DOI: 10.14256/JCE.1015.2014

Građevinar 5/2014

Primljen / Received: 22.1.2014.
Ispravljen / Corrected: 3.3.2014.
Prihvaćen / Accepted: 26.3.2014.
Dostupno online / Available online: 10.6.2014.

Assessment of structural performance of historical Ishan church

Authors:

Ferit Cakir, PhD. CE
Amasya University, Turkey
Department of Architecture
ferit.cakir@amasya.edu.tr

Assist.Prof. Burcin S. Seker, PhD. CE
Amasya University, Turkey
Merzifon Vocational School
senol.seker@amasya.edu.tr

Prof. Adem Dogangun, PhD. CE
Uludag University, Turkey
Department of Civil Engineering
adogangun@uludag.du.tr

Professional paper

Ferit Cakir, Burcin S. Seker, Adem Dogangun

Assessment of structural performance of historical Ishan church

This study focuses on the historical Ishan Church in Artvin, Turkey and its structural behaviour. The main purpose of this study is to investigate structural behaviour of the church. Therefore, Ishan Church is modelled numerically, and analyzed by means of static and dynamic analyses. Analysis results and literature review prove that the cracks identified in the structure are caused by external effects and excessive load. Moreover, critical stresses are frequently observed in the skewback of main arches, and these parts are considered to be risky in terms of structural performance.

Key words:
masonry churches, structural performance, static and dynamic analyses, finite element model

Stručni rad

Ferit Cakir, Burcin S. Seker, Adem Dogangun

Ocjena konstrukcijske učinkovitosti povijesne crkve Ishan

U ovom radu razmatra se povijesna crkva Ishan, smještena u turskom gradu Artvinu, te njena konstrukcijska učinkovitost. Glavni cilj istraživanja je određivanje konstrukcijske učinkovitosti povijesne građevine. Rezultati analiza i podaci iz literature dokazuju da su pukotine nađene u konstrukciji uzrokovane vanjskim utjecajima i prekomjernim opterećenjima. Uz to su kritična naprezanja uočena i na nekoliko mjesta u uporištu glavnih lukova, pa se ta mjesta smatraju rizičnima u smislu konstrukcijske učinkovitosti.

Ključne riječi:
zidane crkve, konstrukcijska učinkovitost, statičke i dinamičke analize, model konačnih elemenata

Fachbericht

Ferit Cakir, Burcin S. Seker, Adem Dogangun<

Zustandsbewertung der Baustruktur der historischen Ishan Kirche

In dieser Arbeit wird die historische Ishan Kirche in der türkischen Stadt Artvin in Bezug auf das Tragwerk erforscht. Das Hauptziel des Forschungsvorhabens ist die Bestimmung der Leistungsfähigkeit der Baustruktur des historischen Bauwerks. Daher ist ein numerisches Modell der Kirche erstellt und mittels statischer und dynamischer Berechnungen analysiert worden. Die Resultate und ein Literaturüberblick weisen darauf hin, dass die identifizierten Risse im Tragwerk durch äußere Einflüsse und übermäßige Lasten verursacht sind. Außerdem sind mehrfach kritische Spannungen an den Bogenlagern beobachtet worden, die als Gefahr für die Baustruktur eingeschätzt werden.

Schlüsselwörter:
Kirche aus Mauerwerk, Strukturleistungsfähigkeit, statische und dynamische Analyse, Finite-Elemente-Modell

1. Introduction

Thanks to its position at the intersection of several distinct civilizations, Turkey currently has a wide variety of historical traces from past civilizations. Some of these historical structures have survived in their original form, while some have been damaged because of various influences, and have lost their initial functions. Therefore, the protection of historical structures and their safe transfer to next generations is one of main challenges of the today's world.

Artvin, which is located in the northeast of Turkey, is one of the most popular cities of Turkey with its historical and cultural landmarks, and natural beauties. This city has kept to this day historical traces of several different cultures, and it can therefore be stated that it has been a loyal host to different civilizations. One of the most important structures seen in the city centre is Ishan Monastery, located in the area of Yusufeli. It is considered to one of the most important pieces of Georgian architecture. Ishan monastery, situated at the periphery of Ishan village, comprises the Ishan Church and the main Chapel of Virgin Mary (Figure 1). According to various sources, priest Seba, who was the nephew of priest Khandza (759-861), built the monastery with the financial support of King Andernese. The construction of the monastery started in 955 during the sovereignty of Georgian King David, and was completed in 1027 during the reign of Bagratli King Magistros [1].

Externally, the Ishan Church measures 35.00×35.00×20.70 m and is designed as a cross-shaped structure. The square-plan middle section is covered with cone-shaped cornets, which rest on four main supportive columns. This central square area is enlarged with cross arms which spread in four directions. A semi-circular apse is located in the east direction of the cross arm. The apse of the church proves its originality in terms of its eight-column arrangement, with columns connected by arches (Figure 2).

Figure 1. Ishan Church and Main Chapel of Virgin Mary

Figure 2. The apse at the east arm and columns that connect the apse

Figure 3. Partition wall built when the church served as a mosque

There are two storey pastophorion rooms right next to the apse. In the external facades of the church, there are several plant forms, geometric motifs, and ornaments on the sections that encompass entrance and window sides. Moreover, there are fresco remains on the main dome of the structure, and also at the north, south, and west arms, walls, and windows.

