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Evaluation of Material Characteristics and Structural Dynamic Properties of a Historical Church: The Case of 19th Century Bursa Derekoy Church (Ayia Paraskevi)

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Abstract

Derekoy (Ayia Paraskevi) Church, built by the Orthodox Greeks in Bursa, is one of the prominent monuments built in the 19th century. The structure, which lost its community with the population exchange (1923) between Turkey and Greece, has since then been out of service and a rapid deterioration process has begun. Analysis works are frequently implemented for this purpose and become crucial in Turkey, of which a large part is within the earthquake zone. However, the majority of the studies on the preservation of historical buildings are lacking in detailed material analysis and numerical methods. Conducting a series of material tests and numerical analyses for the structure provides more reliable and qualified interventions since they influence the decisions on the reinforcement and protection methods employed for historical buildings. For this purpose, the material characterizations of the mortar, plaster and stones used in the church were carried out by performing physical, chemical, mechanical, petrographic and mineralogical tests on samples taken from the church. Afterwards, mechanical tests of the walls and vibration tests were conducted to determine the dynamic behavior of the building. Based on the results obtained from the analyses, a series of intervention methods were proposed. It is understood that the flat-jack, shear and vibration tests are vital for determining the real structural behavior of the building. Furthermore, it is recommended that vibration tests are carried out on both the overall structure and individual walls to determine the dynamic behavior of similar structures where only outer walls remain standing.

Keywords

19th century church, restoration, material characterization, dynamic analysis

1 Introduction

The Derekoy Church built in 1857 has a basilical plan and a barrel-vaulted roofing system. The church was used until the "Convention Concerning the Exchange of Greek and Turkish Populations" signed in 1923. After the church was abandoned, a rapid deterioration process began. This fact points out the significance of restoration implementations to preserve Derekoy Church and pass it on to future generations.

International charters, doctrinal texts and articles such as the Carta Del Restauro, 1931 and Venice Charter, 1964 highlight the importance of conservation through restoration work and the scientific approaches in restoration tasks. It is also emphasized that the work in the scope of restoration needs proficiency and that the use of authentic materials is considered to be essential [1, 2].

The ICOMOS Charter titled "Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage" published in 2003 emphasizes the significance of a thorough knowledge of the structure and material properties in conservation practices. Moreover, it is highlighted in the charter that the original state of the structure at the time of its construction, the techniques adopted during the construction, the changes affecting the structure and the other potential effects are key parameters to be required as well as a comprehensive knowledge regarding the current state of the building. Protection of architectural heritage includes analysis, diagnosis, treatment (or repair) and control steps (similar to medical approaches). Since each of the cultural properties has its own unique characteristics, these structures must be handled with special care. Diagnosis is performed consistent with historical, qualitative and quantitative approaches. The qualitative approach depends on the historical and archaeological research as well as on direct observations of structural damages and

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material deteriorations. In the quantitative approach, material and structural experiments, monitoring and structural analysis results are employed [3]. In this study, the research and diagnosis stages, which are in the protection step of the regulation, are handled with qualitative and quantitative approaches. In this context, in situ studies and laboratory analyses were carried out. Articles focusing on church buildings exist in the literature and they point out the importance of analyses and revealing the properties of materials before restoration of historical buildings [4–7].

In this study mortar, plaster and stone/rock samples were taken from different parts of the church (such as the basement, nave, and narthex) and from different elevations. In order to determine the characteristics of building materials, physical, mechanical and chemical tests, and petrographic and mineralogical analyses were performed on samples. Moreover, flat-jack and shear tests were performed to understand the mechanical characteristics of the walls [8–12]. Finally, the operational modal analysis (OMA) test method was used for determining the natural frequencies, mode shapes and damping ratios of the structure [13–19]. Results were compared with the finite element model of the structure and appropriate calibrations were made for representing real behavior of the structure.

2 The architectural features of Derekoy Church

The church is located in Derekoy Village of Bursa City. The main entrance is from the street on the west side. The view from inside the church and the east façade can be seen in Fig. 1 (a)–(d) [20]. The church has a rectangular plan with dimensions of 26.85 x 17.25 m. It has three naves in the east-west direction (Fig. 2) [21]. The structure consists of a basement floor (the substructure, which is entered through the low-arched doors on both sides of the entrance staircase), a ground floor and a gallery floor. The plan has a rectangular narthex, three naves, and a bema with an apse. The naos has two rows of six pillars that divide the naos into three naves.

Barrel vaults are used as load-bearing elements that carry the loads transferred from the roof system.

The main walls of the church are constructed by using brick, rubble and cut stone in an alternating technique. Large cut stone blocks are utilized at the corners of the structure. The wall thickness is approximately 85 cm. The roof system, the gallery floor and the wooden pillars in the naos have not survived to the present day.

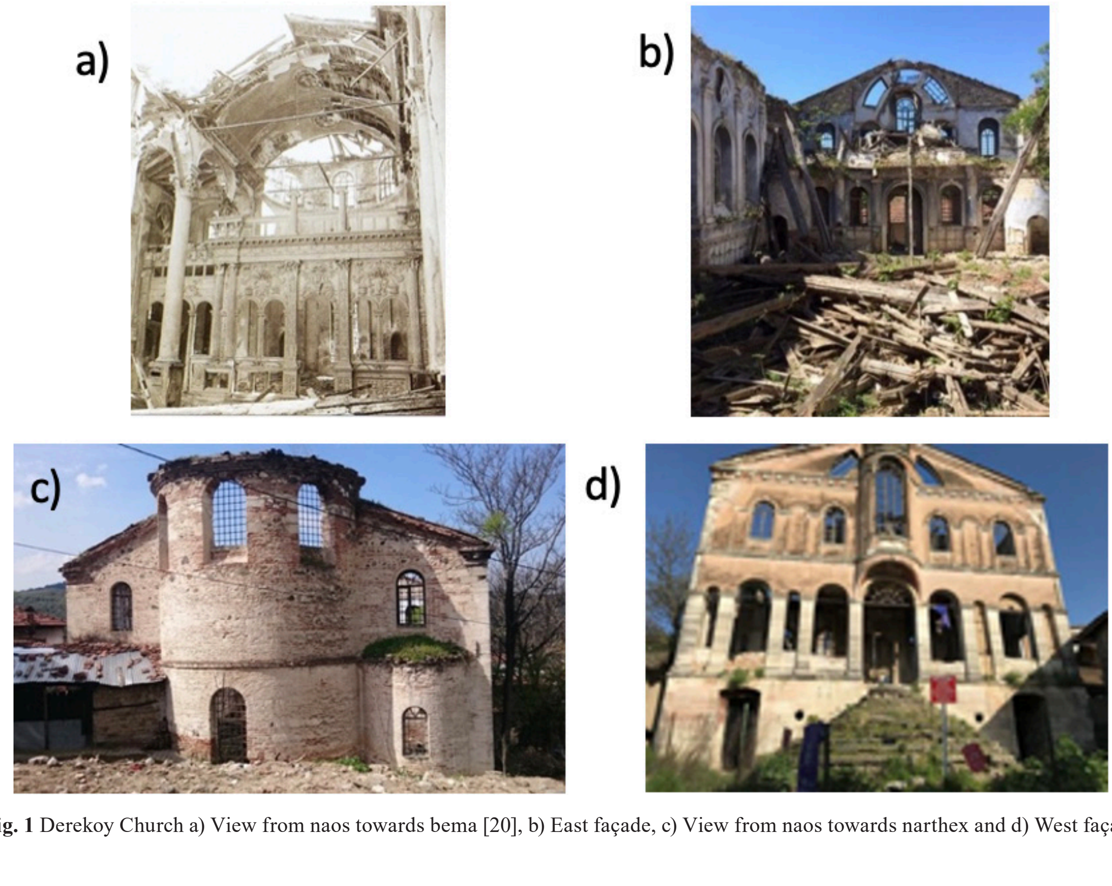


Fig. 1 Derekoy Church a) View from naos towards bema [20], b) East façade, c) View from naos towards narthex and d) West façade

