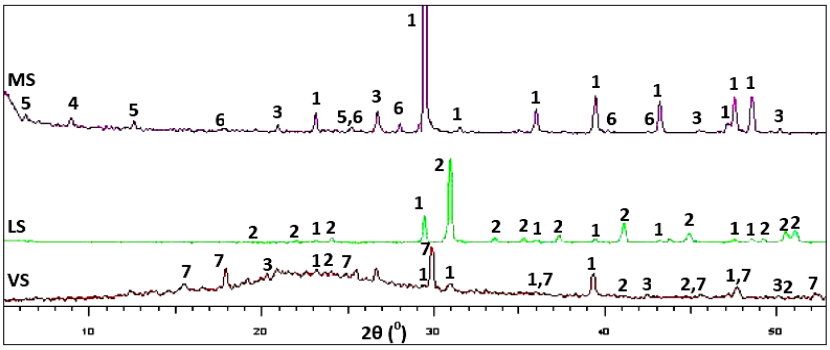

Fig. 13. XRD patterns of the three types of masonry materials (LS, MS and VS);
1: Calcite; 2: Dolomite; 3: Quartz, 4: Muscovite, 5: Clinochlore, 6: Anorthite, 7: Alunite.

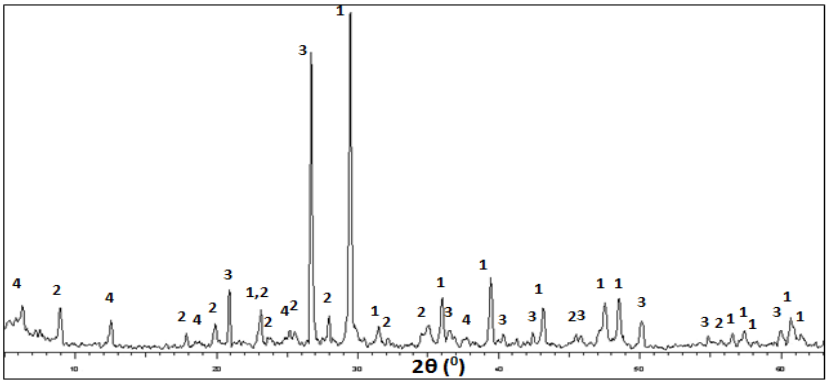

Fig. 14. XRD pattern of mortar sample, 1: Calcite, 2: Muscovite, 3: Quartz, 4: Clinochlore

Following to this, an appropriate specimen was prepared for optical microscopyexamination. The same sample, passing the 0.63mm sieve, was treated by a 10% w/w 0.1N HCl acid, in order to dissolve calcite. The filtered residual was dried at 105°C and examined by optical microscopy. It was found that a finely ground glassy phase exists in the sample (Fig. 15), which mostly is attributed to a pozzolanic material.

Fig. 15. Optical microscopy photographs of the mortar sample

Mechanical characterization

The mechanical characteristics of the samples were established from uniaxial compression tests. The samples chiseled out of the walls were machined to form cubes, whereas those cored out from larger stones had their end faces abraded so as become cylinders with a height-to-diameter ratio of 2. All specimens were weighted before testing. The specimens' dimensions and weight are shown in Tables 3 and 4. The cubes were used to assess strength only. The axial and transverse strains were measured by placing electrical resistance strain gauges within the middle zone of the cylinders at diametrically opposite each other in the axial and circumferential directions. The testing arrangement for the cubes and cylinders are shown in figure 16. The values of the compressive strength obtained from the tests are given in Table 4, whereas typical stress-strain curves are shown in figure 17.

