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# EVALUATION OF THE MATERIALS OF A HISTORICAL BUILDING IN TERMS OF RESTORATION: THE CASE OF ANKARA KALECİK CASTLE

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## ABSTRACT

Transferring the historical accumulation of a society to future generations is of great importance for the continuity and identity of that society. Kalecik Castle, built in 200 BC, has witnessed many civilizations since the Galatians period. The protection of historical buildings, which serve as a bridge from the past to the future, can be ensured by appropriate technique and material choices. In this study, the selection of appropriate materials and techniques in the restoration of historical buildings is discussed in the case of Ankara Kalecik Castle. Studies were carried out with samples taken from 4 facades of the castle (north, south, east, west). Physical tests and electron microscope analyzes (SEM and EDS) were performed on the samples taken from the castle. As a result of these analyzes, compressive strength, porosity, water absorption, density and unit volume weight values of the materials used in the structure were obtained. As a result of the EDS analysis, it was observed that the percentages of silicon-dominant elements on the north and south facades and calcium-dominant elements on the west and east facades were prominent. As a result of SEM analysis, it was determined that the particles exhibited a homogeneous distribution. In terms of compressive strength, the highest value was measured on the east facade and the lowest on the north facade. The results of other physical tests showed that the values of the four facades were close to each other. In the light of the data obtained from the samples, the castle was modeled with SAP 2000 program and the static condition of the structure was evaluated. As a result of numerical modeling and analysis, it was determined that the structure was stable under dead loads and it was predicted that the structure could be damaged under live loads.

**Keywords:** Ankara Kalecik Castle, Material, Restoration, Physical experiments, Numerical analysis.

# 1 INTRODUCTION

The transfer of a society's historical accumulation to future generations is critical for social continuity and identity preservation [1-3]. Anatolian lands, which have been home to many civilizations throughout history, serve as a bridge between the past and the future. Strategically located in the center of Anatolia, Ankara has provided a living space for various communities from past to present. However, it has a critical importance not only historically and geographically but also in terms of the establishment of our Republic and was at the center of the War of Independence.

Historic buildings have meaning and value as long as they are preserved and maintain their physical existence. In this context, many historical buildings have been restored today [4]. The most decisive factors in the success of restoration works are the selection of appropriate materials and methods [5]. The materials used in historical buildings reflect the characteristics of the period and are usually easily available in the vicinity of the region where the building was built [6,7].

with single Balcony]. Today, in parallel with the developments in technology and transportation, the variety of materials has increased significantly [8].

Before the restoration works, the building materials within the historical building should be analyzed [9]. If the materials to be used in renovation works do not have appropriate qualities, static problems may arise on the historical building. In this case, which is not limited to the selection of materials, it is also important to choose the appropriate method [10]. The strengthening and restoration of historical buildings in accordance with their originals, without disturbing their historical texture, is only possible with the selection of appropriate materials and methods [11].

There are important studies in the literature on material analysis and modeling of historical buildings. The sections of these studies that include numerical modeling techniques and analysis types used in historical structures and test methods for determining material properties are examined.

Kurugöl and Güleç (2012) conducted a study to determine the material properties of the mortars used in the historical Yoros Castle. In the study, they stated that the mortar material used in the castle was original. They emphasized that albumin was used as an organic additive in the mortar and this confirmed the use of egg white. They stated that the vaterite formation detected in XRD analysis also supports the use of egg white. It was stated that the historical

castle was partially damaged and the durability of the mortars was low. They stated that this low durability was largely due to the pozzolanic brick powders and tuff additives in the binder phase and well-graded aggregates as well as gravel-like residues in the mortars. In this case, they suggested that the mortars can be classified as low density concrete. As a result of the study, they argued that it could be a reference study for the selection of materials required for restoration works [12].

Jonaitis et al. (2018) presented the physical and mechanical analysis of the mortar in the historical retaining wall of Gediminas Castle. As a result of the tests performed on core samples, they revealed that the mortar consisted of hydraulic lime, quartz sand and brick crumb aggregates. They attributed the high compressive strength of the tested mortar to the use of aggregates consisting of lime and ceramic brick crumbs. Analysis of XRD test results revealed a high intensity peak for calcite (CaCO3) in mortar samples collected from the deepest boreholes. Microstructure tests revealed that samples collected from 3.5-7.7 m depth had a dense structure, while samples collected from shallower boreholes contained more pores and voids. They showed that the density and compressive strength of the mortar increased with the depth from which the samples were taken. They showed that the data obtained as a result of these tests and image analysis can help in the selection of appropriate materials for the restoration of the historical building [13].

Dereje (2018) analyzed the historical Mentwab Castle with numerical modeling and determined the material properties with physical tests. Following the conduction of physical tests, the shear strength values, cohesion and friction coefficient of the building material were determined. As a result of the physical tests, cohesion and friction coefficient, which are shear force parameters, were 0.15 MPa and 0.76 MPa, respectively. The following text is intended to provide a comprehensive overview of the subject matter. The modulus of elasticity was measured at 2.35 MPa, and it was stated that the average modulus of elasticity is equivalent to 38 MPa. In light of the numerical modelling undertaken, it was determined that the structure is only stable in the presence of vertical loads, that is to say, its own weight. The stress levels exhibited under this loading condition were found to be lower than the bearing capacity of the wall [14].

Stavroulaki et al. (2018) investigated the structural behavior of Frangokastello Castle, a medieval masonry castle located on the island of Crete, Greece. The finite element method was used to determine the structural behavior. They stated that the modeling was based on the existing geometry, the history of the monument and its interventions, the quality of the building

materials, and investigations of the subsoil conditions. They stated that the large vertical crack in the entire height of the north face of the northwest tower is a risk factor for the tower and assessed that part of the tower could collapse in the event of an earthquake. They noted that the irregularity of the wall in the center of the south wall appears to be due to out-of-plane bending after the earthquake. This failure mode was confirmed by nonlinear analysis under real earthquakes. In parallel, they stated that the south wall vibrates at the first frequency as shown in the modal analysis. They gave their opinions on the appropriate interventions for the restoration works to be carried out in the historical castle. They stated that the wall sections were completely or partially damaged and the mortar was damaged and as a result, they determined that the wall material and mortar should be replaced [15].

Yatkın (2019) investigated the deterioration of a historical building and the selection of suitable materials for restoration in Ankara Castle. In the study, various physical tests were applied to the samples taken from the castle. As a result of the study, it was observed that the compressive strength of the samples taken from the east facade was high, while the compressive strength of the samples taken from the west facade was low. According to the results of the water absorption tests, the average water absorption values of the samples from the east side were the lowest and the average water absorption values of the samples from the west side were the highest. It was stated that the highest values in porosity tests were observed in the west facade specimens and the highest values in strength tests were observed in the east facade specimens. In terms of thermal conductivity, it was reported that the highest values were observed in the east facade samples. In the study; in terms of mechanical and physical properties, it was explained that the building materials used on the south and east facades have higher strength compared to the building materials on the other facades [16].