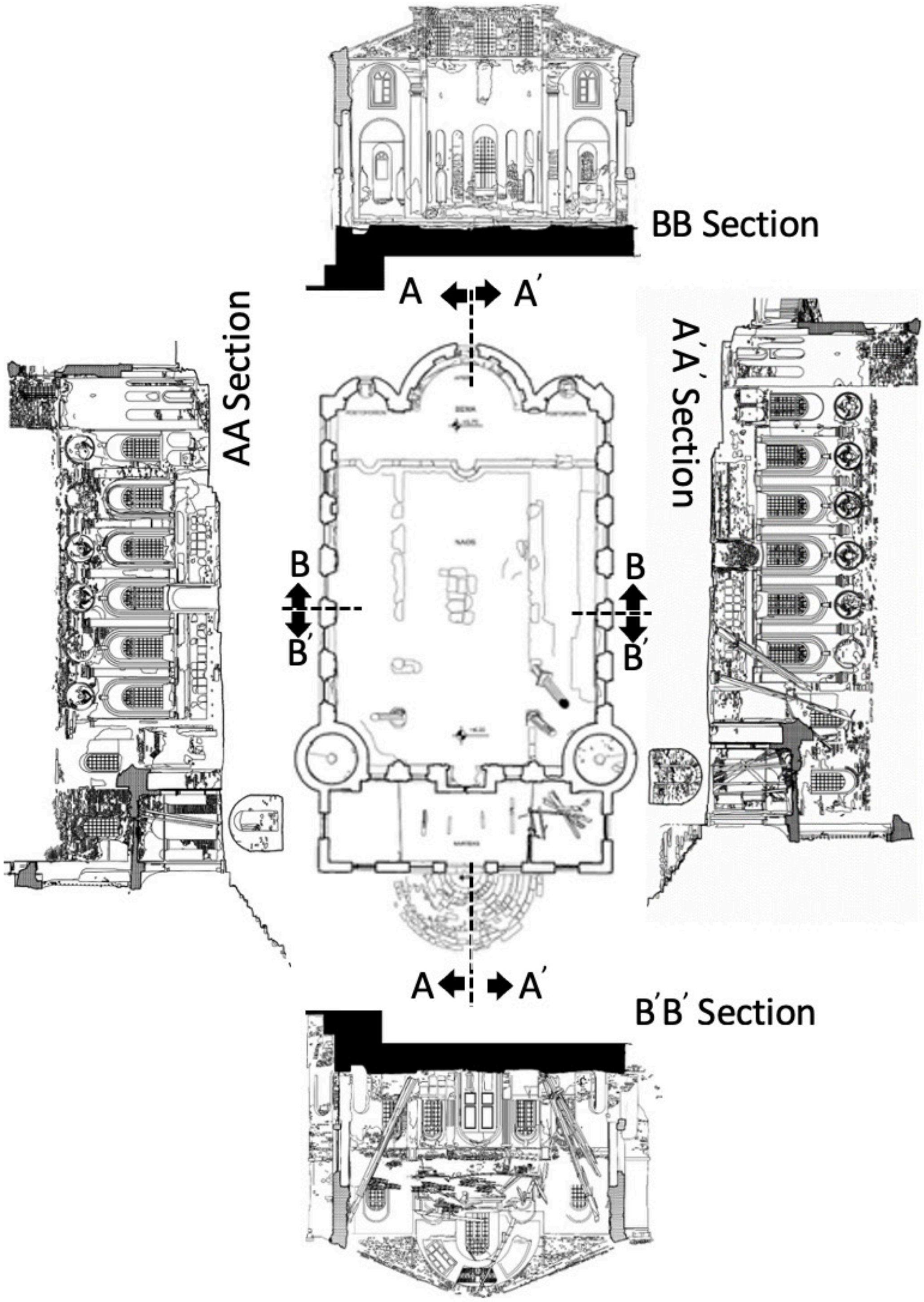


Fig. 2 Derekoy Church plan and sections [21]

3 Laboratory tests

3.1 Sampling

In sample coding, initials are used to represent the direction, location of the church section where the sample was taken from and material type, whereas numbers are used for the order of samples. The locations from which samples were taken are the bema, pastophorion, narthex, nave and staircase tower as seen in Fig. 3. The bema is coded as B, the pastophorion as P, the nave as N, the narthex as Na and staircase tower as T. Moreover, the capitals M, P and S are used to imply mortar, plaster and stone/rock for materials, respectively. For instance, NBM1 stands for the sample taken from the north (N) and bema (B) of the church, whereas 'M' and '1' imply the mortar material and

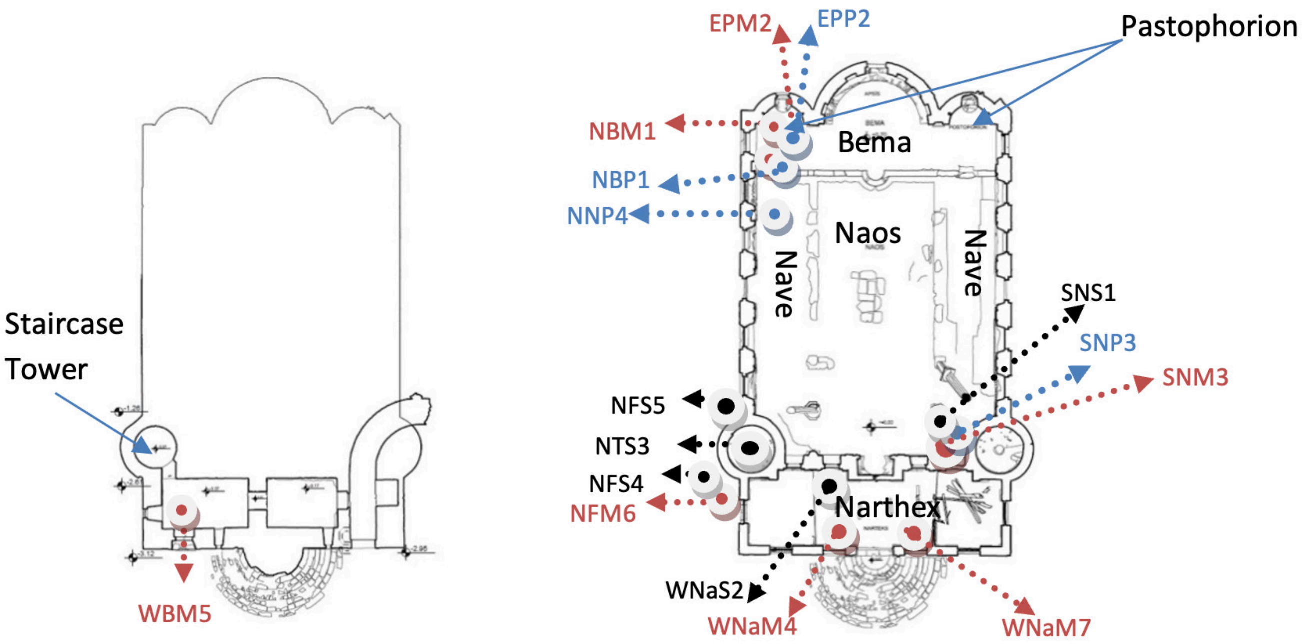


Fig. 3 Sampling locations in basement (−1.28) and ground floor plans (+1.85)

the order of the sample (i.e. the first sample), respectively. The places where the samples were taken from the building were recorded in the plans Fig. 3, and the information about the samples is given in Table 1.

