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Investigation of material deterioration and seismic behavior of Fertek and Hançerli Churches in Cappadocia Region

Kapadokya bölgesindeki Fertek ve Hançerli Kiliselerinin malzeme bozulmalarının ve sismik davranışlarının incelenmesi

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Abstract

Cappadocia is one of the rare natural and cultural centers on earth with its fairy chimneys, underground cities, rock churches, stone buildings and natural beauties. Among these artifacts, Fertek and Hançerli Churches that are subjected to the scope of the study are very original buildings with their superior construction techniques and rich workmanship according to the period they were built. In this study, the architectural features of Fertek and Hançerli Churches which were built in the 19th century and located within Niğde province in the Cappadocia Region were examined and material deteriorations were determined. In the light of the determinations, the existing static properties of these buildings were examined using Dynamic Finite Element Analysis program. Discoloration, vegetation, crack formation, humidification and partial mortar and stone loss were detected in both churches. When the analysis results are evaluated it has been determined that the buildings need repair and conservation depending on the region and soil class and considering the earthquake forces.

Keywords: Cappadocia, Church, Historical monument, Seismic performance, Stone deterioration

Öz

Kapadokya Peribacaları, yeraltı şehirleri, kaya kiliseleri, taş yapıları ve doğal güzellikleri ile yeryüzündeki ender doğal ve kültürel merkezler arasında yer almaktadır. Bu eserlerden çalışma kapsamına alınan Fertek ve Hançerli Kiliseleri, yapıldıkları döneme göre üstün yapım teknikleri ve zengin işçiliği ile oldukça özgün yapılardır. Bu çalışmada Kapadokya Bölgesinde yer alan Niğde ili sınırları içerisinde bulunan ve 19. yüzyılda inşa edilen Fertek ve Hançerli Kiliselerinin mimari özellikleri incelenmiş ve malzeme bozulmaları tespit edilmiştir. Bu tespitler ışığında yapıların mevcut statik özellikleri Dinamik Sonlu Elemanlar Analizi programı kullanılarak incelenmiştir. Her iki kilise yapısında da renk bozulması, bitkilenme, çatlak oluşumu, nemlenme, kısmi harç ve taş kayıpları tespit edilmiştir. Analiz sonuçları değerlendirildiğinde, yapıların bulunduğu bölgeye ve zemin sınıfına bağlı olarak ve deprem kuvvetleri dikkate alınarak onarım ve korumaya gereksinimlerinin olduğu tespit edilmiştir.

Anahtar kelimeler: Kapadokya, Kilise, Tarihi anıt, Sismik performans, Taş bozulması.

1 Introduction

Cappadocia, the cradle of important settlements in history has been a region where different cultures lived for centuries. Christian population who escaped from oppression between the centuries made this region an important center of Christianity at especially 7-13 centuries [1]. Cappadocia is located on the UNESCO World Heritage Site. The province of Niğde constitutes the southern borders of the Cappadocia Region. There are underground cities, Gümüşler Monastery, the ruins of Tyana Ancient City, Roman Pool, Kemerhisar Aqueducts, churches, mosques and historical monument belonging to different periods. This province is different from other cities in the region because it has many churches that can reach to the present day [2]. There are almost 25 churches that almost all of which belong to the first half of the 19th century in center, town and village settlements. Fertek and Hançerli are notable for with its historical, architectural and artistic values among these churches. Both churches have a common style of 19th-century buildings and also exhibit their own unique style. [3]. While many churches in the region have been abandoned and not used, these two buildings continue to be used in mosque function. Fertek Church deserves a great importance in terms of art history with its wall paintings. The apsis paintings in the building are referring to the art of Western painting rather than the works in Anatolia with their iconographic features and style [4]. The exterior facade arrangements of the Hançerli Church are richer than the other churches in the region. Fertek Church have been used as mosque since 1925 and Hançerli Church have been used as mosque since 1930-1940. Since these buildings continue to be used with a similar function to their original functions, they have survived to the present day largely preserved.

Needs arising from new actions caused by social and economic changes in societies may require adaptive reuse for new purpose in buildings [5]. Serious damage can occur over time due to lack of maintenance in abandoned buildings that have not been used for a long time and even in some cases the building is completely lost [6]. Re-functioning the structures that cannot participate in life with their original

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functions is also important in terms of preserving their architectural identities under today's conditions.

It is very important to know the architectural properties and structural system of the buildings and taking into account the loads on the structure in the repair and reinforcement works of the conservation of historical buildings, in order to transfer the buildings to future generations with its original structural systems. Although there are international studies in the field of material degradation, static analysis and conservation proposals in historical buildings, the number of studies conducted in the region is limited [7-10]. In particular, there has been no comprehensive study concerning the material deterioration and strength problems of these two historical buildings. For this reason, this study also serves an important purpose for transfer of buildings with similar functions to future generations in the Niğde-Cappadocia Region where is quite rich in terms of historical monuments.

In this study, the architectural and structural features of the Fertek and Hançerli Churches belonging to the 19th century of the late Ottoman period were examined and compared. The seismic performance of these historical buildings also investigated. In the light of the findings, suggestions for the conservation of the mentioned monumental structures are presented.

2 Historical significance and architectural definition

In this section, the historical and architectural properties of the two historical buildings that are the subject of the study are presented.

2.1 Fertek Church

Fertek Church is located in a large garden in the center of Fertek Village of Niğde Province. It was built in 1831 by Hadji Nikola. The building is basilica style plan with three naves [3]. It was built in the masonry system, using yellow tuff cut stone (commonly used in the Cappadocia region), basalt and andesite (Figure 1-a). The monumental structure with rectangular plan has a 16-column narthex that surrounds it on the north, south and west (Figure 2). The middle part of the narthex is semi-circular and outward. The narthex columns have simple stalactites. There is an inscription in the Karaman dialect (which is not exist today) on the exterior of the semicircular narthex. The ceiling of the narthex has classic wooden craftsmanship. In the middle of the split ceiling in the form of cassettes, a large medallion is decorated with an interesting "pen-work" consisting of curved branches and flower petals (Figure 1-b) [3]. It is entered from the narthex by three doors. The nave is divided into three sections with double-row columns. The naves are covered with barrel vault. Column headings on high pedestals have wooden ornaments.

