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SEISMIC VULNERABILITY ANALYSIS OF THE HISTORIC SULTANIYA DOME

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SUMMARY

This paper presents the results of seismic vulnerability analysis of the historic sultaniya dome constructed for the tomb of Uljaytu. This monumental building is 47 meter high brick masonry structure with a dome type roof. The roof is a two layer shell structure with a base diameter of 25.5 meters. The building was constructed about 700 years ago and is now one of the largest masonry structures in the world. Finite element analysis is used for the structural analysis. Static push-over analysis is performed to assess the seismic resistant of the building for three level of seismic hazard. For an earthquake with return period of 75 years some portions the structure cracks but main portion of the structure remains intact. For an earthquake with return period of 475 years the cracking pattern is similar to the previous case. However due to higher tensile stresses, the crack widths are expected to larger than the previous case. There may be local compression failure in some of main pillar of the structure but the structure is not expected to collapse at this seismic level. For an earthquake with return period of 2500 years the structure is expected to collapse due to compression failure of main pillars.

INTRODUCTION

The Ilkhanid dynasty, one of the Mongol successor tribes centered in north-western Iran, rose to power in the years after the early thirteenth-century Mongol invasions of Iran. From their capital of Tabriz, Ilkhanid rulers adopted Persian culture and were enthusiastic patrons of architecture, instituting large-scale building campaigns including the foundation of the new royal city of Sultaniya.

The monumental Sultaniya dome is all that remains of city of Sultaniya, the much praised Mongol city founded about 700 years ago in 1285 by the IlKhan Arghun and dedicated as the capital by his son, Sultan Uljaytu Khudabanda. The construction of this building lasted 10 years between years 1302 and 1312. This shows the exceptional knowledge of the engineers/architects at that time. This is the largest dome type building in Iran and before construction of the famous Cathedral of Santa Maria del Fiore in Florence and

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the aya Sofia mosque in turkey was the largest dome type structure in the world. This monumental building is 47 meter high brick masonry structure with a dome type roof. The roof is a two layer shell structure with a base diameter of 25.5 meters. According to professor Sanpaolesi [1], there can not be found any two layer shell dome before construction of this building neither in the West nor in the East. Figure 1 shows a picture of the building.

Figure-1 Soltaniya Building

The plan comprises an octagon with a rectangular burial chamber protruding from the southern side. The exterior is built out with triangles on the northern end, extending the north, east, and west facades. The dome rests on the upper terrace, carried on the interior by the corbels of a thick wall. Minarets rise from the upper terrace at each of the eight corners. The interior is divided into two stories of eight-bay arcades. A third arcade runs below the base of the dome, opening to the exterior and not the interior. Figure 2 shows the architectural representation of main feature of the octagonal structure [1].