Fırat (2020) modeled Geben Castle (Kahramanmaraş) in SAP 2000 program and performed its structural analysis. It was asserted that the material properties to be employed in the modelling process had been obtained from studies of a literary nature. The results of the analysis performed under dead load and gravitational force demonstrated that the compressive stresses in the model's wall remained at a level of 0.5 MPa, while the tensile stresses maintained a level of 0.3 MPa. It has been stated that the occurrence of collapse in the aforementioned historical structure is contingent upon the specific combination of moving load and the application of earthquake forces. Therefore, it was posited that works of reinforcement should be carried out in the castle in order to restore the original wall horizontal load transfer condition to the structure. [17].

Belovacıklı (2022), Analysis study using finite element method in historical castles realized. Sinop Castle was analyzed. In the study, the structural system of the building material properties of the elements were obtained from literature studies. Sinop region modeling using earthquake data, the displacement of the historic Sinop Castle in terms of rigid behavior has been shown to be largely rigid. Dead loads and earthquake of the maximum stress values occurring under the loads at the corner of the castle bastion points [18].

In the summarized studies, the material properties of the historical buildings are presented. Electron microscopy analyses and numerical modeling analyses are mentioned in the summarized studies. In this study, the materials used in the construction of Kalecik Castle in Kalecik district of Ankara province were analyzed. There are studies on the archaeometric properties of the stones of Kalecik Castle. However, there is no study evaluating its structural properties [19]. This shows the originality of our study. Samples taken from Kalecik Castle and belonging to 4 different facades were subjected to physical tests and the materials used in the historical building were physically analyzed. In addition to physical tests, SEM and EDS analyses were performed on the samples by scanning electron microscopy. The chemical components of the samples taken from the castle were determined and images of the particle structure of the samples were obtained. In line with the data obtained as a result of these tests, inferences were made regarding the selection of the most appropriate materials and methods that can be used in restoration works.

Using the material properties obtained from physical tests, the historic building was modeled in SAP 2000 program. As a result of the modeling, how the structure behaves under its own weight, earthquake and other factors are modeled and the results are presented.

As a result; the criteria for determining the material properties to be used during restoration works in a historical building have been investigated in the case of Ankara Kalecik Castle and it is aimed to provide information about the materials and methods to be used.

## 2 MATERIAL AND METHODOLOGY

The samples taken from Kalecik Castle, which is the subject of our study, were subjected to physical tests.

Kalecik Castle (Figure 1) was partially restored in 2001, but this work was insufficient. In order to determine the appropriate restoration techniques that can be carried out in Kalecik Castle, a detailed research and study was carried out by taking stone samples from the castle.

The materials affected by climate parameters and environmental impacts were taken from the castle and used as test samples. In accordance with the permission received from the relevant institution, samples were collected from the pieces that broke off from the castle.



***Figure 1. Walls restored with the integration technique at Kalecik Castle.***

The following experiments were carried out on the samples taken from Kalecik Castle in Gazi University Faculty of Technology Building Materials Laboratory: Compressive strength test, density test, porosity test and water absorption test. Scanning Electron Microscopy Analyses SEM and EDS were performed at the SEM Laboratory Unit of the Department of Metallurgical and Materials Engineering, Faculty of Technology, Gazi University.

## 2.1 Preparation of Test Specimens

The samples taken from Kalecik Castle were prepared in appropriate sizes and dimensions (50mm×50mm, 48×48mm) to be used in experimental studies. Images of the prepared samples are presented in Figure 2 Samples A and B are materials consisting of volcanic rock fragments.




***Figure 2. Samples taken from Kalecik Castle.***

## 2.2 Compressive Strength Test

The compressive strength test on the specimens taken and prepared for the test was carried out as specified in TS EN 1926. The standard states that "Test specimens should be cubes with sides of (40 ± 1) mm. These surfaces should be formed by wet cutting with a stone cutting saw. The force application surface and the seating surface of the specimens should be parallel to each other. The specimens obtained from Kalecik Castle were prepared as cube specimens. Before the test, they were dried in an oven for 24 hours and subjected to compressive strength.

## 2.3 Porosity Test

The porosity of a natural stone is the ratio of the void volume to the whole volume. Porosity values, which have an important place as an engineering property, are necessary in solving many engineering problems. The necessary studies on porosity were carried out in accordance with TS EN 1936 Natural stone test methods (2007) standard and porosity calculation is shown in Equation 1.

$$P = \left(1 - \frac{\rho_b}{\rho_r}\right) * 100 \tag{1}$$

$$\rho_b = \frac{m_d}{m_s - m_d} * \rho_{rh} \tag{1a}$$

$$\rho_r = \frac{m_e}{m_2 + m_e - m_1} * \rho_{rh} \tag{1b}$$

P : Porosity

$\rho_b$ : Apparent density of sample (kg/m3)

$\rho_r$ : True density of sample (kg/m3)

$\rho_{rs}$ : Density of water (kg/m3)

$m_d$ : Dry sample mass (g)

$m_s$ : Saturated sample mass (g)

$m_h$ : Sample mass immersed in water (g)

$m_e$ : Grounded and dried sample mass (g)

$m_1$ : Pycnometer mass filled with water and ground sample (g)

$m_2$ : Pycnometer mass filled with water (g)

## 2.4 Unit Volume Weight Test

For the test specimens, two unit volume weights were calculated as dry unit volume weight and saturated unit volume weight. To be used in the calculations, the samples were saturated by soaking in water for 24 hours. Afterwards, the samples were weighed in water on an Archimedes scale.

The saturated unit volume weight ϒd is the ratio of the weight of the sample with completely saturated voids to the total volume. The saturated unit volume weight equation is shown in Equation 2.

$$\gamma_d = W_{Saturated}/V_{total} \tag{2}$$

The samples were dried in an oven at 105°C and their dry weights were measured for dry unit volume weight experiments. Dry unit volume weight is the ratio of the oven-dried sample weight to the total volume. The dry unit volume weight calculation is shown in Equation 3.

$$\gamma_d = W_{Dry}/V_{total} \tag{3}$$

## 2.5 Density Experiment

The samples crushed in the compression test were ground in a ring grinder and passed through a 63-micron sieve for the actual density test.

Experimental samples were prepared by weighing 50 g of the samples passed through the grinder. Their volumes were found with the help of Le Chatelier flask and their densities were calculated. The calculated density is the actual density and does not include the volume of closed pores.

Apparent density can be calculated as the ratio of the sample weight to the apparent solid volume. The apparent volume includes the volume of powder and the volume of closed pores. The equation for density calculation is shown in Equation 4.

$$\rho = m \,/\, V \tag{4}$$

## 2.6 Water Absorption Test

Water absorption test in question provides information regarding the amount of void space present in the sample. Water absorption can be determined as the percentage of water absorbed by weight or volume. The equations for water absorption by weight and by volume are shown in Equations 5 and 6.

$$S_a(\%) = (W_2 - W_2) * 100/W_1 \quad (5)$$

$$S_h(\%) = (W_2 - W_2) * 100/V_1 \quad (6)$$

## 2.7 Scanning Electron Microscopy Analysis (SEM) and Energy Dispersive Spectrometry (EDS)

Scanning electron microscope (SEM) is a type of electron microscope that obtains images by scanning the sample surface with a focused electron beam. Structural and morphological elemental analysis of the samples were carried out in the light of the images taken by scanning electron microscopy and the data obtained from the EDS outputs.