The west arm of the church is three times longer than the other cross arms. The church served as a mosque for several years and a separator wall was built between the west cross arm and main centre to divide the structure into two parts at the west arm (Figure 3). Two entrance doors at the south and west arms were closed in the period when the structure served as a mosque. The south door was used as a mihrab (a niche in a mosque pointing to the direction of Mecca) of the mosque, while the west door was used as the community place. However, the structure is abandoned and is currently not in use.

2. Structural deformation of Ishan church

The Ishan Church, which is the subject of this study, is located in the Yusufeli County in Artvin. This first phase of the study is an in-situ investigation that relies on visual analysis carried out by the authors in the Ishan Church and Artvin. Visible signs of deterioration to the structure were visually examined in the light of structural features and architectural characteristics. Deteriorations observed in the church were mainly caused by the damage to structural elements and the decay of structural materials. Main structural problems are the damage to structural elements, the loss of material, and the decrease in structural strength. One of the facades of the structure was partly demolished at stone walls, and many irregular micro cracks were observed on the inside of the walls. The inspection also revealed several different types of damage to structure

Figure 4. View of the west arm of the church and completely demolished roof

Figure 5. The view of the detached west wall and the south wall

due to environmental conditions, lack of proper care, and general dilapidation. The tile roof, main arches that carry the roof, and the vault superstructure, are completely demolished and the structure is in an unprotected condition (Figure 4).

Furthermore, several different-size mature cracks were detected on the upper parts of walls of the structures, and in different zones. A notable example is one significant crack on the west façade that runs along the height of the wall (Figure 5). Therefore, this crack is the greatest threat to the structure's safety since it significantly separates the two walls.

This significant wall that connects the west wall and the south wall stretches from the upper part of the wall to the foundation. On-site measurements have revealed that the crack width varies between 2 and 15 cm, and the crack caused a gap between the south wall and the west wall. Figures presented in Takaichvili's studies, conducted in 1952 and 1960 [1, 2], show that the crack on the west side existed already in 1917, and that the width of that crack is similar to the width of the present-day crack (Figure 6). Nevertheless, the pictures also show that the demolished vault did not exist in 1917 and that these sections were covered with a wooden roof during the period when the structure served as a mosque. It can therefore be stated that the west façade cracks and vault deformations occurred at least 100 years ago and that these deformations have not changed to this date.

The upper parts of the apse at the east arm are totally demolished, and pastophorion rooms on the sides of the apse are heavily demolished. Vaults connecting pastophorion rooms to the apse are completely demolished, as can be seen in Figure 7. Some small cracks can be seen on the east façade of the structure, mostly in upper parts. The repair and reinforcement studies must concentrate on the entire supporting system, and on the deep crack on the west side. Moreover, drainage excavations prove that the foundation soil is in a good condition, and that there is no significant damage to the structure's foundations.

Figure 6. Ishan Church in 1917 [2]

Figure 7. Demolished vault roof of pastophorion rooms, and external view of gallery section

3. Experimental testing of materials

The use of materials for historical constructions depends on their local availability. Sandstones, limestones, and handmade bricks have been the most commonly used materials in masonry structures in Anatolia because of their availability, high strength, and softness [3]. Among those, the principal materials used for masonry structures in Turkey are stones and handmade bricks. It has been determined that construction materials dominant in Ishan Church are hewn stones and handmade bricks.

In this study, some laboratory tests were conducted on masonry specimens in order to determine their mechanical properties. Thus, representative stone and brick samples were randomly collected from the church area and were then prepared so as to obtain specimens measuring 50 mm × 50 mm × 50 mm, and 50 mm × 100 mm × 200 mm (Figure 8). Experimental tests were conducted to obtain information on the compressive strength, tensile strength, and density. Therefore, the stone and bricks were subjected to compressive tests and three-point bending tests. In the experimental examination, the compressive strength of samples was obtained from compression tests conducted on five cubes in accordance with guidelines contained in TS 699, Turkish Building Code (Table 1) [4]. The tensile strength of material samples was obtained by three-point bending

Figure 8. Preparation and testing of specimens: a) collected masonry units; b) preparation of specimens; c) compression test; d) three-point bending test

tests conducted on five prisms according to TS EN 1467 and 1469, Turkish Building Code (Table 3) [5, 6].

The compressive strength values of stone specimens varied between 39.98 MPa and 42.25 MPa. According to compression tests, an average compressive strength of stone specimens amounted to 41.20 MPa. The tensile strength generally varied between 2.79 MPa and 3.01 MPa. The average tensile strength value was found to be 2.91 MPa. With regard to handmade bricks, compressive strength values ranged from 19.15 MPa to 21.02 MPa, and the average compressive strength amounted to 20.23 MPa. The tensile strength varied between 1.32 MPa and 1.51 MPa, and the average tensile strength obtained was 1.42 MPa. According to the Turkish Earthquake Code 2007 [7], the modulus of elasticity (Ed) for masonry units can be calculated from Ed = 200fd, where fd is an average compressive strength of masonry units. The equivalent density values for construction materials were determined through test results for ten specimens. Mechanical properties used in all numerical analyses are summarized in Table 5.

