Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Earthquake Analysis of Historical Church of St. Sergius and Bacchus, Istanbul-Turkey

Ali Koçak
Yildiz Technical University, Department of Civil Engineering, Istanbul, Turkey

A. Gökhan Demir
İstanbul, Turkey

ABSTRACT: Conservation and preservation of the historical buildings are the common heritage of the human beings. There are a considerable number of massive historical structures in Turkey and they are mostly located in the earthquake zones throughout the country. Some of these buildings were severely damaged during the destructive recent earthquakes. Earthquake resistance analysis of such structures is a contemporary subject and has become a very important issue in the recent years. As every historical building is unique and being built by different materials and has different structural behavior it is vitally important that each structure should be examined and analyzed individually. In this research, the oldest historical structure in Istanbul, "The Church of St Sergius and Bacchus" is analyzed as a case study. This study includes a survey of the original design of the building, destructive and non-destructive material tests, soil tests and finite element analysis due to vertical and earthquake loads.

1 INTRODUCTION

1.1 Basic Information

Before any conservation, preservation or restoration process for any historical building or any monument, it is of great importance to obtain all the relevant data about the structure. It is essential to know the load bearing mechanisms of these buildings that have endured various battles, fires, earthquakes and natural disasters in order to understand the characteristics and strength of the materials used during their construction. Such approach in preservation activities would prevent the deterioration of the building from architectural, historical and artistic meaning point of views.

Historical buildings have been examined architectural, historical, material and structural system point of views by various researches over the years. Many of these methods and results have varied considerably from each other. Many of these analyses are based on the material examinations or modeling the infilling walls or the structure of the building.

Among these researches; Ahunbay and et al. (1997), Erdik and et al. (1990), Cakmak and et al. (1992), Durukal (1992), Erdik and Durukal (1993) have determined the characteristic resistance of the materials and the attributes of the mortar used as well as the peripheral vibrations of the St. Sophia in Istanbul were determined. In this research first a survey of the original design of the building was made and the location and the sizes of the present cracks were determined. Then the building was modeled by Finite Element Method (FEM) in order to perform the linear and non-linear analyses. Bozinovski and Velkov (1993) worked on two historical, buildings built of stone, namely the church of St. Sophia and Sponza Palace which are located in Ohrid-Macedonia and Dubrovnik, respectively. The researches included laboratory works and on site testing of materials, as well as various studies on the structural models of the buildings. Karaveziroglu and et al. (1997) carried out a set of experiments in order to determine the brick and lime quality of historical buildings and the effect of brickwork upon deformation and strength. Pichard (1976) reported the repair and maintenance of a temple at Pagan Plateau in Burma centre and Chinese Pagodas which were damaged during the earthquake on July 8th, 1975. Gavrilovic (1993) carried out works on methodology, methods and techniques for repair and strengthening of historical monuments taking as case studies; the repair of historical monuments of Budya, fortification and the repair of Kursunlu Han in Uskup and the Abbey of St. Pantelemon in Uskup Nerezi which were all damaged during the earthquake of Montenegro in 1979. Di Pasquale (1988) worked on the dome of Santa Maria Del Fiore Cathedral according to the characteristics and the material behavior of stone built walls. The dome was modeled by FEM and the results were examined. Lourenco and et al. (1997), Lourenco and Rots (1997) and Lourenco and et al. (2002) worked theoretically and experimentally on the walls used in massive constructions. In the theoretical studies the walls were modeled by FEM and non linear analysis was realized. Researches of Mathews (1971), Eyice (1978) and Mainstone (1988) on St. Sophia and St. Sergius and Bacchus, includes explanatory reports concerning the writings on their walls, their architectural plans and the sizes of the buildings.

1.2 The Church of St. Sergius and Bacchus

In this study, The Church of St. Sergius and Bacchus, which was built during 527-536 AD in times of Justinian Regina, is examined. The building was constructed as a massive construction and is the oldest Byzantine building in Istanbul and still in use. The building is modeled by Finite Element Method whilst its characteristic features, material resistance and the ground conditions are taken into consideration. It is located 20 meters away from the city ramparts. The church has an irregular, rectangular plan with the narthex on the west and a semi hexagonal abscissa on the east. Placed within this rectangle there is an octagonal central space which is extended with semi circular niches called exedra on the edges. On the edges of the central space, between polygonal piers, two columns are placed in order to provide integrity between the central space and the abscissas. Corridors that provide transition from the central space to the rectangular form of the building affix the narthex to the abscissa.