3.2 Physical and mechanical tests

Properties obtained from physical tests as well as the ones from the other analyses provide essential insights into repair materials in historical buildings and help to determine their features [22].

The physical and mechanical experimental stage included capillary, total water absorption, open and total porosity, apparent and real density and pressure tests, besides ultrasound experiments. Tests were conducted in laboratory conditions based on relevant standards to characterize porous building materials and to assess the degree of deterioration [23–25].

Ultrasonic wave velocities have been used by many researchers for determination of physical and mechanical properties of rocks [26–29]. Ultrasonic

Table 1 Mortar, plaster and stone/rock samples

Sample Index	Location and properties of the samples	Distance from the ground level
NBM1	From the brick-brick gap in the northern main wall, the border of the naos and the bema	110 cm
EPM2	From the brick-brick gap of the niche in the left side apse	60 cm
SNM3	From the brick-brick gap on the dividing wall separating the narthex and the naos, in the direction of the naos	60 cm
WNaM4	From the brick-brick gap in the narthex arches, where bricks are mostly used	60 cm
WBM5	From the stone-stone gap in the left room, located in the basement of the church	120 cm
NFM6	From the stone-stone gap in the northwest stair tower	130 cm
WNaM7	From the space in the narthex, which was closed by using mortar and laths	100 cm
NBP1	A finishing material, prepared to look like a stone.	60 cm
EPP2	From the niche in the left side of apse. A thin layer of paint was on the surface.	60 cm
SNP3	From the dividing wall in the narthex and the naos. A thin layer of paint was on the surface.	80 cm
NNP4	Example of plaster taken from the north wall	110 cm
SNS1	From the dividing wall between the narthex and the naos, from the naos part	60 cm
WNaS2	From the dividing wall between the narthex and the naos, from the narthex part	400 cm
NTS3	From the northwest stair tower	120 cm
NFS4	From outside the stair tower in the northwest	130 cm
NFS5	From the main wall on the north façade	130 cm

velocity measurements were performed with NDT James Instruments Inc. V-Meter Mark II ultrasonic velocity measuring device. Results of physical and mechanical tests of stone/rock samples are given in Table 2.

The SNS1 stone is abundant on the inner walls of the building. WNaS2 is used as an ornamental element on the western façade of the building. This easily shaped stone with dusting characteristics is used along the west façade, which is the entrance façade. NTS3 stone is also observed in the main walls in various locations in addition to the staircase towers.

The capacity of a rock to absorb water is closely related to its porosity. In general, the higher the effective porosity is, the higher the total water absorption becomes. However, a stone /rock's ability to absorb total water under normal conditions is related not to its total porosity, but to the percentage of pores that water can access [30]. Supporting this statement, water absorption values by weight and capillary water absorption coefficients were found to be high in samples with high porosity.

3.3 Spot tests and conductivity analysis

Salt analyses including determination of nitrate, chlorine, sulfate, and carbonate ions were carried out in order to detect the presence of salts that cause deterioration in materials in the samples taken from the studied structures. In addition, conductivity values are given. Building materials are exposed to various types of deterioration due to chemical, physical and biological events caused by atmospheric factors [31]. Results of spot tests and conductivity analysis of mortar and plaster samples are given in Table 3.

Total conductivity values are important in determining the rate of exposure of mortars and plasters to salt pollution. This finding also plays a role in determining strength and weather resistance in original mortars [32]. Maravelaki-Kalaitzaki et al. determined the total conductivity values as 61.93–265.15 µs/cm in their analysis with lime mortars in Crete [32]. According to the obtained results, they stated that the mortars and plasters they worked with were greatly affected by salt pollution. The minimum conductivity value in the mortars and plasters of the Derekoy Church was determined as 226 µs/cm, which reveals that the conductivity values of the church mortars and plasters are quite high.

As a result of the salt tests, it was determined that the rate of SO_4 salts was high in the mortar and plaster samples taken from the Derekoy Church. The most important source of sulfate salts is pollution in the atmosphere. Apart from that, sea water also contains some sulfate salt.

Table 2 Results of physical and mechanical tests of stone/rock samples

Sample	Capillary Water Absorption, C ($g/m^2s^{0.5}$)	Water Absorption by Weight (%)	Real Density p_r (kg/m^3)	Total Porosity p (%)	Open Porosity p_0 (%)	Modulus of Elasticity (N/mm^2)	Compressive Strength (N/mm^2)
SNS1	0.73	0.38	2.68	0.57	1.02	50724.0	156.7
WNaS2	19.11	21.01	1.97	17.51	34.12	3072.8	6.2
NTS3	3.85	1.82	2.75	1.97	4.91	40018.9	103.9
NFS4	0.31	0.34	2.71	0.52	0.91	7560.4	9.6
NFS5	8.77	19.94	2.02	16.78	33.54	5256.8	7.8

Table 3 Salt, protein, oil and conductivity analysis

Sample	NO_3^-	Cl^-	SO_4^{-2}	CO_3^{-2}	Protein	Oil	Conductivity (µs/cm)
NBM1	++	+	++	−	+	+	394
EPM2	++	++	-	−	−	+	356
SNM3	++	+	±	−	−	+	253
WNaM4	++	+	−	−	−	+	226
WBM5	+++	+++	±	−	−	+	614
NFM6	++	+	++	−	−	+	688
WNaM7	++	±	−	−	+	+	257
NBP1	+	−	++	+	−	+	691
EPP2	++	±	++	+	+	+	405
SNP3	++	+	++	++	+	+	393
NNP4	++	+	++	+	+	−	286

−: none, ±: there is a detectable amount, +: there is a small amount, ++: there is a considerable amount, +++: there is an ample amount

In addition, these salts can be added to the structure by the capillarity method in places close to agricultural areas. Derekoy Church is located on the periphery of the settlement and close to agricultural lands.

The presence of chlorine and nitrate salts was detected in the samples. Until a few decades ago, nitrate salts originated from some natural pollutants, fertilizers used in agricultural lands, groundwater and some animal feces (birds, etc.). But today the main source of NOx gases is the combustion of fossil fuels, both in industrial activities and in transportation [31]. Chlorine salts can be found in sea water and some building materials. If the sand used in the building is sea sand, Cl^- ions may be found in the salt tests because sea sand contains salt. In addition, water-soluble salts in the environment are added to the structure by the rise of groundwater along the structure by capillary water absorption. As a result of the incorporation of water-soluble salts into the building material, the decomposition and wear process of the materials is accelerated.