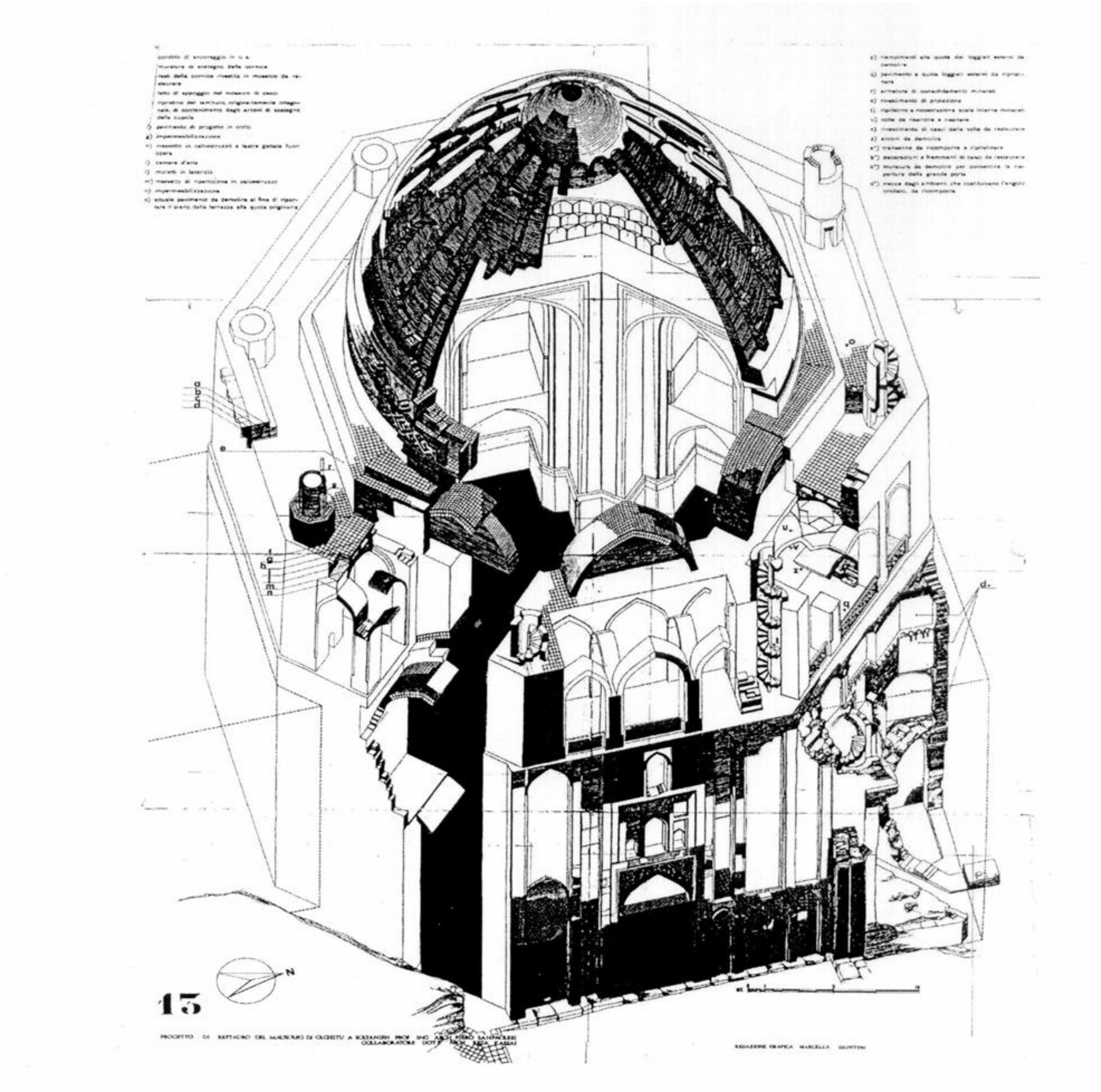

Figure-2 The architectural representation of main feature of the structure [1]

RESULTS OF FINITE ELEMENT ANALYSES

Description of the Finite Element Model

In this study only the main building is analyzed and the burial chamber and minarets are disregarded. Shell elements with both bending and membrane capabilities are used to model the double crust domes and the ribs that connect the outer crust to the inner crust. Figure 3 shows the finite element representation of the dome structure. Structural solid elements are used for modeling the rest of the structure. Figure 4 shows a cross section of the finite element model which indicates all vaulted elements and arches within the structure is adequately represented in the mathematical model.

