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Investigation of mechanical properties of masonry in historic buildings

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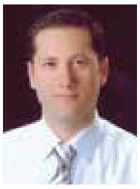

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Original scientific paper - Preliminary report

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Investigation of mechanical properties of masonry in historic buildings

Mechanical properties of masonry from the historic Beylerbeyi Palace are analyzed in the paper. The indirect procedure was used as the owner did not allow usual testing. The mineralogical structure of the original mortar was initially determined. This was followed by preparation and laboratory testing of mortar and masonry samples. Mechanical properties obtained were corrected through dynamic identification so as to determine the real modulus of elasticity of the masonry. To this aim, an ambient vibration survey was performed, and the finite-element model of the palace was constructed and tuned. Finally, the strength parameters of the masonry were corrected.

Key words:
historic buildings, masonry, mechanical properties, mineralogical study, modal tuning

Prethodno priopćenje

Fuat Aras, Gülay Altay

Istraživanje mehaničkih svojstava zida povijesnih građevina

U ovom se radu određuju mehanička svojstava zida povijesne palače Beylerbeyi. Primijenjen je posredan postupak jer vlasnik nije dopustio uobičajena ispitivanja. Na početku je određena mineraloška struktura prvobitno ugrađenog morta. Kasnije su pripremljeni i u laboratoriju ispitani uzorci morta i zida. Dobivena mehanička svojstva korigirana su dinamičkom identifikacijom da bi se odredio stvaran modul elastičnosti zida. U tu je svrhu obavljena analiza okolnih vibracija te je za palaču izrađen i podešen model konačnih elemenata. Na kraju su korigirani parametri čvrstoće zida.

Ključne riječi:
povijesne građevine, zide, mehanička svojstva, mineraloško ispitivanje, modalno podešavanje

Vorherige Mitteilung

Fuat Aras, Gülay Altay

Untersuchungen mechanischer Eigenschaften des Mauerwerks historischer Mauerwerksbauten

In dieser Arbeit werden mechanische Mauerwerkseigenschaften für den historischen Palast Beylerbeyi ermittelt. Da der Eigentümer herkömmliche Prüfungen ablehnte, wurden indirekte Verfahren angewandt. Zunächst wurde die mineralogische Struktur des ursprünglichen Mörtels ermittelt. Danach wurden Mörtel- und Mauerwerksproben vorbereitet und im Testlabor untersucht. Die mechanischen Eigenschaften wurden mittels dynamischer Identifikation korrigiert, um den wirklichen Elastizitätsmodul zu bestimmen. Dazu wurden Umgebungsschwingungen analysiert und ein Finite-Elemente-Model des Palastes wurde erstellt. Schließlich wurden die entsprechenden Festigkeitsparameter korrigiert.

Schlüsselwörter:
historische Bauten, Mauerwerk, mechanische Eigenschaften, mineralogische Untersuchungen, Modalanpassung

1. Introduction

Difficulties inherent in the analysis of all historical structures, and the restricted use of available resources due to historical and architectural importance of cultural heritage structures, always make the assessment harder. This study presents the investigation procedure for the study of materials incorporated in the historical Beylerbeyi Palace. The permission required for a regular material investigation procedure, including non-destructive and destructive tests, could not be obtained from the owner, Regional Directorate of National Palaces. As a result, an indirect procedure consisting of the mineralogical survey, laboratory testing, and modal identification, was applied (Figure 1).

The initial step in material investigation is the chemical and mineralogical survey of mortar residue from the original structure. The original mortar residues were subjected to Thin Section (TS), Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD), and Energy Dispersive X-Ray (EDX) analyses. The mineralogical structure of the mortar was determined, and the mortar was classified as the Horasan type lime mortar, widely used in Ottoman times.

Secondly, mortar and masonry specimens were produced to test and determine basic material properties. Two different mortar formulas were used for the specimens [1, 2]. The compression and flexure test specimens were prepared for mortar, while only the compression test specimens were prepared for masonry. The specimens were tested after the six-month curing time.

Since the tested specimens were produced in laboratory, and as they do not belong to the original structure, the obtained data are an estimate only, and must be corrected. The dynamic identification with the Ambient Vibration Survey (AVS) was conducted to determine the modulus of elasticity of the masonry that forms the main carrying system of the structure. The process resulted in three different moduli of elasticity for brick masonry in the palace. Finally, the strength parameters of the masonry were discussed. Flexure tests, being the most reliable methodology, were conducted for the mortar to determine the compressive and tensile strength values of the masonry.