There are three semi-circular apses at its east end. There is a window at each apse. On the sides of the apse, there are gates to the north and south. There is a niche in the left apse. Outside, main space, corner spaces and apse are covered with double-sloping roof. Naos has a gallery floor in north, south and west directions [11]. The U-shaped mezzanine floor has a total of 28 small columns. In the north and south, there are three oval-shaped windows on the top. The interior of the building is covered with a barrel vault, and externally; covered with a three-part gable roof with inclined in two directions (Figure 2). On the upper floor, there are fresco ruins on the left [12].

Some restoration and repair applications have been applied to the building until today. However, the building has reached today by preserving the original shape of the main elements such as plan scheme, and facade layout. An independent minaret is established to the southwest corner of the building which is used as a mosque today and a mihrab, sermon pulpit and other building elements have been added.

2.2 Hançerli Church

Hançerli Church built in 1832 is in Hançerli Village and is located in a large courtyard with a sloping terrain (Figure 3-a). High retaining walls are formed in the south, west and east directions of the building. The building is built in the masonry system with three naves basilica plan type.

The building is built in rectangular form and has three externally round apses in the east, and six columns narthex with five pointed arches in the west (Figure 3-b). Three different doors are used to pass from the narthex to the naos [11]. Inside, columns with high pedestals form double rows and five groups and column headings are plain impost shaped. The cover system of the naves is a barrel vault in the east-west direction. The apse is covered by a half-dome, and the narthex is covered by a barrel vault in the north-south direction [3]. The single-storey building has a gable roof on the outside and is covered with stone plates (Figure 4). The northern facade of the building which sits on sloping land rising to the north, rests on the road remaining at the upper elevation. Therefore, a large part of the northern facade of the building is buried. The arch traces are seen on this facade (Figure 3-b).

There are six windows opening to the south. One of the windows in the south is closed and a mihrab is added here. Six windows on the left are closed. There is also a minbar and room added to the right. There are niches in the left and middle apse. Inside, there is a closed door at the top left. In the west, there are three small windows with a triangular pediment on the narthex [3,11]. On the retaining wall of the courtyard in the south of the building, there is a fountain that has two arches with fringes on it, and an inscription in the Karaman language on it [12].

3 Structural definition

It is important that the conservation and restoration of historical buildings should be planned based on detailed studies of structural systems and their strength and deformability and the dynamic response of the structure [13]. The structural information and material properties obtained from field studies are presented in Table 1 for use in static analyses.

In Fertek Church, wall thicknesses are ranging from 80-110 cm on the ground floor and between 70-85 cm on the upper floor. Gray-black and yellow cut stones of Cappadocia Region are also used on the facades of Fertek Church (Figure 1).

(a) (b)

Figure 1. Fertek Church (a) front facade (b) narthex ceiling

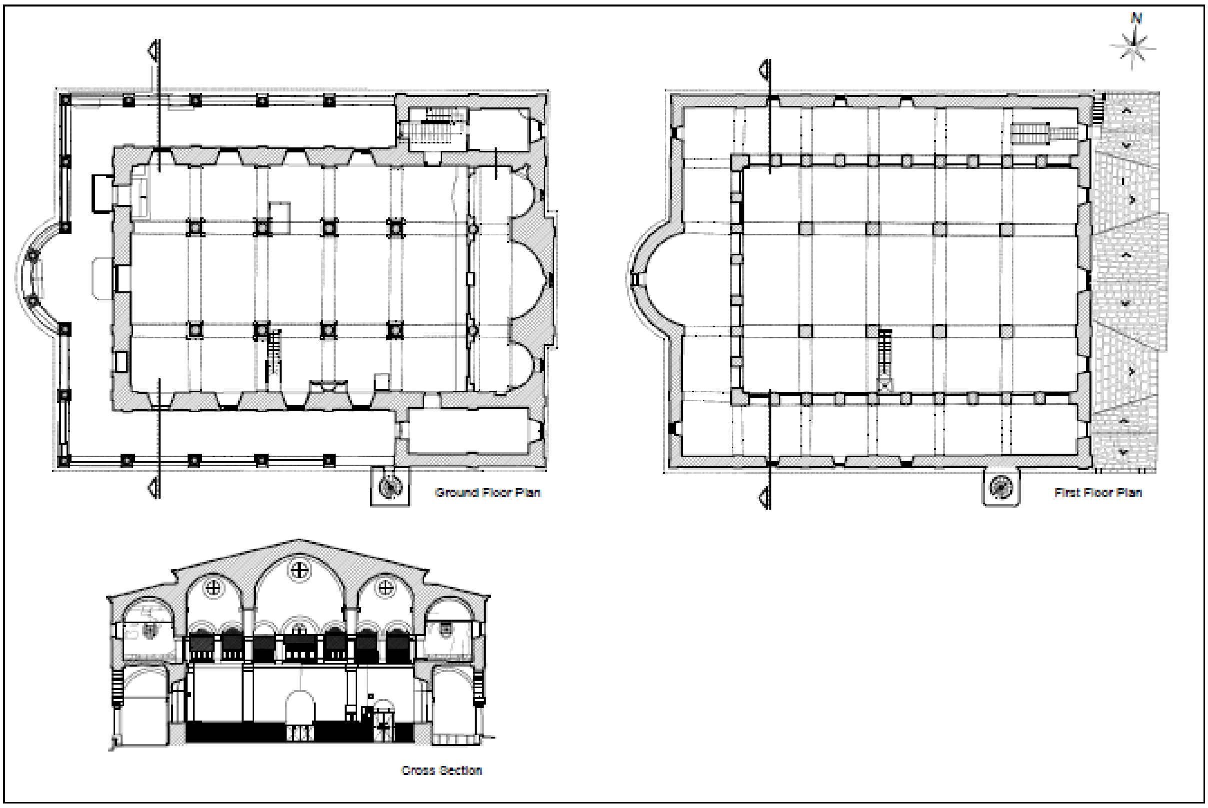
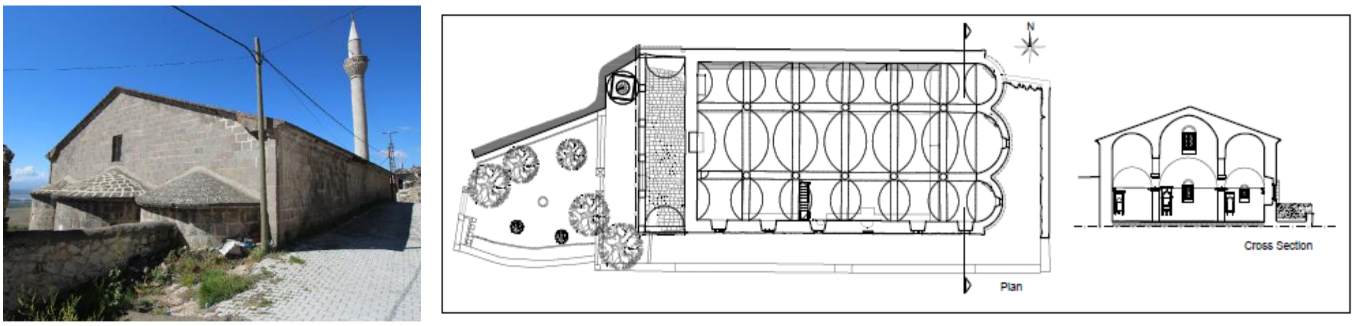


