STRUCTURAL BEHAVIOR AND ASSESSMENT OF BAJRAKLI MOSQUE IN WESTERN KOSOVO

A THESIS SUBMITTED TO
THE FACULTY OF ACHITECTURE AND ENGINEERING
OF
EPOKA UNIVERSITY

BY

FATON RAMADANI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

JANUARY, 2017

Approval of the thesis:

STRUCTURAL BEHAVIOR AND ASSESSMENT OF BAJRAKLI MOSQUE IN WESTERN KOSOVO

Submitted by Faton Ramadani in partial fulfillment of the requirements for the degree of **Master of Science in Department of Civil Engineering, Epoka University** by,

Prof. Dr. ……………...______________________
Dean, Faculty of Architecture and Engineering

Prof. Dr. ………….. ______________________
Head of Department, **Civil Engineering, EPOKA University**

Prof. Dr. …………… ______________________
Supervisor, **……………….Dept., EPOKA University**

Prof. Dr. …………… ______________________
Co-Supervisor (if any), **…………..Dept., …………..University**

Examining Committee Members:

Prof. Dr. …………….. ______________________
………………. Dept., ………….. University

Prof. Dr. ……………. ______________________
………………. Dept., ………….. University

Assoc. Prof. Dr. ,,,,,,,,,,,,,,,,,,,,, ______________________
………………. Dept., ………….. University

Date: 27.01.2017

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: …………………………..

Signature:

ABSTRACT

STRUCTURAL BEHAVIOR AND ASSESSMENT OF BAJRAKLI MOSQUE IN WESTERN KOSOVO

Ramadani, Faton

M.Sc., Department of Civil Engineering

Supervisor: Assoc. Prof. Dr. Huseyin Bilgin

Historic structures have a significant role in the social and cultural heritage of Kosovo. Many of the old monuments in Kosovo are mosques of Ottoman period, and the construction material used is mostly stone masonry. The majority of those mosques are still functional serving for religious purposes. Due to the aging of the structures, seismic activities, temperature changes, weather conditions, inappropriate maintenance, and lack of studies caused many structural deficiencies. In order to provide a fundamental understanding for the origin and impacts of structural defects, structural assessment of a related case should be done. Since it is required a representative model, Bajrakli Mosque located in western Kosovo is selected as a case study.

The first assessment of the study involves visual inspection of the structure for identifying cracks and other structural deficiencies. During the observations, many cracks are found in structural elements such as domes, pendentives, arches and load

bearing walls. One of the causes of the cracks is the stress concentration of the critical regions of the structure.

For a better and detailed understanding of the structural deficiencies, finite element analysis is prepared in SAP2000 for Bajrakli Mosque. During the analysis, structural behavior of the undamaged model is observed through static and dynamic loads.

Finite element analysis provided important data on identifying the critical regions of the structure. The maximum displacement for load combination of self-weight and earthquake load is found in the middle dome and around the arches of the entrance hall with a value of 7.1 mm and 8.0 mm for X and Y direction respectively. Furthermore, the highest stress concentration values are found to be in the small domes of entrance hall, in the openings around the main domes and its connection with arches, and around the openings of the load bearing walls. The output values of the stresses in the roof system exceed the allowable limits defined in the study. The results provided by finite element analysis correspond to the findings from visual inspections.

Keywords: Historic Structure; Stone; Structural Behavior; Finite Element Analysis; Stress Concentration;

ABSTRAKT

SJELLJA DHE VLERËSIMI STRUKTUROR I XHAMISË BAJRAKLI NË KOSOVËN PERËNDIMORE

Ramadani, Faton

Master Shkencor, Departamenti i Inxhinierisë së Ndërtimit

Udhëheqësi: Assoc. Prof. Dr. Huseyin Bilgin

Strukturat historike kanë një rol të rëndësishëm në trashigiminë kulturore dhe shoqërore të Kosovës. Shumica e monumenteve kulturore janë xhami të perandorisë Osmane të ndërtuara nga guri. Një numër i madh këtyre monumenteve janë akoma funksionale dhe shërbejnë për arsye fetare. Për shkaqe të vjetërsisë së strukturës, aktiviteteve seizmike, ndryshimeve të temperaturës, ndryshimeve të motit, mirëmbajtjeve të parregullta, dhe mungesa në studim kanë shaktuar shumë dëme strukturore. Në mënyrë që ti kuptojmë cështjet themelore të origjinës dhe ndikimet e dëmeve strukturore, vlerësimi strukturorë i një rasti duhet bëere. Pasi që duhet një shembull tipik, Xhamia Bajrakli në Kosovën perëndimore është zgjedhur për studim.

Vlerësimi i parë i studimit përfshinë inspektimin vizual të strukturës për të identifikuar çarjet dhe defektet tjera strukturore. Gjatë obzervimeve, shumë çarje janë gjetur në elementet strukturore si kupola, pendetivët, harqet, dhe muret mbajtëse. Njëra nga shkaqet e këtyre çarjeve është koncentrimi i shtypjeve në regjionet kritike të ndërtesës.

Për ti kutpuar më mire defektet strukturore, analiza “finite element” është përdorur për Xhamin Bajrakli në SAP2000. Përgjat analizës, sjellja e modelit të pa dëmtuar të strukturës është përcjellur në varësi të peshave statike dhe dinamike.

Analiza “finite element” ka dhënë informata të rëndësishme në identifikimin e regjioneve kritike të strukturës. Zhvendosja maksimale për kombinimin e forcave të peshës vetjake dhe forcës seizmike gjended në kupolën e mesme dhe harqet e korridorit hyrës, me vlerë 7.1 dhe 8.0 mm në X dhe Y.

Koncentrimi më i lartë i shtypjeve/stresëve jane gjetur në kupolat e vogla të korridorit hyrës, në hapjet përgjat kupolës kryesore dhe pjesëve bashkuese me harqet, dhe përgjatë hapjeve të murit mbajtës. Vlerat e streseve në sistemin e çatisë kalojnë vlerat limite të përcaktuara në studim. Rezultatet e gjetura nga analiza korrespondojnë me konkluzionet e arritura nga inspektimi vizual.

Fjalët kyçe: Strukturë Historike; Guri; Sjellje Strukturore; Analiza Finite Element; Koncentrimi i Shtypjeve;

ACKNOWLEDGEMENTS

I would like to express my special thanks to my supervisor Assoc. Prof. Dr. Huseyin Bilgin for his continuous guidance, encouragement, motivation and support during all the stages of my thesis. I sincerely appreciate the time and effort he has spent to improve my experience during my graduate years.

I would also like to thank Dr. Enea Mustafaraj for his support during modeling of the structure.

I am also deeply thankful to my family for their continuous support.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

FRP	Fiber Reinforced Polymer
FEA	Finite Element Analysis
FEM	Finite Element Method
PGA	Peak Ground Acceleration
γ	Unit Weight
E	Modulus of Elasticity
v	Void ration
d	Diameter of the Dome
s	Diameter of Arches
m	Number of Shell Divisions in Z Direction in Domes
n	Number of Angular Divisions in Domes
R	Radius
$f_{m(compressive)}$	Allowable Compressive Stress
$f_{m(tensile})$	Allowable Tensile Stress
τm	Wall Limit Shear Stress
τo	Allowable Wall Failure Stress
m	Friction Coefficient
σ	Wall Vertical Stress
T	Period
Δx	Maximum Displacement in X
Δy	Maximum Displacement in Y
G	Self-weight of the Structure
EQx	Earthquake Load in X
EQy	Earthquake Load in Y
S22	Radial Stresses

S12	Shear Stresses
ag/g	Horizontal Ground Acceleration
R	Reduction Factor

CHAPTER 1

INTRODUCTION

1.1. Overview

Cultural heritage is one of most significant concerns in the modern society, since it carries different social and historical values. Among the stock of cultural heritage, historical monuments are the greatest contributors to the values in many aspects. Thus, the preservation of structural monuments is an important field to be supported. Knowing that structural engineering is a broad field, it involves many different areas of study and application. In other words, structural engineering can be classified in different topics considering the purpose of use, the area of application, the material, the social role and many other fields. Considering this statement, structural engineers play a huge role in the preservation of cultural heritage.

Stone is one of oldest materials used in construction, and for this reason, many historical monuments are built of stone. Considering the age of the structures, stone has shown a good performance as a construction material.

For the time being built, the structures were constructed without any rule or standardized regulations, without any research or study, relying only in the experiences from the past. Due to weather conditions, natural disasters, historical events and human involvement, those structures have gone through different changes.

The structures that have experienced changes should be studied in more details. Analysis should be performed and important data should be attained. According to those data, the deficiencies of the building and its critical regions can be identified. Thus, the data found can be used for finding solutions to the damages found.

Contribution to building new structures is very important in the social and engineering world. In addition to that, conservation and restoration of the existing buildings is highly significant as well. Saving of such monuments is challenging, and particular skills for proper evaluation are needed. Thus, the study will provide with analysis and understanding of the defects shown in the stone masonry structures.

1.2. Brief History of the Case Study

The selected case study for the analysis of historical masonry structures is Bajrakli Mosque. The Bajrakli Mosque was built in the center of Peja, western Kosovo, at the so called Old Bazaar, an outdoor market which is a characteristic of Albanian cities. The mosque was a legacy of Sultan Mehmet Fatih who also supported the building of Grand Mosque in Prishtina. The Bajarakli Mosque was built on 1471. It is an old monumental building consisting of all elements. The mosque is made of the prayer hall, entrance hall and a minaret. The whole structure is covered by a big dome, covering the prayer hall. Also, the entrance hall is covered by three small domes of commonly proportional characteristics. The interior of the mosque is covered by wall paintings, and citations from Quran. It also consist other elements such as sculptures, framing of portal and windows etc. In the serving history of the mosque, it is important to mention that the mosque was burnt by Serb forces during the war of 1998-1999. The restoration of mosque was done after the war, at both architectural elements and the sculpture paintings. [Trashigimia Kulturore e Kosoves, 2016]

Figure 1. Bajrakli Mosque [Kuipers, 2009].

1.3. Problem Statement

The purpose of this section is to demonstrate the reasons and the importance of choosing this topic. There are different structural monuments in Kosovo which were built ages and centuries ago. Some of the buildings may not be properly maintained and are getting weak during time. There are mosques which are being used, and considering their ongoing performance, it is important to evaluate their structural/seismic performance. Moderate or strong earthquakes may cause severe damages or even failure of the structures, causing harm to the society. Moreover, the mosque is a religious monument meaning that it is highly used by the society. Thus, considering all of the above, this topic has a great significance since it focuses on an important monument with high social and religious value, and the main points of the topic identify the critical regions of this structure.

1.4. Aim of the Study

The aim of this study is to conduct a structural performance evaluation on a historic monument in Kosovo. Since there are different categories of monuments in Kosovo, this study is based on the analysis of a mosque, constructed during the ottoman rule, as a possible representative of other mosques built in the same era.

The structural evaluation is performed on the structure selected for analysis in order to examine the structure under loads such as static and dynamic. After the analysis, the weakest regions of structure are found due to the applied loads. The selected structure is of stone masonry structure.

Finite Element Method is used in this analysis. With the linear analysis, a general assessment and the behavior of the building will be simulated with SAP 2000, for determining the mode shapes, the behavior the structure under static and dynamic loads, and by this analysis the weak points which may be critical are identified.

The nonlinear analysis is of course of great importance, especially in the case of retrofitting. This analysis involves the elastic properties, strength of materials, and inelastic properties of the material as well. Therefore, conducting this type of analysis is impossible for this project, since this analysis requires exact and precise information on the material, and for historical buildings, such information may not be available, due to restrictions on conducting tests.

After performing the analysis, the FEA results are compared to the findings from visual inspections, and so highlighting the main causes and impacts of the defects found in the structure.

CHAPTER 2

LITERATURE REVIEW

2.1. Values of Historical Building

While emphasizing the importance of this study, it is important to mention the values of historic buildings based on the listed items below: [Guney, 2015]

1. Historical Concern
   a. Importance of the structure related to historical event
   b. Importance of the structure related to historical character
   c. Importance of the structure to social and historical development
   d. Age of the building
2. Architectural Value
   a. It is an important model of particular architectural categories.
   b. The architectural model, ornamentation, painting, technology, and materials of the structure have a great merit to the location.
   c. The presence of the structure emphasizes the beauty of the surroundings.
3. Group Significance
   a. Importance in a group of the structures in a pleasant design and style or as an essential part of historical era.
   b. The significance of the structure shows some certain cultural value of peoples in a city or characterizes a phase in the history of a city.
4. Social Importance and Local Concern

a. Has developed importance in the aspect of symbols and visual representation of a certain case.
b. Characterizes the community by showing some “cultural identity” and care for the cultural development.

5. Authenticity
    a. In case the structure has experienced any changes, they caused some influences on the historical importance and architectural integrity of the structure.
    b. Changes to the building can alter the cultural setting and the related cultural landscapes.
6. Scarcity
    a. Whether the structure is scarce due to architectural design, historical significance cultural representation, social importance, group value and local concern.

