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# Investigation of Earthquake Behavior of the Church of St. Sergius and Bacchus in Istanbul/Turkey

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**Abstract**: In this study The Church of St. Sergius and Bacchus was modeled by Finite Element Method and was put through various tests to determine its structural system, earthquake behavior and structural performance. The geometry of the structure, its material resistance and ground conditions isn't enough to model a historical structure. Additionally, you need to calculate the dynamic characteristics of the structure with an experimental approach to come up with a more realistic and reliable model of the structure.

Therefore, a measured drawing of the structure was acquired after detailed studies, material testing were made both at summer and winter to examine the seasonal changes and soil conditions were determined by bore holes and exploratory wells dug around the structure. On the other hand, vibration tests were made at The Church of St. Sergius and Bacchus to analyze the structural characteristics and earthquake behavior of the building. Structural modeling of the building, modeled by the Finite Element Method, was outlined by determining its free vibration analysis in compliance with experimental periods. Vertical and earthquake loads of the structure were determined by this model.
Keywords: Finite element method, earthquake behavior, church

## Introduction

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 et al. 1995). The outer and inner view of the building is given in Fig. 1 and Fig. 2 respectively.

*Figure 1: St. Sergius and Bacchus Outer View*

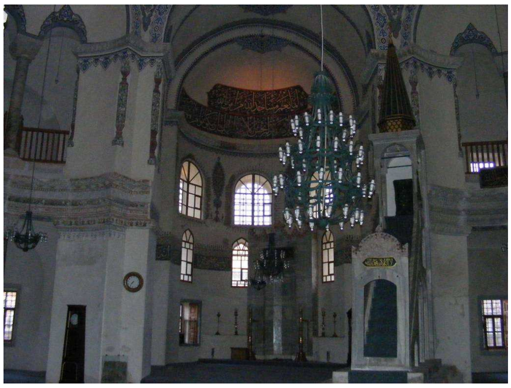


*Figure 2: St. Sergius and Bacchus Inner View*

**Tests and Observations of the Structure**

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. Many a historical building has been examined architectural, historical, material and structural system point of views by various researches over the years. 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. 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.

In this study, The Church of St. Sergius and Bacchus, which was a masonry structure built during 527-536 A.C. was modeled with Lusas Finite Element Methods Program by using its material strength, structural characteristics, ground conditions and free vibration.

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.

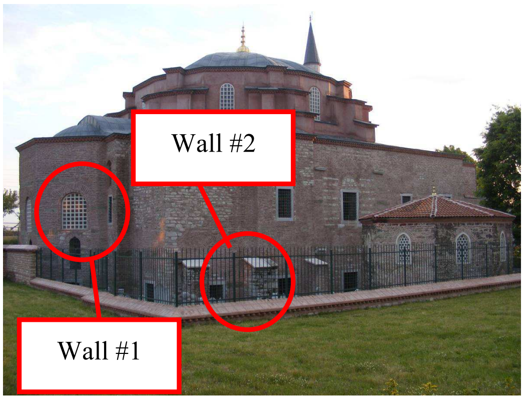



*Figure 3: The Walls of St. Sergius and Bacchus*

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).

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 gal-

lery 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. The cohesion value (c) is taken as 3.5 Mpa while the angle of friction ( $\phi$ ) is considered to be $35^{0.}$

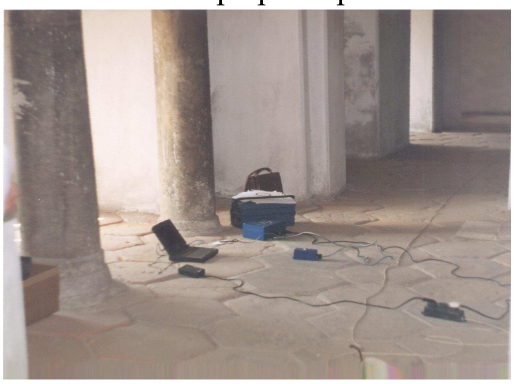
Soil conditions were determined by bore holes and exploratory wells dug around the building. Geotechnical data show that the soil where the church is located and the surrounding area are on a layer of clay and marl from the early Pliocene Age. In other words, the soil is thin in size and cohesive. The exploratory well No.1, which was 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 layers in the second exploratory well show almost the same properties as the other exploratory well. The second exploratory well 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.