Fig. 16. Testing of the samples: cube and cylinder

Table: 3 Dimensions and weight of cubic specimens

Specimen name	Material type	Dimensions (cm)			Weight (Kg)
		Side a	Side b	Height	
D1-MS	Marble	5.6	5.4	6.5	0.508
D3-MS	Marble	7.9	7.7	10.5	1.636
D4-MS	Marble	7.9	8.00	8.00	1.364
D5-VS	Volcanic stone	8.2	7.2	8.5	0.556
D6-VS	Volcanic stone	8.2	8.00	7.00	0.490
D7-MS	Marble	5.5	4.5	4.5	0.306
D13-VS	Volcanic stone	8.2	8.0	8.00	0.532

Table: 4 Dimensions of and weight cylindrical specimens

Specimen name	Material type	Dimensions (cm)		Weight (Kg)
		Diameter	Height	
D8-LS	Limestone	4.5	11.00	0.318
D2-LS	Limestone	4.5	4.5	0.142
D9-LS	Limestone	4.5	11.3	0.438
D10-LS	Limestone	4.5	9.5	0.480
D11-LS	Limestone	4.5	11.00	0.428
D12-MS	Marble	4.5	9.4	0.402

For specimens D10, D11, D12, the stress-strain curves obtained from testing specimens in uniaxial compression are shown in figures 17-19. For each curve, only the branch corresponding to low deformation level is presented, as for larger deformations strain gauges do not perform reliably, due to their local detachment from the specimens.

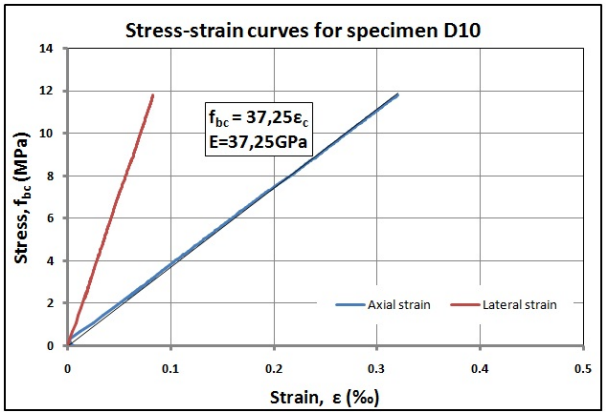

Fig. 17. Typical stress-strain curves obtained from testing specimens D10 in uniaxial compression

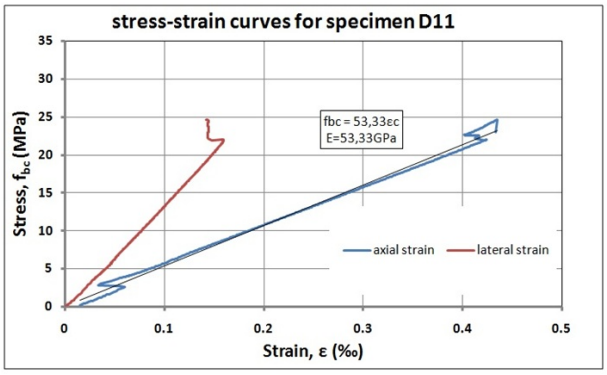

Fig. 18. Typical stress-strain curves obtained from testing specimens D11 in uniaxial compression

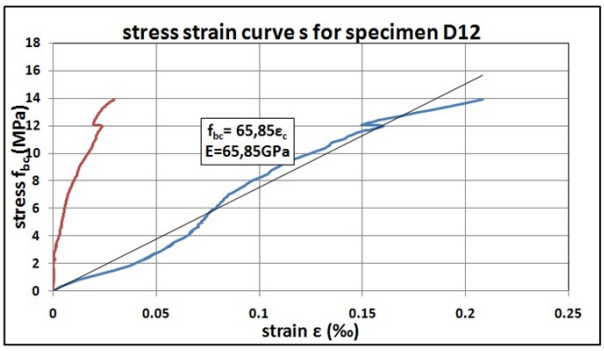

Fig. 19. Typical stress-strain curves obtained from testing specimens D12 in uniaxial compression

Assessment of masonry mechanical characteristics

For the assessment of the masonry mechanical characteristics it was assumed that the compressive strength of the mortar was f_{mc}= 0.4MPa. The assessment of the mechanical characteristics of the masonry materials was based on the experimentally established strength values of the samples (see Table 5). These values were introduced in the empirical formulae proposed by Tassios and Chronopoulos in 1987 [7] (see Table 6) and the resulting characteristics are given in Table 7. The assessment of stone compressive strength f_{bc} was based on the mean value of the constituent materials [8, 9].