Table 1. Compressive test results for stone specimens

Speci-mens	Depth [mm]	Length [mm]	Height [mm]	Density [kg/m^3]	Compressive strength [MPa]
1	49	51	51	2661	42,25
2	51	50	50	2626	41,54
3	50	51	49	2610	41,90
4	50	50	51	2669	40,32
5	51	50	50	2632	39,98

Table 2. Three-point bending test results for stone specimens

Speci-mens	Depth [mm]	Length [mm]	Height [mm]	Density [kg/m^3]	Tensile strength [MPa]
1	50	201	100	2652	2,93
2	51	200	100	2643	2,85
3	51	201	100	2659	3,01
4	50	200	101	2657	2,96
5	50	200	101	2698	2,79

Table 3. Compressive test results for brick specimens

Speci-mens	Depth [mm]	Length [mm]	Height [mm]	Density [kg/m^3]	Compressive strength [MPa]
1	49	50	50	1909	20,42
2	51	50	50	1901	19,15
3	50	51	49	1910	19,98
4	50	50	50	1899	20,59
5	51	51	50	1900	21,02

Table 4. Three-point bending test results for brick specimens

Speci-mens	Depth [mm]	Length [mm]	Height [mm]	Density [kg/m^3]	Tensile strength [MPa]
1	50	200	100	1929	1,51
2	51	201	100	1898	1,32
3	50	201	101	1910	1,36
4	50	200	101	1903	1,49
5	51	201	100	1899	1,43

Table 5. Mechanical properties of materials

Mechanical properties / Structure elements	Modulus of elasticity [N/mm^2]	Poisson ratio	Unit weight [kg/m^3]
Walls	8200	0,15	2650
Arches	8200	0,15	2650
Columns	8200	0,15	2650
Roof	4000	0,18	1900

4. Numerical models

Proper determination of structural behaviour and proper selection of reinforcement methods, aimed at solving possible structural problems, are crucial in reinforcement studies for historical structures. However, these studies can not be conducted with traditional engineering approaches. Therefore, the use of computer models, and the analyses made with these models, is a reliable method for structural assessment of historical structures. In this study, numerical models realized to determine the Ishan Church's structural performance, and the level of damage, were generated using the ANSYS Workbench software [8] (Figure 9).

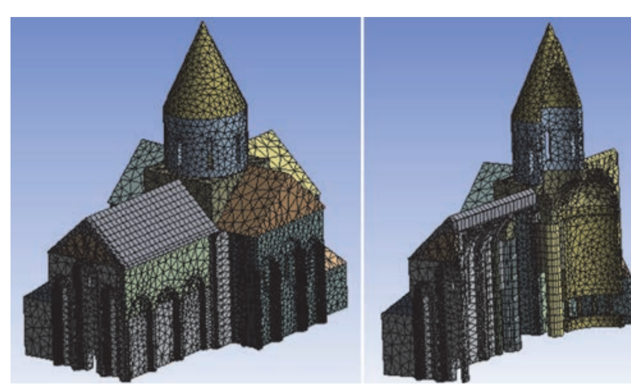

Figure 9. Finite element model of the church

The architectural, repair and restoration designs were taken into consideration at the modelling phase, and all models were created based on measurements and details shown in design documents. Moreover, 222701 nodes and 113909 solid elements (Solid186) were used in the numerical model.

Material properties are very important in the analysis of structural behaviour. However, it is quite difficult to determine the material properties to be used in the analyses of the historical structures. Therefore, in this study, material properties are determined taking into consideration previous studies, and general assumptions are made because of the complexity involved in the determination of the material properties. That is why, in our study, the material properties have been quoted from similar studies [9-12] (Table 1).

4.1. Static analysis

This study primarily focuses on the static analysis of the Ishan Church under its own weight, which is why the vertical load analysis was conducted. The analysis results show that the maximum displacement occurred vertically and at the conical section of the church. The maximum value of 1.86 mm was obtained (Figure 10).

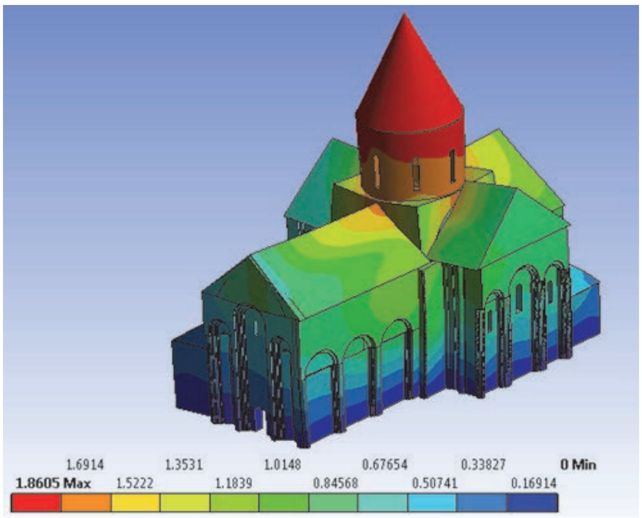

Figure 10. Vertical displacements of the church, dimensions in [mm]

The examination of the compression and tension stress values proves that the maximum compression strength occurred at the bottom parts of main supporting columns, and at the bottom parts of the main columns that carry roof tiles. The maximum value amounts to 3.99 MPa (Figure 11). Tensile stresses are highly pronounced at the skewbacks of the arches, and side walls, and also at the cone shaped supportive arches. Furthermore, enforcements were observed at the bottom parts of the arches, and the maximum tensile stress attained the value of 2.18 MPa (Figure 12).