The purpose of protein and oil tests is to determine whether protein and/or oil-based substances are used in the applications made to the material and to determine the quality of the binder, preservative and strengthener to be applied in the protection-repair study.

The presence of protein varies according to the type of sample. The presence of protein detected in mortar or plaster samples is usually caused by protein-based additives in the material such as eggs, blood, casein, tow, plant fibers, and animal hair [33–35].

3.4 Chemical analysis

Chemical (ignition loss, acid treatment) and physical (size distribution analysis of aggregates, types and approximate ratios, etc.) analyses are performed on the samples to determine the content of the production material of the structure, the quality and proportions of binders, aggregates and additives, as well as the state of preservation and sources of problems [36]. Ignition and acid loss analyses are employed to determine losses and residues (such as silicate materials that do not react with acid, etc.). Comparing the results of these analyses, the quality, binder, and silicate aggregates of the material are identified. For this purpose, the acid loss and ignition loss values of the samples were compared. The ignition loss results, the aggregate and binder ratios after acid treatment, and the approximate ratios values obtained by sieve analysis of aggregates are given in Table 4.

Acid loss rates of Derekoy Church mortars are high. According to the XRD analysis data applied to the samples in this regard, the fact that this church also has components that show loss when treated with acid, such as dolomite, can be shown as the reason. The $CaCO_3$ ratio was determined to be very low in the WNaM7 mortar. This is because WNaM7 is a repair mortar made for this church in the later period. It was determined that the mortar is mudbrick mortar consisting of soil and fibrous additives.

After the sieve analysis, the aggregates were grouped according to their size, as shown in Fig. 4 [37]. In studies on aggregate granulometry, the regular size of the grains is associated with the quality of the mortar. Moreover, a good mixing process is recommended during mortar preparation in order to ensure homogeneous distribution of aggregates [38].

WNaM7 has a quite different curve from other samples and the standard. After the sieve analysis, the aggregates were examined under the microscope, and varying amounts of volcanic rock, quartz and feldspar, and a small amount of slag, broken brick and fibrous additives were observed. In the WNaM7 sample, on the other hand, it was determined that the rate of fibrous additives was quite high.

Table 4 Ignition loss results, aggregate and binder ratios, and approximate ratios values of aggregates (%)

Sample	Aggregate %	Binder %	Ignition Loss Analysis $CaCO_3$	63 µ	125 µ	250 µ	500 µ	1 mm	2 mm	4 mm	8 mm
NBM1	38	62	56	18.2	22.9	35.7	57.0	76.1	89.8	98.1	100
EPM2	51	49	50	13.4	17.6	29.4	46.9	64.9	81.5	97.1	100
SNM3	38	62	61	16.7	20.1	29.6	43.5	58.3	74.5	91.4	100
WNaM4	22	78	80	19.9	27.7	53.0	71.7	79.5	85.4	95.1	100
WBM5	42	58	63	14.5	17.1	25.2	38.9	51.7	62.0	74.2	83.8
NFM6	33	67	64	17.7	20.2	27.6	39.3	54.7	76.8	92.2	100
WNaM7	85	15	9	33.4	51.5	74.7	86.4	91.5	95.0	97.9	100
NBP1	43	57	69	41.7	61.9	96.3	100	100	100	100	100
EPP2	57	43	46	16.0	19.8	30.7	47.3	69.2	87.3	100	100
SNP3	37	63	55	18.6	24.0	39.0	58.4	74.8	88.4	100	100
NNP4	42	58	50	22.2	24.7	38.2	60.1	78.7	92.1	100	100

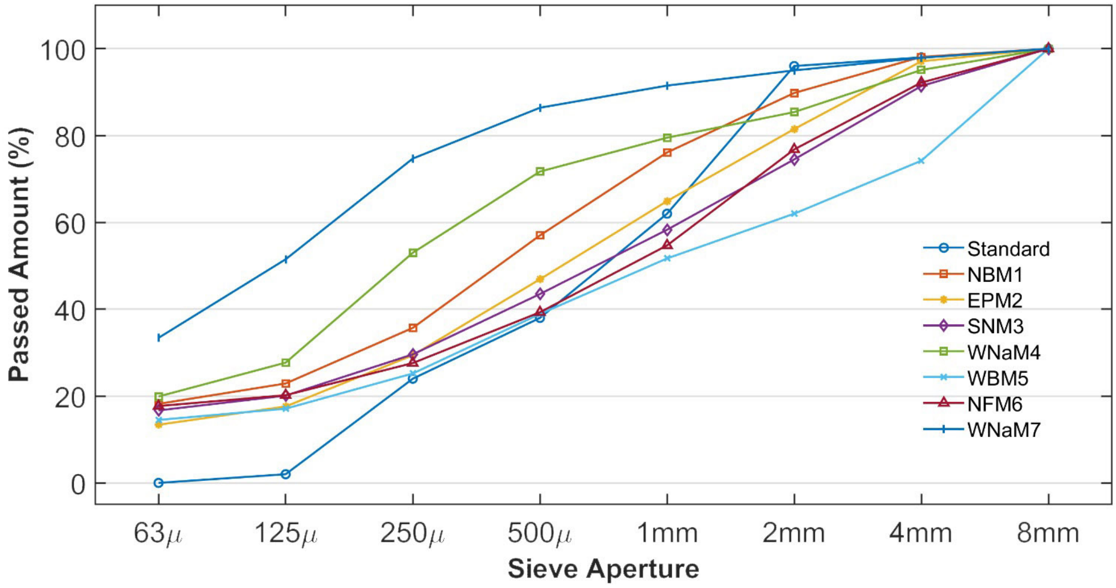


Fig. 4 Cumulative aggregate grading curves; aggregate from church mortars and plasters; standard aggregate according to EN 196-1 [37].

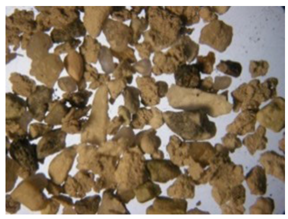
Table 5 shows the microscope images of the aggregates. For these images, the size that most accurately expresses the aggregate properties from each sample was chosen.

Lime was used as binding material in mortars and plasters, and river sand aggregates were used as filling material. The samples were grouped by considering the similarity of binder and aggregate ratios and aggregate types. Mortars of the Derekoy Church were placed in 3 different groups. While the NBM1-EPM2-SNM3-WBM5 mortars taken from the interior of the church are similar among themselves, the WNaM4-NFM6 mortars taken from the exterior spaces are similar between themselves. WNaM7, which was also taken from the outside, is a mortar taken from a recent repair. Plasters were evaluated in a single group. XRD and SEM-EDX analysis was carried out for the NBM1 sample from the NBM1-EPM2-SNM3-WBM5 mortars of the Derekoy Church. WNaM4 from the WNaM4-NFM6 mortars and NNP4 from the plasters were examined.