Upon the central space there is a 16 foiled dome which 8 of them are cylindrical on 8 big piers and the other 8 of them are elliptical paraboloid. The corridors are covered with vaults, forming the upper gallery. On the gallery floor, the upper sections of the exedras are elapsed on semi domes that are carried by three arches. There is no load transmission between the semi domes and the octagonal cortes.

Stretching on the east-west direction, the distance between abscissa and the outer walls is 44 meters. On the north-south direction, the width is 28 meters. The dome is 30.69 meters high from the sea level. The diameter of the dome is 16.5 meters on the east-west and 16 meters on the north-south directions. (Ozsen and et al. 1995). The outer view and the plan of the building are given in Fig.s 1 and 2 respectively.

1.3 The Material Characteristics of St. Sergius and Bacchus

The materials used for the bearing elements of St. Sergius and Bacchus are mainly brick, stone and mortar. On the outer walls bricks that are bind together with mortar of 4-5 cm. thickness are reinforced with wide apart stone rows. Physical and mechanical characteristics of the materials in the piers, in the inner and outer walls during the summer and the winter seasons were determined by destructive (core) and non destructive (ultra sound, Schmidt hammer) tests. A correlation is formed between the destructive and non destructive compression tests (Akoz and Yüzer 1995).

Figure 1 : Outer view of the St Sergius and Bacchus Building.

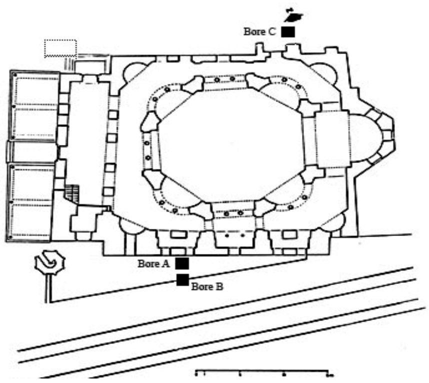


Figure 2 : Plan of the St Sergius and Bacchus Building.

Sound transmission velocity (V) and surface hardness (R_{min}) of the wall elements are given bellow.

For brick, $f_{teo}= e^{1.698+0.006(R*V)}$ (R=0.956)
For mortar, $f_{teo}=e^{0.925+0.013(R+V)}$ (R=0.973)
For stones $f_{teo}=e^{1.778+0.005(R*V)}$ (R=0.921)

Utilizing these correlations and the results of the non destructive tests (R_{min}, V) the compression strength (f_{teo}) of the areas are derived. The elasticity modules of the materials were determined by $E=10^5V^2\beta(1/9.81)$. The mechanical properties of the materials used are determined by these data are presented in Table 1.

Table 1 : The mechanical properties of the materials.

Material	Winter		Summer	
	E (N/mm^2)	f_{teo} (N/mm^2)	E (N/mm^2)	f_{teo} (N/mm^2)
Brick	9029	11.89	8605	11.77
Mortar	8860	5.24	7948	5.21
Limestone with fossil shells	13727	8.31	15699	8.85
Travertine	55462	28.44	55332	31.15
Limestone with clay	14923	10.92	17233	11.77

1.4 The soil conditions of St. Sergius and Bacchus

Soil conditions were determined by bore holes and exploratory wells dug around the building shown in Fig. 2. Geotechnical data show that the soil where the church is located and the surrounding area are on a layer of clay and marl from the early Pliocene Age. In other words, the soil is thin in size and cohesive.