Figure 2. Plan and section of Fertek Church (Alper Restorasyon)



(a) (b)

Figure 3. Hançerli Church, view from the upper road (a) plan and section (b)

These stones that are also used in many local historical buildings are yellow tuff (ignimbrite) and andesite. The stones of the church are chosen according to their location in the building. Dark gray-colored andesite and basalt stones are more resistant than yellow stones. For this reason, in the apse and bema section of the building, dark stone material is used up to five or six rows height from the floor and up to two rows height on the other fronts. Thus, the damage from the ground water is minimized. Dark colored andesite and basalt stone are also used in columns and arches, lintels, sills, in the flooring of naos and narthex sections and in some corners of the facades. The arches of the gallery floor are protruding on the facades and divided the facades into sections. Some of these protrusions are made of completely basalt stone. In some of them, basalt stone is used for the beginning and ending stones. The apses with triangular pediment at the east side of the structure are all basalt.

Table 1. Comparison of structural and material properties of the monumental structures

Properties	Fertek	Hançerli
Wall material	Yellow tuff, andesite and basalt	Andesite and basalt
Joint	Lime mortar	Lime mortar
Column material	Basalt	Basalt
Column section	Circular column-square prism base	Circular column- square prism base
Column diameter	60 cm inside 40-45 cm (narthex)	60-70 cm inside 55-60 cm (narthex)
Column distance	3.65-4.30 m	3.5-4.0 m
Tension bars	Present	Present
Narthex form	U shape	Rectangular
Vault	Barrel vault	Barrel vault
Roof	Two-sided gable roof	Two-sided gable roof
Roof material	Basalt	Basalt
Arch	Segmental, semi-circular and pointed	Pointed
Floor	Wooden floor	-
Lintel	Basalt	Basalt

The wall thickness of the Hançerli Church varies between 65-120 cm. Due to the thickness of these stone walls which are continuous elements that transmit the loads coming from the structure to the foundation, the tensile stresses due to the load are minimized and the compressive stresses are increased at the same rate. In all facades of the Hançerli Church gray-black andesite and basalt stones unique to Cappadocia Region are used (Figure 3). Because these stones are highly resistant to external factors, the buildings that are built with these stones have survived for many years. The columns of the buildings are presented in Figure 4.

4 Material deteriorations

Fertek Church has survived to the present day while preserving its structural system characteristics. No large cracks are detected that could affect the structural system. Partial stone deterioration occurs due to natural conditions. Especially discoloration has occurred in the stones close to the ground level and the stones under the cornices due to moisture and rainwater. Efflorescence that is a result of the evaporation of the salts carried in the rising moisture from the floor on the surface of the wall may cause deterioration of the physical and chemical properties of the wall. In addition, superficial spill and stone losses are formed due to moistening in the ignimbrites. Also, another problem that is seen between the joints on the exterior is vegetation. Other problems such as stone cracks, stone melts and plaster losses are also detected in the structure (Figure 5).

(a) (b)

Figure 4. The column bases in Fertek (a) and Hançerli (b) Churches

Hançerli Church which is built on the platform formed by the retaining walls due to the slope has survived to the present day by preserving its structural system properties to a great extent. One of the problems observed in the structure is that the northern front leans against the road elevation at a high elevation. This causes the vibrations on the road to be transmitted to the structure and creates a dynamic effect. In addition, the building which is located on a sloping topography is exposed to rain and snow waters coming from the upper road. This situation causes moisture problems in the structure. The stones have been damaged by moisture which can lead to a decrease in strength. In addition, because of the accelerating effect of water on biological degradation, lichen formation on the stone roof at Hançerli Church is observed [8,14]. There are no large cracks in the building that could affect the structural system. Similar to the Fertek Church, there are problems such as mortar losses, stone cracks, humidification problems and vegetation due to the natural conditions (Figure 6).