Table 5. Compressive strength and specific weight of stone specimens

Specimen	Material type	Compressive strength f_{bc}(MPa)	Specific weight (kN/m^3)
Marble			
D1-MS	Cube	15.76	25.84
D3-MS	Cube	24.31	25.61
D4-MS	Cube	24.10	32.31
D7-MS	Cube	32.90	27.47
D12-MS	Cylinder	29.01	26.91
Mean value		**25.21**	**27.63**
Limestone			
D8-LS	Cylinder	18.53	18.19
D2-LS	Cylinder	43.62	16.48
D9-LS	Cylinder	54.10	24.38
D10-LS	Cylinder	18.00	31.79
D11-LS	Cylinder	33.17	10.04
Mean value		**33.48**	**20.18**
Volcanic stone			
D5-VS	Cube	4.87	11.10
D6-VS	Cube	5.84	10.67
D13-VS	Cube	5.23	10.13
Mean value		**5.31**	**10.63**

Table 6. Empirical formulae used for assessing the masonry mechanical characteristics

	formulae
Horizontal mortar layers – Volume of mortar	25-30mm, Vmortar≈0.30/0.40
Material safety factor γ_m	2.00
Wall compressive strength normal ($\perp$) to horizontal masonry layers (f_{wc}, $\perp$)	$\left(\frac{2}{3}\sqrt{f_{bc}} - a\right) + 0.5 \cdot f_{mc}$
Wall compressive strength parallel (//)to horizontal masonry layers f_{wc}, //)	For incomplete mortar filling $f_{wc,//} = (0.50 - 0.65) \cdot f_{wc,\perp}$
Wall tensile strength normal ($\perp$) to horizontal masonry layers ($f_{wt,\perp}$)	$f_{wt,\perp} = f_{mt}$
Wall tensile strength normal (//) to horizontal masonry layers ($f_{wt,//}$)	$f_{wt//} = 2 \cdot f_{mt}$
Shear strength(horizontal sliding)	$f_{wv,0} = 0.05 + 0.25 * \left(\frac{3}{4} \cdot \sigma_o\right) \approx 0.05 + 0.20 \cdot \sigma_o$
Shear strength(diagonal cracking)	$f_{wv,d} = \frac{2}{3} \cdot f_{wt,d} \cdot \sqrt{1 + \frac{0.85 \cdot \sigma_o}{f_{wt,d}}} = f_{mt} \cdot \sqrt{1 + 0.5 \frac{\sigma_o}{f_{mt}}}$
Modulus of elasticity	$E = 800 \cdot f_{wc,\perp}$
Shear modulus	G=0.40E
Poisson's ratio	0.25

Table 7. Masonry mechanical characteristics

Material	Stone compressive strength,f_{bc} (MPa)	Wall compressive strength,f_{wc} (MPa)	Modulus of Elasticity,E (MPa)	Poisson's ratio, v	Shear modulus, G (MPa)
Ground floor					
Marble	25,21				
Limestone	33,48	1,81	1448	0,25	296
Mean value	29,35				
1st floor					
Marble	25,21				
Limestone	33,48	1,25	1000	0,25	400
Volcanic stone	5,31				
Mean value	21,33				

Conclusions

The Aktaiou building is a two-storey masonry building with basement. The bearing walls forming part of its structural system were built with inert semi-chiseled stones (limestone, marble, and volcanic stone) bound together with mortar in two interlocking layers.

The damage suffered by the building as a result of aging, construction faults, lack of maintenance, seismic and environmental actions was mainly inclined and vertical cracking with a relatively small width not extending throughout the wall thickness, fragmentation of masonry mortar, extensive detachment and loss of wall plaster, large deflections of the bearing members of the roof structure, and collapse of timber balconies.

The chemical composition the mineralogical characteristics of the materials used were established by XRF and XRD, respectively, analyses and the mechanical characteristics from uniaxial compression tests on specimens shaped from samples taken from various locations of the walls at the ground and first floor levels through the use of chisel or by drilling cores out of larger stones.

The test values were used to establish the mechanical characteristics of the masonry.

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