According to these results, the ground is deducted to be a filled ground. (Özaydın et al. 1994).

**Vibration Measurements 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. 4 and Fig. 5). Free vibration measurements were taken by a seismometer, signal conditioner, analogue- digital converter and a laptop computer.



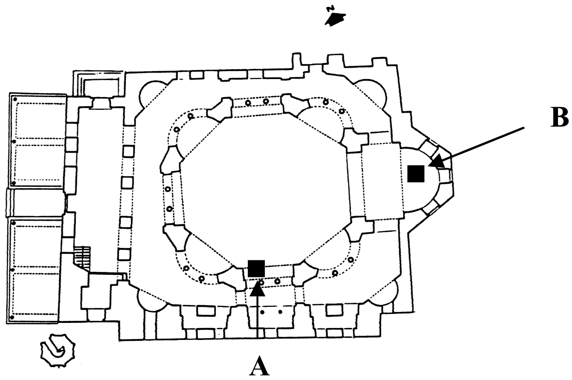



*Figure 4: Free vibration measurements of the Church of St. Sergius and Bacchus (Readings at the gallery floor)*

*Figure 5: Positions of free vibration measurments*

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 digitalized 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. (Table 1).

The movement of the structure for the first 3 modes is shown at Fig. 6-8. In addition to these values, the extra vibrations that will affect the structure due to the presence of a nearby railway was calculated as well. The aforementioned railway was built in 1870-1871 and constructed 5-10 meters away from the southern wall of the Church of St. Sergius and Bacchus. According to Mathews (1971), this wall was rebuilt in 1877 with the Ottoman bond style because the stones of the wall were falling down as the trains passed. The railway which was 1 meter over the ground in the past was moved up to 3 meters by embanking a 2 meters high wall between the fortifications in the 1950s. This railway has been in use for almost 120 years with an ever increasing train traffic and

frequency. Today, this route is used by local trains, the Balcan Express and freights, every 10 minutes, 6 hours and 12 hours, respectively. The freights in particular, caused dust and rendering particles to fall off the structure. Therefore acceleration and vibration measurements were performed twice at the Church of St. Sergius and Bacchus. During the first set of tests, the trains passed by slowly due to the railway reconstruction as opposed to the second set of tests while they were moving at full speed because the reconstruction process was over. These test values were shown at Table 2 and 3.

*Table 1: Free Vibration Values of the Structure*

| | *Vibration Mode* | *Frequency (Hz)* | *Direction* |
|---|---|---|---|
| 1 | 1st Vibration Mode | 4.47 | North - South |
| 2 | 2nd Vibration Mode | 5.15 | East - West |
| 3 | 3rd Vibration Mode | 5.65 | Torsion |
| 4 | 4th Vibration Mode | 7.00 | Opening and closing Inside and Outside |
| 5 | 5th Vibration Mode | 7.65 | Vertical Vibration |