2.2. Complexity of Analyzing Historical Masonry Structures

Considering the value of the historical monuments, the analysis of it can be difficult. For further exploration, it is important to identify some of the points which make the analysis of historical buildings a complex task. Some of them may be considered as the followings [Lourenco, 2002]:

- Geometry records may be rare or cannot be found at all
- The data about the inner core of the elements found in the structure may be lost
- Classification and description of the material properties used is challenging and costly
- Huge inconsistency of mechanical properties due to work quality and use of natural resources
- Substantial changes in the core of and composition of essential elements of the structure due to long periods of construction

- The damages caused in the structure are unknown

2.3. Categorizing Structures According to Different Material Tasks

Considering history of structures, masonry has proven to be an excellent building material with great properties in appearance and durability. Its properties make masonry as one of the most used material in the past. Yet, the quality of the masonry depends highly in the materials used. For serving to its purpose, each mater must conform to the some defined minimum standards. For example, BS3921 identifies the categories as following [Hendry *et. al.*, 2004]:

- Common building blocks are applicable for common construction work
- Facing blocks are applicable for exterior and interior walls, in different purposes as ornamental, with different textures and designs.
- Engineering blocks are strong and solid used for engineering purposes.

Except the above classification, A.W. Hendry, B.P. Sinhaand and S.R. Davies classified blocks according to frost and the maximum soluble salt content [Hendry *et. al.*, 2004].

1. Classification according to frost resistance:

- Frost resistant (F): These types of materials are durable resisting to water exposer or thawing. They can be used in all building cases.
- Moderately frost resistant (M): These bricks are strong when exposed to normal conditions except in the cases of being exposed to repeat freezing and thawing.
- Not frost resistant (O): These types of building blocks can be used for internal use. In case of using for external façade, the have to be protected with, otherwise they can be damaged by freezing and thawing.

2. Classification according to maximum soluble salt content:

- Low (L): These building blocks must adapt to the limit prescribed by the building codes for maximum soluble salt content.
- Normal (N): There is no distinctive limit for soluble salt content.

Mortar is the second component in masonry. For loadbearing structures, the mortar should be composed of cement: lime: sand mix. Depending in the structural use purpose, the ratio of components is selected. When deciding for the type of mortar to be used, A.W. Hendry, B.P. Sinhaand and S.R. Davies defined the properties which must be considered [Hendry *et. al.*, 2004]:

- Early strength development.
- The ability to work or spread easily.
- The mortar capability to keep water against the suction of brick. (In case the water is not retained, the loss of water can cause insufficiency thus resulting into poor bond between mortar and brick/block.
- Properly bonding between bricks/blocks.
- Resisting to cracks and opposing rain penetration.
- Frost resistance and chemical reaction resistance.
- Short and long term performance.

2.4. Previous Researches

Before going with the research of a particular study, it is important to through provisions set by different standard codes, Researchers like C. Modena, F. Casarin, F. Porto, E. Garbin, N. Mazzon, M. Panizza, M. Valluzi prepared a paper which presented some critical review of Annex C, section 5 of the Eurocode 8 Part 3 mainly concerning with the structural interventions for existing masonry buildings. The paper discusses about the possible structural interventions to improve deficiencies. Some of the interventions may be the improvement connections and it is very important to take into account when dealing with the seismic behavior. Another intervention is to increase the masonry strength for establishing the original mechanical properties of materials. This intervention can be achieved in different methods as are underlined in the paper. Other interventions may as fixing the flexibility of floors and their consolidation and interventions in reducing thrust of vaulted arches and their strengthening [Modena *et. al.*, 2009].

After going through the requirements, it is important to identify some particular method ideology which should followed during the preparation the project. Gulkan and Wasti, investigated the challenges and solutions needed, to ensure the structural longevity of historic structures. The paper involves case studies including mosques, and gives discussion on those studies. Furthermore, he presented a method which is practical for assessment of historic structures. The method ideology states that the load carrying mechanisms of the structure should not be changed since it may cause further problems. He also states that realistic computer modeling of complicated structures requires expertise. The best way is to start with the simplest realistic model and then develop the model to reflect the structural complications of the structure. The paper gives details for seismic assessment and rehabilitation of historic structures [Gulkan and Wasti, 2009].

At the study on the seismic performance analysis of Mehmet Aga Mosque in Istanbul is given great discussion on the analysis of structural buildings. The study concluded that the elements in which subjected to more stresses are the domes. The study also gives solution and methods for strengthening of the elements which are prone to excessive stresses. Moreover, repair and strengthening of the elements are recommended by replacing the missing and the damaged masonry units and repairing cracks and the damages by using specially designed mortar to secure integrity of the structural elements [Gedik and Celep, 2008].

After the seismic behavior of Mustafa Pasha Mosque in Skopje is done the evaluation of the effectiveness of strengthening with FRP is carried out. The proposed retrofitting interventions for Mustafa Pasha mosque consist in the placement of FRP in the wraps of the domes, and in the strengthening of the foundation. The comparison of seismic capacity and the demand for the original model with the strengthened model shows that the seismic performance is increased of about 50% by strengthening with FRP [Portioli *et. al.*, 2010].

The review or restoration of historical structures includes historical heritage, materials, structural members, computational strategies and computational analysis techniques. In order to check for deeper analysis, computational analysis such as Finite Element Analysis Method is required. This method analyzes the ultimate behavior of these structures. For the non-linear behavior, the analysis is performed with the Finite Element Model. It indicates the deformation development and crack patterns. The results obtained can be the stress distribution, the strain behavior and collapse mechanism of the structure. This analysis considers the application of the vertical loads and a system of horizontal force increasing monotonously until the limit conditions are reached [Ayidin, 2009].

Another useful paper related to the topic is the one by T. Jeff Guh, and Arash Altoontash. The authors provided a general survey of the technical issues related to the seismic retrofit of historic buildings. Post tensioning is the option which provides strength and ductility to the overall structure. In this process a core hole is placed down through the masonry wall and a high-strength steel rod is inserted. The bottom of the rod is anchored in the floor or foundation. A jack is then used at the top of the wall to place high levels of tensile force in the rod. Base isolation technique is used to decouple the building response from the ground motion so in case of earthquake, the isolators will serve as reductant of the structural damages by shifting the structure natural period Composite wraps or carbon fiber jackets are used to increase the strength and ductility of structural elements. Micro-piles are used in foundation for to reduce the foundation deflection and enhance the foundation ultimate capacity. Epoxy is one of the most adaptable materials used in structural retrofitting by providing binding between reinforcement and concrete to restore bond degradation or provide anchorage for new concrete [Guh and Altoontash, 2006].

At 2010 Ustundag, Sesigur and Cili presented the seismic evaluation and retrofit of the Mihrimah Sultan Mosque, a 16th century single domed mosque built between 1562 and 1565. This mosque suffered severe damages during some earthquakes in 1719, 1814, 1894 and 1999. The main reasons suggested being the bad soil conditions and the probable damages of the iron tension bars. Thus, this study involved the three dimensional model for simulation of the static and seismic behavior before and after retrofitting, and then the system is analyzed under gravity and seismically originated forces using FEM. The retrofitting includes improving of the ground conditions underlying the foundation by injecting of concrete under foundations and filling the voids under them. Also the additional steel tie-rod is proposed for the case of the stone arch at the altar side. For checking and evaluation, some analysis is performed. Thus the analysis is carried out for gravity loads and seismic loads, before and after proposed strengthening. The analysis showed under gravity loads the application of steel tension rods reduced the compressive stress at the arch support by 29% to 54%. The overall distribution of axial and shear stresses are improved. The figure below shows the first mode shapes before and after reinforcement. The following below represents the modeling and plan view of the mosque [Ustundag *et. al.*, 2010].

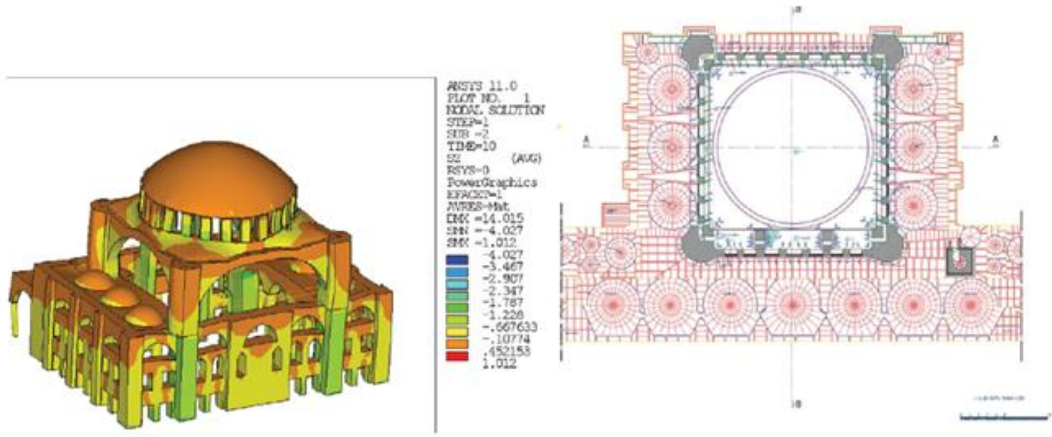


Figure 2. Modeling of Mihrimah Sultan Mosque [Ustundag *et. al.*, 2009].

Another related study is the on conducted on the structural and earthquake response of the Little Hagia Sophia Mosque investigates the structural and earthquake response of the Little Hagia Sophia Mosque which is one of the oldest historical buildings in Istanbul. The materials of the mosque are mainly stone brick and plaster. As a method for structural investigation is considered the elastic analysis and under vertical earthquake loading, and it seems as a reasonable method for basic understanding of response of ancient masonry building formed by complex components. The analysis shows that the transversal earthquake motion is more effective than the longitudinal one. The stress distribution results show an increase at the lower level of the walls. After the results, strengthening techniques are proposed. For repairing the structural system, fiber reinforced polymer (FRP) or steel plates are proposed for providing confinement to the ring beam of the dome. For the foundation, micro piles with a diameter of 165mm are proposed in order to support the main walls [Guler *et. al.*, 2004].

At 2003 Temel summarized the steps that a masonry building may undergo through analysis in order to find the performance of the building. As a case study for this project, Maiden’s Tower, one of the best known historic monument in Uskudar, has been investigated and analyzed to obtain reliable results. The paper has summarized the results of the analysis done before and after restauration. From the original shapes, in restoration, steel bracing frames are attached to the tower section. A second modification is done in the first floor slaps by connecting the west side walls to east side by steel beams. The following picture is the SAP2000 modeling of the structure. While comparing the analyses, it is found that after the restoration is applied, the stresses value decreased considerably. Furthermore, also the maximum displacement values are decreased [Temel, 2006].

Vasseghi, Eshghi, Jabbarzadeh, and Fariborz Nateghi , at 2004 presented the results of seismic vulnerability analysis of the Sultaniya dome in 1302 and 1312. Finite Element Method is used for structural analysis. Static pushover analysis is performed for assessing the seismic resistance of the structure for three levels of seismic hazards. For an earthquake with return period of 75 and 475 years, some cracks would appear at a portion of the structure while for an earthquake of return period of 2500 years, the building is expected to collapse. The seismic analyses are performed for three levels of earthquake hazards with returning period of 75, 475, and 2500 years. For the earthquake of returning period of 75 years and PGA 0.23g, the analysis resulted to a maximum drift of 10mm at the top of the dome and maximum compressive stresses of 1704 kN /m2 which occurs at the corner of the main columns . For the earthquake with return period of 475 years, and PGA=0.44g, the analysis gave results of a maximum drift of 19.6mm at top of the dome and a maximum compressive stresses of 2480kN/m2 at the corner of one of the main columns. The analysis for an earthquake with return period of 2500 years with PGA 0.76g shows the maximum drift of 33.9mm and maximum compressive stresses of 3725 kN/m2. This stress exceeds the maximum compressive strength and indicates crushing at the location [Vasseghi *et. al.*, 2004].

CHAPTER 3

METHODOLOGY

3.1. Introduction

Different source materials are used in order to do a proper study on this topic. For a great description of the topic and for literature review, past works are discussed and analyzed. A case study is added considering the historical monuments and the procedure of this analysis is considered as representative of other monuments built in that era. The records of information are taken from trusted sources. Thus, the case study provides a stronger understanding toward the topic. The structure will be modeled and analyzed in SAP2000.

3.2. Failure Mechanisms

During the lifelong service, historical masonry structures should resist dynamic action beside vertical loads. Such kind of lateral dynamic loads may induce partial failure of elements or even a total failure of the structure. Such kind of vulnerability of historical structures to seismic actions may occur as result of improperly connection of structural elements. Thus, old historical masonry buildings may already have undergone through such loads and experienced damages, therefore such factors should be neglected.

Masonry structures are subjected to out-of-plane and in-plane inertia forces. Under the out-of-plane forces, the structure may overturn towards the outside of the wall if the walls are not built properly. Under the in-plane inertia forces, if the connection of units is weak, cracks may occur in the major part of the walls. Masonry units may lose connection and move out of the order, so the wall may not function properly.

Thus, from the previous paragraphs, it can be concluded that failure mechanics are one of the most important factors which must be identified when dealing with engineering structures. The following figure and explanations are given by Ayala and Speranza. Figure 3 shows the subgroups of out-of-plane and in-plane failure mechanisms.

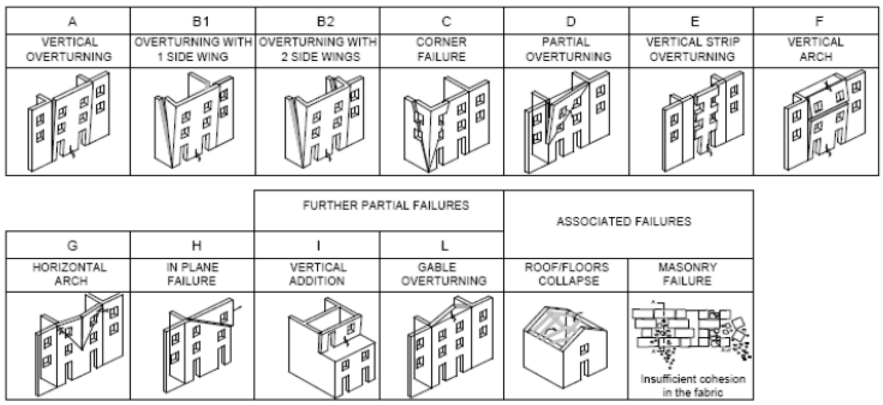


Figure 3. Failure Mechanisms [Ayala and Speranza, 2002].