3.5 Petrographic analysis

With this analysis, the minerals that make up the rocks, the texture formed by these minerals and the weathering of the minerals are determined. The analysis was done by the MTA (Turkish General Directorate of Mineral Research and Exploration) laboratories. The size of the samples given for analysis was 5×5×5 cm. Photographs of the

Table 5 Microscope images of aggregates in mortar samples

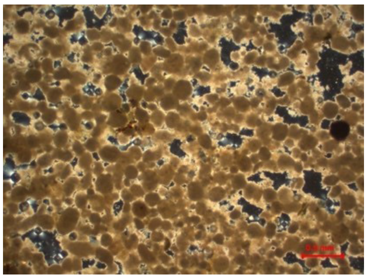
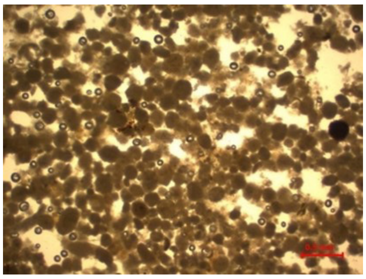
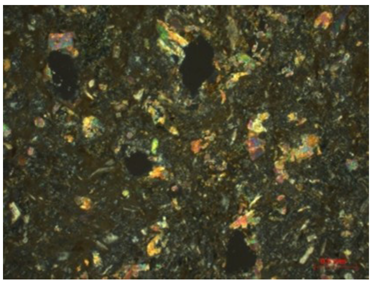
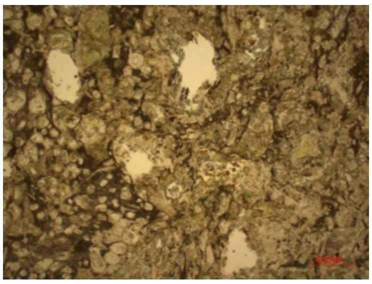
Image				
	NBM1 – 500 μ	EPM2 – 500 μ	SNM3 – 4 mm	WNaM4 – 1mm
Image				
	WBM5 – 2 mm	NFM6 – 2 mm	WNaM7 – 2 mm	

thin-sectioned samples were taken with a polarizing microscope. Mineralogical compositions, textural and alteration properties of the samples were determined, and the samples were named according to the appropriate classification systems in the TS EN 12407 standard for natural stone test methods – petrographic examination [39]. Description is given in Table 6. According to the analysis, the samples taken from the Derekoy Church are SNS1, WNaS2 (pelmicrite rock), NTS3 (sandstone), NFS4 (recrystallized limestone), and NFS5 (limestone) samples [40].

3.6 X-Ray Diffraction (XRD) analysis

In addition to chemical and microscopic analysis, X-ray diffraction (XRD) analysis can be used to identify the types of binders and aggregates in the mortar in crystalline form [41]. Following a qualitative assessment using visual analysis, binders (lime, gypsum, cement and other hydraulic components) and aggregates (silica, calcareous and other natural or artificial aggregates) can be identified by X-ray diffraction analysis (XRD) [36]. This analysis was carried out in the Laboratories of Izmir Institute of Technology. Standard qualitative mineral analysis was carried out by X-ray diffraction (XRD) method, the samples were pulverized, XRD diffractograms were taken and detailed mineralogical definitions were carried out in accordance with the diffractogram. The test was carried out with the ground sample. The diffraction phase diagrams obtained after XRD are given in Fig. 5. Moreover, component details of the EPM2 sample examined in the MTA laboratory are given from high to low rate: calcite, quartz, feldspar group mineral (plagioclase), dolomite, mica group mineral (biotite), chlorite, kaolinite, smectite and very little sphalerite. As a result of the XRD analysis, it can be said that the main compound forming the binding parts of the samples is calcite.

Table 6 Petrographic description of stone samples

 WNaS2 thin section (2 nicols)	 WNaS2 thin section (1 nicol)	Composition: pelloids, microfossil – fossil shell fragments (small amount, small grained and homogeneously distributed), extraclasts/epiclastics (quartz fragments, plagioclase fragments, mica fragments, altered mineral and/or rock fragments), and substrate consisting of carbonate minerals (micrite).
 NTS3 thin section (2 nicols)	 NTS3 thin section (1 nicol)	Its main components are: rock fragments, mineral fragments (feldspar minerals), and microfossil – fossil shell fragments. There are thin and medium-thickness filled fractures and veins in the sample.
 NFS4 thin section (2 nicols)	 NFS4 thin section (1 nicol)	Its components consist of fine-grained, homogeneously distributed carbonate minerals and filled fractures and veins. Widespread recrystallization continues in the formed carbonate minerals.

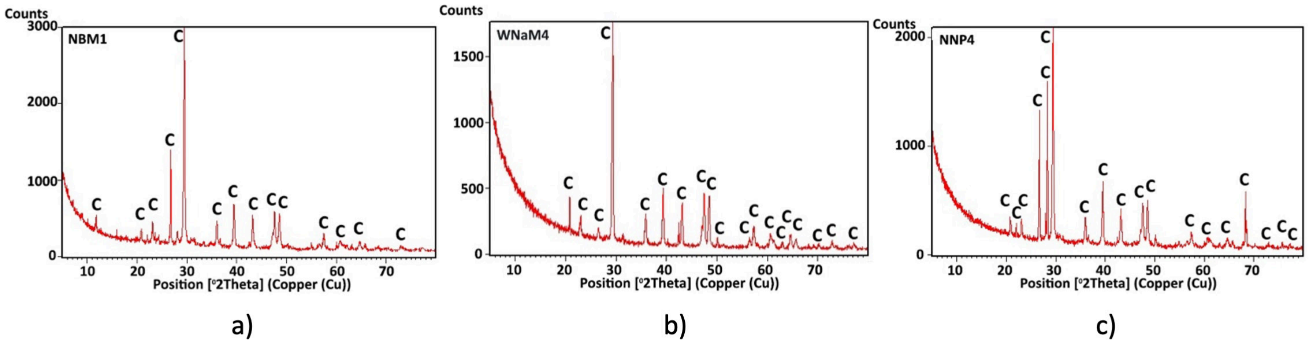


Fig. 5 X-ray diffraction phase diagrams of samples a) NBM1, b) WNaM4 and c) NNP4

3.7 Scanning Electron Microscope (SEM) analysis

The scanning electron microscope (SEM) is an electron microscope that displays the surface of the sample to be analyzed by scanning it in stripes with high-energy electron beams. Qualitative determination of the chemical elements in the components of the sample can be possible if the SEM is equipped with an X-ray detector (EDX, WDX) [41]. EDX spectrums and SEM images of samples are given in Table 7.

The chemical components of the samples were determined by analysis and the calcium oxide (CaO), silicon dioxide (SiO2), aluminum oxide (Al_2O_3), magnesium oxide (MgO), and iron (II) oxide (FeO) values they contain are given in Table 8. NBM1 from the 1st group (NBM1-EPM2-SNM3-WBM5) mortars belonging to the Derekoy Church, WNaM4 from the WNaM4-NFM6 mortars in the 2nd group, and NNP4 from the plaster group were examined within the scope of the analysis. As a result of the analysis, it was determined that the mortars of the Derekoy Church had lime-weighted and non-hydraulic binders. The good condition in terms of their strength shows that the carbonation is completed.