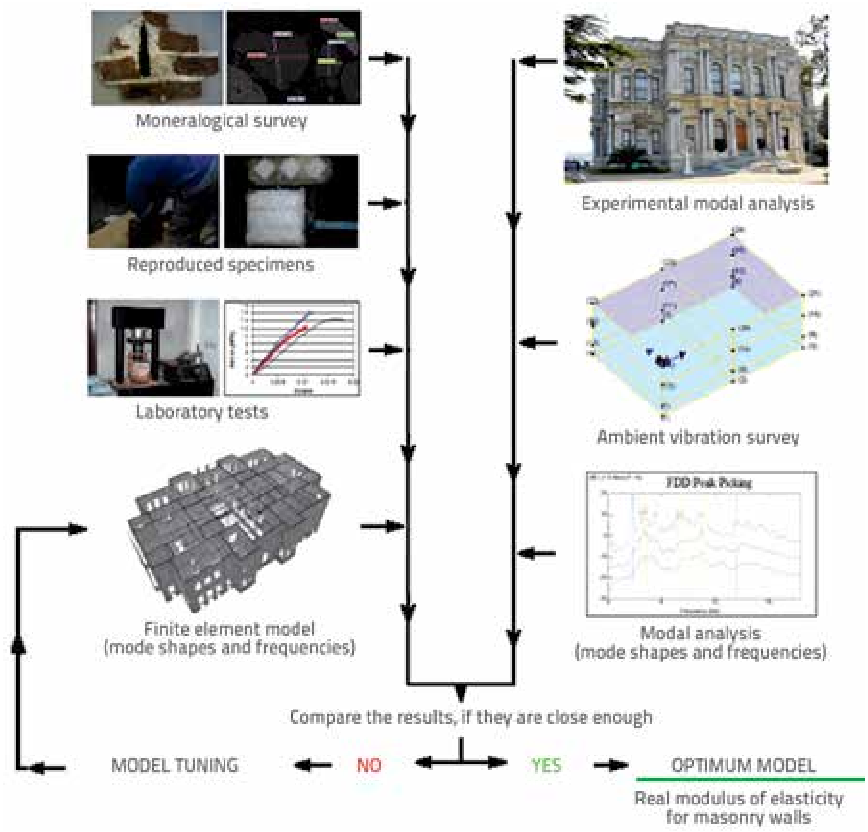

Figure 1. Material investigation algorithm

Figure 2. Beylerbeyi Palace and its interior spaces

2. Building description

Beylerbeyi Palace, built between 1861 and 1865, is located on the Asian shore of Bosphorus in Istanbul [3]. It is a three-storey building with one basement and two ordinary floors. The building measures 72 m in length (along the shore), and 48 m in width in the perpendicular direction.

The story height at the basement level varies between 1.5 and 2.5 m, and this floor is partly under the ground level. The height of the remaining two levels ranges between 7 and 9 m. The structural system of the palace is formed of the stone and brick masonry walls and timber floors. At the basement floor, stone masonry walls measure 1.4 m, and this wall system also forms the foundations of the palace. The thickness of brick masonry walls at the first and second floors amounts to 0.8 and 0.6 m, respectively. The cast iron reinforcement (metal clamps) is incorporated in the masonry walls on the first and second floors.

The palace is under protection of the Regional Directorate of National Palaces and is currently used as a museum. It has two main salons and many rooms decorated with pieces of art, including drawings and carvings on the ceilings and walls. The stucco plaster, lime plaster, and wood covering, are used at the interior faces of the wall, whereas the exterior façade is clad with küfeki stone and lime plaster (Figure 2).

3. Mineralogical analysis of original mortar used in Beylerbeyi Palace

The state authorities did not give permission for a regular material investigation including non-destructive testing. However, the damage caused by metal clamps placed within the masonry walls provided a good opportunity for mortar investigation. The oxidation of a cast iron clamp caused swelling and finally wall cracking in a palace room. This damage resulted in a wall separation measuring 50 x 50 cm^2 in size. Figure 3 shows masonry walls in the palace and the damage caused by the metal clamp oxidation. This damage enabled the authors to obtain original mortar samples for the mineralogical and chemical survey.

Recent mortar characterization schemes involve optical microscopy as the first step in identifying the aggregates, various mineral additions, binder type, binder-related particles, and pore structure. The SEM analysis, together with the XRD analysis, is the most valuable second step in the characterization of historic mortars. The SEM equipped with an EDX-detector can be used to obtain valuable information on the mineral phase composition [4]. In that respect, the chemical and mineralogical composition of the mortar residue was determined by Thin-Section analysis, Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) analysis, and X-Ray Diffraction (XRD) analyses.