The first six failure mechanism depends on the level and type of connections of façade and walls. In other words, the first six failure mechanisms are depended on the geometry of masonry units and the connection quality between the orthogonal walls.

Type A of the failure occurs when there is no connection of the edges of the walls or the geometric dimensions of the elements are not accurate. Type B1 and B2 occur when the level of connections is sufficient to when one or both party walls is involved into overturning, due to the level of connections. Thus, it develops a diagonal crack in the walls and a horizontal hinge on the façade.

Mechanism C occurs when there is a good connection at the further end but poor quality of the plane fabric, and so both party walls are involved. In the case when both, the weak connections and poor wall fabric occur, then mechanisms type D occurs.

Mechanism type F occurs when there are ties or ring beam at the roof level of façade. Mechanism type G occurs when a vertical or horizontal arch effect develops depending on the connections of elements as a whole structure. Type H Mechanism occurs when horizontal actions in the plane of façade cause diagonal cracks.

As noted, horizontal structure may as well be involved in failure mechanisms, since roof and floors transfer loads vertically by adding mass to the overturning forces and creating restraining actions by friction of structural elements. Same, horizontal structures should be involved in failure mechanisms.

3.3. Material Properties and Methods of Investigation

3.3.1. General Overview

Engineering analysis and design requires proper information on mechanical properties of the materials, as stated in the previous chapter in the European Standards. Due to the serving for the applied loads and other environmental changes, masonry undergoes changes. Thus, for a correct structural assessment, some investigations must be considered. The structure should be checked and identified for cracks and other damages. Those changes can be identified through on-site and laboratory experimental examinations. After determining and obtaining the proper data, appropriate models and analysis for evaluation of historical masonry building can be applied and final diagnosis can be obtained. Accordingly, conclusions can be drawn for proposing rehabilitation and strengthening methods.

There are many differences in types of masonry structures because of different reasons. Those reasons are because of different construction techniques, different ground conditions, and different use of materials. The units are brick, blocks, ashlar, irregular stones, and many other. For use of mortar in the joints may be clay, bitumen, chalk, lime or cement, glue, or other construction materials. Thus, this variability of different materials used as units and mortar is the reason of the differences in types of masonry structures. Each of the materials has different material characteristics, resulting into different performances of the building. Thus, in order to examine properly and effectively, there are different types of methods and computational tools for the assessment of mechanical behavior and the present condition of historical masonry structures. Each of the methods has its own way, and depends in the conformity and availability with the methods, so a proper selection can be made. However, each of the method has its own characteristics as well. They all have different complexity levels, different costs, and different requirements. If conducted properly, the methods can give same results with slight differences. Thus, the method can be chosen according to the numerical model of the structure. The methods for determining the material properties are divided into three categories [Sen, 2006]:

- Destructive Testing
- Non-destructive Testing
- In-situ Testing

Material properties are important data for this project. Since the case study involves a historical heritage structure, it is impossible to conduct any test. In order to define the material properties in the most proper way possible, a literature survey is carried out. The following sections give information on each of the three categories for obtaining material properties, and also another section is added to discuss the selected properties.

3.3.2. Destructive Testing

Destructive tests are tests which are mostly used for material properties assessment, but in some cases such as cultural heritage structures, those tests may not be applied. In the destructive tests, samples are taken and sent to laboratories for testing. In the case that samples of the materials are required for destructive tests they should be taken from the elements with the condition of causing minimal harm to the structure. The samples taken must be in a good condition in order to represent the materials of the structural elements.

The destructive testing is a useful method for identifying some important characteristics of the constructed buildings. This method can identify to describe the material from a chemical, physical and mechanical perspective, to distinguish its starting or creation point, to measure its decay, to know its composition to select proper materials for repair.

Since it is difficult to take samples representative to the walls, only small components are removed for testing. While sampling, some principles have to be applied in order for the samples to represent the all the types of deficiencies in the existing building.

3.3.3. Non Destructive Test Methods

This type of methods is highly preferable since it involves nondestructive activities. For cultural heritage structures, it is very significant to not cause any harm or any change in the structure, since the structure as a whole represents a social value and cultural heritage. However, nondestructive test methods results may be questionable in accordance with material properties of masonry. Yet, this type of method can provide a general understanding of the quality. Therefore, in order not to cause any complication, they can be used for obtaining basic properties. The following table summarizes the nondestructive methods [Sen, 2006]:

Table 1. Nondestructive test methods.

Test Method	Use
Rebound Hammer Test	To find the compressive strength of concrete. As the plunger is pressed against the surface, the output value leads to the compressive strength. An average of 15 readings must be conducted.
The Impact Echo	It is used for assessment and evaluation of material properties. The instrument, with the transient stress waves, locates and classifies the flaws of the material. It is applied for evaluating the thickness of a concrete member, locating poor consolidation and voiding in reinforced concrete.
Stress Wave Transmission	It uses pulse transmission in order to detect pores and other flaws in the material.
Metal Location	in the case of the structural steel members are implanted within the structure, metals may be detected up to 1 m within the structure.
Tomographic Imaging	It is mainly used to check for internal anomalies or voids being present in the material.
Surface Penetrating Radar	It checks for anomalies being present in the sample. Data gathered is analyzed in the time domain and can investigate masonry conditions such as voids, retaining wall thickness, grout location, deteriorations and internal damages, moisture and salt content.
Infrared Thermography	It is used for investigating masonry defects such as subsurface voids, cracks, variations in wall construction, displacements, moisture rise, air leakage, differences in moisture content, previous repairs, internal cavities etc.
Ultrasonic Velocity Testing and Sonic Velocity Testing	Ultrasonic Velocity Testing and Sonic Velocity Testing are both nondestructive methods used to determine the internal construction of walls, voids, damages etc.

3.3.4. In-Situ Testing

In case that the removing of samples for tests in laboratories is not available, then the method of In-Situ Testing is applied. They can provide data on the material properties that cannot be obtained during Nondestructive Laboratory Testing. One application of using this method is the removal of joints, in this case mortar, for inspection of loading services. Some of the methods of in-situ testing are described in the following table [Sen, 2006]:

Table 2. In-situ testing.

Test Method	Use
Borescope	It is inserted into holes in mortar and for identifying the anomalies or other dysfunctions and components of internal walls.
Mortar Evaluation	In order to avoid laboratory testing, this technique makes it able to evaluate properties of mortar by by pendulum rebound hardness, pull-out resistance, drilling resistance etc.
Flatjack Test Method	It is used to evaluate stress and behavior of masonry under uniaxial compression.
In-site Shear Test	Shear strength of masonry is determined and is usually known as ‘push’ test.
In-situ Bond Test	This device can determine the bond strength of the material and so can be detected the out-of plane cracking.

3.3.5. Literature Survey for Material Properties

Considering the fact that the structure being part of cultural and heritage monument, and since it is impossible to conduct any tests, a literature survey is carried out. Material properties are important data for this project, therefore it is important to select the most proper values for assumptions. The values for material properties from some of the previous studies are shown in the table below.

Table 3. Material properties from previous studies.

Proeprties	Mustafaraj	Gedik & Celep	Harsanica&Medic	Ustundag&Cesigur	Beeson, Kubin, Unay
Unit Weight γ(Kn/m^3)	21	20	20	17.658	24
Modulus of Elasticity E (MPa)	1740	2000	3000-5000	2000	450
Void ratio v	0.2	0.2	-	-	-
Tensile Strength(MPa)	1.42	-	-	-	0.135
Compressive Strength(MPa)	4.06	-	5	-	0.9

From the above table, the most suitable material properties are selected for modeling and analysis of Bajrakli Mosque. From those values, those that are more realistic and applicable will be applied to our study. The values are selected considering the factors such as time being built, location, historical era etc. Chapter 5 will provide more details about the chosen values.

3.4. Modeling of Historical Masonry Structures

3.4.1. General Overview

Modeling is a significant phase in the analysis of historical masonry structures. There can be many limitations which may result into difficulties while modeling. The structure may have gone through changes that generally are not documented. Thus, sometimes it may be difficult to identify structural elements from ornamental ones. Considering the availability of the sources, a method of modeling should be selected for defining the state of preservation for the structure to be restored.

The modeling methods are separated in detailed micro-modeling, simplified micro-modeling, and macro-modeling. Each of the modeling methods are described briefly in the following paragraphs. The figure below illustrates how each of the method is considered in modeling [Li and Atamturktur, 2014].

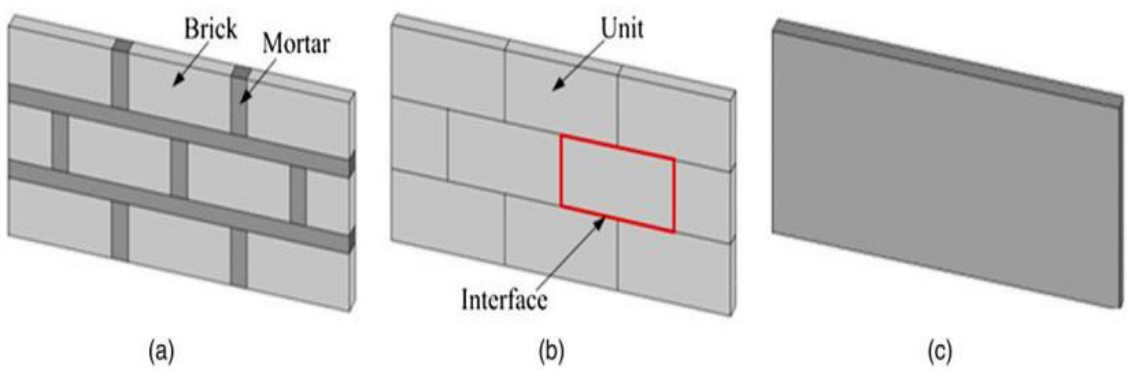


Figure 4. Modeling schemes [Li and Atamturktur, 2014].

3.4.2. Detailed Micro-modeling

For this modeling strategy, inelastic and material properties of units and mortar are taken into account. Both are represented separately and are assigned with different properties individually. It gives the most realistic representation of masonry system. In order to avoid bond-slip failures in this type of modeling; the degrees of freedom of the nodes are coupled at the interface. Since micro-modeling requires for a very detailed mesh, it demands a considerable computational power [Li and Atamturktur, 2014].

Micro-modeling uses elements for masonry, mortar, and masonry mortar interface. The combined action of unit mortar and interface is studied under magnification from the fact that the interface represents a slip plane with initial imitation stiffness to avoid interpretation of continuum. Furthermore, this strategy considers the inelastic properties of the material [Lourenco, 2002].

Note that due to complexity, micro-modeling is not used for the analysis of historical masonry structures and other structures with similar geometrical properties. Therefore in our study, this type of modeling method is not used

3.4.3. Simplified Micro-Modeling

In contrast to the previous modeling, this technique is used for simplifications. In this modeling strategy the units are modeled as continuum elements whereas the mortar joints are lumped into interface elements. In other words, simplified micro-modeling considers the interface of mortar and unit-mortar as elastic blocks [Li and Atamturktur, 2014].

3.4.4. Macro-modeling

The macro-modeling technique is the most used strategy for studying large structures and the effect of global factors. In this strategy, the whole masonry is considered as one continuum element with homogenous material properties, showing elastic behavior. This method is suitable for numerical and for analytical modeling as well, since it does not require detailed modeling into separate discontinuum elements [Abdellatef, 2011].

3.5. Methods of Analysis

3.5.1. Analysis in General

In structural engineering there are different methods of analysis. Each of the methods has differences between each other considering the information and data on the material. Except this, each of the analysis methods has its levels of complexity. They differ from one another according to the input data needed for the analysis to be performed. In this chapter, three methods of analysis and behaviors of structures are going to be discussed, thus outlining the basic information on modeling and analysis of historical masonry building.

3.5.2. Linear Analysis

In order to conduct a linear analysis, elastic properties of the materials and maximum allowable stresses are required before proceeding. With the linear analysis, deformational behavior and stress distribution of the structure are found. This type of analysis has been widely used to analyze historical masonry structures. Linear elastic analysis assumes that the material obeys Hook's Law. By this statement, nonlinear behavior of the material is neglected. In the linear analysis, important information of the structures can be obtained such as stress distribution, and modal information [Sen, 2006].

3.5.3. Nonlinear Analysis

Nonlinear analysis is one of the most complex analyses in structural engineering. Before proceeding with this type of analysis, information such as elastic properties, strength and additional inelastic properties of the materials are required. Nonlinear analysis makes it able to observe the complete response of structures from the elastic state and behavior through cracking up to the complete failure of the structure.

Nonlinear analysis consists of different types which can be combined. The physical analysis involves the nonlinearity of the material; geometric part involves the changes of the points of load application with the increase of actions; contact part involves the addition or removal of supports to the change of contact between bodies with the increase of action. Nonlinear analysis can be used for both, the Ultimate Limit States and Serviceability Limit States [Sen, 2006].

However, even though nonlinear is of great importance for this topic, there are some complexities which may occur. In the conference paper called "Mitigating Seismic Risks in Historical Masonry: An Example Project" by Bal, Smyrou, and Iliki, it is stated that nonlinear analysis in historical masonry structures is "meaningless" in practical engineering applications. The computational power in not satisfactory because a high number of elements may be too high. They also stated that in projects of assessment related to historical masonry structures, there are no rules and guidelines, to outline how to create a FE model and ii) by what means the results of the FE model will be interpreted to clarify the estimated damage [Ilki, *et. al.*, 2015].