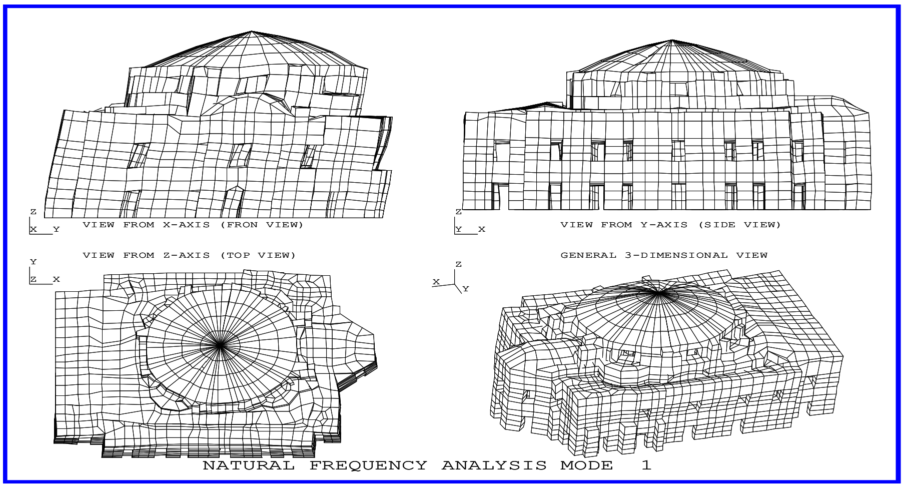



*Figure 6: First Mode Shape*

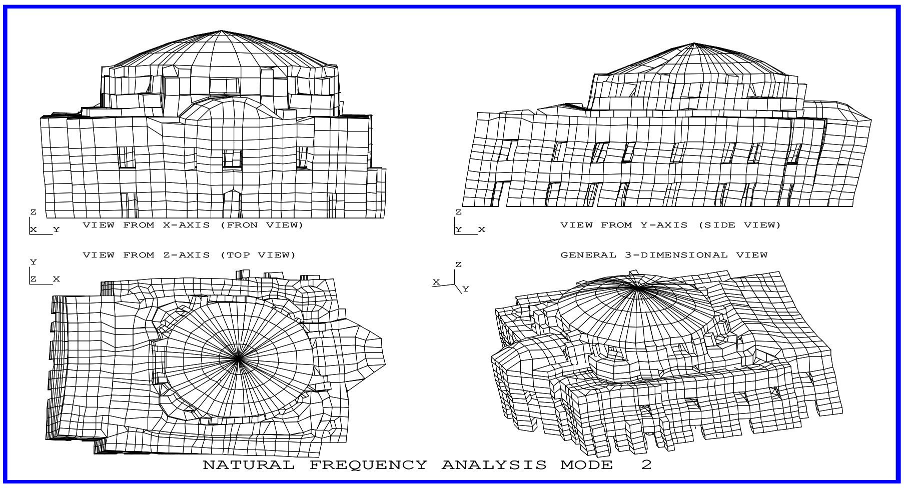



*Figure 7: Second Mode Shape*

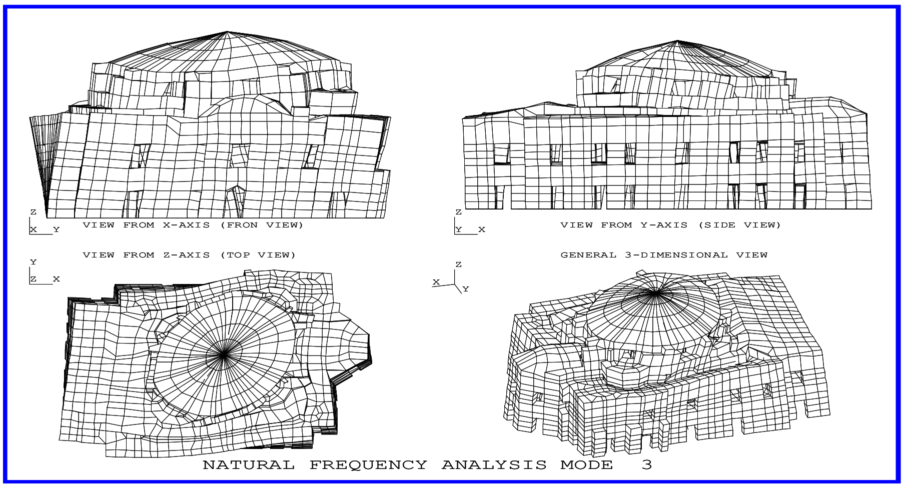



*Figure 8: Third Mode Shape*

*Table 2: Acceleration, Frequency and Velocity values of the first part of the structure*