EDS (Energy-dispersive X-ray spectroscopy) is a method used for elemental analysis or chemical characterization of samples. It is a technique based on the interaction of an X-ray excitation source with the sample.

Typically, a minimum of 3 to 5 representative samples were prepared and analyzed to ensure the reproducibility and reliability of the SEM and EDS results. Each sample was selected to represent the overall batch or material under investigation. Samples were chosen to be homogeneous, defect-free, and representative of the bulk material. Surface conditions such as roughness, cleanliness, and absence of contamination were ensured to optimize imaging and elemental analysis quality. Samples were cut into small sections (usually around 5 mm × 5 mm or smaller, depending on the analysis requirements) using a precision saw or appropriate cutting tool to minimize mechanical deformation. The specimens were mounted on standard SEM stubs using conductive carbon tape or adhesive to ensure electrical conductivity and mechanical stability during imaging. To obtain a smooth and flat surface, samples were sequentially ground with silicon carbide abrasive papers (typically from 600 to 1200 grit), followed by polishing with diamond suspensions down to 1 µm particle size. After polishing, samples were ultrasonically cleaned in ethanol or acetone for 5–10 minutes to remove any residual debris or contaminants. Non-conductive specimens were sputter-coated with a thin layer (~5 nm) of gold,

platinum, or carbon to prevent charging effects during SEM imaging. Prepared specimens were stored in a clean, dust-free environment before analysis to maintain surface integrity.

# 3 RESULTS AND DISCUSSION

Samples taken from the historical Kalecik Castle were subjected to experiments in the laboratory environment. Compressive strength, porosity, unit volume weight, density and water absorption tests were performed on the samples. Scanning electron microscopy analyses (SEM and EDS) were performed in the laboratory. The results of these experiments are given below.

## 3.1 Scanning Electron Microscopy Analysis (SEM) and Energy Dispersive Spectrometry (EDS)

Compressive strength tests were performed on samples taken from the north, south, west and east directions and the results are shown in Table 1.

***Table 1. Results of compressive strength test***

| Location | Dimensions | | Area | Load | Stress | Mean | Standard deviation | Standard deviation | Standard deviation |
|---|---|---|---|---|---|---|---|---|---|
| | Width | Height | ($mm^2$) | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) | (MPa) |
| North-1 | 48 | 48 | 2304 | 113324 | 49.19 | | | | |
| North-2 | 47 | 47 | 2209 | 111506 | 50.48 | 54.4 | 7.9 | | |
| North-3 | 45 | 45 | 2025 | 128645 | 63.53 | | | 1.5 | |
| West-1 | 48 | 48 | 2304 | 118222 | 51.31 | | | | |
| West-2 | 48 | 48 | 2304 | 120395 | 52.25 | 56.5 | 8.3 | | |
| West-3 | 42 | 42 | 1764 | 116520 | 66.05 | | | | 8.8 |
| South-1 | 50 | 50 | 2500 | 156252 | 62.50 | | | | |
| South-2 | 50 | 50 | 2500 | 174450 | 69.78 | 69.17 | 6.4 | | |
| South-3 | 46 | 46 | 2116 | 159188 | 75.23 | | | 1.8 | |
| East-1 | 48 | 48 | 2304 | 181435 | 78.75 | | | | |
| East-2 | 46 | 46 | 2116 | 145805 | 68.91 | 71.7 | 6.2 | | |
| East-3 | 48 | 48 | 2304 | 155393 | 67.44 | | | | |

The average compressive strength on the north facade was 54.4 MPa, while the average compressive strength on the west facade was 56.53 MPa. While the average compressive strength on the south facade was 69.17 MPa, the average compressive strength on the east facade was 71.7 MPa. In the light of the results, the compressive strengths of the samples taken from the north and west facades were close to each other. Likewise, the compressive strengths of the samples taken from the south and east facades were found to be close to each other. Natural stones used in historical buildings have high values in terms of bearing capacity and

compressive strength, but lower values in terms of tensile strength. It has been observed that on windy facades (North and West), the stone wears out more with rain. On windless facades, the stone maintains its strength as it did on the first day. Average compressive strengths are presented in Figure 3.

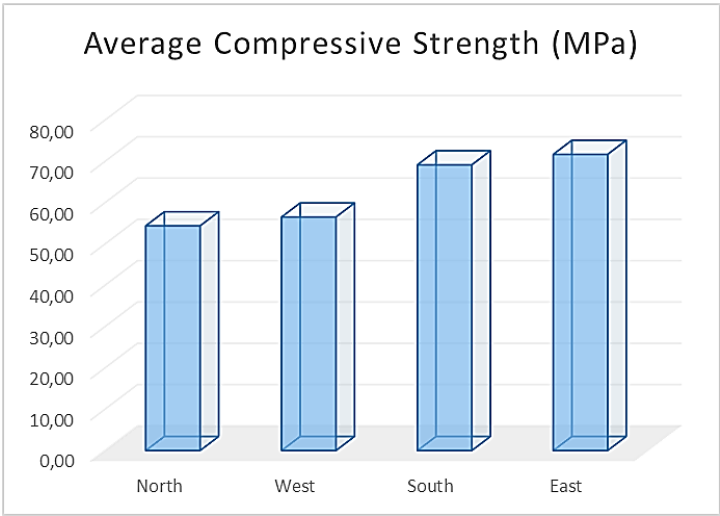



***Figure 3. Average compressive strengths (MPa).***

## 3.2 Porosity Test

Samples taken from 4 different facades in Kalecik Castle were subjected to porosity testing and the results are shown in Table 2.

***Table 2. Porosity test results***

| Location | Porosity (p) | Standard Deviation |
|---|---|---|
| North-1 | 0.13 | 0.006 |
| North-2 | 0.14 | |
| North-3 | 0.14 | |
| West-1 | 0.13 | 0.000 |
| West-2 | 0.13 | |
| West-3 | 0.13 | |
| South-1 | 0.13 | 0.000 |
| South-2 | 0.13 | |
| South-3 | 0.13 | |
| East-1 | 0.13 | 0.006 |
| East-2 | 0.13 | |
| East-3 | 0.14 | |

## 3.3 Unit Volume Weight Test

The dry and saturated unit volume weights of the samples taken from the north, south, west and east facades were determined. The results obtained are shown in Table 3.