CHAPTER 4

MODELING OF BAJRAKLI MOSQUE

4.1. Geometrical Data

Understanding the geometrical data of the main elements composing the structure is the first and essential step in modeling. This section provides a brief overview for the geometrical data of Bajrakli Mosque. The data is based on architectural drawings.

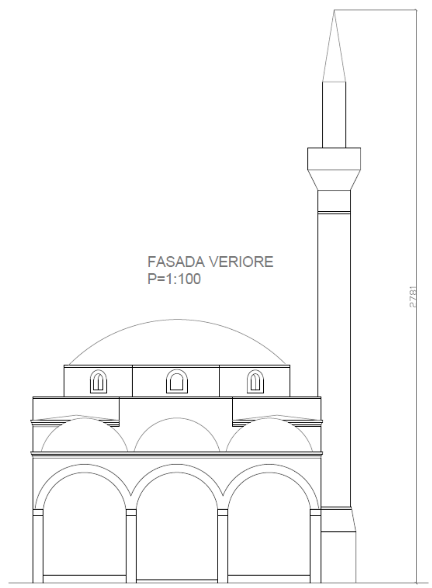


Figure 5. Geometrical drawing [Gorani, 2014].

The ground floor has a total of 18.87 m by 13.95m. From the total area of 263.24 m2, 68.77m2 belong to the entrance hall, while the rest belong to the prayer hall. The prayer hall is covered by the main single dome, while the entrance hall is covered by three small domes. The mosque contains one minaret. In the north façade, there are four marble columns at which the small domes are supported on. The height of minaret reaches about 28m, while the dome reaches about 13m. The drawing at Figure 5 shows the geometrical shapes and elements composing the mosque. The exact dimensions and geometric data can be found at Appendix A.

4.2. Modeling of the structure in SAP 2000

Modeling of structure is one of the most important steps for structural evaluation since it determines the flow of the loads or forces applied. It varies depending on the type of structure, its element content, and its complexity. For this case study, macro-modeling approach is used. Structures such as historical monuments are usually more complex and challenging due to different elements composing the structure

Each part of the structure has its own techniques and its own difficulties, and each of them affects the overall behavior of the building. As stated previously, the Bajrakli Mosque is composed of a big single dome, four semi domes, three small domes, arches, walls and columns. The first and important step in modeling with Sap 2000 is defining the grid system of the structure. This grid should be arranged in accordance to geometrical data representing the mosque. After the grid is built and element sections are defined, modeling of the mosque can start.

Different from usual structures, modeling of the monuments with domes such as mosques should start with modeling of roof system first. The figure 6 shows some finite element models of roof systems from the study “Structural Analysis of Doomed Roof Systems in Architect Sinan’s Works” by Huseyin Bilgin:

Figure 6 is very helpful in understanding the technique to be used for dome system modeling. The major dome of Bajrakli Mosque is built on a hexagonal system as it is shown on the figure 7.

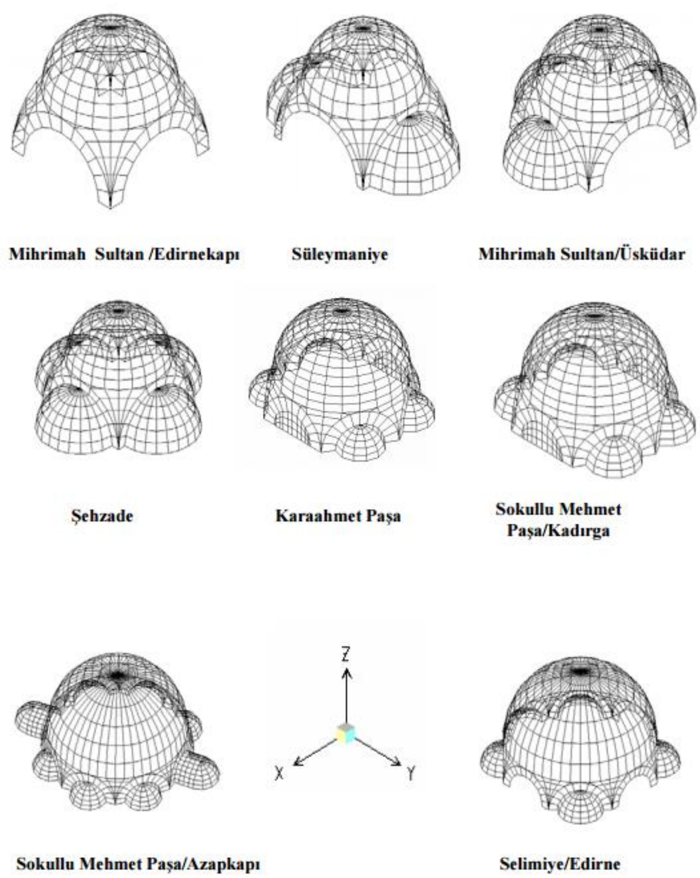


Figure 6. Finite element models of domed roof systems [Bilgin, 2006].

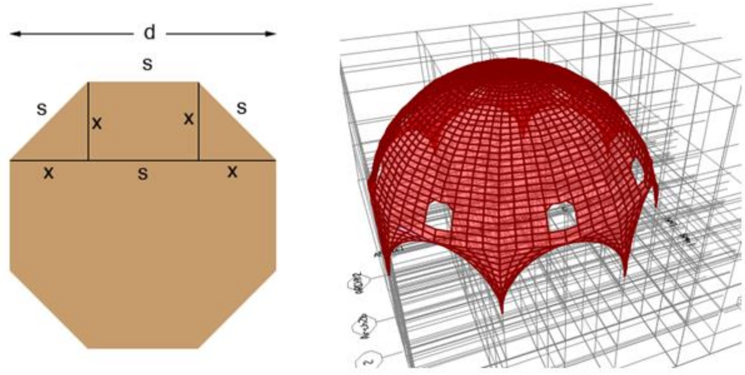


Figure 7. Modeling of main dome.

In the previous figure it is shown the main spherical dome and its pendentive. Pendentive elements are essential in transferring the loads from the main dome to other structural parts. The hexagon shown in the figure helps understand the system the dome is relied on. The letter S shows the diameter of the arches and semi domes. By considering geometrical rules, the grid and dimensions of the elements are defined for modeling of the dome system.

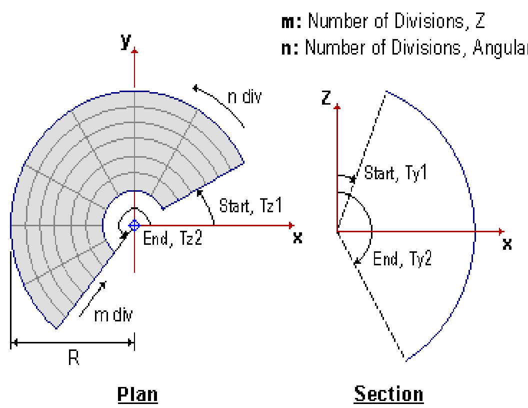


Figure 8. Inputs of modeling semi-domes.

After the main dome is modeled, arches semi domes and pendentives are defined. Semi domes are more challenging then main dome, since it requires understanding the 3d system of the modeling provided by Sap 2000. The figure above shows the mentioned key data that should be defined for semi dome modeling. The first step is to locate the origin according to three dimensional modeling. The origin coordinates should be precise; otherwise it can cause error in load transferring and wrong output data after analysis. Another important step is the number of Z division and number of angular divisions. Those should match with the meshing system created from the main dome and arches. After the roof system is modeled, walls and other elements can be defined. Hinge supports are used for the base of the structure. Figure 9 illustrates the overall Sap 2000 modeling of Bajrakli Mosque:

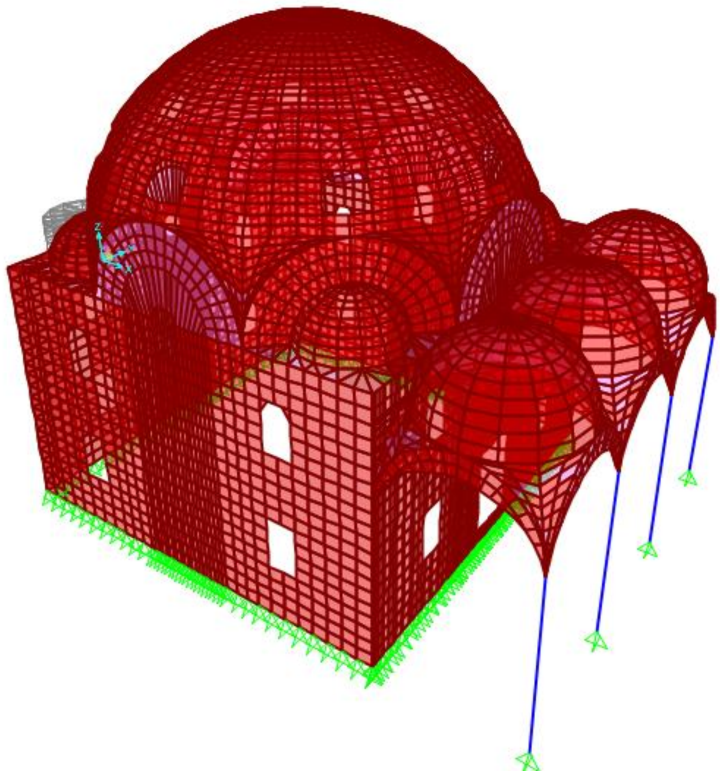


Figure 9. SAP2000 modeling of Bajrakli Mosque.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. Visual Inspections

The first examination of the structure is carried out by visual inspections. It is important to check for deficiencies that can be determined visually. As the geometrical data is obtained, the structure is visited at site and cracks and other irregularities are identified. Thus, from this inspection, some basic conclusions can be made. After the visual inspections, a FEM model is prepared for analysis. Thus, the behavior of the structure is checked to determine the regions with highest stress concentration.

5.1.1. Crack Assessment

It is important to mention that the Bajrakli Mosque has undergone an architectural restoration; no structural reinforcement or structural improvements are made to the mosque. Therefore, because of architectural restorations, the cracks and other deficiencies may be covered by plastering and cannot be identified easily. However, during the site inspections, some of the cracks could be seen.

While checking in the interior of the structure, there are found some cracks in the domes, pendetives and arches. Considering the fact that those cracks can not only be plaster cracks but structural cracks as well, it is important to identify them as structural deficiencies. Cracks may have been development from different factors such as bad maintenance, aging of the materials, weather conditions, improper isolation, moisture, earthquake loads. The following figure show the interior cracks of domes, arches and pendetives.

Figure 10. Crack inspection at domes, arches and pendentives.

Generally, damages in masonry structures occur in the main body of load bearing systems. From site inspections, many cracks can be identified in the load bearing walls of the structure. All of the façades of Bajrakli Mosque suffer from structural cracks. Many of the cracks can be seen close to the edges of the windows, and extending along the walls. Some of the reasons for the cracks developed in load bearing walls are such as, the compressive stress as a result of vertical loads, shear stress as a result of lateral force, tension forces, cracks due to earthquake forces etc. The following picture shows the cracks on the bearing walls of the structure.

Figure 11. Crack inspection at load bearing walls.

5.1.2. High Porosity of Masonry Blocks

Material properties are the basic general parameters in FE modeling of structures. The selected parameters are selected considering the literature survey method from the previous chapter. Some initial information on the material can be also perceived visually. During the site investigations, it is seen that stone masonry blocks used for building the Bajrakli Mosque show high porosity. Figure 12 is a picture taken during site visit.

Figure 12. Stone porosity inspection**.**

Porosity of materials is an important factor affecting the stony masonry. It is one of issues that lead to some property changes in the material. Environmental conditions are one of the causes that cause changes in the masonry block, because of high porosity. The pores present in the masonry may allow amount of water to move through the stone. Thus, such process may cause changes in the durability of stone. With the water moving through the stone, there may be some problems such as frost attack, and/or the transported salt through the pores with moving water.

5.1.2.1. Frost Attack

Frost attack is one of the major agents that cause the eroding of masonry structures. It is a common problem that is caused with the movement of water to the pores. During the low temperatures, the water turns into ice and thus results into an increase in its volume. Thus, with this statement it can be concluded that the increased volume causes an extra stress within the masonry. Besides the frost attack comes from low temperatures, also the rapid freezing and thawing process can lead to a deterioration and erosion of the masonry [Morton, 1990].

5.1.2.2. Soluble Salt in Masonry

Salt content is one of the main agents that causes the decay of porous material is a big concern for preservation of historical buildings. Salt is an element which can be transported by water and can be accumulated in the pores, thus causing damages to the material. Salt’s behavior is unpredictable since they can remain inactive for some time and later they can become active and causing weakening surfaces and natural decaying [Woolfit, 2000].

This process is caused from the wetting and drying cycles of the materials. Since the pores contain water, and thus from the water different salts may be dissolved. When the material is dried out rapidly, it causes the salt to crystalize. The effects are mainly same as the from frost attack, but in this case, instead of causing increased volumes, it is related more with salt crystals. Thus, by the process happening in the pores of the masonry affect the durability of the material [Sowden, 1990].

5.2. Finite Element Analysis

5.2.1. Pre-analysis phase and inputs

The finite element model of Bajrakli Mosque shown in the figure 9 of previous chapter consists of 9690 nodes; 9515 shell elements for the main dome, arches, semi domes and small domes; and 4 frame elements for the columns in the entrance hall. The material properties of the finite element model are assumed as the mortar and masonry units are a single material. Since there was impossible to conduct any test main characteristics are selected based on previous studies and proposed assumptions. The selected characteristics are as in the table below:

Table 4. Selected material properties.