It is important to solve the moistening problems in both monumental structures. Because water is the main factor in physical, chemical, and biological degradation processes in stones [15]. This problem causes a decrease in the strength of the walls which is one of the important elements of the structural system of the building, and poses a threat to the life of the building. Salt and other substances carried by rainwater and ground water entering the stones cause chemical deterioration especially due to the moisture effect [16]. In order to solve the humidification problem road level should be lowered especially in Hançerli Church.

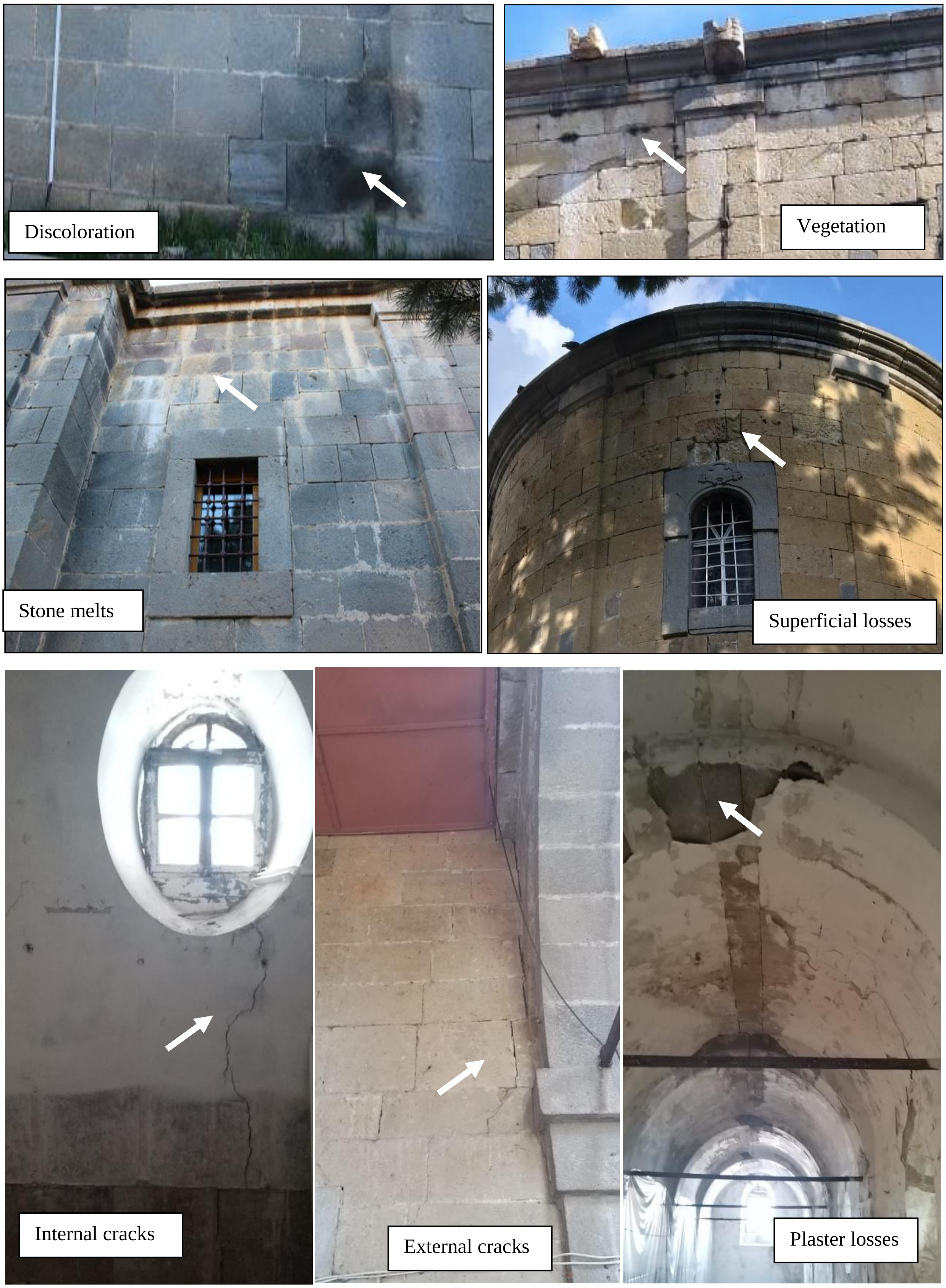


Figure 5. Deterioration problems at Fertek Church.