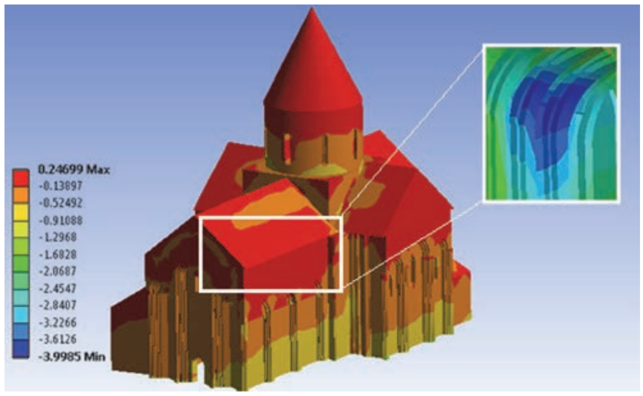

Figure 11. Compression stress contours obtained by static analysis, dimensions in [MPa]

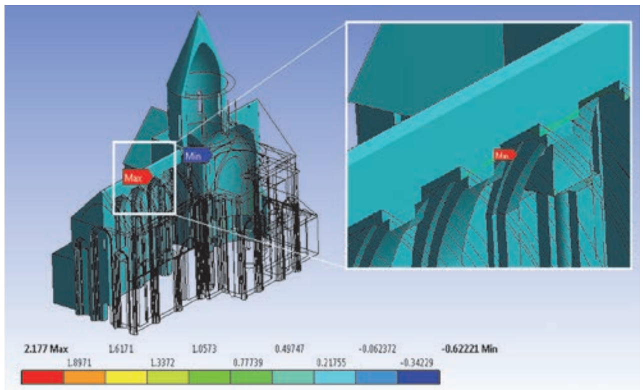

Figure 12. Tensile stress contours obtained by static analysis, dimensions in [MPa]

4.2. Modal Analysis

The modal analysis is primarily used for the dynamic analysis of structures. Sufficient numbers of vibration modes are determined in accordance with the Turkish Earthquake Code (TEC). According to [7], a sufficient number of vibration modes should be used to take into consideration the fact that the sum of effective mass participation ratios should be greater than 90% of the total mass of the building for each direction. Modal analyses are considered for the first 30 modes, and the first

Table 6. Frequency and effective mass participation ratio for effective modes

Mode	Frequency [Hz]	Effective mass participation ratio [Axis X]	Effective mass participation ratio [Axis Y]	Effective mass participation ratio [Axis Z]
1	5,10	0,0053	0,6371	0,0003
2	6,68	0,1227	0,0045	0,15E-6
3	6,90	0,2617	0,0132	0,20E-4
9	10,98	0,1405	0,0025	0,0003
15	15,70	0,0002	0,0047	0,1487