Characteristics	Stone
Unit Weight γ(Kn/m^3)	21 [Mustafaraj, 2012].
Modulus of Elasticity E (MPa)	450 [Beeson *et. al.*, 2014].

The other three characteristics in this study are the allowable compressive, allowable tensile strength, and allowable shear stress. According to those characteristics, the mosque structure is analyzed and checked for drawing final conclusions.

It is also important to note that during earthquake load analysis, no reduction was made to earthquake load, and reduction factor is considered as R=1. As the authors Beeson, Kubin, and Unay stated in their study "Seismic Vulnerability of Structures with Irregular Symmetry", Turkish Earthquake Codes suggest the compressive allowable stress as fall =0.3 Mpa. The authors suggested that those values to be tripled and used as the limits. The below equations are proposed for determining the allowable compressive, tensile stresses, and shear stresses [Beeson *et. al.*, 2014]:

$$f_{m(compressive)} = f_{all} \text{ x } 3 = 0.3 \text{ x } 3 = 0.9 \text{ Mpa} \quad (5.1)$$

While the tensile strength is assumed to be as 15% of the specified allowable compressive stress, and it is defined as the following equation [Beeson *et. al.*, 2014]:

$$f_{m(tensile)} = 0.15 = 0.9 \text{ x } 0.15 = 0.135 \text{ Mpa} \quad (5.2)$$

The limit values for shear stress are defined from the below equation in which τm is wall limit stress, τo is allowable wall failure stress and assumed to be 0.3 MPa, μ is the friction coefficient (assumed to be 0.5) and σ is wall vertical stress, which are summarized in table 5.2[Beeson *et. al.*, 2014]:

$$\tau_m = \tau_o + \mu \cdot \sigma \text{ where } \sigma = f_{m(compressive)} /2 \quad (5.3)$$

And the limit shear stress value for stone in domes, arches and walls is resulted to be"

$$\tau_m = 0.3 + 0.5 \text{ x } (0.9/2) = 0.53 \text{ MPa} \tag{5.4}$$

Table 5. Selected allowable stresses.

Characteristics	Allowable compressive stress	Allowable tensile stress	Allowable shear stress
Stone	0.9 MPa	0.135 MPa	0.53 MPa

The dynamic analysis of Bajrakli Mosque involves the response spectrum which is selected based on Eurocode 8 with 0.25g acceleration, as shown in the figure below.

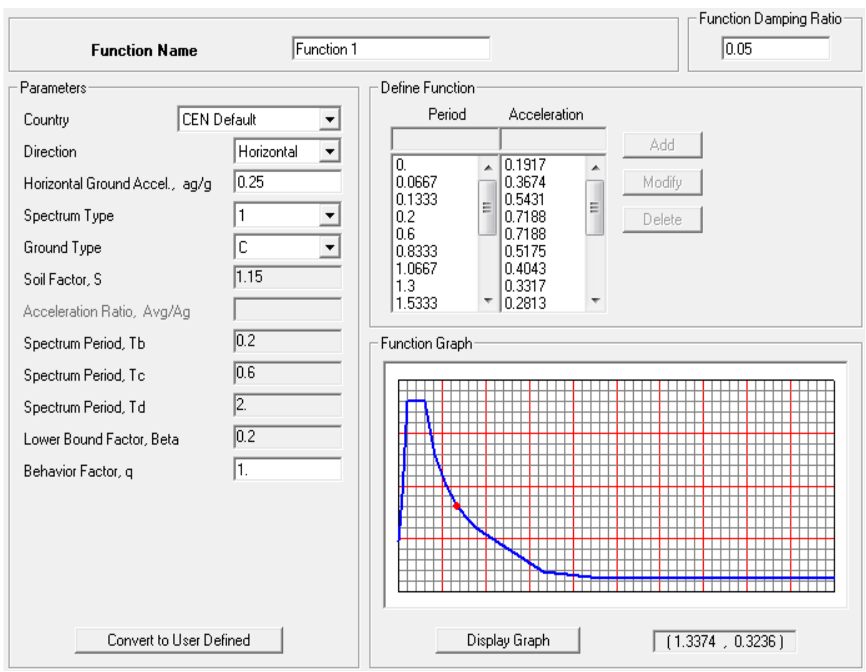


Figure 13. Response Spectrum Inputs.

5.2.2. Modal Eigenvector Analysis of Bajrakli Mosque

For the analysis of Bajrakli Mosque, linear analysis will be performed. Thus, the analysis will provide the data for deformational behavior and stress distribution throughout the structure. The first type of analysis is the eigenvector modal analysis. It will show free vibration mode shapes and through periods and frequencies of the system.

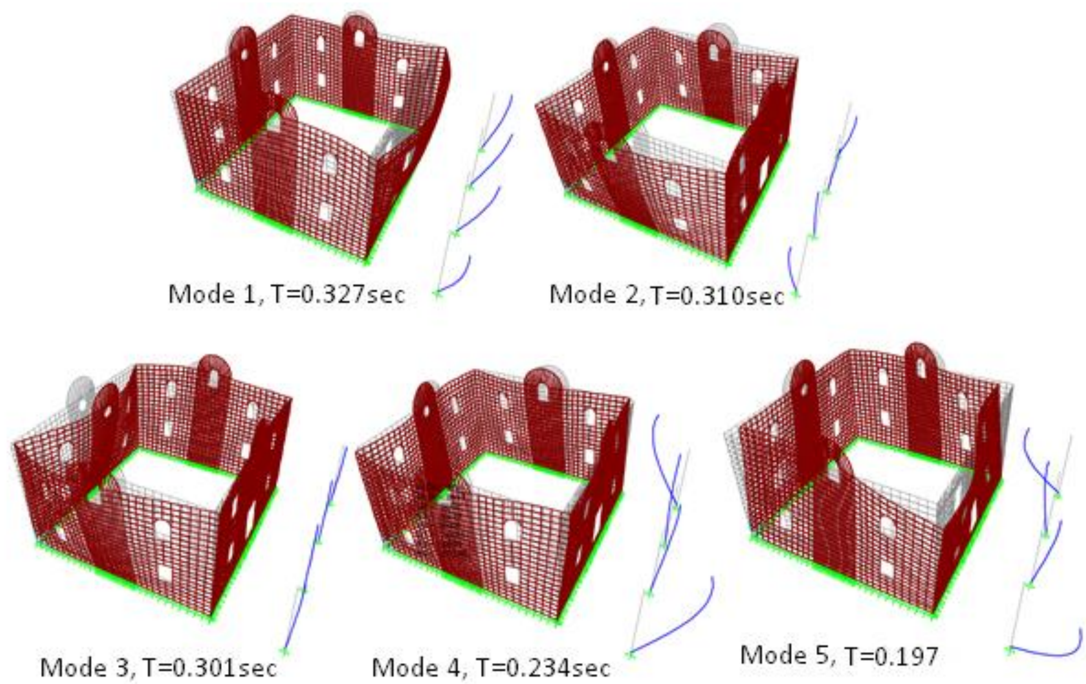


Figure 14. Modal shapes of the structure.

The figure above shows the modal shapes derived from modal eigenvector analysis. In the first mode it can be seen the deformation of the mosque along X lateral direction, with a period of 0.327 sec and a mass participation factor of 0.4067 in X. The second mode shows the deformation of the mosque along Y lateral direction, with a period of 0.310 sec and a mass participation factor of 0.6446 in Y direction. In the third mode, an inside-out of plane deformation of structure can be seen, with a period of 0.301 sec and mass participation factor of 0.2094 in X direction and 0.012 in Y direction. In the fourth mode it is shown the torsional mode shape with a period of 0.234 sec and mass participation factor of 0.048 in Y, while in the fifth mode, it can be seen the breathing deformation mode with period of 0.197 sec and mass participation of 0.0071 in Y. In order to provide a brief summary, a table is provided. All the data for the first five modal shapes of the mosque are presented below.

Table 6. Modal data of the structure.

Mode	Period (sec)	Mass participation x	Mass Participation y	Mass Participation z	Modal Shape
1	0.327	0.4067	0.0003	0.0006	X lateral
2	0.310	0.0011	0.6446	0.0000	Y Lateral
3	0.301	0.2094	0.0012	0.0000	Squeezing
4	0.234	0.0000	0.0048	0.0000	Torsional
5	0.197	0.0000	0.0071	0.0000	Breathing

5.2.3. Analysis under Static and Dynamic Loads Combined

This section discusses about the analysis for shell stresses under static and dynamic loads. Static loads are represented by the dead load or self-weight of the structure, while dynamic loads are represented by earthquake loads. All of the results are highly dependent on the macro-modeling phase of the structure. For the results to be more accurate, two different loading conditions are considered for the linear analysis of Bajrakli Mosque. These loading conditions consist of dead load (self-weight) of the structure and earthquake load defined by the response spectrum function for both directions. The load combinations are as following: G + EQx, and G+EQy for gravity load and earthquake load in x and y direction respectively. The results are compared to the allowable compressive, tensile and shear stresses for the structural elements.

Before checking for stress distribution, displacement is observed through G+EQx and G+EQy earthquake loading conditions separately. The maximum displacement for G+EQx is Δx = 7.1 mm and maximum displacement for G+EQy is Δy = 8.0 mm, as shown in the figure below. As the color becomes darker, the displacement value is higher.

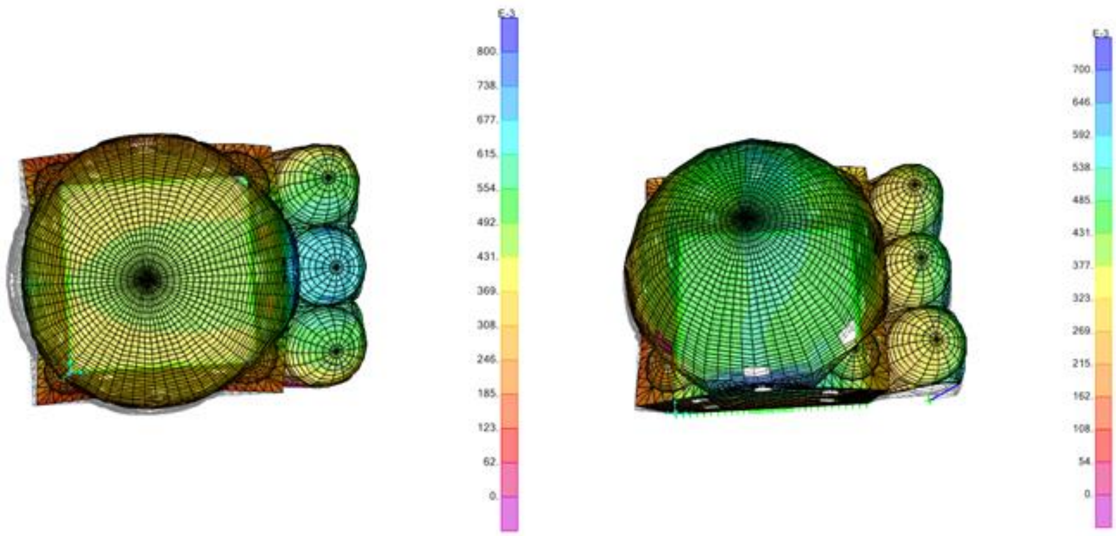


Figure 15. Maximum displacement for G+EQx (left), and G+EQy (right).

In order to show more detailed information and analysis, displacement of the structure is observed through main elements of roof system. Table 7, table 8, and table 9 provide more detailed displacement data for the top of the main dome, the top of small domes, and the top of the main arches of the structure. For each table there is a figure to show the location of the observed values.

Table 7. Displacement values at top of the main dome.

	Displacement in G+EQx (mm)			Displacement in G+EQy (mm)		
Location	Horizontal X	Horizontal y	Vertical Z	Horizontal X	Horizontal y	Vertical Z
Top of the main dome	2.7	0.1	-4.6	0.8	2.3	-4.7

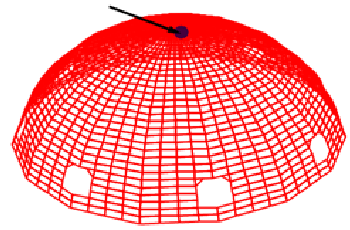


Table 8. Displacement values at top of the small domes.

	Displacement in G+EQx (mm)			Displacement in G+EQy (mm)		
Location	Horizontal X	Horizontal y	Vertical Z	Horizontal X	Horizontal y	Vertical Z
Top of the small dome 1	6.0	0.8	-5.1	4.6	1.8	-4.9
Top of the small dome 2	7.1	0.1	-5.5	4.2	1.8	-5.2
Top of the small dome 3	6.1	0.8	-5.2	4.7	1.9	-4.9

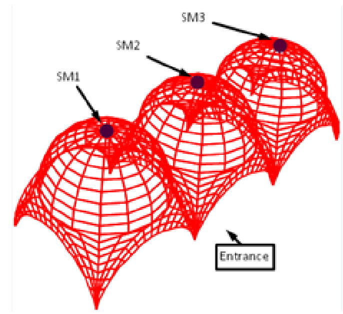
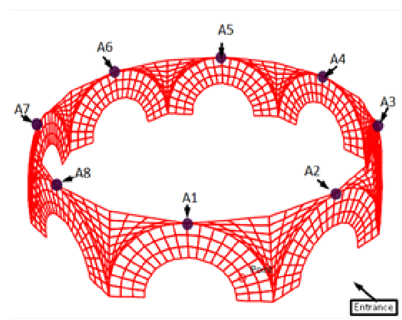


Table 9. Displacement values at top of the main arches.