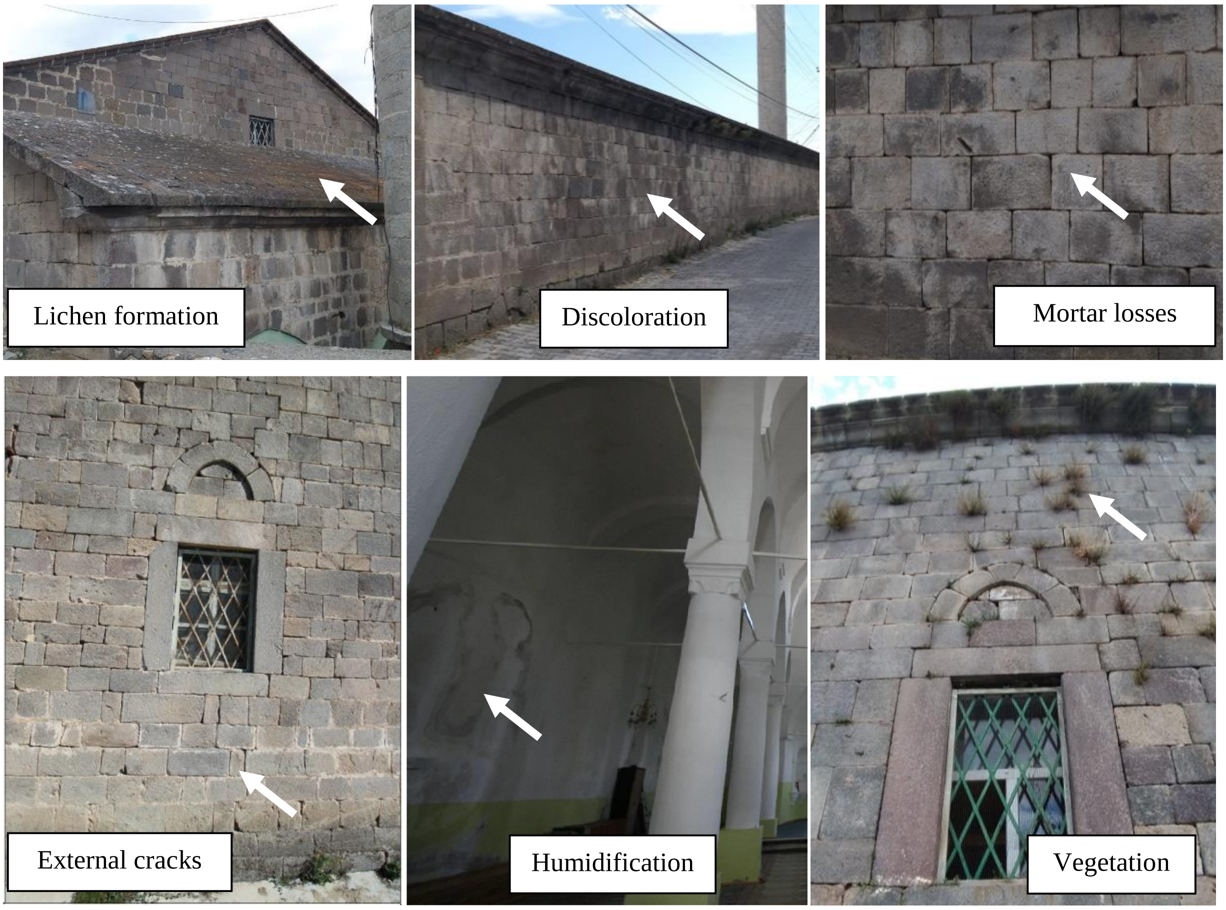


Figure 6. Deterioration problems at Hançerli Church.

5 Seismic analysis

The repair and strengthening of historical monuments are dependent on the ground as well as the materials and methods used for their construction [17]. In this section performance evaluation of the Fertek and Hançerli Churches under the influence of vertical loads and earthquake forces is presented. In order to achieve this goal, the required geometrical and mechanical properties of the monuments were obtained from preliminary studies. The performance evaluation of Fertek and Hançerli Churches has been performed using finite elem ent analysis for the buildings with their current conditions in the direction of on-site inspection and observations and also examining restoration projects.

For the structural analysis of historical buildings and monuments, the finite element analysis- method is often used [18-21]. In the modeling, geometric arrangement and simplifications are needed for walls and other structural elements. Since masonry structures are applied in terms of construction techniques by combining several different materials, they exhibit different behaviors in different directions. Some idealizations and simplifying assumptions are made in order to represent these behaviors in the modeling. The structural walls of the building are composed of at least three major materials, i.e., stone, brick and mortar (plaster). However, in the construction of the model, the building is assumed to be of a single material regarding its modulus of elasticity and specific density [22]. In the modeling, walls, domes, vaults, arches, columns and tension bars that form the structural system are used. The masonry walls, domes and vaults are modeled by using three-dimensional solid elements and the arches, columns and tension bars are modeled by using frame elements. All structural system elements are divided into parts according to appropriate finite element sizes. However, the coating and filling materials on these elements are not modeled and only their loads are determined and affected by the related elements. In addition, the snow load specified in TS EN 1991-1-3 [23] is added. The three-dimensional (3D) finite element model of the churches used in the analysis is shown in Figure 7.

Since the general behavior of the structures is taken into consideration in the modeling of churches, it is assumed that the structural elements consist of a single material and the tension bars between the columns are made of St37 steel. The mechanical properties of the materials used are given in Table 2 [24, 25]. The analysis of the structures under the effect of earthquake is carried out in Turkish Earthquake Code-2018 [26] by using the parameters corresponding to soil type ZC and earthquake motion level DD-2 and given in Table 3.

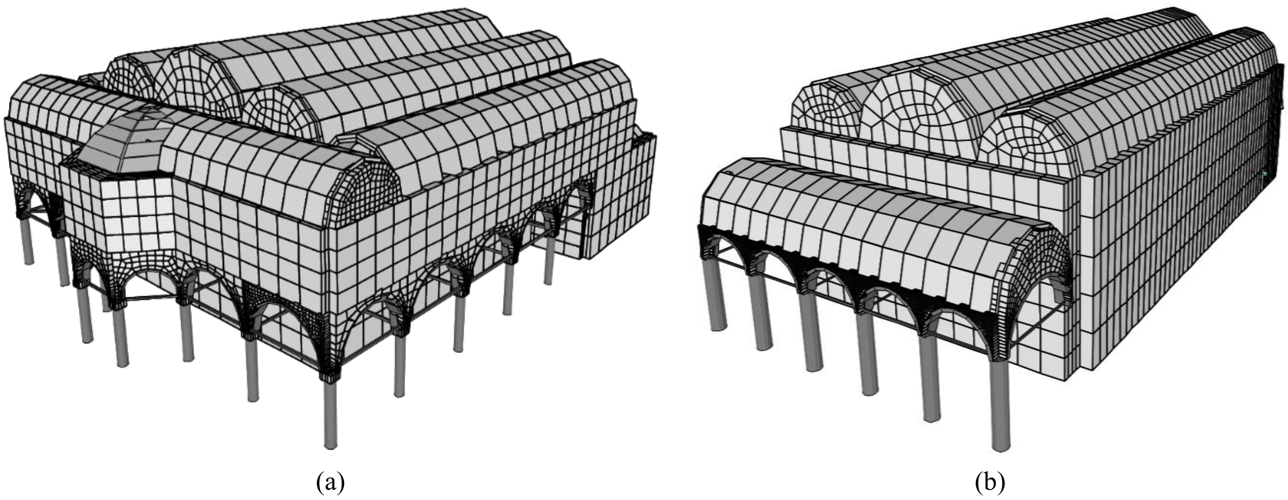


Figure 7. 3D finite element models of (a) Fertek, (b) Hançerli Churches.