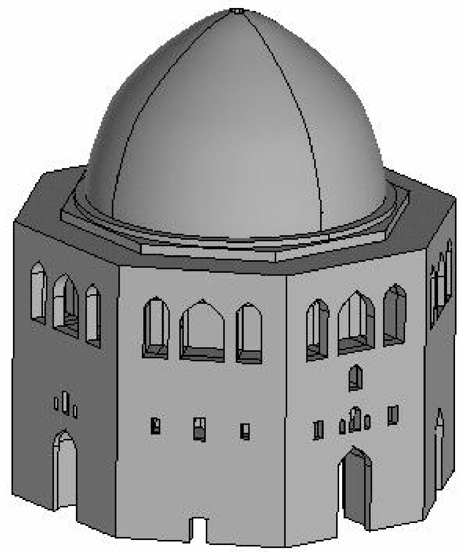

Figure-3 Finite element representation of the dome structure

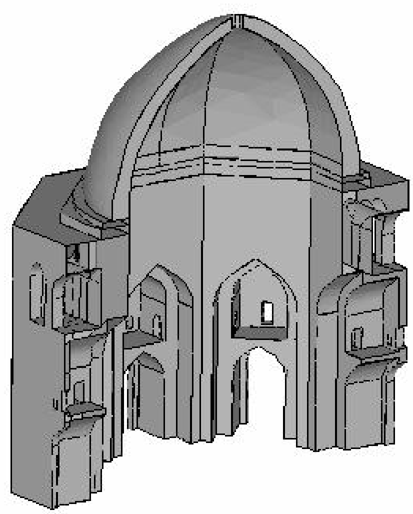

Figure-4 Cross section of the finite element model

The mathematical model consisted of 1624 shell elements and 112009 structural solid elements with a total of about 100000 degrees of freedom. Because of the large size of the model and limited hardware capabilities, linear material behavior is used in analyses. Of course with this method cracking and crushing of masonry material is not considered in the analyses. However, after post-processing of the results and comparing that with failure surface in principle stress space of such brittle material, the locations where the structure cracks or crushes under high tensile or compressive stresses are identified. Figure 5 shows an example of a failure surface in principle stress space in where f_p is the ultimate compressive stress in uniaxial loading condition [2].

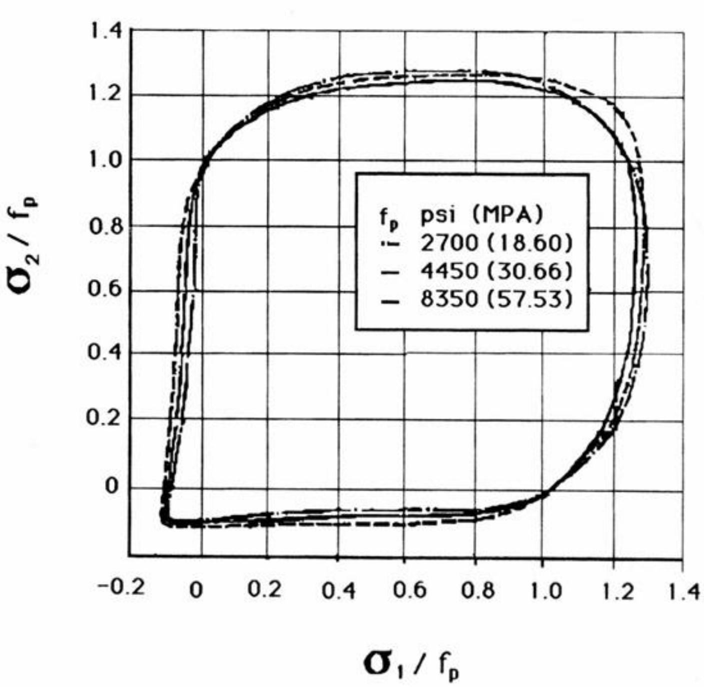

Figure-5 Failure surface in principle stress space [2]

The materials of Soltaniya building consist of brick masonry and lime/gypsum mortar. Based on test results [1] the ultimate tensile stress f_t and ultimate compressive f_c are respectively taken as 175 kN/m^2 and 3000 kN/m^2. In the space where principle stresses are compressive, we conservatively ignore the principle stress S_2 and use Kupfer [2] Formulas in the principle stress state.

Compression failure:
$$\left(\frac{s_1}{f_c}+\frac{s_3}{f_c}\right)^2+\frac{s_3}{f_c}+\frac{3.65s_3}{f_c}=0$$

Tensile cracking:
$$\frac{s_1}{f_t}=1+\frac{0.8s_3}{f_c}$$

The specific weight of material is 1.6 ton/m^3 and elastic modulus and poisson's ratio are taken as 200 Mpa and 0.15 respectively.

Modal Analysis

Modal analysis of the building is performed using fixed boundary condition at the base of the building. The first and second modes are translation in ortagnol directions with fundamental period of 0.34 second. Figure 6 shows the first mode shape. The third mode is a torsional mode with a period 0.22 second. Figure 7 shows the torsional mode shape of the building.