	Displacement in G+EQx (mm)			Displacement in G+EQy (mm)		
Location	Horizontal X	Horizontal y	Vertical Z	Horizontal X	Horizontal y	Vertical Z
Top of the arch 1	1.5	1.6	-3.5	0.6	2.5	-3.5
Top of the arch 2	5.2	0.0	-2.7	2.1	1.5	-2.6
Top of the arch 3	1.5	1.3	-3.9	0.6	2.3	-3.9
Top of the arch 4	1.4	1.8	-2.2	0.5	3.7	-2.1
Top of the arch 5	2.0	1.1	-3.1	1.4	1.7	-3.1
Top of the arch 6	3.1	0.0	-2.1	0.5	1.1	-2.0
Top of the arch 7	2.0	1.1	-3.0	1.3	1.8	-3.1
Top of the arch 8	1.4	1.6	-2.2	0.4	3.6	-2.2



The seismic behavior of Bajrakli Mosque is explained through S22 vertical stresses which show the tensile and compressive stresses, and S12 shear stresses. The results obtained through G + EQx, and G+ EQy load combination analyses are shown visually and compared to ultimate limits defined previously. The following paragraphs show the results obtained from the analysis of the roofing system and walls separately for each of the loading conditions and shear stresses for tensile, compressive and shear.

The S22 compressive and tensile stresses and S12 shear stresses for the roofing system are given in the figure 16 and figure 17 respectively. The allowable tensile stress for stone masonry fm(tensile) = 0.135 Mpa , is exceeded at the roofing systems with a maximum value of 1.980 Mpa for G + EQx, and 1.794 MPa for G+EQy. Same, the allowable compressive stress for stone masonry fm(compressive) = 0.9 Mpa is exceeded with a value of 3.050 MPa for G + EQx, and 2.979 MPa for G+EQy. Figure 16 shows the S22 stress distribution, in which the darker colors are near or exceed the allowable limits. Note that the range of values (maximum and minimum) is decreased in order to emphasize more the areas of stress concentration. Values are shown in kN/m^2.

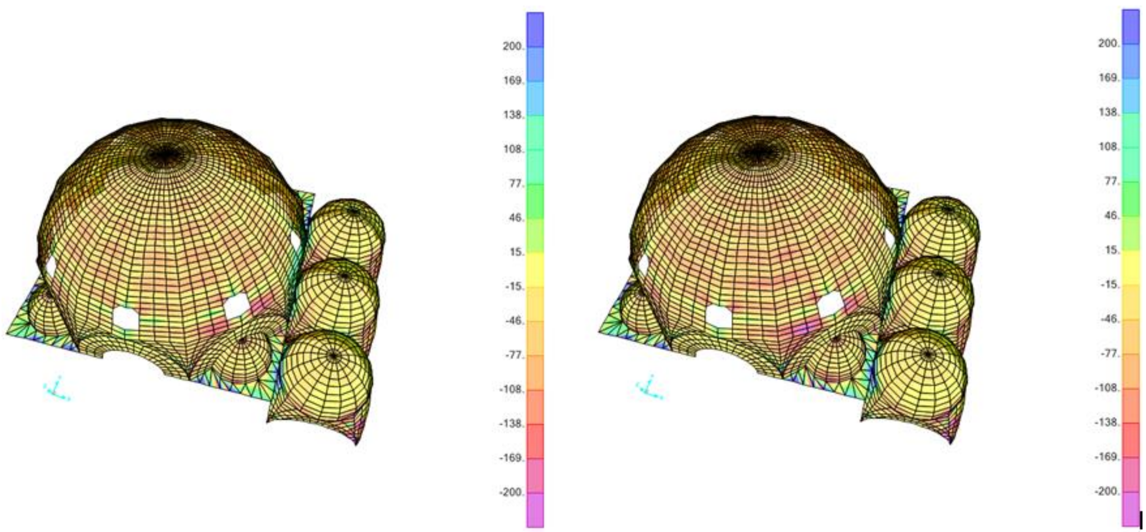


Figure 16. Tensile and compressive stress distributions at roof system for G+EQx (left) and G+EQy(right).

Recalling from previous section, the calculated allowable shear stress for stone masonry is τm = 0.53 MPa. Shear stresses are represented with S12 values defined in the software. In the analysis for the loading conditions as G + EQx, and G+EQy, shear stresses exceed the allowable limit with a maximum value of 0.990 MPa and 1.090 MPa respectively. Shear stress concentration is found to be higher in the pendentives of small domes and in the connections between them. The shear distribution of the structure for both loading combinations is shown at the figure below in which darker values show increase in stress. In order to emphasize more the areas of stress concentration the range of values (maximum and minimum) is decreased. Values are shown in kN/m^2.

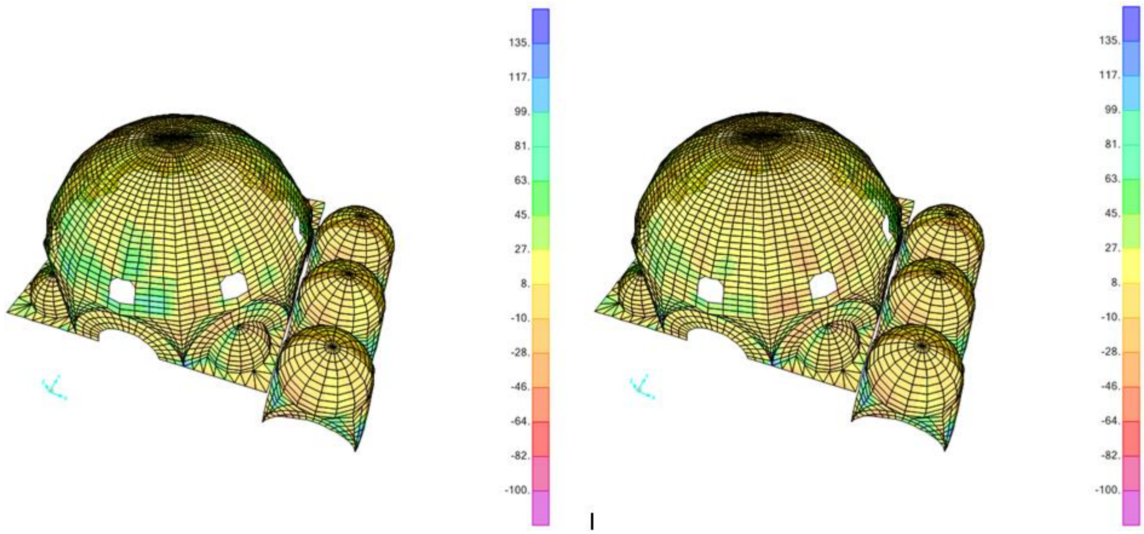


Figure 17. Shear stress distribution at roof system for G+EQx (left) and G+EQy (right).

As the roof system results are received, the same procedure is applied for load bearing wall analysis as well. The outputs obtained by the assessment of the walls using FE analysis show that the tensile stresses derived from S22 stresses exceed the allowable stresses for stone masonry fm(tensile) = 0.135 Mpa with a maximum value 0.254 MPa for load combination in X direction and 0.255 in Y direction. Regarding the compressive stresses, the values derived from S22 do not exceed the allowable compressive stress fm(compressive) = 0.9 Mpa. Maximum value is found to be 0.668 MPa for G + EQx, and 0.747 MPa for G + EQy. Regions with highest stress concentration are found to be near the openings such as windows and door. In the front wall, a high concentration of compressive stresses is shown from the analysis result. This is due to the openings and the connection of with the roof system of entrance hall. The following figure shows the S22 stress distribution for the walls, where the darker colors show increase in stress. Values are shown in kN/m^2

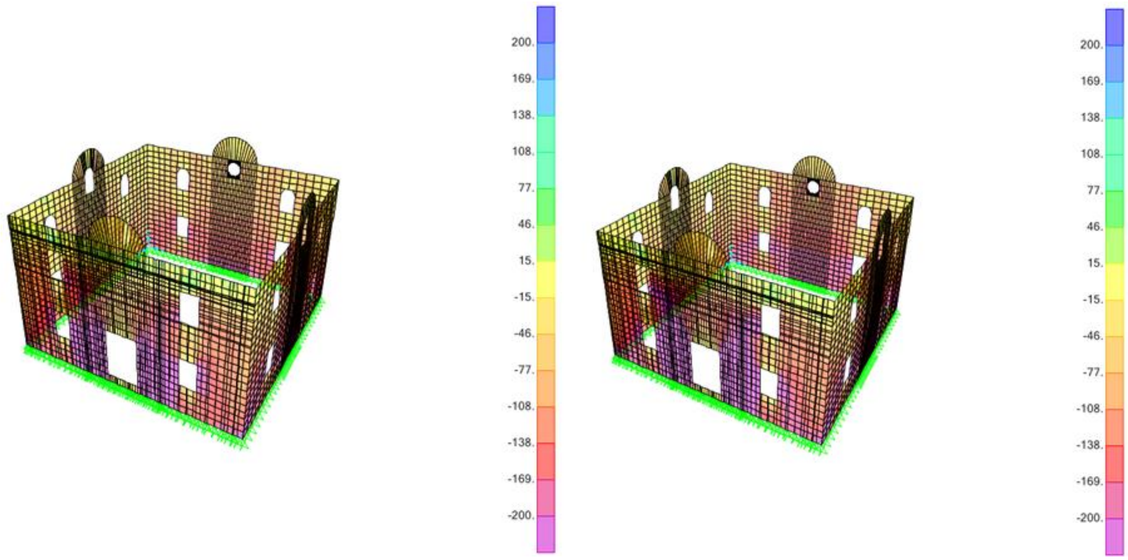


Figure 18. Tensile and compressive stress distribution at load bearing walls for G+EQx (left) and G+EQy(right).

Same as roofing system, walls are analyzed for shear values as well. The S12 values found from the analysis are compared to the limits defined. After the analysis, results show that for both load combinations G + EQx, and G+EQy, S12 values do not exceed the allowable shear stress $\tau m = 0.53$ MPa. The maxim value for shear stresses in G+EQx is 0.311 MPa, while the maximum value for shear stresses for G+EQy is 0.291 MPa. Same as for tensile and compressive stresses, shear stress concentration is found to be higher near the openings of the load bearing walls. By this result it can be stated that openings affect the concentration of the shear stresses of the structure, thus impacting the behavior of the structural elements under loading conditions. In the following figure, the shear stress S12 distribution through the walls is shown (darker colors represent higher values). The range of values is decreased in the figure, in order to emphasize more the stress distribution around the structure.

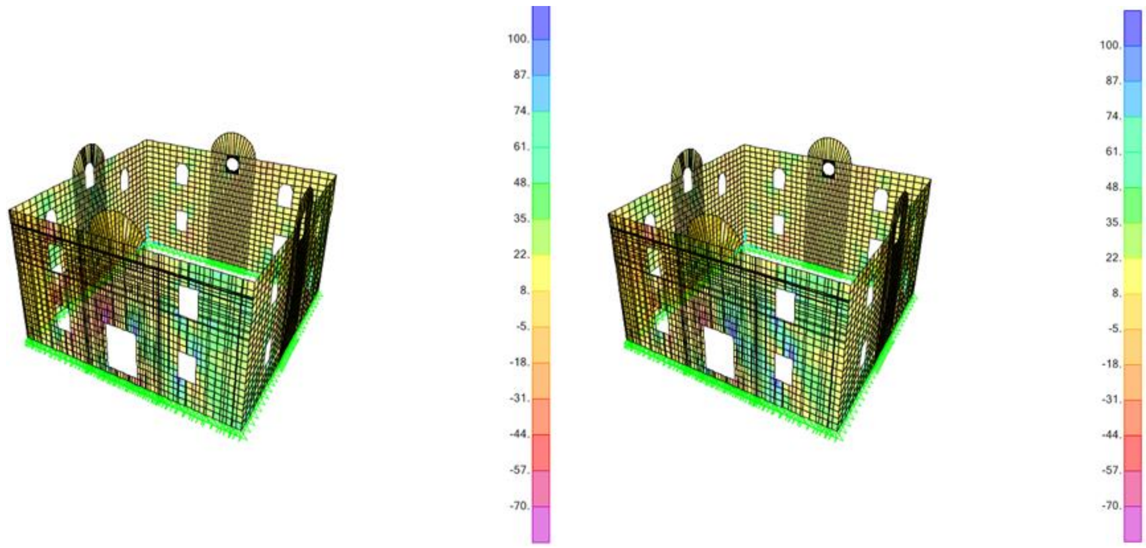


Figure 19. Shear stress distribution at load bearing walls for G+EQx (left) and G+EQy(right).

From all the analysis done to the structure, the location with high stress concentration can be identified. For the roofing system, the highest stress concentration is seen at small domes of the entrance halls, pendentives and arches, and at the opening locations at the major dome. Similar, for the wall system, the highest stress concentration is shown at the openings and at the connections with the arches of the small domes. Table 10 provides all the data regarding the compressive and tensile stresses for top and bottom surfaces for roof system and load bearing walls, under both load combinations as G+EQx, and G+EQy. Table 11 provides all the data for the S12 shear stresses for the roof and load bearing walls for both loading conditions.

Thus, comparing to the cracks observed in section 5.1, it can be stated that the stress analysis match with the actual occurrence of the cracks through the structural elements, as it is shown in figure 20 and figure 21.