The 2.0 m deep exploratory well, labeled Bore C in Fig. 2, were dug at the bottom of the south over looking wall around the minaret, showed that the ground was covered with infill soil all up to the surface. However this infill soil has two different levels. On the surface zone and 75-90 cm below the surface is a combination of new infill soil and vegetal soil. In the infill soil pieces of bricks are also present. The second level at the bottom, stretched down to the bottom of the exploratory well (2.0 m), was filled with old infill. Within old infill plant roots were rarely observed. However, 20-30% was made up of pale grey limestone pebbles surrounded by clay marl lithology. Also within this layer coal, glass and vase particles were also observed. The other two bores labeled B and A was dug deeper up to the depth of 2.07 m. Observation of the Bore Hole C can be seen in Fig. 3.

The layers in the second exploratory well, shown in Fig. 4, show almost the same properties as the other exploratory well. The second exploratory well which is 2.0 meters deep, showed that up to 60-90 cm below the surface, the ground was a mixture of new infill plus vegetal soil, silt, sand, pebble, tile and human skeleton particles. Below this zone lies the old infill layer made up of clay, sand and pebble particles.

With the bore holes and the exploratory wells, information about the soil conditions were obtained as deep as 4.25 meters starting from the mausoleum side and 3.70 meters starting from the railway side to the upper height of the mosque's floor level.

Observations through the exploratory wells and bore tests, as can be seen from the logs of the exploratory wells, showed that infill soils are present along the depth examined. The penetration numbers shown in the exploratory well logs in Fig. 5, represent the amount that the test baton sinks down into the ground after 10 strokes.

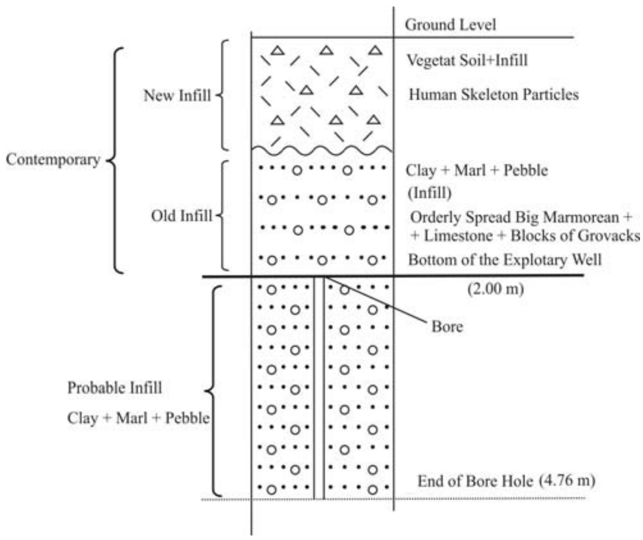


Figure 3 : Section through the exploratory well no 1.

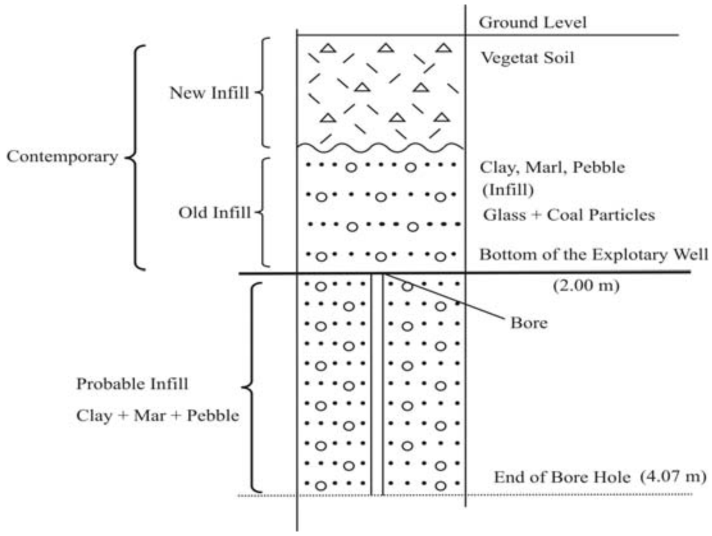


Figure 4 : Section through the exploratory well no 2.