Five thin sections were investigated in this scope of this study. It was determined that about 60 % of the mortar consists of the binding material, while the remaining material can be classified as grains. These grains contain mineral particles, quartz particles, and clearly identified brick particles. The SEM analysis, with EDX, was conducted in the second step. Three mortar specimens were analysed using the Philips XL30ESEM-FEG&EDAX, Environmental SEM equipment. A good connection between particles and binding material was established, and no gaps or cracks were determined. The general grain size varies between 50 μm and 1200 μm for mortar. The EDX analysis revealed that the mineralogical origin of the particles is quartz, SiO_2. Feldspar minerals (Na, Al, K) were also occasionally seen through the EDX patterns of aggregates. Finally, four pulverized mortar specimens, different from those used in previous methods, were analysed by the Cu Kα radiation using the Rigaku D/Max-Ultima+/PC XRD device. According to the XRD pattern, the mortar is composed of calcite, quartz and feldspar elements. It was established by mineralogical investigation that the mortar is made of quartz, calcite and feldspar [5]. Some thin section specimens, SEM views, and XRD analyses performed on mortar originating from the palace, are shown in Figure 4.

In two similar studies, Boke et al. [6] investigated mortar at three historic bath buildings in Anatolia while Ipekoglu et al. [7] investigated lime mortar in madrasas, historical educational buildings. They obtained the mineralogical composition corresponding to that established at Beylerbeyi Palace. Another

Figure 3. Masonry details from the palace: a) basement; b) second floor; c) damage due to oxidation of a metal clamp inside the wall

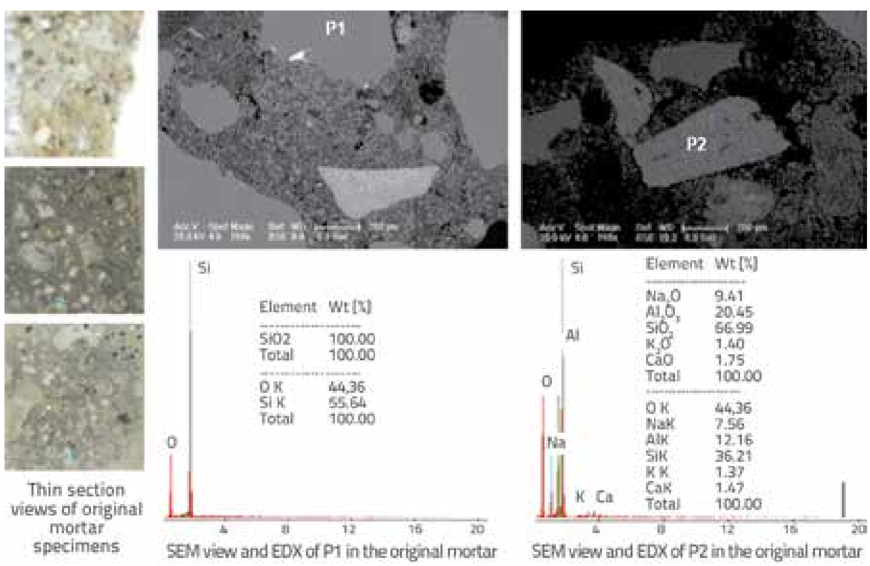

Figure 4. Thin section, SEM and XRD analyses of original mortar

study was conducted by the Regional Directorate of National Palaces with the purpose of characterizing the mortar originating from the historical Dolmabahce Palace. It was established that the main components of the samples were the lime, fine sand, brick powder and marble powder, but the proportions of these materials vary. A type of fibre was also seen in some samples [8]. These studies classify the mortar as the general lime mortar known as Horasan. This mortar was used in Byzantine, Seljuk and Ottoman empires. The binding material of this mortar is carbonated lime. The aggregate was formed of the river sand, pebbles, brick pieces and powder, combined with hay, horse hair and goat hair, which served as fibres [1, 9]. In the light of the mineralogical survey, recent studies, and historical information about the construction period of the structure, it can be concluded that the mortar from Beylerbeyi Palace is the Horasan mortar.

4. Laboratory testing of reproduced specimens

Mechanical properties of the material used in the structure are the basic and important input data for the analysis. Highly valuable information can be obtained by establishing the force-deformation relationship. The compressive and tensile strengths, modulus of elasticity, Poisson ratio and unit weight of the material are of primary concern [10]. In this respect, the mortar and masonry test specimens were produced and tested so as to obtain initial data for establishing the behaviour and mechanical properties of the masonry originating from Beylerbeyi Palace.