***Table 3. Unit volume weight test results***

| Location | Weights | | | Volume | Unit volume weight mean | | | |
|---|---|---|---|---|---|---|---|---|
| | Saturated surface weight (gr) | Weight in water (gr) | Dry weight (gr) | ($cm^3$) | Dry unit weight ($gr/cm^3$) | Standard deviation ($gr/cm^3$) | Saturated unit weight ($gr/cm^3$) | Standard deviaton ($gr/cm^3$) |
| North-1 | 1572.48 | 933.08 | 1512.99 | 638.40 | 2.37 | | 2.46 | |
| North-2 | 1420.34 | 837.05 | 1365.06 | 582.38 | 2.34 | 0.015 | 2.44 | 0.015 |
| North-3 | 778.58 | 462.68 | 742.66 | 315.41 | 2.35 | | 2.47 | |
| West-1 | 1900.59 | 1131.81 | 1822.17 | 767.58 | 2.37 | | 2.48 | |
| West-2 | 755.61 | 449.66 | 722.19 | 305.47 | 2.36 | 0.006 | 2.47 | 0.006 |
| West-3 | 472.35 | 281.76 | 451.56 | 190.29 | 2.37 | | 2.48 | |
| South-1 | 512.82 | 305.40 | 491.74 | 207.10 | 2.37 | | 2.48 | |
| South-2 | 2627.78 | 1565.08 | 2516.88 | 1061.04 | 2.37 | 0.000 | 2.48 | 0.000 |
| South-3 | 1473.14 | 877.53 | 1407.81 | 594.68 | 2.37 | | 2.48 | |
| East-1 | 1671.47 | 994.05 | 1600.02 | 676.36 | 2.37 | | 2.47 | |
| East-2 | 796.35 | 475.06 | 762.01 | 320.79 | 2.38 | 0.010 | 2.48 | 0.006 |
| East-3 | 419.36 | 249.58 | 399.83 | 169.52 | 2.36 | | 2.47 | |

## 3.4 Density Experiment

The data obtained as a result of the density test performed on samples from 4 different facades taken from Kalecik Castle are shown in Table 4.

***Table 4. Density experiment results***

| Location | Apparent density ($gr/cm^3$) | Standard deviation ($gr/cm^3$) | Real density ($gr/cm^3$) | Standard deviation ($gr/cm^3$) |
|---|---|---|---|---|
| North-1 | 2.61 | | 2.723 | |
| North-2 | 2.59 | 0.036 | 2.723 | 0.005 |
| North-3 | 2.66 | | 2.731 | |
| West-1 | 2.64 | | 2.723 | |
| West-2 | 2.65 | 0.010 | 2.723 | 0.005 |
| West-3 | 2.66 | | 2.731 | |
| South-1 | 2.64 | | 2.723 | |
| South-2 | 2.65 | 0.010 | 2.731 | 0.005 |
| South-3 | 2.66 | | 2.731 | |
| East-1 | 2.65 | | 2.723 | |
| East-2 | 2.66 | 0.010 | 2.731 | 0.005 |
| East-3 | 2.67 | | 2.731 | |

## 3.5 Water Absorption Test

Water absorption tests were performed on the samples taken from Kalecik Castle and the water absorption rates by weight and volume are shown in Table 5.

***Table 5. Water absorption test results***

| Location | Apparent density | Standard deviation | Real density | Standard deviation |
|---|---|---|---|---|
| North-1 | 3.93% | | 9.32% | |
| North-2 | 4.05% | 0.49% | 9.49% | 1.15% |
| North-3 | 4.84% | | 11.39% | |
| West-1 | 4.30% | | 10.22% | |
| West-2 | 4.63% | 0.18% | 10.94% | 0.41% |
| West-3 | 4.60% | | 10.93% | |
| South-1 | 4.29% | | 10.18% | |
| South-2 | 4.41% | 0.18% | 10.45% | 0.41% |
| South-3 | 4.64% | | 10.99% | |
| East-1 | 4.47% | | 10.56% | |
| East-2 | 4.51% | 0.23% | 10.70% | 0.52% |
| East-3 | 4.88% | | 11.52% | |

## 3.6 Scanning Electron Microscope Analyses (SEM) and Energy Dispersive Spectrometry (EDS)

Samples of four different facades taken from Kalecik Castle were subjected to SEM analysis. Figure 4 show the SEM analysis photographs of four different facades.

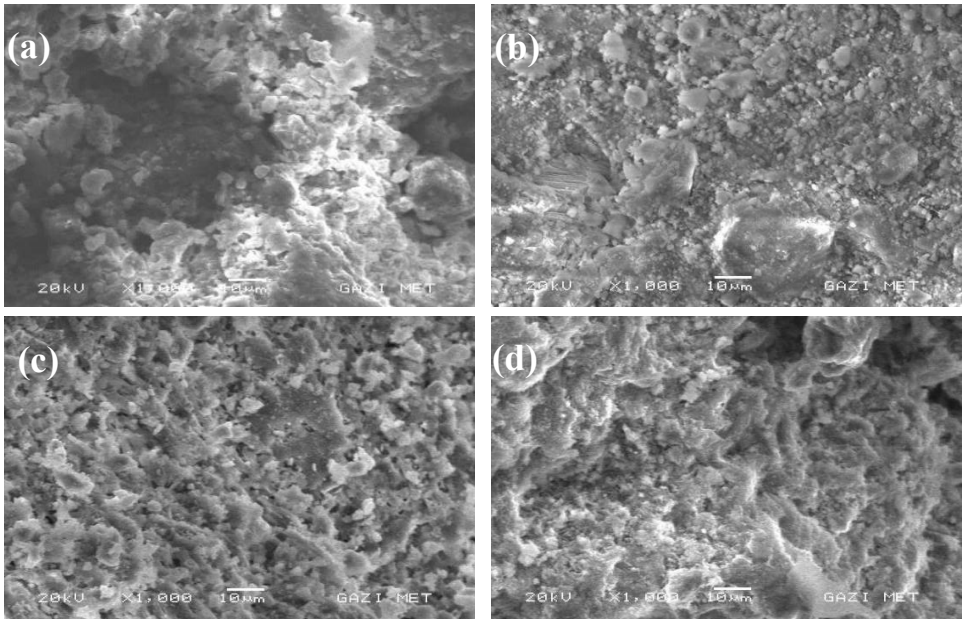



***Figure 4. SEM analysis photographs (a) North facade (b) West facade (c) South facade (d) East façade.***

As a result of SEM analysis, the particles show a homogeneous and similar distribution in the samples taken from 4 different fronts. The distances between the particles are narrow. The sizes are approximately 0.35-0.91 µm. In the photographs obtained as a result of the analysis, it was observed that the particles of different sizes and shapes were close to each other in color tones. Some parts are dark gray and some parts are light gray and white. A homogeneous structure was generally observed. It was evaluated that the particles were in a tight form, excessive voids and very large particles were not observed.

Samples from 4 different facades taken from Kalecik Castle were subjected to EDS analysis. EDS analyzes of four different facades are presented in Figure 5.