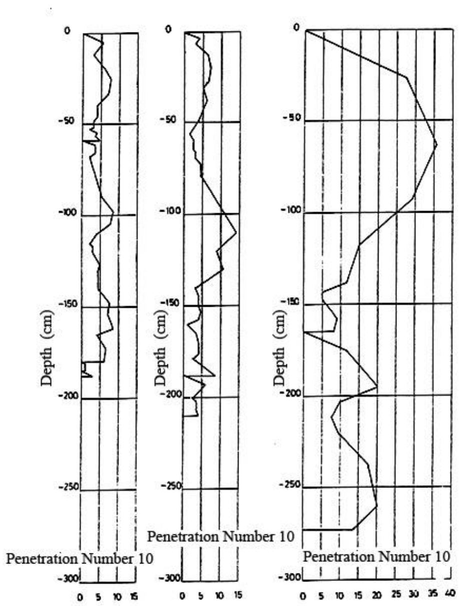


Figure 5 : Penetration values obtained from the exploratory wells.

2 FREE VIBRATION ANALYSIS OF THE CHURCH OF ST. SERGIUS AND BACCHUS

To define the actual the structure of The Church of St. Sergius and Bacchus, a set of free vibration measurements were made. These were carried out on the gallery floor and at the dome ring. (Fig. 6). Free vibration measurements were taken by a seismometer, signal conditioner, analogue- digital converter and a laptop computer.

Figure 6 : Free vibration measurements of the Church of St. Sergius and Bacchus (Readings at the gallery floor).

During the tests, the vibrations of the structure were determined with a seismometer connected to a signal controller, hence, the analog signals received from this mechanism are digitilized with a digital converter loaded to the laptop and finally the data are directly recorded to the magnetic media. The modal vibrations of the structure are determined with the help of these vibration records. As a result, the three frequency values measured are 4.47 Hz, 5.15 Hz and 5.65 Hz.

3 MODELING AND ANALYSIS OF THE CHURCH OF ST. SERGIUS AND BACCHUS

3.1 Finite Element modeling of the building

After the building's measured survey of the original design drawings were prepared and cracks in the building are determined, the structure is modeled by Finite Element Method. (Fig. 7). Except modeling the circular columns, triangular and rectangular solid elements were used. Bar elements were used for columns. Made up of approximately 5630 elements, the model has 4000 triangular and 1600 quadrangular solid elements as well as 30 bar elements. There are total of 28012 nods in the modeling. All the piers, arches, domes and walls are represented with prismatic elements as far as the material and behavioral characteristics are considered.

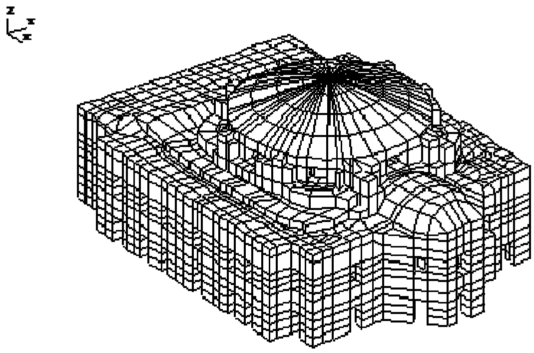


Figure 7 : Finite element modeling of the building.

With this modeling under self and external loads the free vibrations of the building is analyzed and the modes and the periods are determined (Lusas, V.11). These can be seen in Fig. 8 (Fig. 8 a, b, c and d).

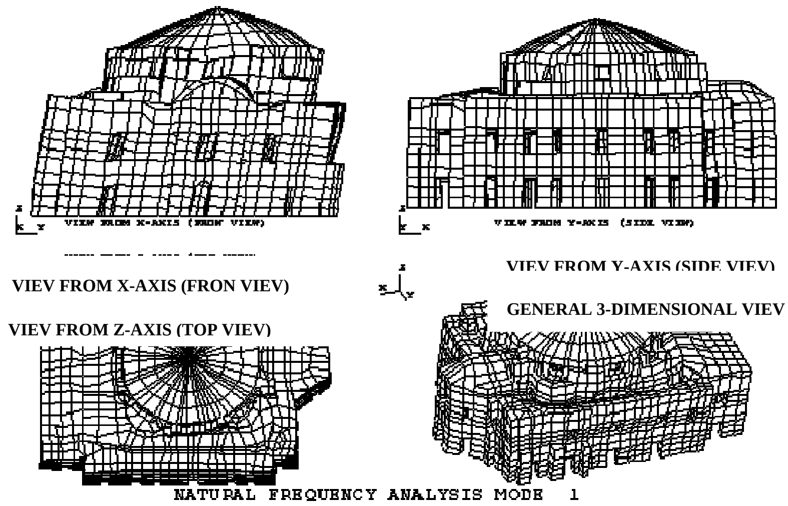


Figure 8 : First mode of the structure.