4.1. Mechanical properties of Horasan mortar produced in laboratory

Two different formulas were used to produce the test specimens. In the first formula (F1), the mortar is the combination of slaked lime, brick powder and water (Table 1) [1]. The second formula (F2) is used for the restoration works of the historical structures by Regional Directorate of National Palaces in Turkey [2] and it is the combination of slaked lime, brick powder, fine sand, fibre, and water (Table 2). In both F1 and F2 the maximum size of the sand and brick powder grain is 2 mm.

Table 1. Proportion of mix ingredients in formula F1

Ingredients	Lime	Brick powder	Water
Proportion (by weight)	1.00	1.22	2.10

Table 2. Proportions of mix ingredients in formula F2

Ingredients	Lime	Brick powder	Fine sand	Water	Fibre
Proportion (by weight)	4.00	4.00	2.00	1.50	0.05

Three-5cm*5cm*5cm cubic specimens, and 4cm*4cm*16cm prismatic test specimens, were created for each formula. After the six-month curing, the compression and flexion tests were performed according to BS-EN-1015-11 [11]. The testing procedures and mortar specimen failure are illustrated in Figure 5. The stress-strain diagrams for compression tests are given in Figure 6. At the failure point, similar crack patterns were observed for both types of mortar specimens. However, there is a clear difference in strain capacities. The secant modulus of elasticity for mortars was also determined as the slope of the line that intersects the origin and one third of the maximum stress on the stress-strain curve of each specimen. Secondly, three specimens were tested for each mortar on the

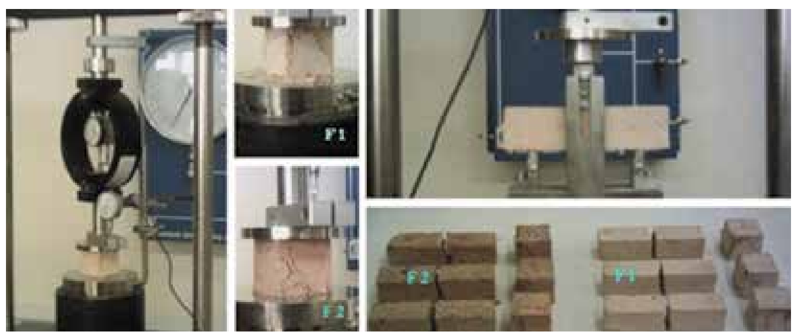

Figure 5. Laboratory testing of mortar specimens

Table 3. Mechanical properties of laboratory made horasan mortar specimens

Specimen	Compressive strength [MPa]	Strain at maximum stress	Ultimate strain	Modulus of elasticity [MPa]	Flexural strength [MPa]
F1-1	4.37	0.019	0.041	902	1.86
F1-2	4.69	0.010	0.039	1748	1.32
F1-3	4.55	0.011	0.041	730	1.53
F1 Average	4.54	0.013	0.040	1127	1.57
F2-1	4.06	0.022	0.054	312	1.63
F2-2	5.59	0.025	0.064	508	1.79
F2-3	4.39	0.017	0.048	599	1.71
F2 Average	4.68	0.021	0.055	473	1.71

three point flexure jig (Figure 5). The specimens exhibit brittle behaviour and they failed via a single vertical crack, which occurred just beneath the load application point. Numerical values of mechanical properties for each test are summarized in Table 3.

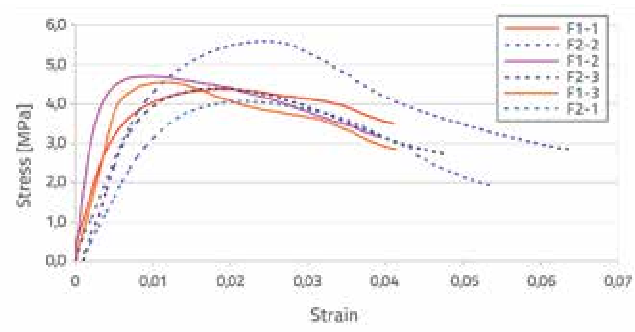

Figure 6. Stress-strain curves of mortar specimens

4.2. Mechanical properties of masonry produced in laboratory, according to Beylerbeyi Palace configuration

The laboratory-made masonry specimens were prepared for compression test by using the aforementioned mortar formulas and normal clay burnt brick since the original bricks were not available for testing. Stone masonry walls are situated at the basement floor of the structure and they are not taken into account, as they are not effective for the structural behaviour of the palace. The test specimen geometry was selected according to original configuration of the masonry seen in the structure. The average mortar thickness is about 18 mm, and the brick height, measured in the original structure, amounts to 65 mm (Figure 3).