Table 10. Maximum values of S22 stress concentration of structure

System	S22 Surface	S22 Stress	G+EQx (MPa)	G+EQy (MPa)
Roof	Top	Tensile	1.758	1.608
		Compressive	-2.980	-2.658
	Bottom	Tensile	1.980	1.794
		Compressive	-3.050	-2.979
Walls	Top	Tensile	0.220	0.233
		Compressive	-0.668	-0.747
	Bottom	Tensile	0.254	0.255
		Compressive	-0.583	-0.617

Table 11. Maximum values of S12 stress concentration of the structure

System	S12 Surface	G+EQx (MPa)	G+EQy (MPa)
Roof	Top	0.982	1.015
	Bottom	0.990	1.091
Walls	Top	0.311	0.291
	Bottom	0.307	0.274

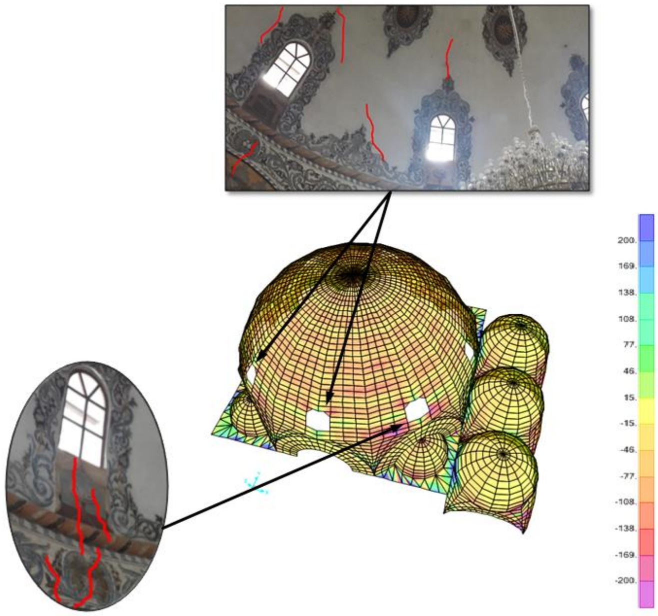


Figure 20. Comparison of visual inspections with finite element analysis for roof system (S22 - G+Eqy)

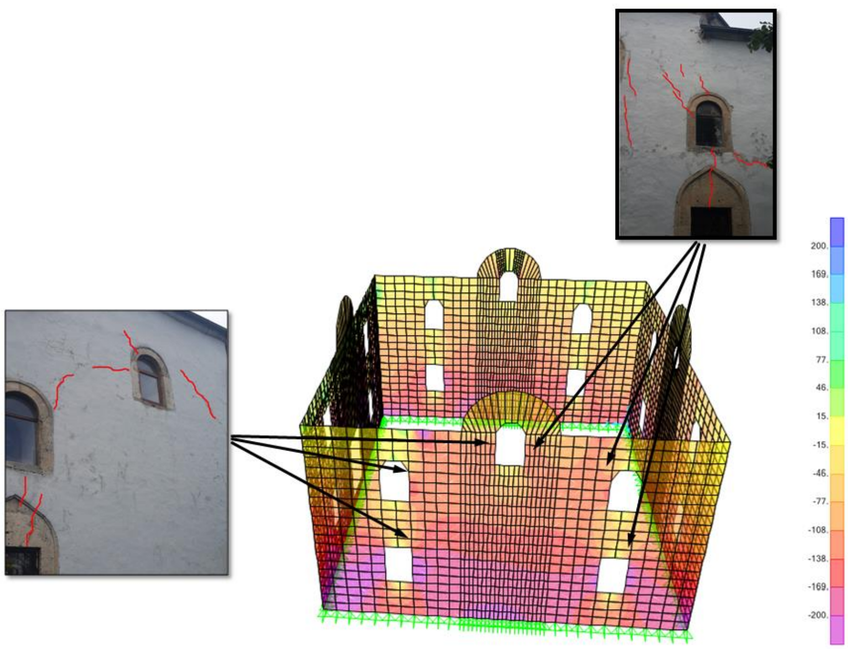


Figure 21.Comparison of visual inspections with finite element analysis for load bearing walls (S22 - G+EQx)

CHAPTER 6

CONCLUSION

6.1. Conclusions of the Study

Due to the importance of historical monuments, this study discusses the structural behavior of historical stone masonry mosque, having the main elements as a representative of the Ottoman mosque, as it is in this case the Bajrakli Mosque in Peja, Kosovo. Such structures emphasize the role and significance of civil engineering in other areas of life. Historical monuments carry important information to historical events, characters, historical development etc. They play a huge role in defining engineering and architectural eras through the history, including the advance of the construction techniques, ornamental models, construction materials and many other related terms. Considering its value in historical phases, construction advances, social and religious importance and the scarcity make this study as a significant and interesting topic.

This study is conducted into two different methods. The first examination of the structure is carried out by visual inspections, and the second method involves FEM analysis. Through visual inspections, cracks and other deficiencies of structure are observed and assessed. Bajrakli Mosque has gone through some architectural restoration, thus not all deficiencies can be seen. However, cracks are found in structural elements such as domes, pendentives, arches and walls, being emphasized in the openings of the structure. Also, though this study, another important property of the stone that affects the performance is identified. The presence of high porosity of the stones may result into high moisture content, frost attack, and creation of soluble salt in stone.

In order to have a better identification of stress concentration, FE model is prepared. Finite Element Model analysis of historical monuments tends to be complex to perform. Some of the geometrical data may be rare or not found at all; material classification is hard and costly; material properties have experienced changes; damages caused through different conditions are unknown. Considering all these statements, modeling of historical stone masonry structures is difficult to be done.

Modeling of Bajrakli Mosque is done based on geometrical data stored by the Institute for Preservation of Historical Monuments. Some of the missing data are substituted and assumed from other studies with similar geometrical properties. For modeling of Bajrakli Mosque, macro-modeling approach is used. Modeling phase is one of the most important phases of FEM analysis, since it determines the flow of loads for the applied loads. In other words, the results are dependent from the modeling of the structure. Different from other structures, mosques with geometrical shape as Bajrakli Mosque should be modeled starting from the roof system. Shell element mesh should be properly defined, so the flow through each element of the structure is correctly assured.

The FE model prepared by SAP2000 involved assumed material properties due to inability to conduct tests. The maximum displacement obtained from the analysis shows value of 7.1 mm for G+EQx and 8.0 mm for G+EQy.

The results of the stresses in the roof system exceed the allowable limits defined in the study. The allowable tensile stress for stone masonry is exceeded at the roofing systems with a maximum value of 1.980 Mpa for G + EQx, while compressive stress limit is exceeded with a maximum value of of 3.050 MPa for G + EQx. Furthermore shear stresses exceed the allowable limit with a maximum value of 1.090 MPa for G+EQy in the roof system. At the load bearing walls, only allowable tensile stress is exceeded with a value of 0.255 MPa for load combinations in Y direction The results provided by finite element analysis match with the findings from visual inspections.

6.2. Recommendation for Further Studies

Considering that this study was done based on material properties assumed through different researches and studies, the analysis of Bajrakli Mosque can be done using actual data which can be found by different laboratory tests and experiments.

In addition, after all data and tests are gathered including foundation and soil properties, nonlinear analysis can be performed for similar structural monuments.

Considering the fact that Kosovo is missing studies on this area, typological classification of cultural structures can be done.

REFERENCES

Lourenco PB., ‘Guidelines for the Analysis of Historical Masonry Structures’. In: Hendriks MAN., Rots JG., ed. Finite Element in Civil Engineering Applications. Tokyo: AA Balkema Publishers, p. 241-249 (2002).

Guney D., ‘Seismic vulnerability of historic and monumental structures and centers’. Causevic A. Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures. Pennsylvania: Igi Global, p. 146-212 (2015).

Hendry AW., Sinha B., Davies, SR., ‘Design of Masonry Structures’. Bricks Blocks and Mortars. London: Spon, p. 22-50 (2004).

http://dtk.rks-gov.net/tkk_objekti_en.aspx?id=1319 (lastly visited on 21 July 2016).

Modena C., Casarin F., da Porto F., Garbin E., Mazzon N., Panizza M., ‘Structural Interventions on Historical Masonry Buildings’, Review of Eurocode 8 Provisions In the Light of Italian Experience’, Napoli: p. 1-20 (2009).

Gulkan P., Wasti, ST., ‘Seismic Assessment and Rehabilitation of Historic Buildings’, Structural Longevity Jounral. Str Tech Science Press’, p. 111-130 (2009).

Gedik Y H., Celep Z., (2008)., ‘Structural Modeling and Seismic Performance Analysis of Mehmet Aga Mosque in Istanbul’, 8th International Conference on Advances in Civil Engineering. Cyprus, p31-39 (2008).

Portioli F., Mammana O., Landolfo R., Mazzolani FM., ‘Seismic Assessment of Historical Mosques under Exceptional Earthquakes: A case study in Skopje’, Urban Habitat Constructions Under Catastrophic Events: Proceedings of the COST C26 Action Final Conference. Naples: p. 415-420 (2010).

Aydin AC., ‘Restoration of Historical Structures: Material and Structural Point of View’, 1st International Conference on Sustainable Built Environment Infrastructures in Developing Countries, Algeria: p. 325-336 (2009).

Guh TJ., Altoontash A., ‘Seismic Retrofit of Historic Building Structures’, Proceedings of the 8th U.S. National Conference on Earthquake Engineering. San Francisco: paper no. 1565 (2006).

Ustundag C., Sesigur H., Cili F., ‘Seismic Evaluation and Retrofit of the 16th Century Mihrimah Sultan Mosque’, 14th European Conference on Earthquake Engineering. Ohrid: 14WCEE, p. 308-314 (2010).

Guler K., Saglamer A., Celep Z., Pakdamar F., ‘Structural and Earthquake Response Analysis of the Little Hagia Sophia Mosque’, 13th World Conference on Earthquake Engineering. Vancouver: 13WCEE, no. 2652 (2004).

Temel ON., ‘Earthquake Effects on Historical Masonry Buildings in Uskudar’, Bogazici University: p. 25-53 (2006).

Vasseghi A., Eshghi S., Nateghi F., Jabbarzadeh MJ., ‘Seismic Vulnerability Analysis of the Historic Sultaniya Dome’, 13 World Conference on Earthquake Engineering. Vancouver: 13WCEE, no. 1309 (2004). .

Sen, B., ‘Modeling and Analysis of the Historical Masonry Structures’, Bogazici University: p. 4-25 (2006).

Lourenco, PB., ‘Computations on Historic Masonry Structures’. Progress in Structural Engineering and Materials, 4 (3): p. 301-3019 (2002).

Ayala DD., Speranza E. ‘An Integrated Procedure for the Assessment of Seismic Vulnerability of Hisotric Buildings’, 12th European Conference on Earthquake Engineering. London: 12ECEE, no. 561 (2002).

Mustafaraj E., ‘A Case Study on Structural Assessment of Otoman Mosques in Albania’, Tirana: Epoka University, p. 28-49 (2012).

Harsanica M., Medic S. ‘Seismic Strenthening of Historical Stone Masonry Structures in Bosnia Herzegovina’, 15th World Conference on Earthquake Engineering. Lisbon: 15WCEE, no. 2141 (2012).

Li T., Atamturktur S., ‘Fidelity and Robustness of Detailed Micro modeling, Simplified Micro modeling, and Macro modeling Techniques for a Masonry Dome’, Journal of Performance of Constructed Facilities, 28 (3): (2014).

Abdellatef, MI. ‘The Development of a Simplified Modeling Technique for the Infinite Element Analysis of Reinforced Masonry Shear Walls’, Washington: Washington State University, p. 10-13 (2011).

Bal IE., Ilki A., Smyrou E., ‘Mitigating Seismic Risks in Historical Masonry: An Example Project’, 2nd ATC & SEI Conference on Improving the Seismic Performance of Existing Building. San Francisco: (2015).

Keypour H., Fahjan YM., Bayraktar A. ‘Analysis and Strengthening Methods for Historical Masonry Structures’, 5th International Conference on Seismology and Earthquake Engineering, p. 1-8 (2007).

Morton J., ‘Deterioration of Materials’, In: Sowden AM., The Maintenance of Brick and Stone Masonry Structures. London: E&FN Spoon, p. 119-137 (1990).

http://www.buildingconservation.com/articles/salts/salts_masonry.htm. (lastly visited on 18 December 2016).

http://ozoutback.com.au/Kosovo/peja/slides/2009062921.html (lastly visited on 15 December 2016).

Gorani A., ‘Geometrical Drawing’, Instituti per Mbrojtjen e Monumenteve. Peja: (2016)

Bilgin H., ‘Structural Analysis of Domed Roof Systems in Architect Sinan’s Works’, Journal of Engineering Science and Technology. Selcuk University, p. 119-128 (2006)

Beeson ST., Kubin J., Unay AI., ‘Seismic Vulnerability of Historical Masonry Structures’, Gradevinar. 67 (2): p.151-158 (2014).