Table 7 EDX Spectrums and SEM Images of samples

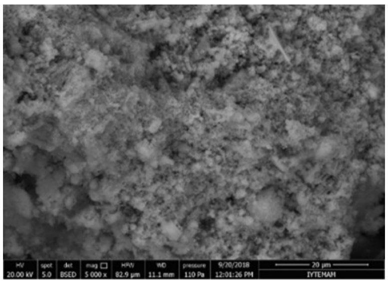
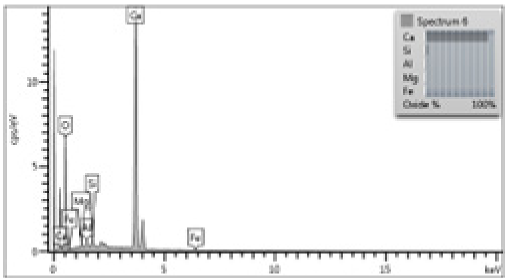
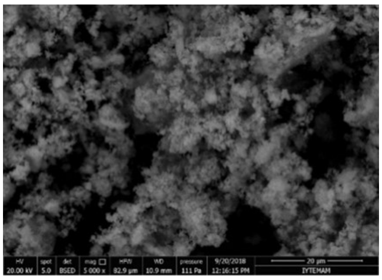
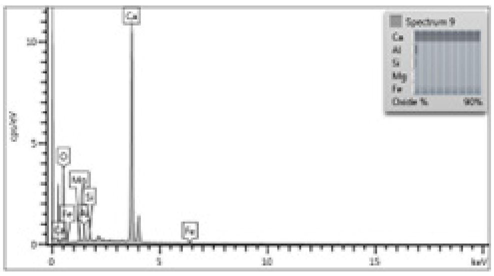
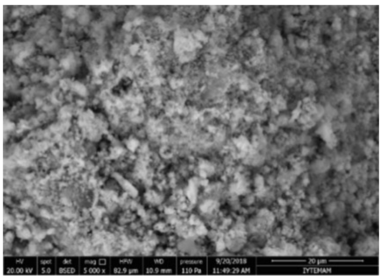
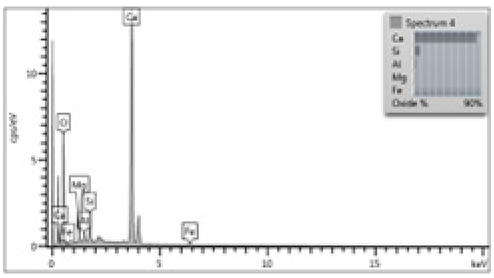
Sample	Image of SEM	EDX Spectrum
NBM1		
WNaM4		
NNP4		

Table 8 Results of the chemical analysis

Sample	CaO	SiO_2	Al_2O_3	MgO	FeO
NBM1	91%	4.58%	2.23%	1.39%	0.79%
WNaM4	88.99%	3.53%	5.58%	0.98%	0.92%
NNP4	84.15%	9.15%	3.07%	1.98%	1.66%

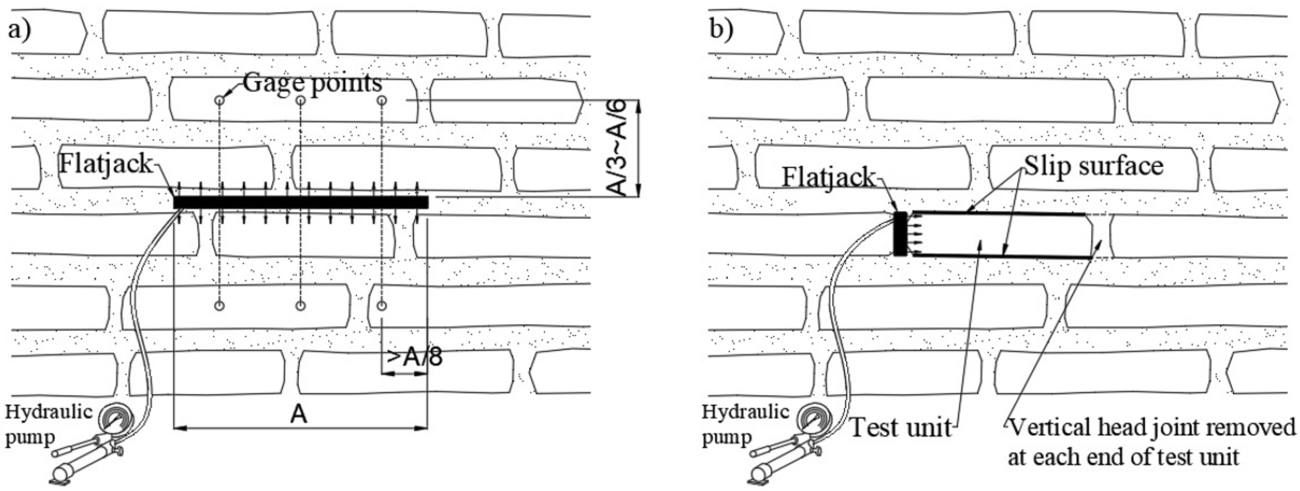


Fig. 6 Flat-jack and shear test a) Single flat-jack test setup b) Shear test setup

4 In situ mechanical and structural tests

4.1 Flat-jack and shear tests

Flat-jack and shear tests were conducted in order to find out the compressive stress, shear stress and elastic modulus of the church walls. A single flat-jack test method according to ASTM Standard C1197-20e1 and method C according to ASTM Standard C1531-09 were used in the flat-jack and shear tests, respectively [42, 43]. In the single flat-jack test method, a cut slot was prepared in the mortar layer and a flat-jack was inserted inside the slot. The displacements and the hydraulic oil pump pressure (psi or bar) were continuously read at the same time. The compressive stresses and elastic modulus of the walls were calculated from the formulas according to ASTM Standard C1314-21 [44]. Two experimental tests in the places shown in Fig. 6 were applied to the walls and the average results were considered for the material properties. In the shear test, a small flat-jack was inserted horizontally at one end of the test unit and the hydraulic oil pressure was applied until a crack or a slip occurred. The test methods can be seen in Fig. 6(a) and Fig. 6(b) [45].

The compressive stress, shear stress and elastic modulus of church walls calculated by in situ tests are presented in Table 9.

Table 9 The mechanical properties of church walls

Compressive Stress (MPa)	Shear Stress (MPa)	Elastic Modulus (GPa)
3.78	0.62	19

4.2 Structural health monitoring tests

The operational modal analysis (OMA) non-destructive test method was used in order to determine the dynamic parameters of church. Mode shapes, natural frequencies and damping ratios of structures can be found out by using this test method. It is based on collecting vibration data when the structure is under operating conditions. The loads are environmental forces and modal identification based only on responses.

Highly sensitive 2400 mV/g mono-axial piezoelectric accelerometers which have 0.01-200Hz bandwidths and ±3g measurement range were used in the tests. The data acquisition device Testbox 2010 which has 8 channels was used in the vibration tests [46].

Thirty-minute test periods were applied for the accuracy of the tests. Accelerometers were placed 1.5 meters under the roof elevation. In the first test, accelerometers were placed on the corners of the whole structure Fig. 7 (a). After conducting test setup 1, the results were also checked by a second test which was conducted on an individual wall of the church in x direction Fig. 7 (b). The bending mode frequencies of the walls were determined with good accuracy and close results were obtained between test setup 1 and test setup 2.

The singular values of the spectral densities, the 3D and the numerical presentation of MAC values, and the first three bending mode shapes in x direction obtained experimentally from test setup 2 are presented in Fig. 8.