Figure 7. Laboratory testing of masonry specimens

Test specimens used in this study were created according to BS-EN-1052-1 [12]. As per specification for the compression test, at least three specimens of 1.5-unit length and 3-unit height of brick should be tested. One row brick depth was adopted since the original knitting of the wall could not be determined. Three masonry specimens were prepared for each type of mortar, and the specimens were tested six month after preparation. The geometry of the specimens, the testing procedure, and specimen failure after testing, are illustrated in Figure 7. The obtained stress-strain diagrams and their average are presented in Figure 8. Difficulties in the manual control of loading during the testing resulted in the change in curve slope, but the average value gave an expected stress-strain diagram. The initial modulus of elasticity and compressive strength values can be determined from the curves.

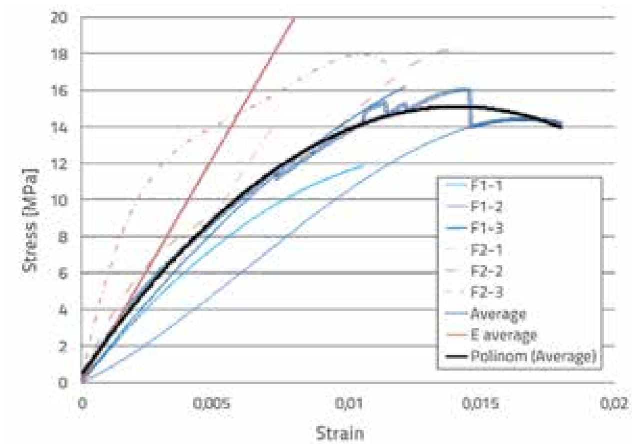

Figure 8. Stress-strain curves of masonry specimens and their average

The typical compressive strength of masonry f_k is determined as the smaller value of either Eqs. (1a) and (1b). Additionally, the Young's modulus of masonry is calculated using the average stress-strain curve. According to Eurocode 6 [13], the typical modulus of elasticity, E_k, is defined as the secant modulus at service load conditions, i.e. at 1/3 of the maximum vertical load.

$$f_m = \frac{f_{pros}}{1\ 2} \tag{1a}$$

$$f_m = f_{min} \tag{1b}$$

Calculated material properties are presented in Table 4. It is important to notice that these values were obtained by experiments on artificial specimens, which do not originate from the original structure. The grain size distribution and pozzolanic nature of bricks affect mechanical properties of mortar considerably. A good level of mortar hydraulicity could be obtained using finely powdered bricks while the brick particles, burnt under high temperatures, i.e. those in excess of 900 °C, lose their pozzolanicity [14]. As a result, mechanical properties are affected by different hydraulic properties of particles used in the laboratory-made specimens compared to original mortar. Moreover, the bricks used in the test specimens are not original bricks. Therefore, the mechanical properties obtained must be corrected. The modulus of elasticity of masonry, which plays an important role in the dynamic behaviour of structures, was corrected by the operational modal analysis, while the strength parameter was evaluated and re-corrected using appropriate formulas found in literature.

Table 4. Mechanical properties of laboratory made masonry specimens

Specimen No	Maximum compressive stress [MPa]	Strain at maximum compressive stress	Ultimate strain	Compressive strength [MPa]	Young modulus [MPa]
F1-1	11.86	0.0106	0.0106	11.8	1455
F1-2	14.43	0.0166	0.018		
F1-3	16.19	0.0121	0.0121		
F2-1	14.28	0.0073	0.0073	14.02	3545
F2-2	17.96	0.0140	0.0145		
F2-3	18.21	0.0105	0.0114		
Average	15.49	0.0119	0.0123	12.91	2500

5. Numerical and experimental modal analyses (Correction of Young's modulus)

The Ambient Vibration Survey (AVS)-based procedure was applied in this study to correct the Young's modulus of the masonry in the palace. It can show great diversity in the palace due to big size of the structure, existing conditions, and metal clamps used within the walls. However, modal identification based on the numerical and experimental study can reveal variations in the modulus of elasticity of the masonry used in the palace.