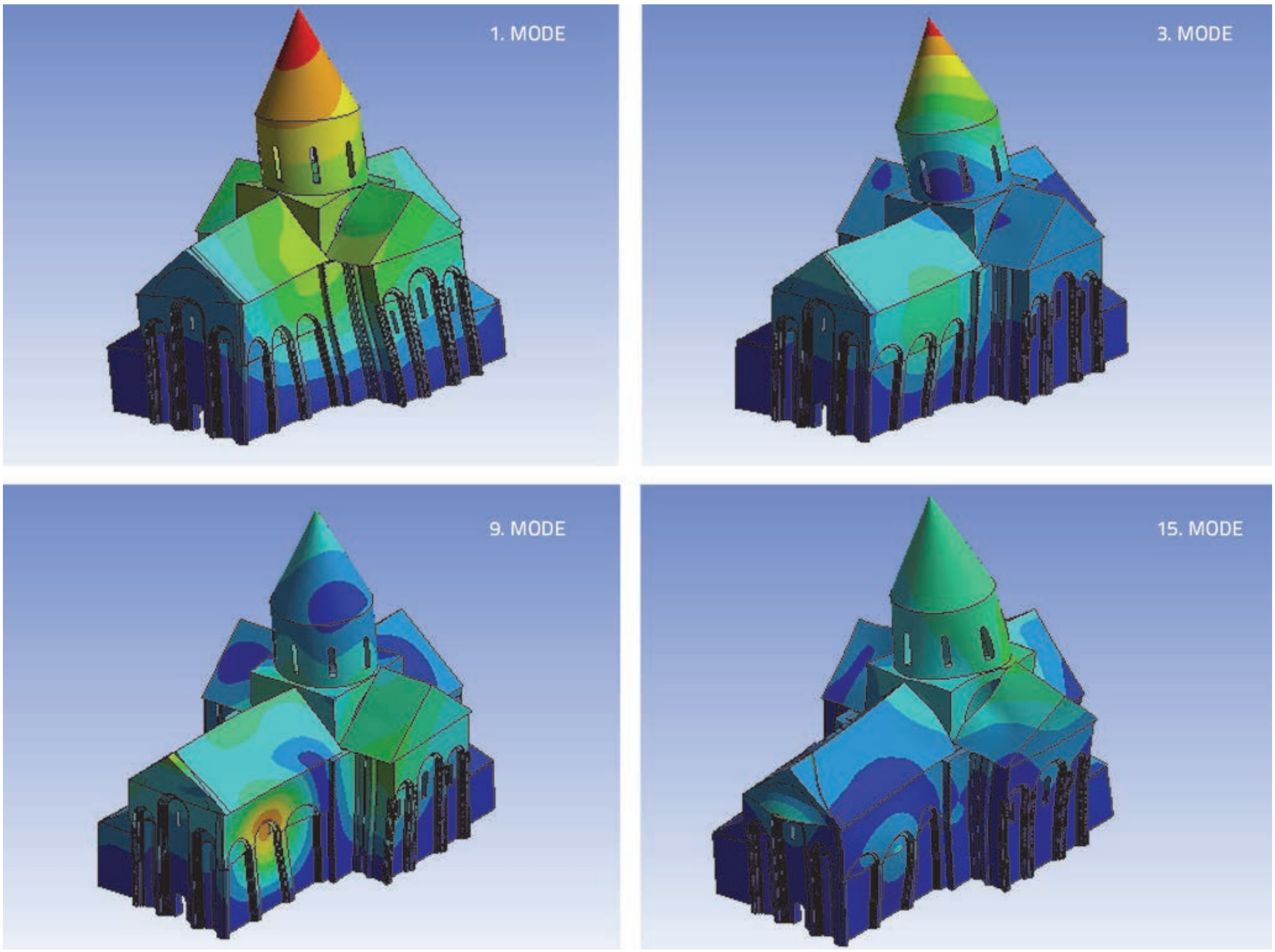

Figure 13. Some mode shapes

five modes that have higher contributions to the effective mass participation ratios. Therefore, in modal analyses, the solution is made for 30 modes, while five of the modes that are considered to be risky deserve careful attention (Table 6).

The modal analyses show that the first mode of the structure has translation in Y direction while the 2nd, 3rd and 9th modes have translation in X direction, while other modes are under the effect of torsion. These modes, which constitute 65 % of the effective mass ratio, reflect the general tendency of the structure's seismic behaviour. Moreover, the frequency values generated (Figure 13-14) prove that Ishan Church is quite a rigid structure, and that it was built in compliance with minimum displacement principles with regard to potential earthquake action.

4.3. Dynamic Analysis

According to the Turkey Earthquake Zone Map, which was prepared by the Prime Ministry Disaster & Emergency

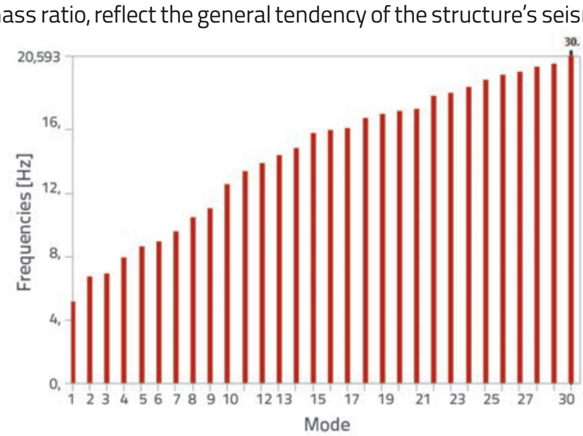

Figure 14. Frequency values for all modes

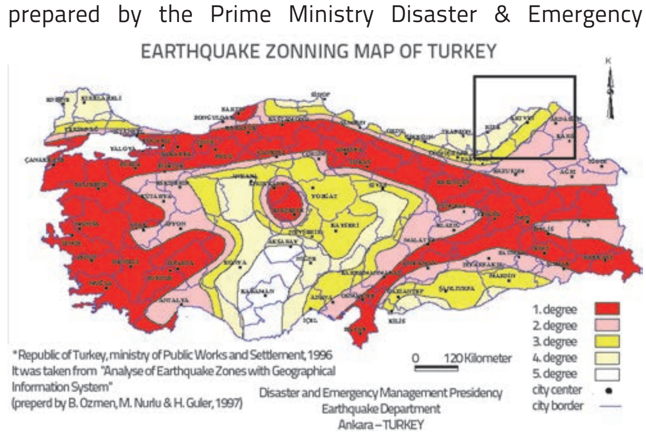

Figure 15. Earthquake map of Turkey [13]

Management Presidency, the area of Artvin and its surroundings are situated in the 2nd, 3rd and 4th earthquake zones [13]. Ishan Church that is the main subject of this study is located in the 2nd earthquake zone where the maximum ground acceleration is 0.3g (Figure 15).