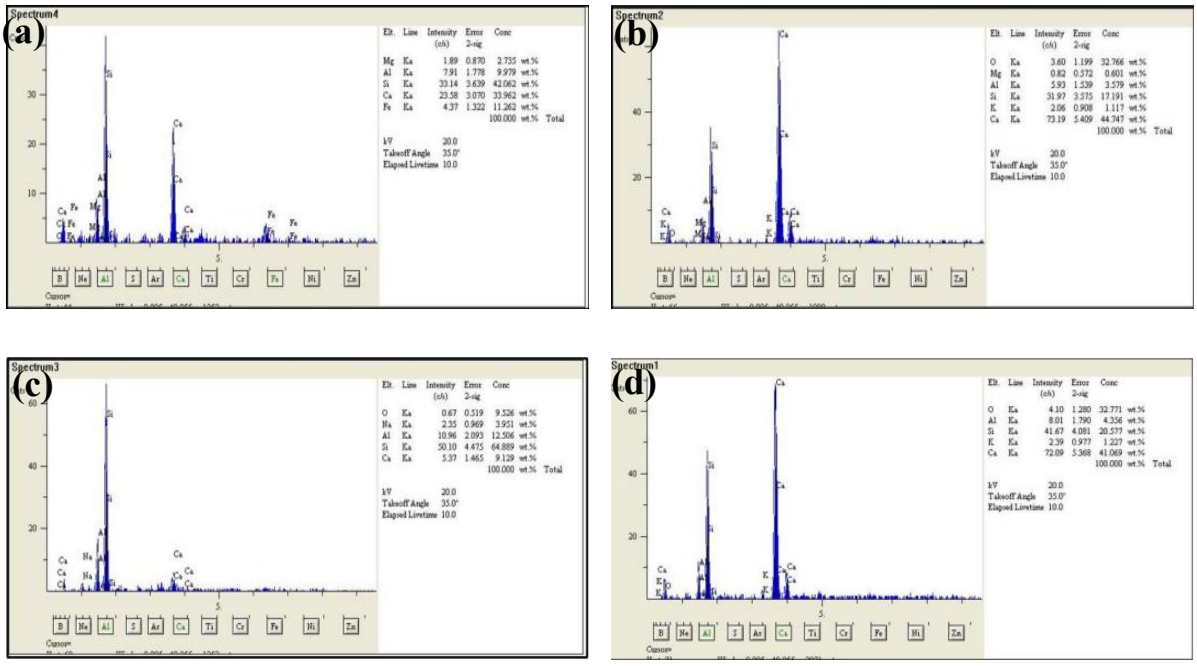



***Figure 5. EDS analysis (a) North facade (b) West facade (c) South facade (d) East façade.***

EDS analyses were performed by focusing on a 10 µm spot and scanning an area of approximately (50 µmx50 µm). This was done with a depth of approximately 2.5 µm. In these analyzes, it was observed that the sample had a pure structure. The element percentages obtained from EDS analysis are shown in the tables in the pictures.

According to the EDS analysis; Material Structure, all facades are dominated by calcite (CaCO3) or lime-based structure. In the south and east facades, it is understood that there is mortar or brick additives due to the additional aluminum and silicon content. Deterioration and decomposition, the north facade has the highest carbon and sodium content and the highest risk of efflorescence and contamination. The west facade contains high calcium and magnesium, so

it is relatively solid but there are some signs of deterioration (Fe). The south and east facades contain low deterioration elements (Na, Fe), meaning they are more stable and solid surfaces.

## 3.7 Modelling and Structural Analysis of The Walls of The Historical Kalecik Castle

### 3.7.1 Castle Dimensions Used in Static Analysis

In the static analysis, the entrance part of the castle was modeled and the results were obtained. The height of the city wall where the entrance gate of the castle is located was determined as 8 m and its width was determined as 7 m. The height of the circular section bastion on the left side of the castle gate was determined as 15 m and its radius as 6 m. The wall thickness was determined as 1 m in the calculation.

### 3.7.2 Modeling the Castle

A section of the walls of Kalecik Castle, which will be used in the modeling, was transferred to the system and drawn in SAP 2000 program according to the modeling features of the program. All the data required for the analytical modeling of the structure were recorded by taking measurements from the castle. The load and other parameters to be used in modeling and calculations are given below

- The structure was modeled as a solid element in SAP 2000 program.
- The material used in the castle is natural stone. Samples were taken from 4 facades of the castle and subjected to physical tests. The data obtained as a result of the experiments were entered into the system and the model was created. In addition, other material properties were entered into the system by taking into account the data obtained as a result of previous studies on this subject, the data published by international refereed journals and the values recommended for masonry structures in the specifications in force by using the relations recommended in the international literature.
- It is assumed that stone and mortar together are a single material in masonry structures. Modulus of elasticity and unit volume weight values were entered into the system based on this assumption.
- On the model created, the load relation was created and applied based on constant loads and earthquake loads. Load combinations were created with the fixed load (G) and

earthquake loads (+EX, +EY, -EX, - EY). In the modeling and analysis phase, G, G+EX, G-EX, G+EY and G-EY load combinations were created in the system.

- The parameters to be used in the calculation of the earthquake force to be used in the calculation were obtained from AFAD according to TBDY 2018.

In order to obtain accurate data during the analysis and modeling phase in historical buildings, it is important to know the properties of the material used in the building. The material properties of the samples taken from Kalecik Castle were obtained as a result of physical tests. It is important to use the physical properties of the samples taken from the castle for a realistic analysis. The modulus of elasticity and Poisson's ratio values to be used in modeling were obtained from previous studies. The modulus of elasticity was taken as (1 000 000 kN/m$^2$) and Poisson's ratio as (0.2).

### 3.7.3 Transferring the Structure to SAP 2000 Program

The 3D model created in the SAP 2000 program is shown in Figure 6 and 7.