5.1. Numerical modal analysis

A three-dimensional numerical model was prepared based on the determined architecture, structural carrying system, and material properties identified during the aforementioned laboratory testing. The masonry walls were modelled by shell elements, and frame elements were used for the column and timber slab members. The pinned connection was assumed for the contact between the timber slab members and masonry walls. The structure was assumed to have a fixed support at the base in the light of the AVS results and the geotechnical report prepared for Beylerbeyi Palace [15, 16]. The numerical model was constructed for the stone masonry (modulus of elasticity, E = 50000 MPa, unit weight, g = 26.5 kN/m^3) [8], brick masonry (modulus of elasticity, E = 2500 MPa, unit weight, g = 22.4 kN/m^3), oak cushion beams (modulus of elasticity, E = 12500 MPa, unit weight, g = 7.2 kN/m^3), and fir slab beams (modulus of elasticity, E = 9700 MPa, unit weight, g = 7.2 kN/m^3) [17]. The model resulted in the total of 15662 nodes, 3808 frames, and 13749 shell elements, and the analysis was made using the SAP2000 software [18] (Figure 9).

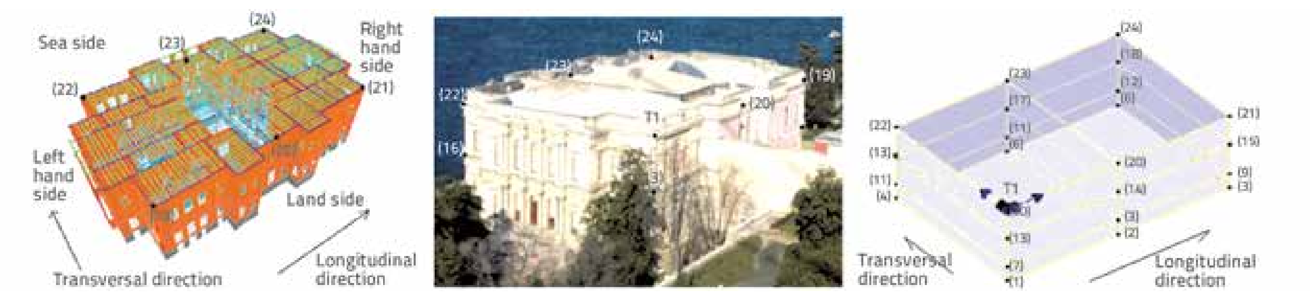

Figure 9. Numerical model and experimental geometry of structure

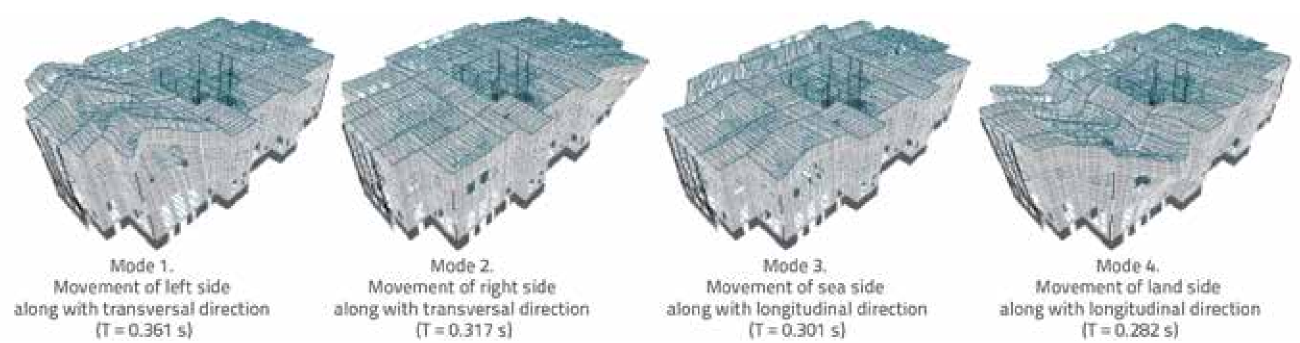

Figure 10. Mode shapes and periods obtained by numerical modal analysis

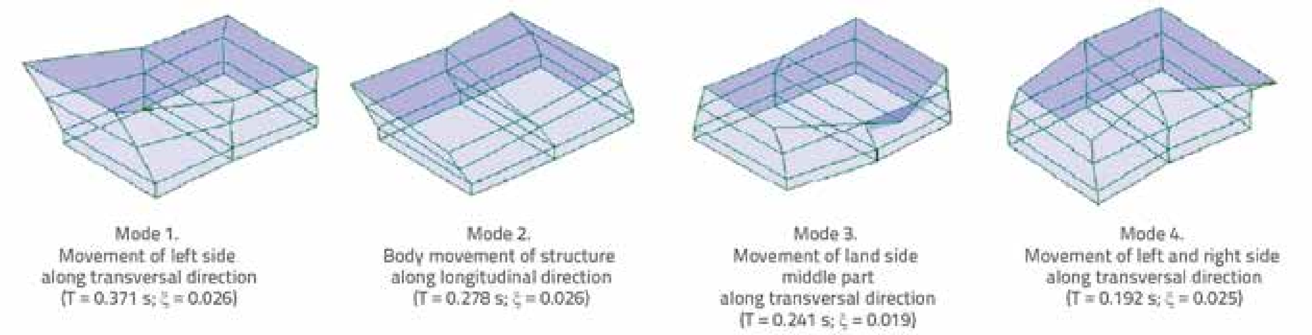

Figure 11. Mode shapes and periods obtained by experimental modal analysis

A dynamic analysis was conducted to identify modal properties. The Ritz-vector analysis was made for 60 modes in order to catch the 90 % mass participation. The dynamic properties obtained revealed important characteristics of the structure. Most important findings are the lack of rigid floors and the mass distribution throughout the height of the palace. In addition, the participation of the thick basement floor in the dynamic modes of the palace was observed on the 59th and 60th modes, which demonstrates that the behaviour of the basement floor is well separated from that of the upper stories. First four modes of the structure, as obtained by numerical analysis, are shown in Figure 10.

5.2. Ambient vibration survey of Beylerbeyi Palace

The ambient vibration testing method is widely applied and highly popular full-scale testing method for the experimental definition of dynamic characteristics. Many methods and applications have been presented in the literature for ambient vibration testing and modal identification of civil structures [19-22]. This fast and relatively simple procedure was accepted by the owner, Regional Directorate of the National Palaces, since it was applied to Beylerbeyi Palace without disturbing the structure's normal function.