3.2 The physical characteristics of the material used in modeling

It is found out that the plaster coat causes the strength loosening of the plaster coated bricks and stones and the structure looses its load carrying capacity just over the mortar strength (Kocak, 1999). In the same study, the infilling walls were also modeled with Finite Element Analysis according to the Drucker-Prager criteria. In the modeling plaster coated infilling walls were taken as a single element and the results were compared with those of experimental models. The cohesion value used in the models was c = 3.5 MPa and angle of frictional value is $\phi = 35^0$.
The approximate compression and tensile strength for brick and stone walls in similar studies are given as follows:

Compressive Strength: f_c

2.0 - 10.5 MPa	(UNIDO, 1984)
3.0 - 12.0 MPa	(VSL, 1990)
1.5 MPa	(ATC, 1978)
1.5 - 2.5 MPa or 20 % of the brick strength %20	(Sheppard, 1985)
2.2 - 3.5 MPa	(Mortar value, Penelis and et al.)
11 - 15 MPa	(Brick value), (Penelis and et al.)

Tensile Strength: f_t

0.1 - 0.3 MPa	(UNIDO, 1984)
0.3 - 0.6 MPa	(ATC, 1978)
0.12 - 0.18 MPa or $0.075 \cdot f_c$	(Sheppard and Tercely, 1985)

Approximate correlation between these values:

$f_t = 0.05\text{-}0.07 \cdot f_c$	(UNIDO, 1984)
$f_t \leq 0.15 \cdot f_c$	(VSL, 1990)

According to these suggestions, compression strengths of the plaster coated infilling walls are taken as 8 MPa at the ground level walls and the tensile strengths are taken as 0.8 MPa. On the gallery floor level the compression strengths are taken as 10 MPa and tensile strengths are taken as 1 MPa. Elasticity module is taken as 10E9 N/m^2 and the Poisson ratio is taken as 1/6.

3.1 *The analysis of structure under vertical and earthquake loads*

The analysis of the structure is performed under self weight of the building and also earthquake analysis and earthquake analysis plus vertical load combination analyses were also examined.
It is believed that the earthquake that will affect Istanbul in an unknown future will be caused by the graben system in the Marmara Sea which is the part of the North Anatolian Fault that passes from 20 km south of the city. The strength of this earthquake is expected to be MS=7 and is likely occur in every 100 years (Ansal 1991 and Tezcan' 1996).

According to the Finite Element Analysis developed in this research and the data obtained from the material characterization of the St. Sergius and Bacchus Church, the model is tested against earthquakes of 5 and 7 in magnitude. Hence, the areas that will be exposed to high compression and tensile strength are determined. When the aforesaid earthquake's location is taken as 20 km south of the city, the peak acceleration of the building will be 0.4 g. (Report by Bogazici University 1991 and Aydan 1997). The pseudo speed spectrum of the earthquake imitated is shown in Fig. 9.