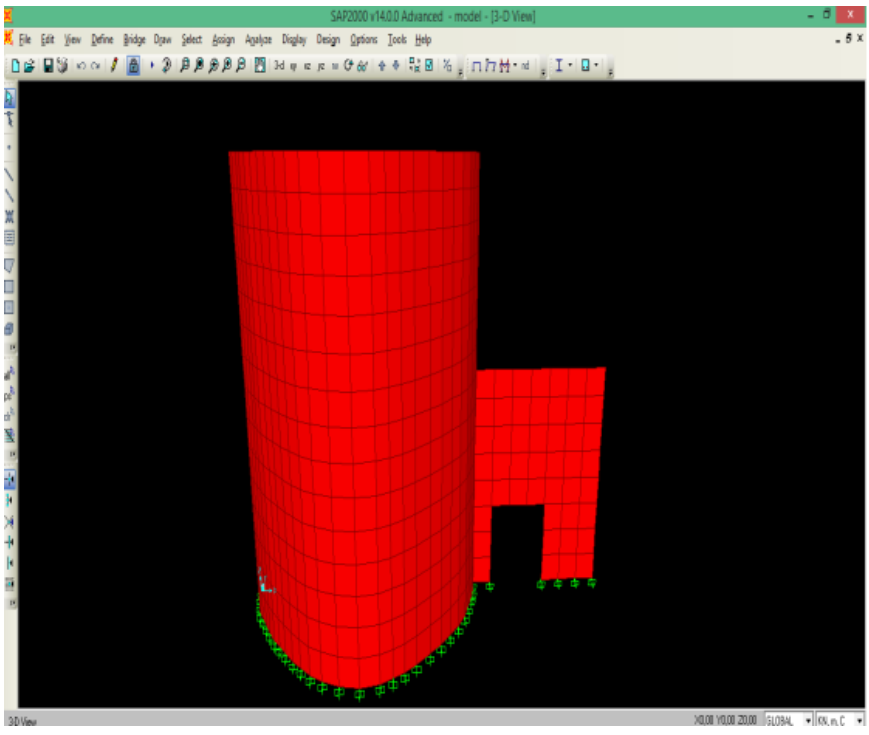


***Figure 6. Analysis model of the entrance of Kalecik Castle.***

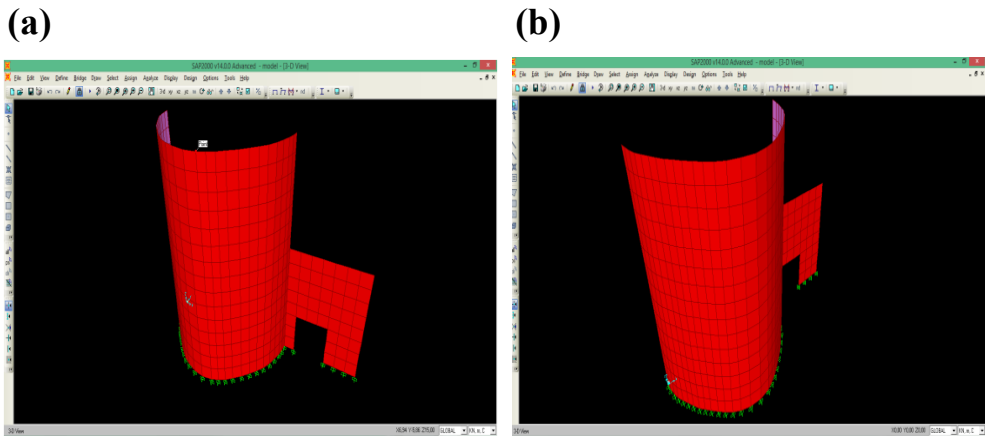



***Figure 7. Kalecik castle entrance castle analysis model (a) right side view (b) left side view.***

The physical properties of the material used in the structure were obtained as a result of the experiments and material properties were defined in the system. The part where material properties are defined to the program is shown in Figure 8.

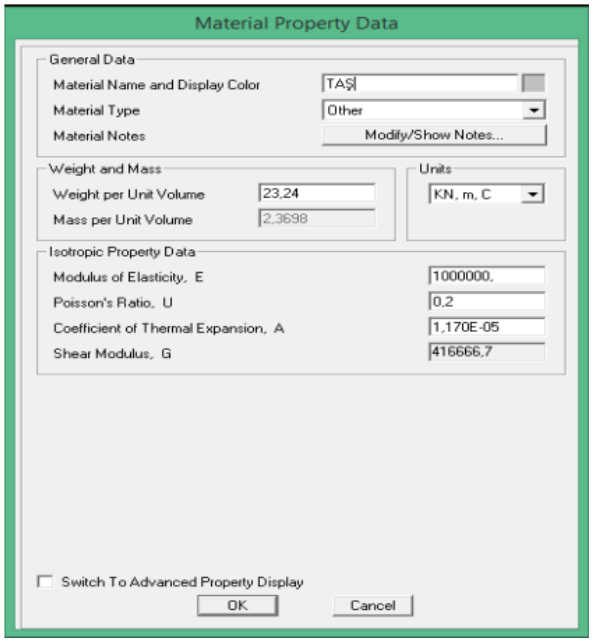



***Figure 8. Material properties defined in the program.***

### 3.7.4 Structural Analysis Under Dead Loads

In the three-dimensional model of Kalecik Castle, stresses under dead weights were calculated and possible crack formation areas were determined as a result of these stresses.

According to the static analysis results obtained, the maximum compressive stress occurring at the x-axis (S11) under dead loads was calculated as 0.117 MPa. In the same case, the maximum tensile stress at the x-axis under dead loads was calculated as 0.132 MPa. The highest compressive stress values are at the lowest parts of the circular cross-sectioned city

wall. The largest tensile stress value in the structure was measured in the upper region of the entrance gate. Naturally, the stress values decrease as you go to the upper levels of the structure. Stress distributions in the x-axis under dead loads are presented in Figure 9.

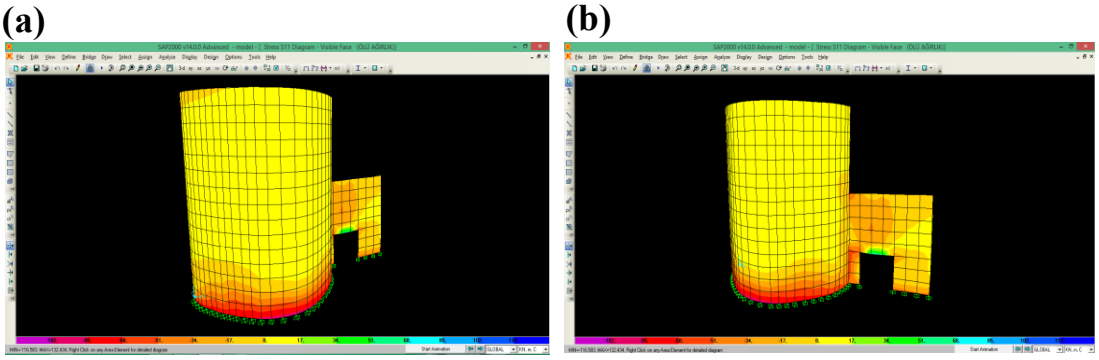



***Figure 9. The stress distribution in the x-axis under dead loads (a) left side view (b) right side view.***

According to the static analysis results obtained, the maximum compressive stress occurring at the y-axis (S22) under dead loads was calculated as 0.5823 MPa. In the same case, the maximum tensile stress occurring at the Y axis under dead loads was calculated as 0.034 MPa. The highest compressive stress values are at the lowest parts of the circular cross-sectioned city wall. The largest tensile stress value in the structure was measured in the upper region of the entrance door. Stress distributions in the y-axis under dead loads are shown in Figure 10.

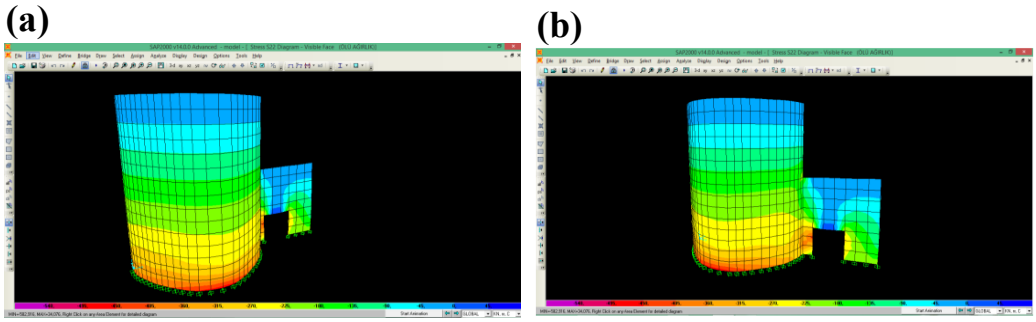



***Figure 10. The stress distribution in the y-axis under dead loads (a) left side view (b) right side view.***

Acceptable safety stresses obtained as a result of literature studies were taken as Head stress (2.4 MPa) and Tensile stress (0.15 MPa).

The maximum compressive stress value in x and y axes was calculated as 0.583 MPa. This value is below the safe compressive stress value. The maximum tensile stress value at x and y axes was calculated as 0.134 MPa. This value is below the safe tensile stress value and

close to the safe tensile stress value. $S_{min}$ value defines the composite stresses due to tensile forces. The maximum principal tensile stress Smax occurring in the structure was calculated as 0.136 MPa. This value was calculated at the top of the castle gate. Images of Smax values under dead loads are shown in Figure 11.