Table 2. Mechanical properties of materials used in the monumental structures.

Material	Elasticity module (MPa)	Poisson's ratio	Compressive strength (MPa)	Tensile strength (MPa)	Unit weight (kN/m^3)
Yellow Tuff	4200	0.2	25.10	4.12	17
Andesite	7390	0.2	69.20	6.24	22.5
Basalt	38420	0.2	142.21	15.59	27

Table 3. Seismic parameters of monumental structures.

	Fertek	Hançerli
F_S	1.3	1.3
F_1	1.5	1.5
S_S	0.308	0.305
S_1	0.085	0.084
S_{DS}	0.400	0.396
S_{D1}	0.127	0.126

Table 4. Maximum compressive and tensile stress values obtained from the analysis (MPa).

Structure	Vertical loads		EQX		EQY	
	Compressive	Tensile	Compressive	Tensile	Compressive	Tensile
Fertek	0.424	2.537	0.209	0.887	0.07	0.622
Hançerli	0.537	1.452	0.07	0.377	0.04	0.477

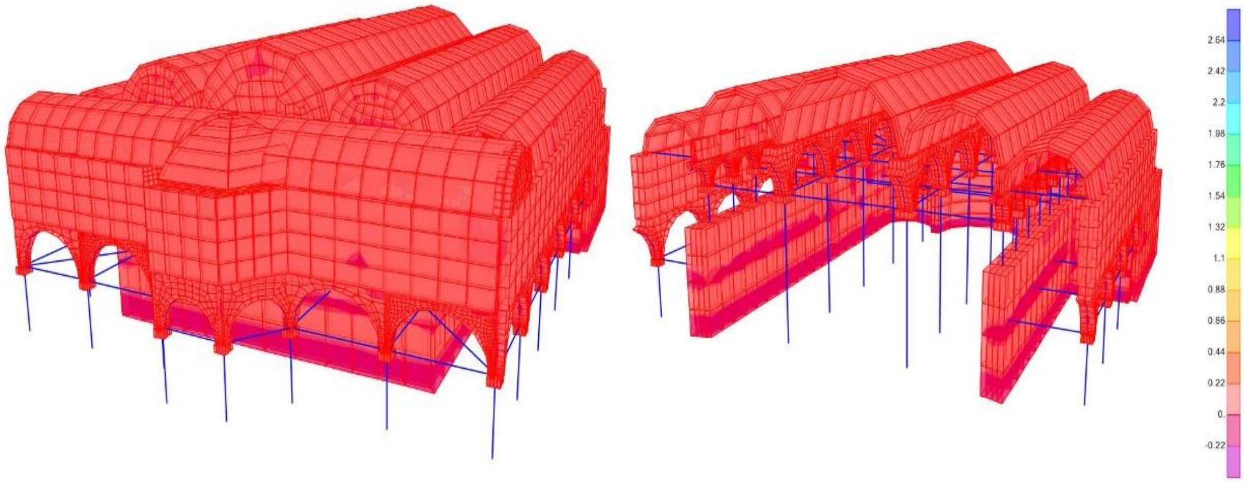
The structural models are analyzed statically under the influence of vertical loads and earthquakes by using the above assumptions and parameters. Figure 8 and Figure 9 show three-dimensional models and cross-sections showing the stress distributions obtained as a result of static analysis of the structures.

As a result of the analysis, maximum compressive and tensile stresses obtained under the effect of vertical loads of monumental structures and earthquake forces (EQX and EQY) applied in X and Y directions are given in Table 4.

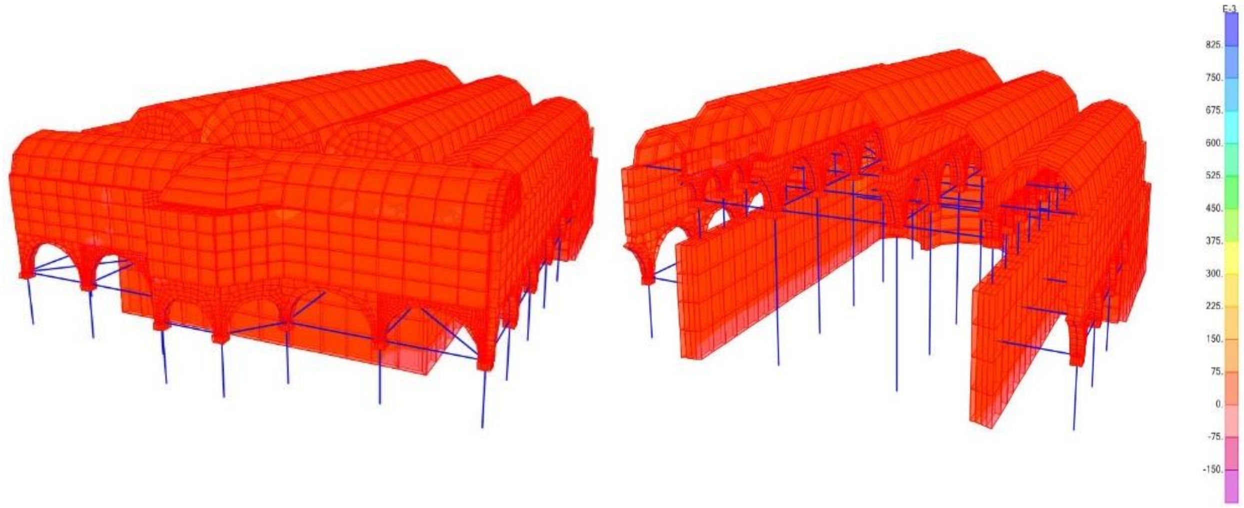
It is seen that the maximum tensile stress in the Fertek Church is 2.537 MPa, the compressive stress is 0.424 MPa, and the maximum tensile stress in the Hançerli Church is 1.452 MPa and the compressive stress is 0.537 MPa. However, it is observed that the tensile stresses were less than 1 MPa for both monumental structures and that the maximum tensile stress values shown in Table 4 are exceeded only in a few regions of the corners of the wall cavities and the lower corners of the wall.