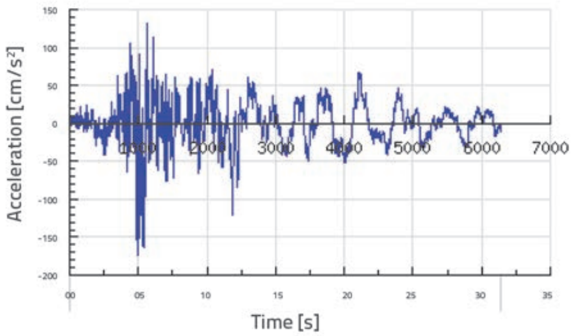

Figure 16. Erzurum - Kars earthquake East-West acceleration component [14]

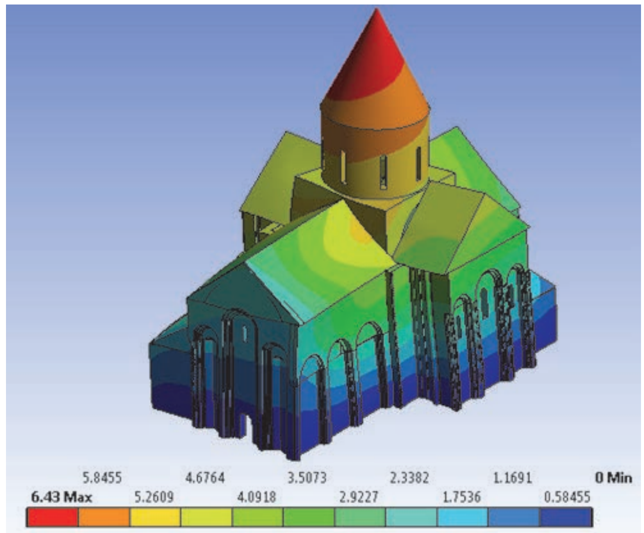

Figure 17. Lateral displacement contours through dynamic analysis, dimensions in [mm]

The Erzurum-Kars Earthquake, which occurred on 30 October 1983 in Erzurum near the town of Artvin, is also considered in this study. The corresponding dynamic analyses were conducted using the time-history analysis method. In the analyses, the Erzurum-Kars Earthquake acceleration records were acquired from Horasan Station, and the East-West (E-W) acceleration component [14] from powerful territory movements was taken into consideration (Figure 16).

The analyses results show that the maximum horizontal displacements take place at the main dome of the church, and at top parts of the main entrance, attaining as much as 6.43 mm at the main dome (Figure 17). The critical stresses generated through the analyses are observed primarily at the supports of hanger arches that carry the main dome and the surroundings of the window spaces. Tensile stresses are particularly pronounced at arch supports that carry the dome, and at the bottom parts of supportive columns. Third principal stresses appear as compressive stresses, and are especially notable at the bottom and upper parts of supportive columns. In addition, stress increases can be noted at the bottom parts of the main dome, and the maximum compressive

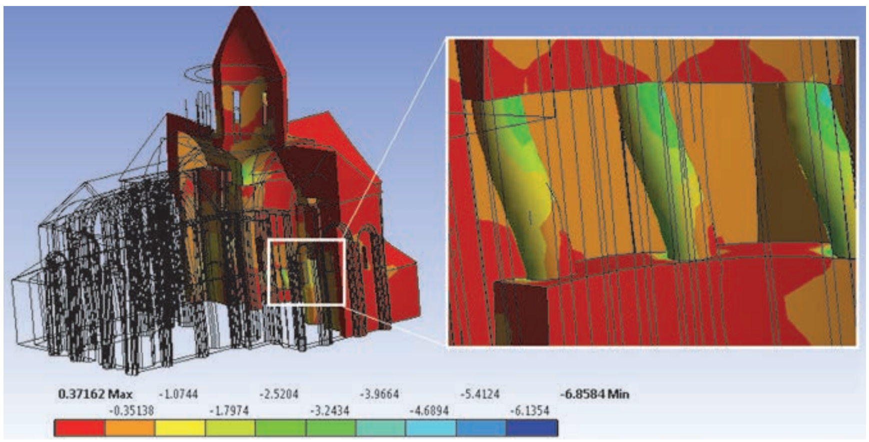

Figure 18. Compression stress contours through dynamic analysi, dimensions in [MPa]