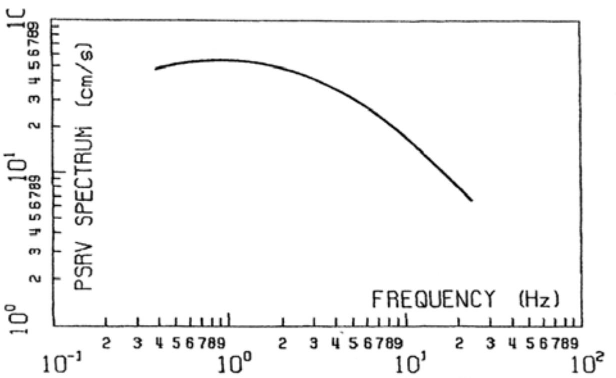
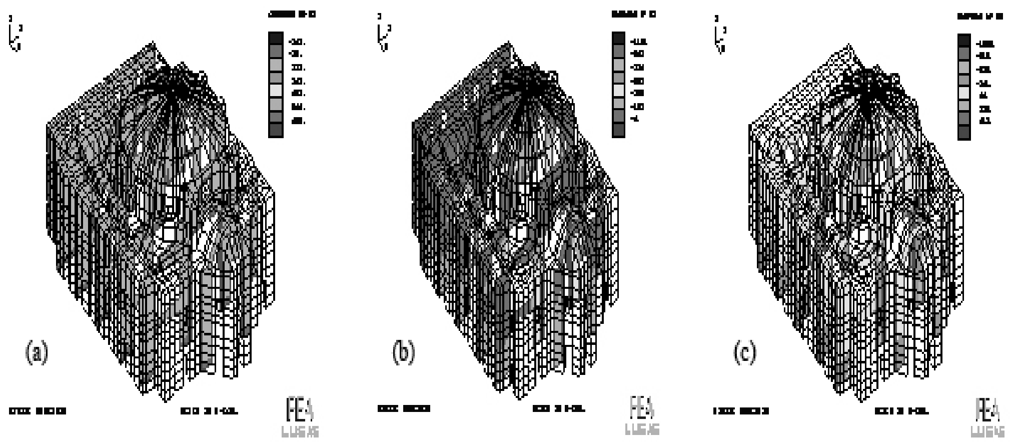


Figure 9 : An imitated Pseudo-Relative Speed Spectrum of MS=7.

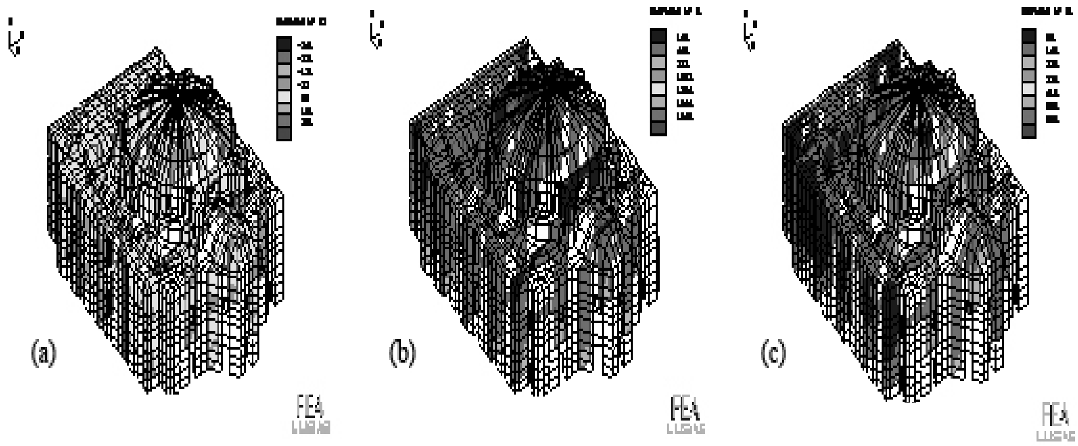
As seen in the images below, the maximum stress of the building under its own weight is (685 kN/m^2), minimum stress is (-1159 kN/m^2) and stress in z direction is between (1095 kN/m^2) and (613 kN/m^2). Stresses on other points are as follows (Fig. 10 a, b and c).



(Static Analysis-Dead Load Only-kN/m^2-Slice in X-Dir.)

Figure 10 (a,b,c) : The static analysis results of the structure under its self weight. (a-Maximum, b-Minimum and in the c-z direction).