Since the compressive strength of the masonry structural elements is much higher than the tensile strength, the tensile stresses in which the monumental structure is weaker are evaluated together with the compressive stresses within the stress values obtained from the analysis. When the maximum compressive and tensile strength values of the structural elements given in Table 2 are compared with the maximum stresses in Table 4, it is seen that the compressive stresses are quite low compared to the compressive strength of the stones and the tensile stresses are lower than the tensile strength of the stones.

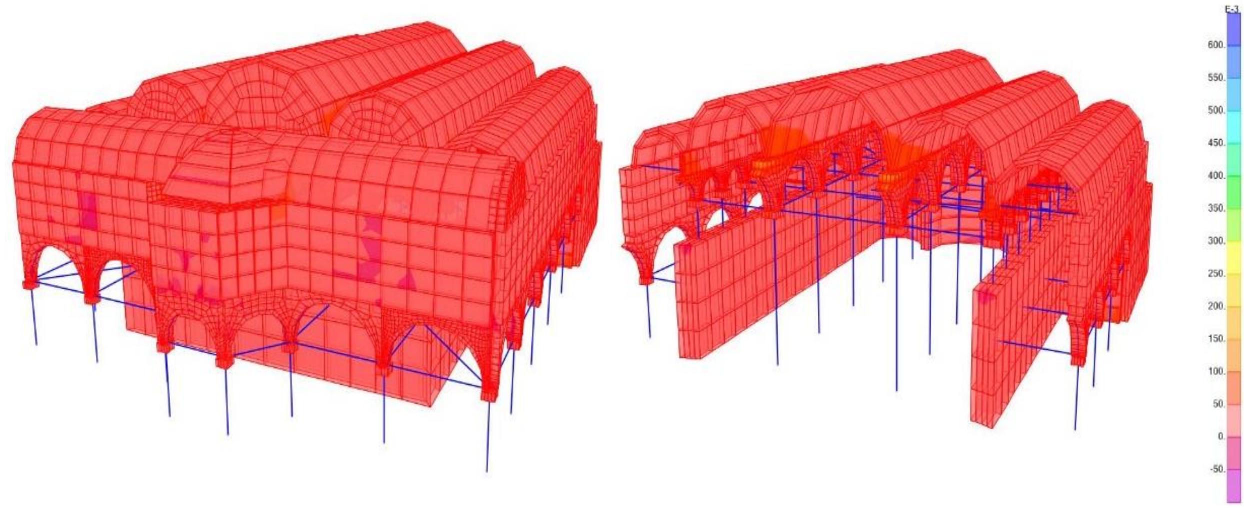
According to the data given in Table 4, both Fertek and Hançerli Churches are found to have more difficulty under vertical loads than earthquake effects. However, when compared with the allowable stress values of the stones, it has been found that both structures can resist the tensile and compressive stresses occurring on them without any damage.



Vertical loads

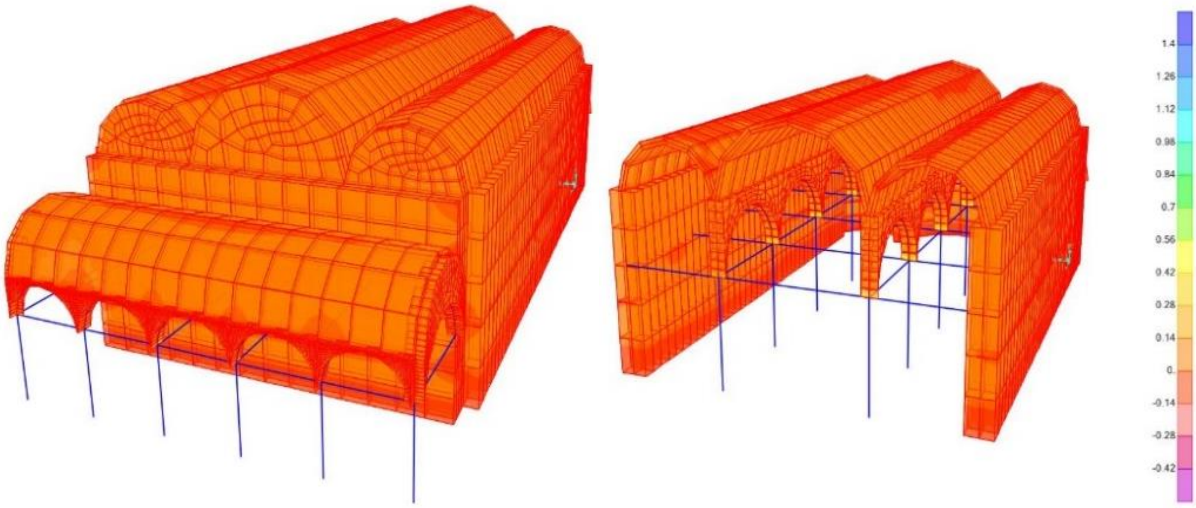


Earthquake forces (EQX)