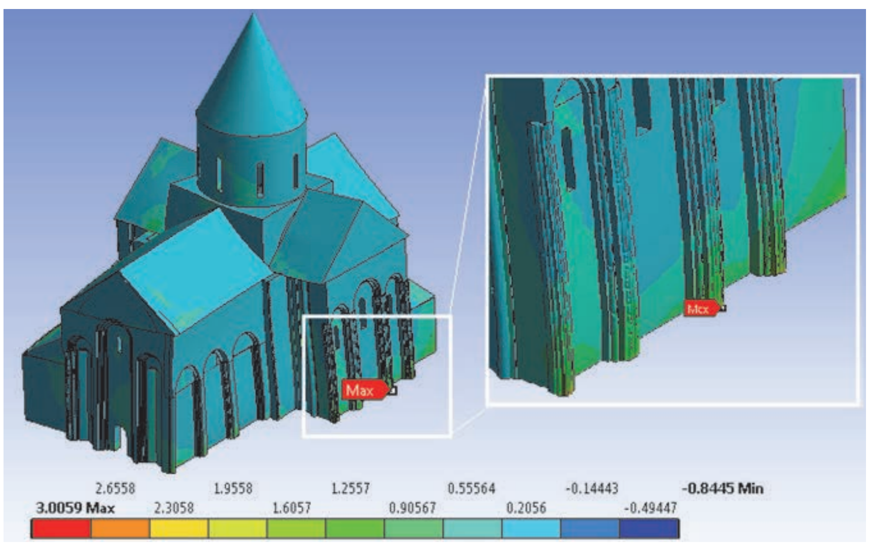

Figure 19. Tensile stress contours through dynamic analysis, dimensions in [MPa]

strength attains 8.06 MPa (Figure 18). Tensile stresses are also observed at arch supports that carry the roof vault in the west arm, and at the upper parts of the main supporting elements, attaining the value of 3.00 MPa (Figure 19).

5. Results and discussions

In this section, experimental test results and numerical analyses are discussed and compared with similar studies presented in literature. Previous experimental tests conducted on masonry materials show that the maximum compressive and tensile stress values amount to 56.0 MPa and 8.2 MPa for stone, while maximum compressive and tensile stress values are 28.0 MPa and 4.0 MPa for handmade bricks [15- 20]. Therefore, experimental test results presented in this study show that the ancient stone and brick materials have retained their mechanical properties, because values comparable to those given in literature have been obtained.

The analyses results prove that in terms of displacements the most risky parts of the structure are the cone shaped top point and freestanding roofs, and that these sections are at risk with regard to vertical deformation. It has also been observed that the highest risk walls are the upper parts of the west façade walls, which are the longest part of church arms, and the bottom parts of the vaults in west arms. Lateral enforcements present at the upper parts of side walls mainly assume loads from vaults in the west arm, and thereby outside openings are detected on the right and left skewback points of the vault. Tensile stresses occur at vertical sections of side walls because of lateral effects of vault elements. The stress increases were observed at the supportive cone shaped arches in the conical part of the structure, and enforcements were detected at the bottom parts of the dome. Nevertheless, it has been detected that the stresses are highly pronounced at the skewback points of the supportive arches where vaults are settled, and those sections deserve careful consideration in terms of structural performance. As shown in Figure 18, the maximum tensile stress amounted to about 3.06 MPa. The tensile strength reached the value that is assumed to be high for stones, bricks and bonding parts.

It can be said that arch supports in the inner sections, and the main dome supports, might be affected during the earthquake, when deformations in mode shapes are considered. Moreover, according to modal analysis, deformations are expected to occur at the freestanding roof that rests on outside walls, and at main domes, since those sections are affected by the out-of-plane motion. It has also been revealed that arch supports carrying the main dome at inner sections of the church deserve special attention since they have a considerable effect on structural performance. It is believed that the cracks due to external effects, observed in the structure stem, occurred in the course of time and are due to excess load. Tensile stresses acting on walls caused permanent deformations since the tensile strength of materials used in masonry structures is quite low [9, 11, 21, 22-24]. However, this is an expected situation for historical structures. The cracks at the upper parts of the walls, advancing towards bottom parts by narrowing down, caused by the tensile stresses in masonry structures, are expected to occur [20]. This kind of structural behaviour and crack forms are typically observed at the walls of Ishan Church. It is estimated that deep crack at the west façade primarily occurred because of tensile stresses at the bottom parts of the roof. This crack advanced through the edge of the ornament zone and foundation zone due to the narrowing on the wall section, which is mainly caused by deep ornaments at the front façade.

6. Conclusion

This study focuses on Ishan Church located in Artvin, which is one of the most important examples of Georgian architecture. In this scope, several analyses are conducted by the finite element method in order to determine structural behaviour, and to investigate causes of damage. The detailed investigation of damage showed that deformations affecting Ishan Church are most pronounced on the roof parts and arch parts. In addition, the detailed numerical analyses prove that stresses are mostly present at the bottom parts of the freestanding roof, and at the skewback points of the main arches that carry roof vaults. Moreover, it has been detected that stress increases are mostly located at the parts where different materials and geometrical shapes coincide, and the structure is damaged in those transition zones. Therefore, the transition points deserve careful attention in terms of restoration and reinforcement works for Ishan Church, and serious measures must be implemented in order to meet stress increases in these transitional areas. In addition, it is predicted that the analyses conducted in the scope of this study, and the results of these analyses, will encourage and inspire other studies. Therefore, it is recommended that similar studies be conducted on historical structures with several different construction materials and different support systems.

Acknowledgements

The Authors would like to thank Professor Haldun Ozkan for his guidance and scientific contributions. Furthermore, the authors would like to extend their thanks to the Erzurum Directorate of Surveying and Monuments and Osman Gülsüm Restoration Cor. for their guidance and contribution in on-site investigations.

REFERENCES

[1] Takaichvili, E.: Archaologische Forschungsreiseindie Südlichen Provinzen Giorgiens 1917, 1960, Tiflis.