| *Measurement No* | *Measurement Time* | *Sensor Direction* | *Correction* | *Filter (Hz)* | *Acceleration (mm/s$^2$)* | *Frequency (Hz)* | *Velocity (cm/s)* |
|---|---|---|---|---|---|---|---|
| 1 | 11:25 | Vertical | 1000 | 25 | 1.14 | 20.8 | 0.009 |
| 2 | 11:40 | Vertical | 1000 | 25 | 1.14 | 20.8 | 0.009 |
| 3 | 11:45 | Vertical | 100 | 25 | 3.20 | 17.9 | 0.028 |
| 4 | 11:50 | Vertical | 1000 | 9 | 1.14 | 25.0 | 0.007 |
| 5 | 11:55 | Vertical | 100 | 9 | 2.00 | 16.7 | 0.019 |
| 6 | 12:25 | Vertical | 100 | 9 | 3.80 | 16.7 | 0.036 |
| 7 | 12:35 | Vertical | 100 | 9 | 2.40 | 17.9 | 0.021 |
| 8 | 12:40 | Vertical | 100 | 9 | 2.60 | 15.6 | 0.027 |
| 9 | 12:45 | Vertical | 100 | 9 | 2.20 | 17.9 | 0.020 |
| 10 | 12:55 | Vertical | 100 | 9 | 1.80 | 19.2 | 0.015 |

*Table 3: Acceleration, Frequency and Velocity values of the second part of the structure.*

| *Measurement No* | *Measurement Time* | *Sensor Direction* | *Correction* | *Filter (Hz)* | *Acceleration (mm/s$^2$)* | *Frequency (Hz)* | *Velocity (cm/s)* |
|---|---|---|---|---|---|---|---|
| 1 | 10:30 | Vertical | 100 | 9 | 4.71 | 9 | 0.030 |
| 2 | 10:40 | Vertical | 100 | 9 | 3.53 | 9 | 0.034 |
| 3 | 10:50 | Vertical | 100 | 9 | 7.65 | 9 | 0.049 |
| 4 | 11:03 | Vertical | 100 | 25 | 5.89 | 25 | 0.037 |
| 5 | 11:04 | Vertical | 100 | 25 | 4.51 | 20.8 | 0.035 |
| 6 | 11:06 | Vertical | 100 | 25 | 4.91 | 20.8 | 0.038 |
| 7 | 11:10 | East - West | 100 | 25 | 6.47 | 20.8 | 0.050 |
| 8 | 11:20 | East - West | 100 | 25 | 3.73 | 16.7 | 0.036 |
| 9 | 11:30 | North - South | 100 | 25 | 8.63 | 20.8 | 0.066 |
| 10 | 11:45 | North - South | 100 | 25 | 6.47 | 22.7 | 0.045 |
| 11 | 11:46 | North - South | 100 | 25 | 7.85 | 22.7 | 0.055 |

**Modeling and Analysis of the Church of St. Sergius and Bacchus**

After the building's measured survey of the original design drawings was prepared and cracks in the building are determined, the structure is modeled by Finite Element Method. (Fig. 9). 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.

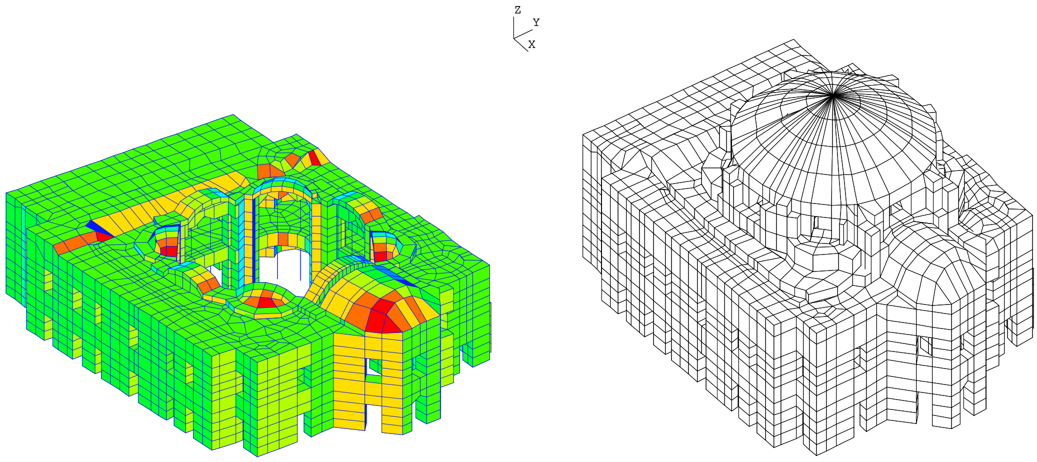



*Figure 9: Finite element modeling of the building*

With this modeling under self and external loads the free vibrations of the building is analyzed and the modes and the periods are determined. The model was designed as a result of correlation between periods at hand and the experimental periods. 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 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. 10.