When the stresses in the diagrams that are formed as a result of the analysis under vertical loads are examined, compression and tensile strengths are considerably lower than the strength of the structural elements. When the compression stress of the structure is considered (8 to 10 MPa) and tensile strength is considered (0.8 to 1 MPa), then a tensile strength of (0.685 MPa) of the structure falls below this value. Likewise, it is possible to say similar arguments for the stresses in the x, y and z directions as well. The stresses seen on the structure upon the analysis under the vertical loads and earthquake loads of an earthquake with MS=7 magnitude can be seen in Fig. 11 a, b and c.



(Response Spectrum-Dead Load (EQK. MAG. 7)-kN/m^2-Slice in X-Dir.)

Figure 11 (a,b,c) : Self + MS7 stress upon the structure during an earthquake of M=7. (a-Minimum, b-maximum and in c-z direction).

The stresses in the structure obtained as the result of the analysis is given in Table 2.

Table 2 : Stress on the structure under self + earthquake loads.

Direction of the Action of the Earthquake	Max tensile stress (kN/m^2)	Max compression stress (kN/m^2)
+x	168 / 1845	-22 / -345
+y	205 / 2305	-68 / -289
+z	55 / 595	-9 / -36
-x	22 / 345	-168 / -1845
-y	68 / 289	-205 / -2305
-z	9 / 36	-55 / -595

4 EVALUTION AND CONCLUSIONS

- According to these results; the building will be under great stress against an earthquake as strong as MS=7. Due to stress diagrams caused by self and earthquake loads it is obvious that during an earthquake as strong as MS=7, it is 3 or 4 times greater than those that may occur under self weights.

- Yet, the whole mass of the building acts as a rigid diaphragm. However the dome under such great stresses during an earthquake as strong as this will be enforced. Especially the tensile stresses are intensified in the areas where the third pier is located.
- Moreover, when those areas whose maximum tensile stresses are over (1 MPa) and especially when those points with even greater tensile stress of (18.45 MPa) are examined severe cracks can be observed.
- The above evaluations show that insignificant earthquakes will do no harm to St. Sergius and Baccus Church however strong earthquakes will cause damages ranging from cracks to destructive dents.

REFERENCES

Ahunbay, M. Z. and et al., (1997), "Non-Destructive Testing and Monitoring in Hagia Sophia", International Conference on Studies in Ancient Structures", Yildiz Technical University, Faculty of Architecture, Yildiz, Istanbul, Turkey, pp.197-207.

Ansal, A.A.,(1991), Earthquake in Istanbul, *Istanbul and Earthquake Symposium*, IMO-Istanbul, Turkey, pp.7-27.

ATC, (1978), "Applied Technology Council, Tentative Provisions for the Development of Seismic Regulations for Buildings", ATC-3-06, Berkeley, CA, USA.

Bozinovski, Z. and Velkov, M., (1993), Concept of Experimental Determination of Bearing and Deformability Capacity of Structural Walls of Historic Monuments, *2nd National Earthquake Engineering Conference*, 10th-13rd March 1993, Istanbul, pp. 222-232.

Cakmak, A.S., Mark, R. and Erdik, M., (1992), "Structural Evaluation of the Hagia Sophia in Istanbul", Princeton University and Boğaziçi University, Istanbul, Turkey.

Di Pasquale, S., (1988), Finite Element Analysis of Masonry Domes, *Proceedings of IASS-MSU International Symposium*, Istanbul, Turkey, pp. 327-336.

Durukal, E., (1992), "A Study on Structural Identification and Seismic Vulnarability Assesment of Ayasofya", M.S. Thesis, Boğaziçi University, Istanbul.

Erdik, M. and Durukal, E., (1993), Earthquake Behaviour of Hagia Sophia, *2nd National Earthquake Engineering Conference*, 10th-13rd March 1993, Istanbul, Turkey, pp. 198-207.

Erdik, M., Yuzugullu, O. and Karakoc, C., (1990), "Determination of the Istanbul Hagia Sophia Museum Structural System and Determination of the Measures Maintaining the Earthquake Reliability", 1st Phase Report, Bogazici University, Department of Earthquake Engineering, Istanbul, Turkey.

Eyice, S., (1978), "Foundations of the Kapuagası Hüseyin Aga", Ataturk University, Faculty of Letters Research Journal, Erzurum, Turkey.