During the ambient vibration measurements at the palace, three Ranger type Kinemetrics seismometers were used, and the measured signal was amplified via a four-channel Signal Conditioner produced by Kinemetrics [15]. To define dynamic characteristics of the Beylerbeyi Palace, the ambient vibration measurements were performed at 24 points of the structure, six points at four different levels – basement, first storey level, second storey level, and roof. The geometry of the measurement points, their respective location at the structure, and explanations for the mode terminology used, are given in Figure 9. The ARTeMIS software [23] was used for the post-processing and analysis of vibrations recorded at all measuring points. Based on the pick picking technique, dynamic mode shapes, periods, and damping ratios, were determined as shown in Figure 11.

5.3. Tuning of numerical model

The tuning process aims to minimize the differences between the modal properties obtained by numerical analysis and AVS by altering numerical model uncertainties such as geometry, boundary conditions, and material properties. For the tuning of the numerical model, the mode shapes and the periods of the structure, obtained by experimental and numerical surveys, were compared and the Young's modulus of masonry was altered in the required part since the geometry of the structure, boundary conditions, such as those at supports and connections, and mass of the constituent parts, are included in the model accurately. On the other hand, the Young's modulus of the material was obtained from laboratory tests conducted on reproduced (not original) specimens, and it did not account for the metal clamps used within the masonry walls in the palace. Presented in another study in more detail [24], this tuning process resulted in three different moduli of elasticity for brick masonry in the palace (Figure 12).

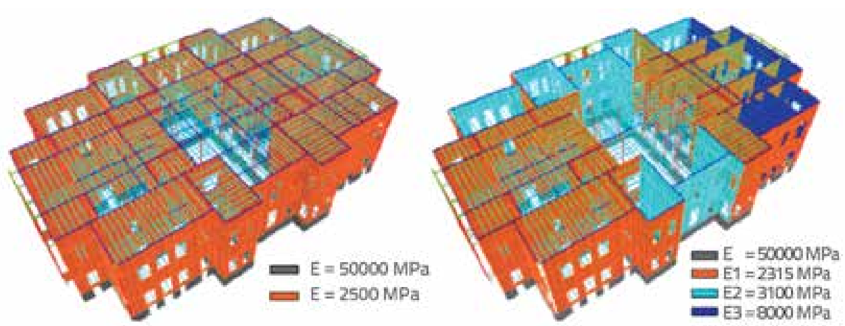

Figure 12. Numerical model of Beylerbeyi Palace before and after the modal tuning

The calibration process revealed that the walls on the left hand side of the structure have smaller modulus of elasticity than those on the right hand side. There may be some reasons behind this difference. The first reason is the cast iron reinforcement used within the masonry walls. Moreover, the oxidation problem was also observed. In this respect, not only the usage of the metal clamps, but also the existing conditions must be investigated. Thirdly, the existing damage plays an important role in this difference. The assumption that damage can be linked to a decrease in stiffness seems to be reasonable for this type of structures, just like for structures built with other materials [22]. The damage assessment study revealed that there are many visible cracks on the masonry walls in the palace. However, many rooms on the left hand side of the palace are covered by timber carvings, which possibly hide the cracks and other types of damage [2].