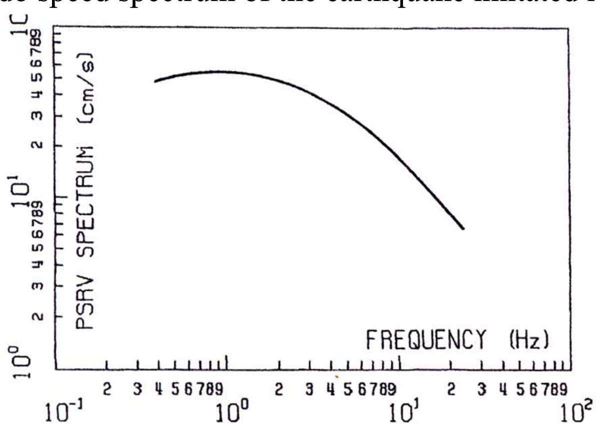



*Figure 10: An imitated Pseudo-Relative Speed Spectrum of MS=7.*

Vertical loads of the structure showed that the structure will has a massive damage and collapse at a strong earthquake situation. Tensile and compressive stress were shown at Fig. 11 and Fig. 12 respectively.

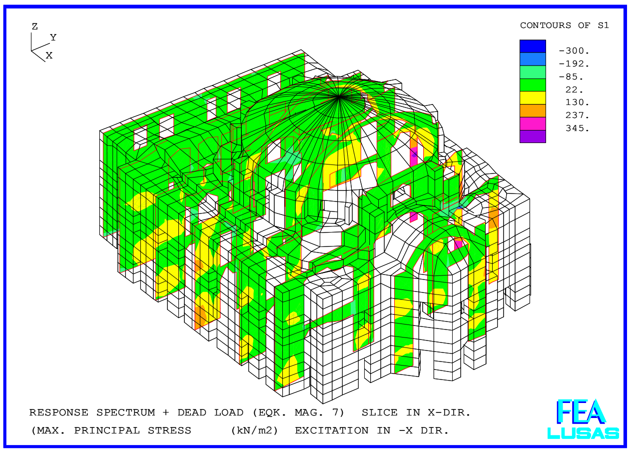



*Figure 11: Tensile stress of the structure at an earthquake of 7 + dead load in magnitude*

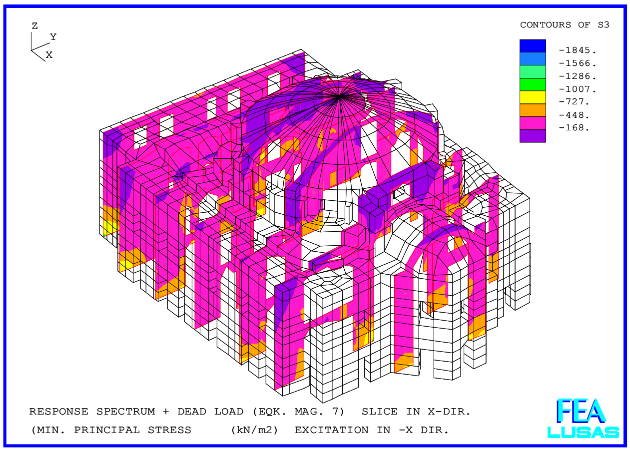



*Figure 12: Compressive stress of the structure at an earthquake of 7 + dead load in magnitude*

## Conclusion

The calculations pointed out a difference between 5% and 10% when compared to the experimental vibrations. The fact that the experimental frequencies were low was related to the current cracks of the structure and the disintegration between brick and mortar.

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), 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.

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