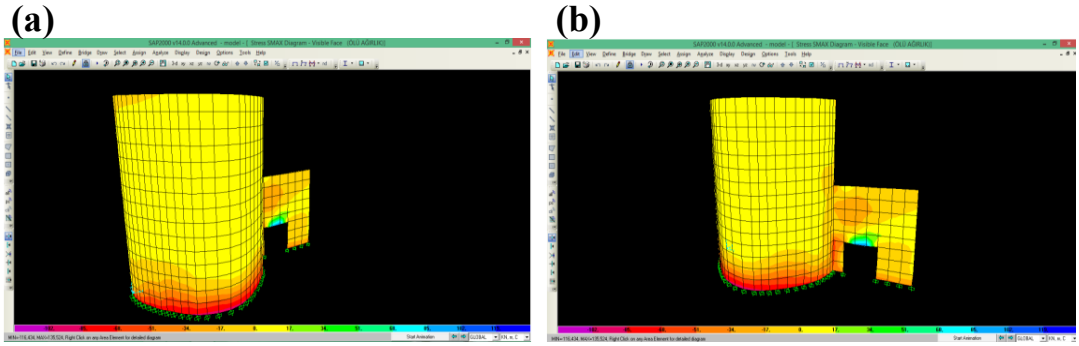



***Figure 11. $S_{max}$ value under dead loads (a) left side view (b) right side view.***

$S_{min}$ values are the composite stresses arising from the compressive forces. The minimum principal compressive stress $S_{min}$ occurring in the model was calculated as 583,065x10-3. This value was calculated at the lowest point of the circular cross section wall. Images of $S_{min}$ values under dead loads are shown in Figure 12.

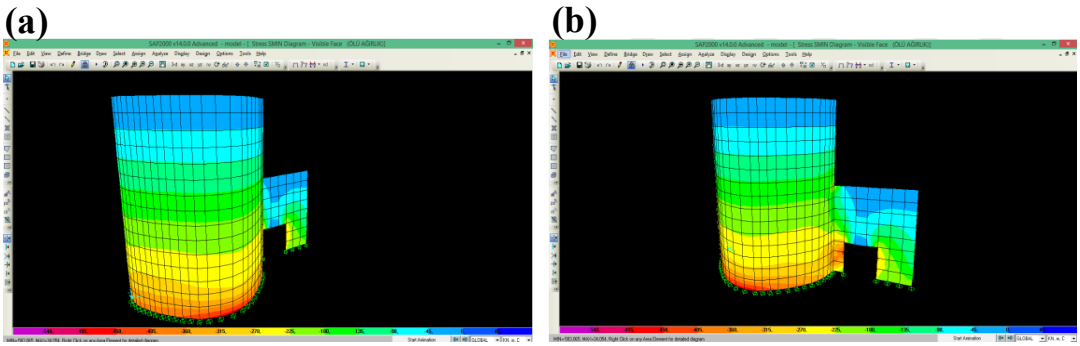



***Figure 12. $S_{min}$ value under dead loads (a) left side view (b) right side view.***

### 3.7.5 Structural Analysis under Dead Load and Earthquake Load

In the previous section, the stresses in the structure were calculated only under dead loads. In this section, the analyses are performed when dead load and earthquake loads act together. The load to be used in these calculations was determined according to the load combinations G, G+EX, G-EX, G+EY and G-EY.

The stress distribution on the x-axis according to the dead and live load combination is shown in Figure 13.

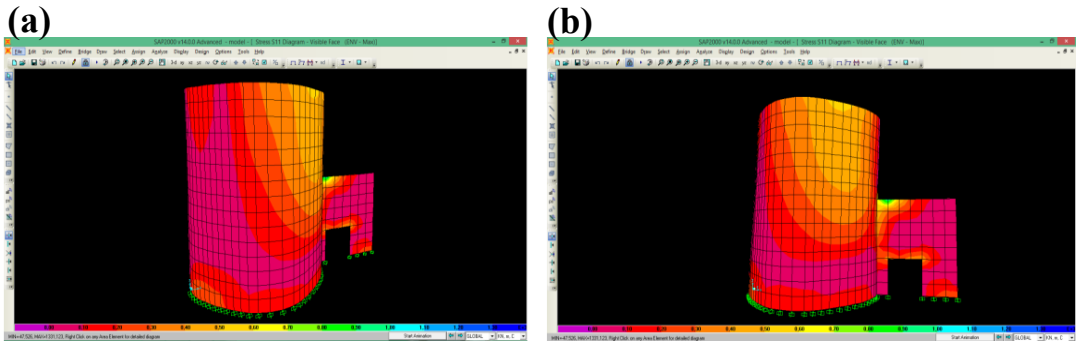



***Figure 13. Stress distribution in x-axis under dead load and earthquake load (a) left side view (b) right side view.***

The maximum compressive stress value in the x direction (S11) occurring according to this load combination was calculated as 0.048 MPa. In the same case, the maximum tensile stress occurring in the x axis under live loads was calculated as 1.331 MPa. The stress distribution occurring in the y axis according to the dead and live load combination is shown in Figure 14.

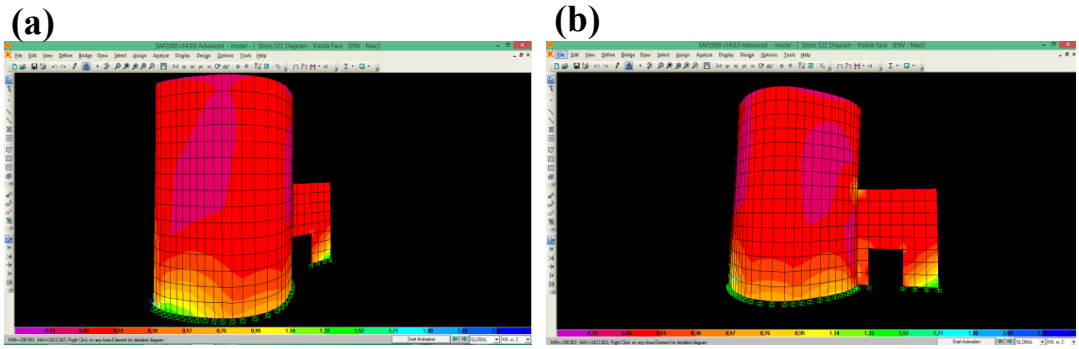
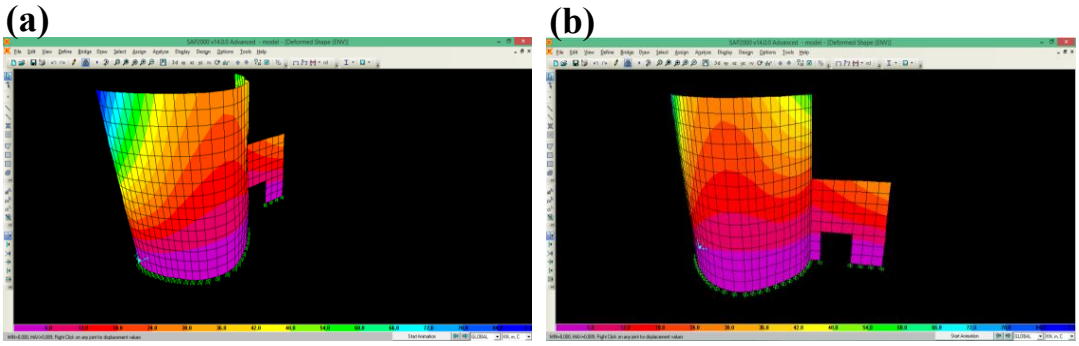



***Figure 14. Stress distribution in y-axis under dead load and earthquake load (a) left side view (b) right side view.***

According to the static analysis results obtained, the maximum compressive stress occurring at the y-axis (S22) under live and dead loads was calculated as 0.299 MPa. In the same case, the maximum tensile stress occurring at the Y axis under live loads was calculated as 2.423 MPa.