6. Evaluation of masonry strength parameters

The tensile and compressive strength values for masonry are important mechanical parameters for evaluating performance of structures. Strength parameters obtained from experimental tests should also be discussed since the tested specimens do not originate from the original structure. Although the mortar was produced with the historical mortar formulas, the bricks used in masonry specimens are normal clay-burnt bricks available on the market. This is why a correction is required.

There are many studies in literature that depict non-destructive tests performed for historical masonry structures [25-28]. Although the obtained strength parameters could be compared with these studies and then interpreted, it is difficult to make generalizations in case of historical structures because every such building has its own characteristics. For this reason, the authors did not attempt to alter the obtained strength parameters by using experimental results obtained for other historical buildings. Mainly masonry and mortar tests were performed in this study. The compressive strength for masonry was obtained by testing laboratory-made unoriginal masonry specimens created with historical mortar and normal clay-burnt bricks. In that case, clay-burnt bricks obviously cause an over estimation of the compressive strength of masonry. Secondly, mortar tests were performed on laboratory-made mortar specimens created with historical mortar formulas that may be valid for the historical Beylerbeyi Palace. Although the obtained results can differ from mechanical properties of the original palace for various reasons [1], they do offer the best available information. Two known parameters (the compressive strength and flexural strength of the mortar) can be evaluated to obtain the compressive and tensile strength of the masonry. Eurocode 6 [13] gives the compressive strength of the masonry (f_k) dependent on the compressive strength of the mortar (f_m) and brick (f_b), as shown in Eq (2). In that respect, it would be impossible to use compressive strength of mortar to determine the compressive strength of masonry, without knowing the compressive strength of brick. However, the half of flexural strength of mortar gives the tensile strength of mortar, and that value can also be assumed to be the tensile strength of masonry. Finally, the compressive strength of masonry can be obtained from its tensile strength. After correlating a large number of tests, Eq. (3) is proposed by Tomazevic [29] to state the relationship between the compressive strength and tensile strength of masonry.

$$f_k = 0{,}55 \cdot f_b^{0{,}7} \cdot f_m^{0{,}3} \quad (2)$$

$$0{,}03\, f_k \leq f_{tk} \leq 0{,}09\, f_k \quad (3)$$

As the average value of flexural tests performed on six mortar specimens was determined to be 1.64 MPa, the tensile strength of the mortar amounts to one half of its flexural strength (0.82 MPa). The tensile strength of the masonry is assumed to be equal to the tensile strength of the mortar and, finally, the compressive strength of the masonry was calculated as 10 MPa by assuming that f_{tk} = 0.08 f_k. This value (10 MPa) is also by 35 % lower than the average compressive strength determined by laboratory tests.

The modulus of elasticity can also be evaluated on the basis of compression strength. In the absence of modulus of elasticity determined by tests, Eq. (4) can be used (Eurocode 6) [13];

$$E = 1000\, f_k \quad (4)$$

However, Tomazevic states that the values of the modulus of elasticity, assessed by Eq. (4), are sometimes far from reality [29]. The actual values vary between 200 f_k and 2000 f_k, Eq. (5);

$$200\, f_k \leq E \leq 2000\, f_k \quad (5)$$

Eq. (5) validates the values of moduli of elasticity obtained from AVS. Even the highest value, 8000 MPa, seems acceptable. Moreover, the uncertain variation of metal clamps is worth noting.

7. Conclusion

Undertaken to determine mechanical properties of masonry in Beylerbeyi Palace, without disturbing the structure, this study has resulted in the following findings.

According to mineralogical survey of the original mortar residue from the palace, the mortar is composed of lime, brick powder, and sand. In the light of the recent studies, the lime mortar from Beylerbeyi Palace can be classified as historic Horasan mortar, used in Ottoman times. The laboratory tests revealed the force deformation relationship of mortar and masonry. Tested on reproduced specimens, these relationships can predict general behaviour of the material.

Experimental and numerical modal analyses were also conducted for this building. The lack of rigid slabs and mass distribution throughout the height of the structure are the key features governing the modal behaviour of the structure. The tuning procedure showed that the modal behaviour of the palace is well represented with three distinct moduli of elasticity (E_1 = 2315 MPa, E_2 = 3100 MPa and E_3 = 8000 MPa.) for brick masonry walls in the first and second storey of the structure. The flexural strength of the mortar was used to obtain the tensile and compressive strength values for masonry, which amount to 0.82 MPa and 10 MPa, respectively.

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