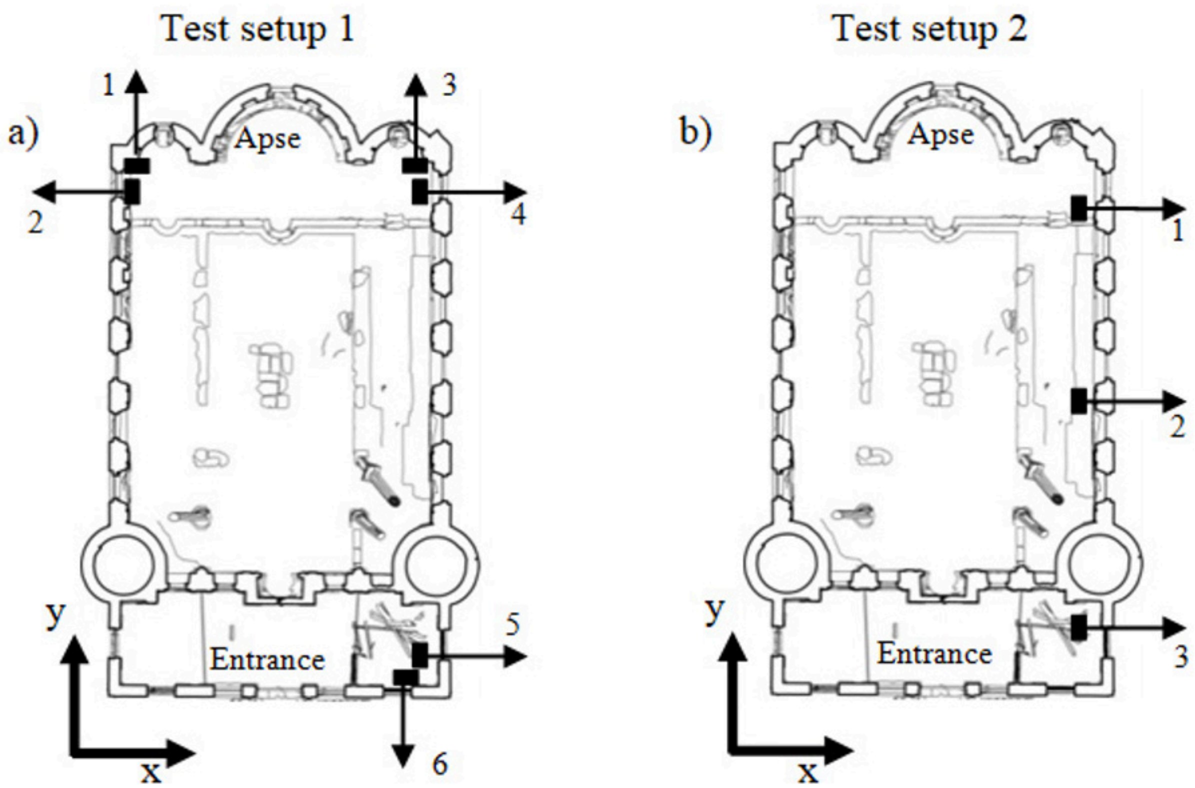
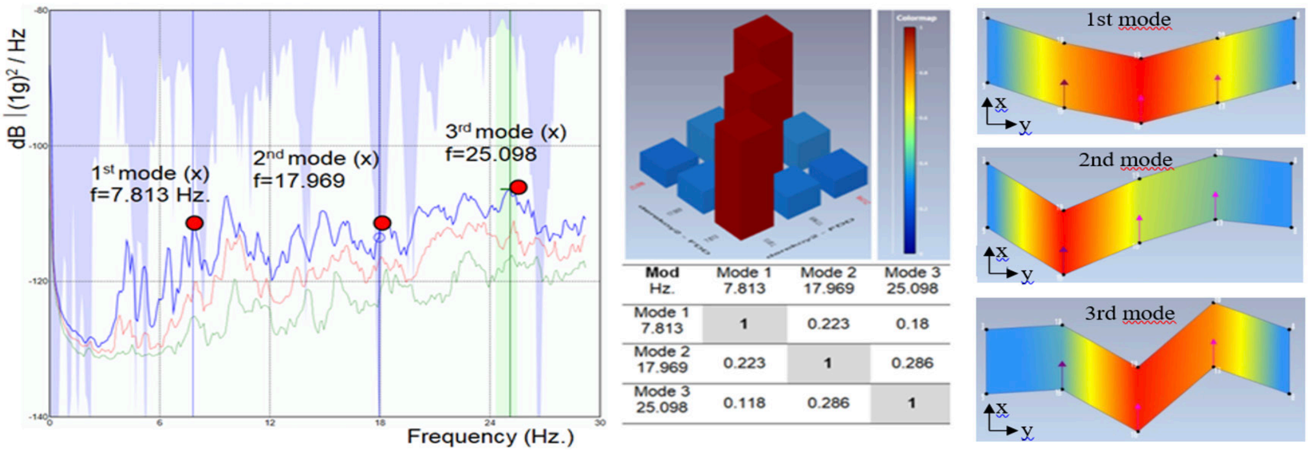


Fig. 7 Plan view of the sensor placements a) test setup 1 b) test setup 2



Mod Hz.	Mode 1 7.813	Mode 2 17.969	Mode 3 25.098
Mode 1 7.813	1	0.223	0.18
Mode 2 17.969	0.223	1	0.286
Mode 3 25.098	0.118	0.286	1

Fig. 8 Singular values of spectral densities, 3D and numerical presentation of MAC values and bending mode shapes of Derekoy Church obtained from test setup 2.

5. Finite element analysis

The mode shapes and natural frequencies of Derekoy Church were investigated by using the Algor V20 finite element analysis (FEA) program. Solid elements (brick, tetrahedral, wedge and pyramid elements) which have three degrees of freedom at every node were used in the mesh of the FEA model. The general wiev of the finite element model shown in Fig. 9. In the finite element model, 5502 solid elements were used in Derekoy Church. After the modal analysis, the FEA model was calibrated in order to represent the real behavior of the structure.

The elastic modulus was obtained as 19 GPa from the flat-jack test results and after the finite element analysis it was calibrated as 15 GPa according to the OMA test results. Thanks to the flat-jack tests, the elastic modulus obtained from the test results are close to the calibrated results which have only a 21% error. The Poisson ratio is taken as 0.16 for the masonry walls [47, 48].

The bending frequencies which were obtained from the OMA tests and finite element analysis were compared with each other. The first three bending mode frequencies

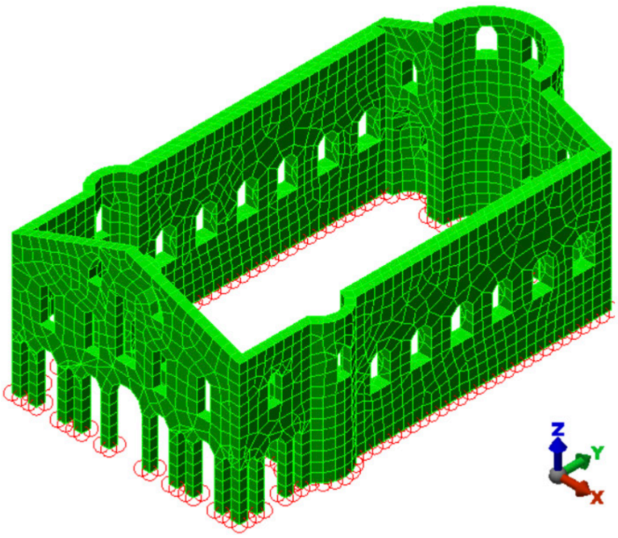


Fig. 9 General view of the three-dimensional finite element model of Church

of the walls in x direction obtained from OMA test setup 2 (Exp.) and the finite element analysis after the calibration (FEA) are shown in Fig. 10. The calculated errors between them are also presented in the figure.