Gavrilovic, P., (1993), Methodology, Methods and Techniques for Repair and Strengthening of Historical Monuments, *2nd National Earthquake Engineering Conference*, 10th-13rd March 1993, Istanbul, pp. 208-216.

Karaveziroğlu, M., Barboutis, C. and Kranas, V., (1997), Behaviour of Masonry with Full Bricks and Lime Mortars, *International Conference on Studies in Ancient Structures*, Yildiz Technical University, Faculty of Architecture, Yildiz, Istanbul, Turkey, pp.225-233.

Koçak, A., (1999), Linear And Non-Linear Analysis of The Historical Buildings under Static and Dynamic Loading: The Study Of Kucuk Ayasofya Mosque, Yıldız Technical University, Institute of Science, PhD Thesis, İstanbul, Turkey.

Lusas, Version 11, "London University Stress Analysis Program" FEA, England

Lourenço, P.B., de Borst, R. and Rots, J.G., (1997), A Plane Stress Softening Plasticity Model for Orthotropic Materials, *International Journal for Numerical Methods in Engineering*, Vol. 40, No. 21, pp.4011-4032.

Lourenço, P.B. and Rots, J.G., (1997), Multisurface Interface Model for Analysis of Masonry Structures, *Journal of Engineering Mechanics*, Vol. 123, No. 7, pp. 660-668.

Lourenço, P. B., (2002) "Computations on Historic Masonry Structures", University of Minho, Portugal, Prog. Structurel Engineering Materials, 301-319.

Mathews, T F., (1971), “The Early Churches of Constantinople”,Pennsylvania State Univ. USA

Mainstone, R.J., (1988), “Hagia Sophia : Architecture, Structure and Liturgy of Justinian’s Greatest Church”, London, UK.

Ozaydın, K. and Yıldırım, M., (1994), “Investigations on the Kuçuk Ayasofya Mosque Foundation Soil”, Yildiz Technical University, Faculty of Civil Engineering, Unpublished Report, Istanbul, Turkey.

Ozşen, G. and Ozkaraman, M., (1995), “Kuçuk Ayasofya Mosque”, XIIIth Technical Congress of Civil Engineering of Turkey, TMMOB, Chamber of Civil Engineering of Turkey, pp.24-26.

Ozşen, G., Aköz, F., Yuzer, N. and Ozkahraman, M., (1995), The Structure of Kuçuk Ayasofya Mosque - St. Sergius and Bacchus- in Istanbul, *International Symposium, Spatial Structures: Herigate, Present and Future*, Milano, Italy, pp. 1261-1270.

Ozşen, G., Aköz, F., Yüzer, N., Ozkahraman, M. and Bayram, E., (1995), “Küçük Ayasofya Mosque -St. Sergius and Bacchus- Investigation of the Crack on the Dome”, XIIIth Technical Congress of Civil Engineering of Turkey, TMMOB, Chamber of Civil Engineering of Turkey, TMMOB, pp. 67-80

Penelis, G., Karaveziroğlu, M., Styliandis, K. and Leontaridis, D., (1992), “The Rotunda of Thessaloniki: Seismic Behavior of Roman and Byzantine Structures in Hagia Sophia from Age of Justinian to the Present”, Ed.by R.Mark and A.Cakmak, Cambridge University Press.

Pichard, P., (1975-76), The Restoration of Pagan-Burma, *Unesco Report* RP/1975/76/3.411.6

Tezcan, S.S., (1996), Probability Analysıs of Earthquake Magnitudes, *Publication of Earthquake Foundation of Turkey*, Istanbul.

Sheppard, P.F. and Tercely, S., (1985), Determination of the Seismic Resistance of an Historical Brick-Masonry Building by Laboratory Tests of Cut-Out Wall Elements, *Proc. 7th. International Brick Masonry Conference*, Melbourne, Australia.

UNIDO, (1984), “Design and Construction of Stone and Brick Masonry Buildings” Building Construction Under Seismic Conditions in the Balkan Region”, V.3, Unido, Vienna, Austria.

VSL, (1990), “Post-Tensioned Masonry Structures”, VSL International, Berne, Swittzerland.