[2] Takaichvili, E.: Arkeologicheskaia Kspeditsia: 1917, Juznije Provintsii Gruzii, 1952, Tiflis.

[3] Uysal, H., Cakir, F.: Static and Dynamic Analyses of the Historical Erzurum Watch tower, TAC Foundation, Foundation for the Preservation of Turkish Monuments an Environmental, Issue-1, pp. 72-80, 2013.

[4] TS 699: 2009, Methods of Testing for Natural Building Stones, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey (in Turkish).

[5] TS EN 1467:2012, Natural stone - Rough blocks - Specifications, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey.

[6] TS EN 1469, Natural stone products - Slabs for cladding - Requirements, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey.

[7] Turkish Earthquake Code (TEC), Specification for Structures to be Built in Disaster Areas, Ministry of Public Works and Settlement Government of Republic of Turkey, Ankara, 2007.

[8] ANSYS: 14.0 Releases, Finite Element Analysis Program, USA.

[9] Seker, B.S.: Investigation of Behaviour of Architect Sinan's Mosques Under Static and Dynamic Loads, PhD Thesis, Graduate School of Natural And Applied Sciences, Karadeniz Technical University, 2011, Turkey (in Turkish)

[10] Ural, A., Doğangün, A., Görkem, S.E.: Stone Masonry Arch Bridges in Turkey and Analysis of a Sample Bridge Including Nonlinear Behavior, 1st International Conference on Restoration of Heritage Masonry Structures Cairo, Egypt, April 24-27, 2006.

[11] Seker, S., Dogangun A., Cakir, F.: Structural Analysis and Assessment of Historical Kara Mustafa Pasha Mosque in Merzifon, Turkey , SDU International Technologic Science, Vol. 5, No 1, 2013, pp. 112-120 (in Turkish).

[12] Dogangun, A., Acar, R., Sezen, H., Livaoglu, R.: Investigation of dynamic response of masonry minaret structures, Bull Earthquake Eng (2008) 6, pp. 505–517.

[13] AFAD: Republic of Turkey Prime Ministry, Disaster and Emergency Management Precidency, Earthquake Department, http://www.deprem.gov.tr/sarbis/Shared/Deprem, Haritalari.aspx , 23.08.2013.

[14] NEMC: National Earthquake Monitoring Center, Bogazici University Kandilli Observatory and Earthquake Research Institute, Turkey, http://www.koeri.boun.edu.tr/sismo/Depremler/tLarge2.htm, 30.08.2013.

[15] Sassoni, E., Mazzotti, C.: The use of small diameter cores for assessing the compressive strength of clay brick masonries, Journal of Cultural Heritage 14S (2013) e95–e101.

[16] Sert, M.: Determination of Physico-Mechanical Properties of Stone Originating In Isparta and Nevsehir Volcanic Terrains And Studying Their Areas of Use, M.Sc. Thesis, Graduate School of Applied and Natural Sciences, Department of Mining Engineering, Isparta University, 2010, Turkey (in Turkish)

[17] Halifeoglu, F.M., Sert, H., Yılmaz, S.: TarihiKurt Köprüsü (MihrapliKöprü, Vezirköprü) Restorasyonu Projeve Uygulama Çalışmaları, METUJFA 2013/2, (30:2), pp. 81-104, (In Turkish).

[18] Kanıt, R., Donduren, M.S.: Bağlayıcı Özelliği Artırılan Harçla oluşturulan Yığma Duvarların Mekaniksel Davranışları, Selçuk Üniversitesi, Teknik Bilimler Meslek Yüksekokulu Teknik-Online Dergi, Cilt 7, Sayı:1-2008 (In Turkish).

[19] Kurugol, S., Tekin, C.: Anadoluda Bizans Dönemi Kale Yapilarinda Kullanilan Tuğlalarin Fiziksel, Kimyasal Ve Mekanik Özelliklerinin Değerlendirilmesi, J. Fac. Eng. Arch. Gazi Univ., Vol 25, No 4, 767-777, 2010, (In Turkish).

[20] Camlibel, N.: The analytically investigate of Architect Sinan's Structures, Associate Professorship Thesis, Graduate School of Natural And Applied Sciences, Istanbul Technical University, 1998, Turkey (in Turkish).

[21] Doğangün, A., Ural, A., Livaoğlu, R.: Seismic Performance of Masonry Buildings during Recent Earthquakes in Turkey, The 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing – China.

[22] Ural, A., Dogangun, A., Sezen, H., Angin, S.: Seismic Performance of Masonry Buildings during the 2007 Bala, Turkey Earthquakes, Natural Hazards, 2012, Vol. 60 (3), pp. 1013-1026

[23] Korkmaz, H.H., Korkmaz, S.Z., Donduren, M.S.: Earthquake hazard and damage on traditional rural structures in Turkey, Natural Hazards and Earth System Science, 2010, (10), pp. 605–622.

[24] Adanur, S.: Performance of masonry buildings during the 20 and 27 December 2007 Bala (Ankara) earthquakes in Turkey, Natural Hazards and Earth System Science, 2010, (10), pp. 2547-2556.