The bending mode frequencies of walls in y direction obtained from finite element analysis are presented in Fig. 11.

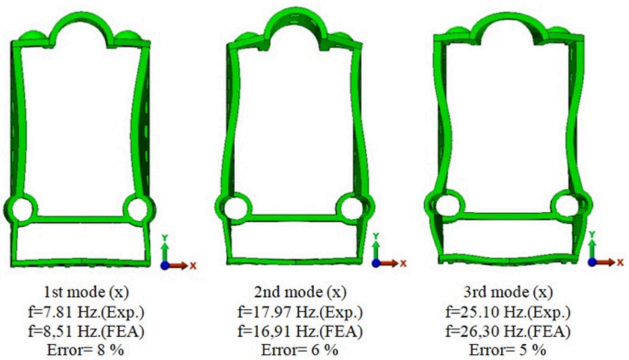


Fig. 10 The first three bending mode frequencies of walls in x direction and errors between experimental and FEA analysis results

The mass participation factors according to the modal analysis were investigated in *x* and *y* directions. The mass participation factor for the first three bending modes and the sum of first three modes of the studied church are represented in Table 10. The sum of the mass participation factors for x and y directions were below or close to 50% percent. It was seen that at least 50 modes should be taken into account to ensure 95% percent of mass participation in order to perform the dynamic structural analysis of the structure.

6 Conclusions

In this study, physical, chemical, mechanical, petrographic and mineralogical tests were carried out order to find out the material characterizations of the mortar, plaster and stones used in the church. The compressive stress, shear stress and elastic modulus of the walls were determined by using flat-jack and shear tests. By finding the natural vibration frequencies of the structures with OMA tests, the necessary material calibrations were made by comparing the mode frequencies found with the finite element analysis. Thus, the reliability of the structural analyses was ensured.

As a result of all these studies, Derekoy Church was evaluated in terms of both its material properties and structural behavior. Based on the results obtained from the analyses, a series of intervention methods were proposed. It would be appropriate to apply the intervention methods presented below.

- Due to the plants growing by wrapping around the surfaces, the surfaces remain moist for a long time.

Table 10 The mass participation factor of the first three bending modes of the studied church in *x* and *y* directions

First mode		Second mode		Sum of first three modes	
x	*y*	*x*	*y*	*x*	*y*
28.66	15.90	11.68	2.48	44.73	28.95

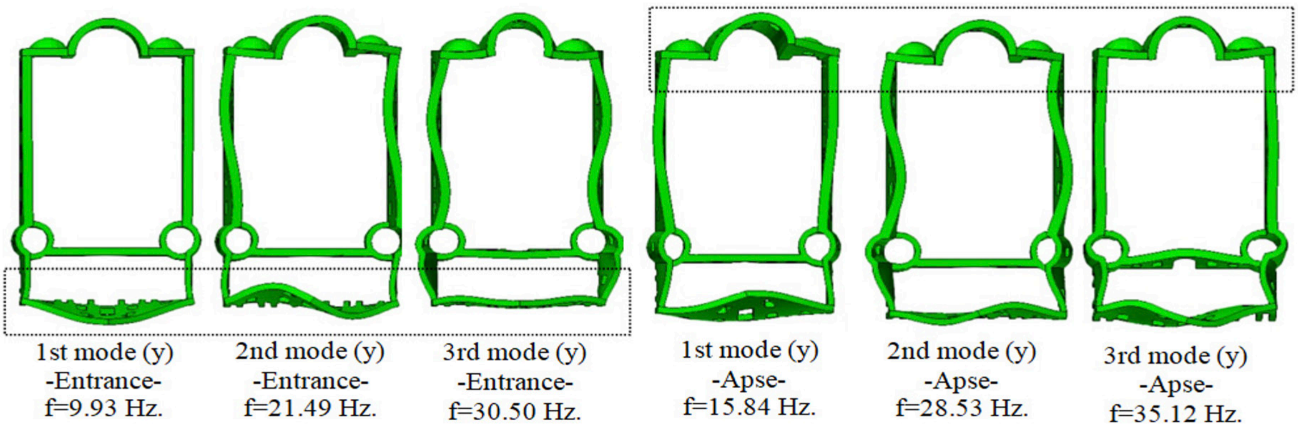


Fig. 11 The first three bending mode frequencies of walls in y direction

This situation makes the surfaces vulnerable to many deteriorations such as current leakage or freezing effects. After cleaning the woody plants by mechanical methods with the help of hands or tools, chemical application should be made to prevent re-growth.

- Due to the fact that the structures are still exposed to external atmospheric conditions, causing more deterioration in the mortar and plaster layers, this causes the mechanical strength of the walls to decrease day by day. It would be appropriate to remove rainwater from the structure.
- The parts where there is pollution/accumulation on the surface should be removed by using appropriate cleaning techniques after the reasons causing deterioration are understood.
- For repair mortars, it is recommended to try a mixture of binder: aggregate: water ratio 1:3:0.46. The binder should consist of slaked lime and the aggregate should consist of quartz-weighted quarry sand.
- For the repair of plasters, it should be known how many layers the plaster consists of and with what kind of technique it is applied to the surface. Especially the color of the repair mortars to be prepared for plasters should be studied in detail in terms of aesthetics and technique. Partial plaster applications and finishing surface trials on the building will facilitate orientation to the right solutions.
- For plaster repairs, trial mixtures can be made by adding fibrous additive (tow) to a mixture of 1 part of cream of lime (containing approximately 50% water) and 3 parts of quartz sand (under 4 mm sieve). The amount of straw/tow can vary between 600-1000 g per 1 m3 of mortar. The tow should be quenched with lime by cutting it in 2-3 cm dimensions.
- Slaked and aged lime should be used in the mortars to be used for repair.
- Aggregates to be used in repair mortars should be selected from water-soluble aggregates that do not contain salt.
- The aggregate sizes selected for the repair mortars should be selected in accordance with the results of the sieve analysis. For aggregates, quarry or stream sands in the region can be used.
- Since only the walls of the buildings have survived, they are extremely vulnerable to out-of-plane effects. Due to the fact that Bursa is located in a 1st degree earthquake zone, it is necessary to support the walls of the buildings and construct the protective roof by taking emergency security measures.
- Flat-jack tests are necessary for determining the mechanical properties of walls for identifying the structural and dynamic characteristics of structures.
- Only the main walls have survived in the structure and no slab, roof, beam or horizontal connection materials exist today. Therefore, the walls do not act as a part of a building but as an individual wall. The vibration analysis should be considered by taking this situation into account. The test measurements should search for the bending modes of the walls.

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