CSI, ‘SAP2000 Linear and Nonlinear Static and Dynamic Analysis and Design of Three-Dimensional Structures’, Computers and Structures, (2012)

APPENDIX A

GEOMETRICAL DATA OF THE STRUCTURE

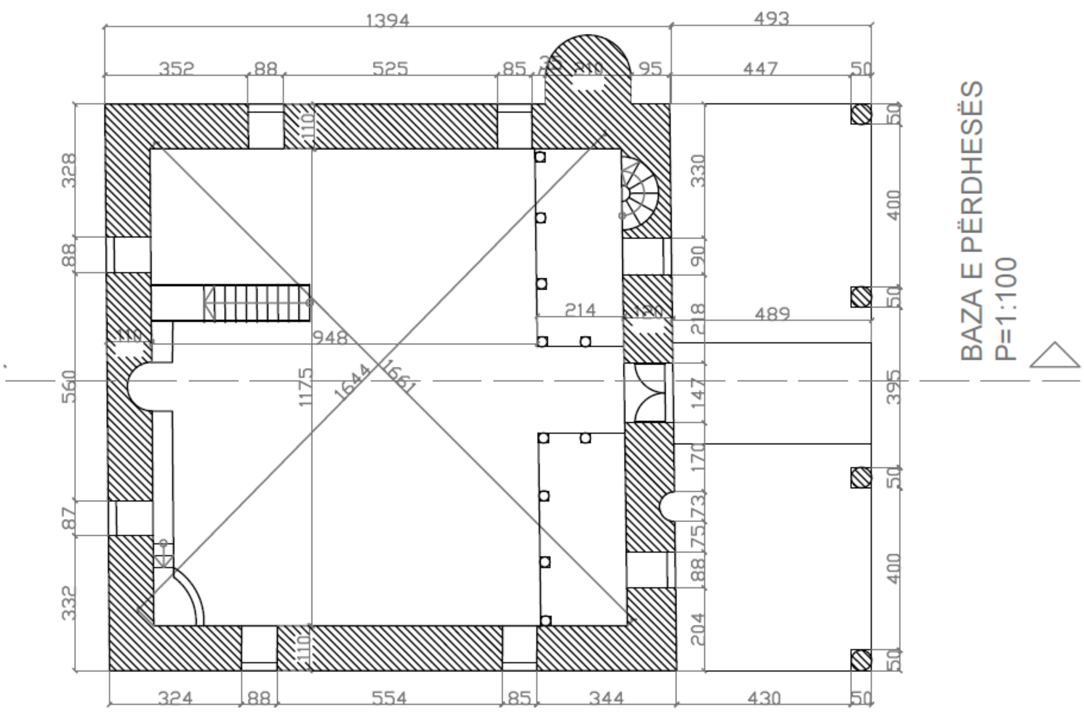


Figure 22. Ground floor drawing [Gorani,2016].

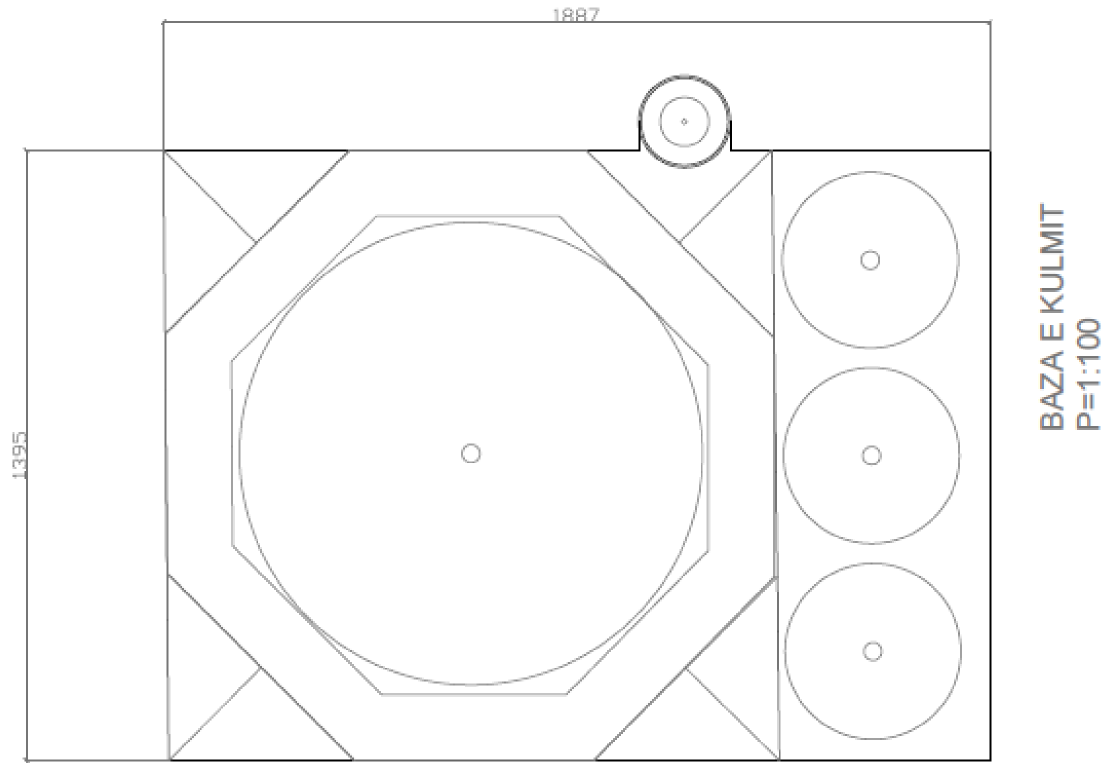


Figure 23. Roof base [Gorani, 2016].

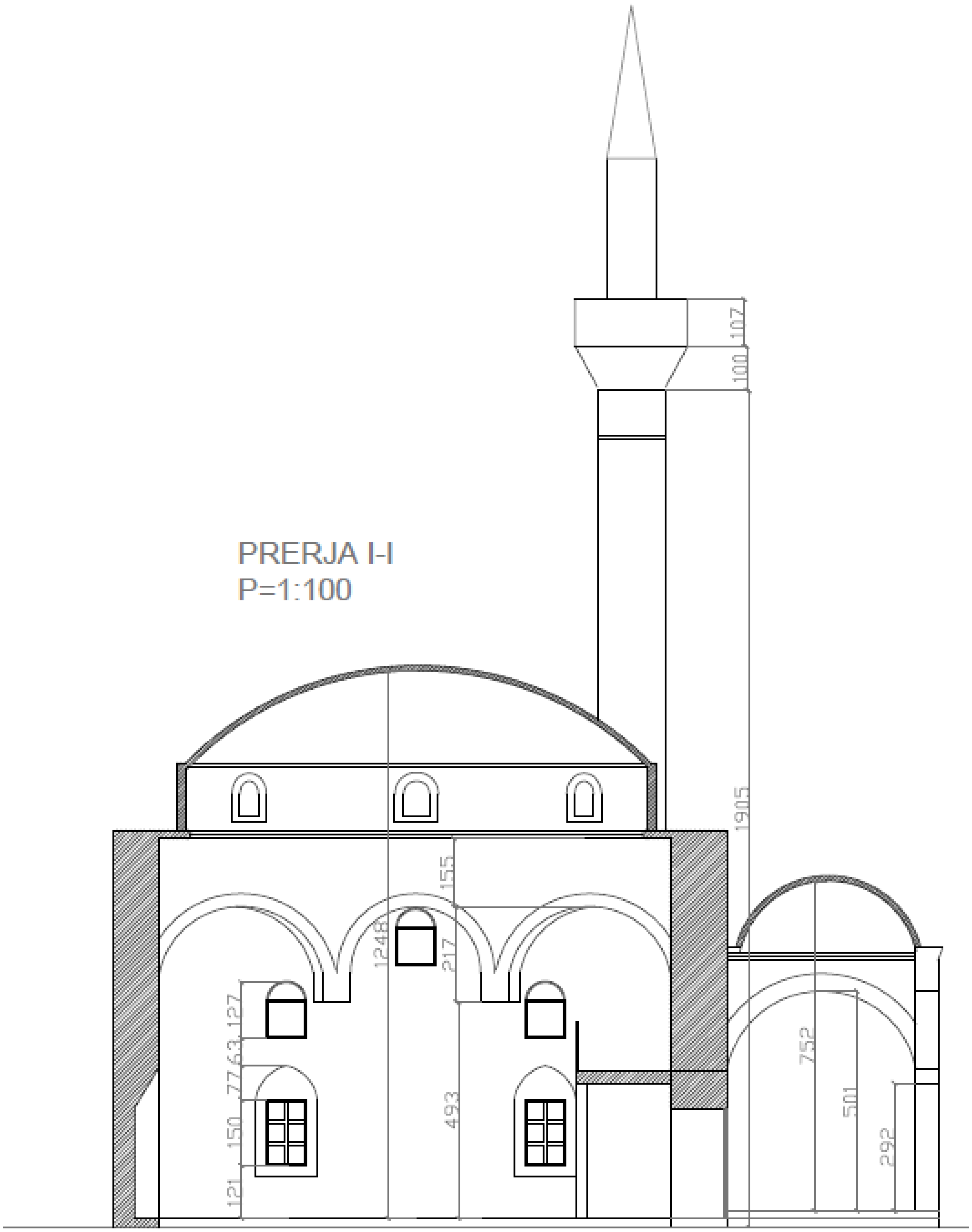


Figure 24. East façade [Gorani, 2016].

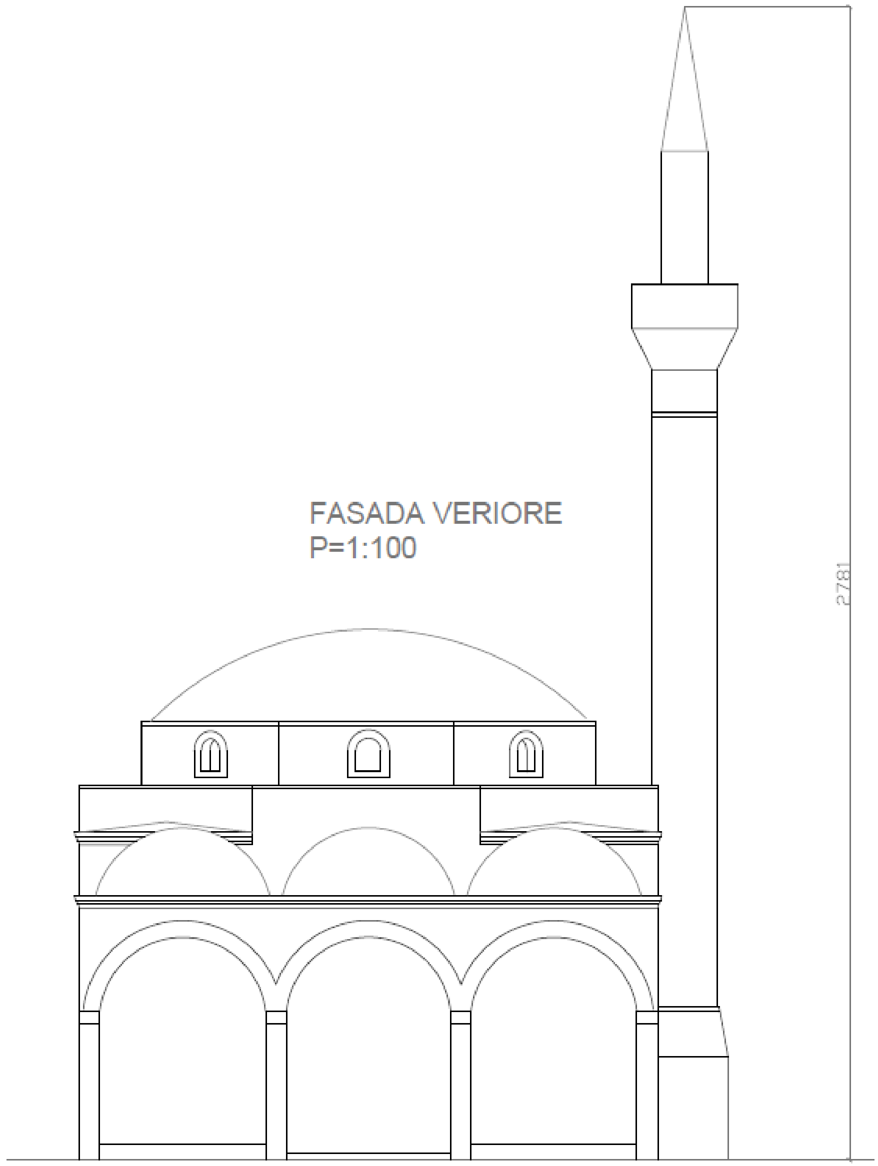


Figure 25. North façade [Gorani, 2016]

APPENDIX B

MODAL INFORMATION

Table 12. Modal periods and frequencies.

Mode	Period	Frequency	CircFreq	Eigenvalue
Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
1	0.327148	3.0567	19.206	368.87
2	0.310059	3.2252	20.264	410.65
3	0.301057	3.3216	20.87	435.57
4	0.233979	4.2739	26.854	721.12
5	0.197254	5.0696	31.853	1014.6
6	0.181746	5.5022	34.571	1195.2
7	0.169786	5.8898	37.006	1369.5
8	0.159357	6.2752	39.428	1554.6
9	0.157694	6.3414	39.844	1587.6
10	0.15736	6.3548	39.929	1594.3
11	0.146861	6.8091	42.783	1830.4
12	0.144102	6.9395	43.602	1901.2

Table 13. Mass participation factors.

StepNum	Period	UX	UY	UZ
Unitless	Sec	Unitless	Unitless	Unitless
1	0.327148	0.40669	0.00027	0.00062
2	0.310059	0.00109	0.64456	1.107E-07
3	0.301057	0.20936	0.00122	0.00003906
4	0.233979	0.00003092	0.00484	4.072E-07
5	0.197254	3.385E-07	0.00714	0.000000275
6	0.181746	0.00709	0.00001407	0.01772
7	0.169786	0.02653	0.00001405	0.00273
8	0.159357	0.00000048	0.06174	0.0000224
9	0.157694	0.00486	0.00137	0.02617
10	0.15736	0.00052	0.0121	0.00209
11	0.146861	0.0449700	0.0000037	0.0023000
12	0.144102	0.0000001	0.0039000	0.0000004