Displacements were also calculated according to the combination of live and dead loads. According to the displacement results, 0.089 m displacement value in z direction and 0.0719 m displacement value in x direction were calculated at the end of the most stressed circular cross section wall. Images of the displacement values under dead load and earthquake load are shown in Figure 15.




***15. Displacement values under dead and earthquake loads (a) left side view (b) right side view.***

## 4 CONCLUSION AND SUGGESTIONS

This study evaluated the material and structural integrity of the historical Kalecik Castle using an integrated methodology combining physical tests, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and modelling and analysis through SAP2000. The objective was not only to characterize the existing condition of the structure but also to provide data-driven recommendations for restoration practices.

The physical test results revealed a notable variation in compressive strength among the facades. The eastern and southern facades demonstrated higher strength values (71.7 MPa and 69.17 MPa, respectively) compared to the north and west (54.4 MPa and 56.53 MPa). This mechanical disparity, if assessed in isolation, might be interpreted as simple material heterogeneity. However, when integrated with microstructural and environmental factors, the picture becomes more nuanced.

SEM and EDS analyses uncovered that the higher compressive strength values in the east and south facades correlate with homogeneously distributed, compact particles and elevated concentrations of silicon and aluminum. These elements suggest the presence of supplementary materials, such as brick inclusions or pozzolanic additives, possibly remnants of earlier restoration phases. In contrast, the north facade displayed higher carbon and sodium levels, pointing toward atmospheric degradation and salt crystallization factors that accelerate efflorescence and microcracking. This microstructural vulnerability matches the mechanical weakness observed and supports the argument that material degradation is not solely due to age, but is heavily influenced by environmental exposure and past interventions.

Interestingly, the porosity results were remarkably consistent across facades (average ~0.13), which may seem to contradict the compressive strength results. However, this highlights

a critical limitation of relying on porosity alone as a degradation indicator. Porosity provides a volume-based metric, yet fails to capture the connectivity, shape, and distribution of voids, all of which strongly affect mechanical behavior. SEM analyses filled this gap by revealing that, although total porosity may be similar, pore morphology and distribution patterns differ significantly.

The density and unit volume weight values also showed limited variation. This reinforces the idea that bulk density is insufficient for evaluating weathering-induced damage in historical materials. Restoration design must therefore avoid over-reliance on such scalar properties and instead adopt a multi-scale evaluation framework combining both macro- and micro-analytical tools.

One of the most impactful findings of this study emerged from structural modeling. SAP2000 simulations revealed that the structure remains stable under static (dead) loads, with compressive and tensile stresses within safe limits. However, when earthquake loads were introduced, tensile stresses at the castle's entrance arch (2.423 MPa) approached or slightly exceeded the allowable tensile stress (2.4 MPa). This localized overstress points to high-risk zones that cannot be detected through surface observations or mechanical testing alone. Moreover, the entrance arch is a critical architectural element, and its structural failure would result in disproportionate aesthetic and functional loss.

From a restoration standpoint, this raises important questions: should interventions prioritize only the visibly damaged areas, or also target those revealed as vulnerable through modeling? The evidence suggests the latter. Strengthening the entrance arch and the base of the bastion both structurally critical should be a priority. Recommended techniques include fiber-reinforced polymer (FRP) laminates, stainless steel tie-rods embedded internally, or compatible injection mortars with improved tensile strength properties. These interventions should be minimally invasive and reversible, adhering to conservation ethics.

Another significant insight arises from the mismatch between material condition and structural performance. Although the northern facade exhibits the lowest mechanical strength, its modeled stress concentrations are not as critical as those in the entrance arch. This challenges the assumption that weakest material zones always correspond to highest structural risk. Restoration planning should therefore distinguish between material integrity and structural vulnerability, addressing both in parallel.

An essential limitation of this study is the linear elastic assumption within SAP2000 modeling. Historical masonry structures exhibit complex, non-linear behavior under dynamic loads due to cracking, sliding, and joint separation. Therefore, future work should incorporate non-linear pushover analysis or discrete element methods (DEM) to more accurately capture failure mechanisms. Likewise, dynamic time-history analysis under real earthquake scenarios would provide a deeper understanding of stress propagation through the structure.

Moreover, while EDS analysis revealed elemental composition, it did not capture mineralogical phases—essential for understanding durability. A future study including X-ray diffraction (XRD) and thermogravimetric analysis (TGA) would improve understanding of mineral transformations, particularly the presence of reactive components such as gypsum, which could compromise long-term performance.

In the broader context of heritage conservation, this study supports the shift from visually based assessments to data-supported restoration strategies. Despite the apparent homogeneity of the castle's stonework, multi-modal analysis revealed subtle yet important differences that impact structural safety and material compatibility. This reinforces the idea that each facade may require a distinct restoration strategy, dictated by its environmental exposure, historical modifications, and structural function.

To this end, the following suggestions are made:

- Restoration efforts should prioritize the entrance arch and the bastion base using reinforcement methods tailored to tensile stress management.
- North and west facades should undergo preventive conservation to mitigate ongoing chemical degradation, particularly salt efflorescence.
- All consolidation efforts must respect the original material properties, avoiding incompatible modern materials that may accelerate deterioration.
- A facade-specific approach should be adopted, rejecting one-size-fits-all methods.
- Further experimental characterization, including mineral phase analysis and capillary water transport behavior, should be conducted to evaluate long-term durability under moisture cycling.

In summary, this study demonstrates that restoration of historical structures like Kalecik Castle cannot rely solely on physical condition or material properties in isolation. Instead, an integrated approach, combining experimental data with microstructural analysis and numerical

modeling, provides a robust and predictive foundation for restoration planning. Such a framework not only enhances structural safety and material compatibility but also aligns with ethical and scientific principles of architectural conservation. The methods and conclusions presented herein may serve as a reference for the restoration of similar masonry heritage structures, particularly those subjected to seismic risk and environmental degradation.

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## Conflict of Interest Statement

There is no conflict of interest between the authors.

## Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

## Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

## Contributions of the Authors

**Ali EMİROSMANOĞLU:** Conceptualization, Methodology, Software, Validation, Writing-review & editing, original draft.

**Ahmet GÖKDEMİR:** Conceptualization, Methodology, Investigation, Writing - review

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