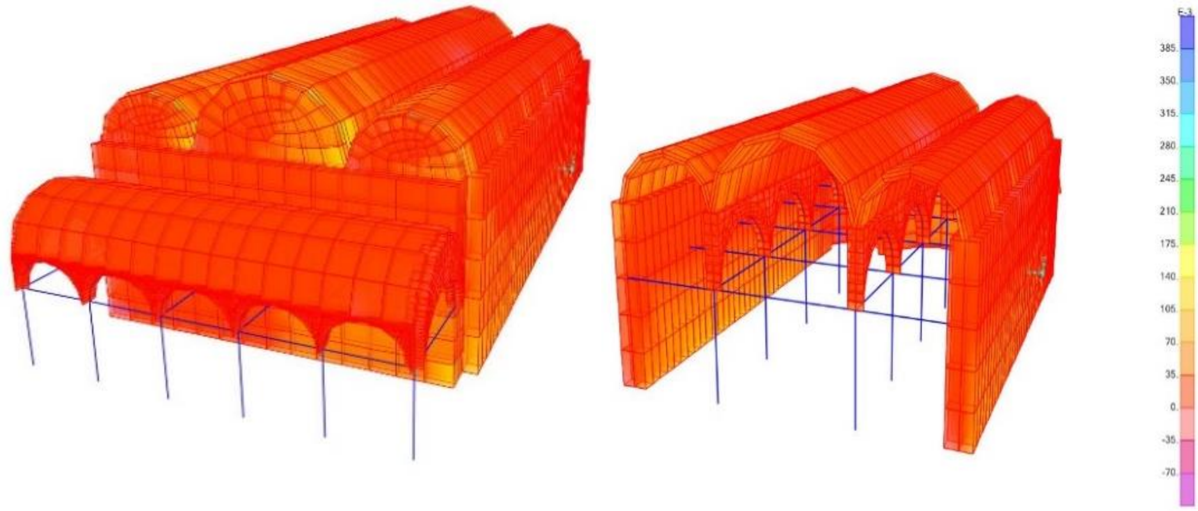


Earthquake forces (EQY)

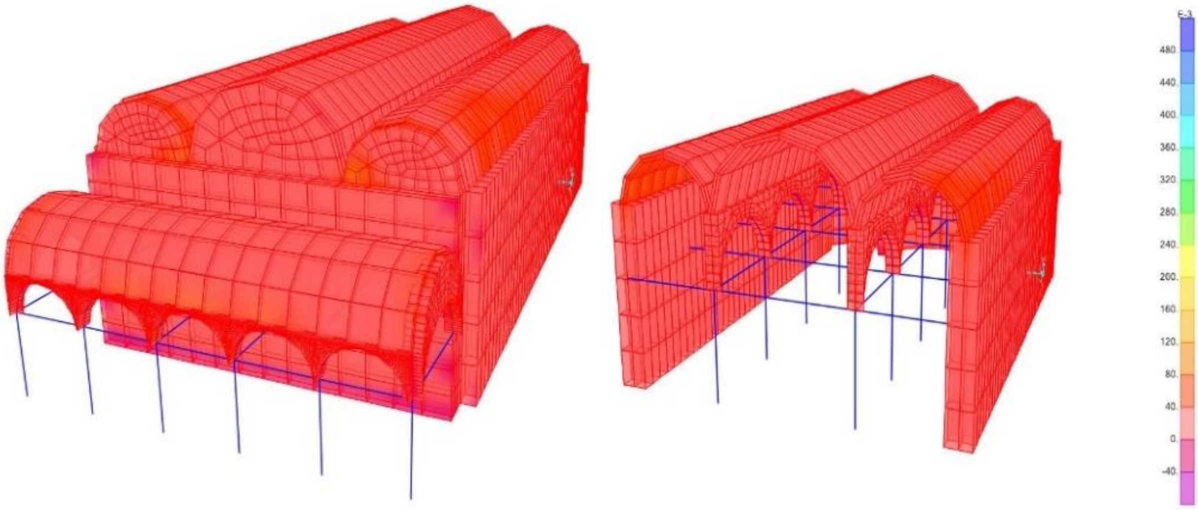
Figure 8. The stress distribution obtained as a result of static analysis of Fertek Church.



Vertical loads



Earthquake forces (EQX)



Earthquake forces (EQY)

Figure 9. The stress distribution obtained as a result of static analysis of Hançerli Church.

6 Conclusions

The results and recommendations to improve the stability of these historical monumental structures can be summarized as follows.

In both monumental structures, no large cracks are detected that could affect the structural system. There are some material problems such as joint discharges, stone cracks, stone melting, superficial losses, vegetation and discoloration in the structures. It is important to make the necessary repairs to the stone walls to prevent the deterioration from progressing. Due to the high elevation of the road on the northern facade of the Hançerli Church, the wall on the northern facade is exposed to lateral thrust and moisture. In order to eliminate this damaging situation, the road level must be lowered. The mortar in the joints between the stones must be repaired and completed. Thus, the integrity of the walls will be ensured and the resistance of the walls against atmospheric conditions and seismic forces will be strengthened.

Since both monumental structures have been used with a similar function to their original functions, no changes have been made to affect the structural systems of the buildings and they have survived to the present day. In both structures, the compressive and tensile stresses are lower than the compressive and tensile strength of the stones. When allowable stress values of the stones are taken into consideration, it has been found that both buildings can withstand the tensile and compressive stresses occurring on them without any damage. As can be seen from the analysis, it is thought that these two monumental structures which are located in a moderate area in terms of earthquake risk can survive for many years if the factors causing the deterioration of the building blocks are eliminated. Structural and static analysis of the other historical buildings in the Cappadocia Region should be done to determine their current strength and conservation measures should be taken to transfer these artifacts to future generations.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): .9%

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