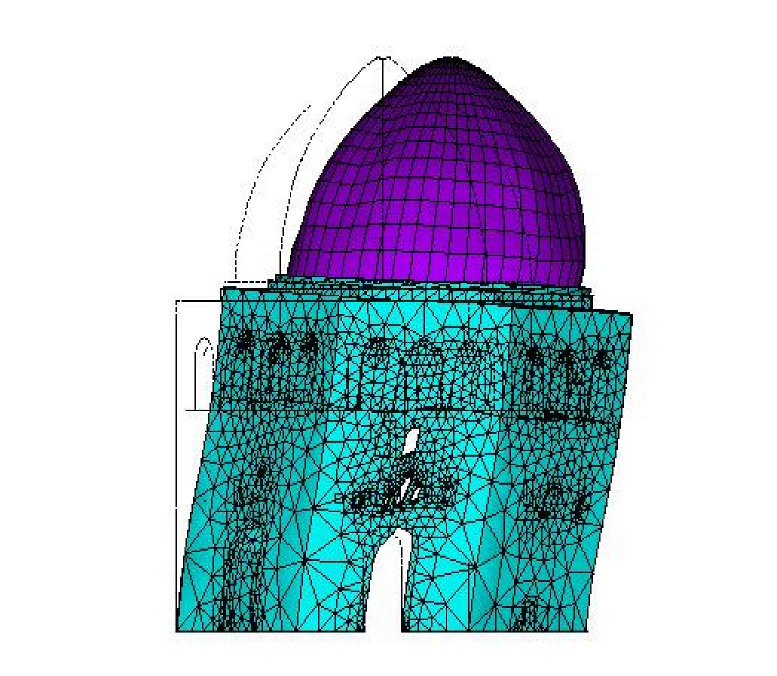

Figure-6 The first mode shape

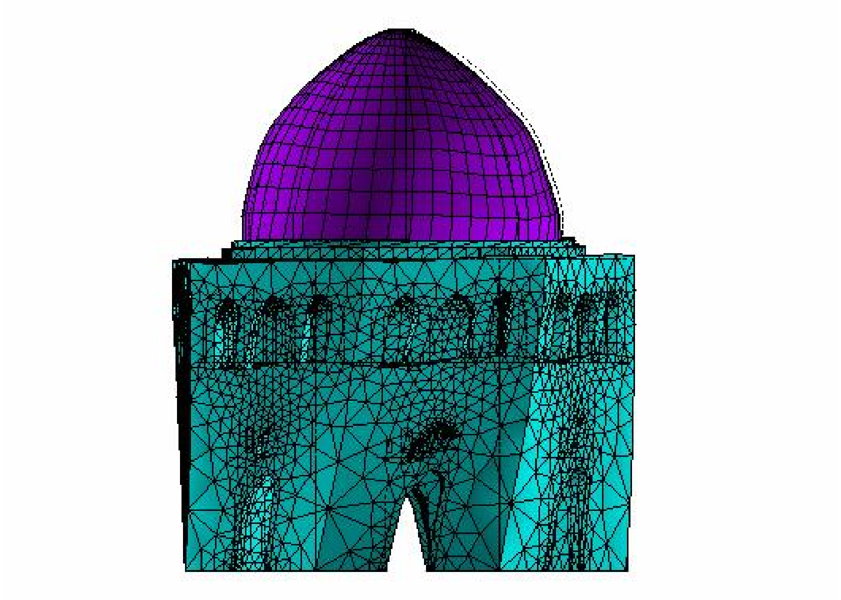

Figure-7 The torsional mode shape

Analysis of the Building under Gravity and Seismic Load

The analysis of the building under gravity load is performed with vertical acceleration of 9.81 m/s^2. The maximum vertical displacement is 7 ^{mm} which occurs at top of the dome. Figure 8 shows the distribution of maximum compressive stress in the building. The maximum compressive stress at the base of dome is 515 kN/m^2. The compressive stress at the base of the main columns is about 500 kN/m^2 while locally at the tip of main arches supporting the dome the maximum compressive stress is 1025 kN/m^2. The maximum tensile stress is also less than the ultimate tensile capacity of the material.

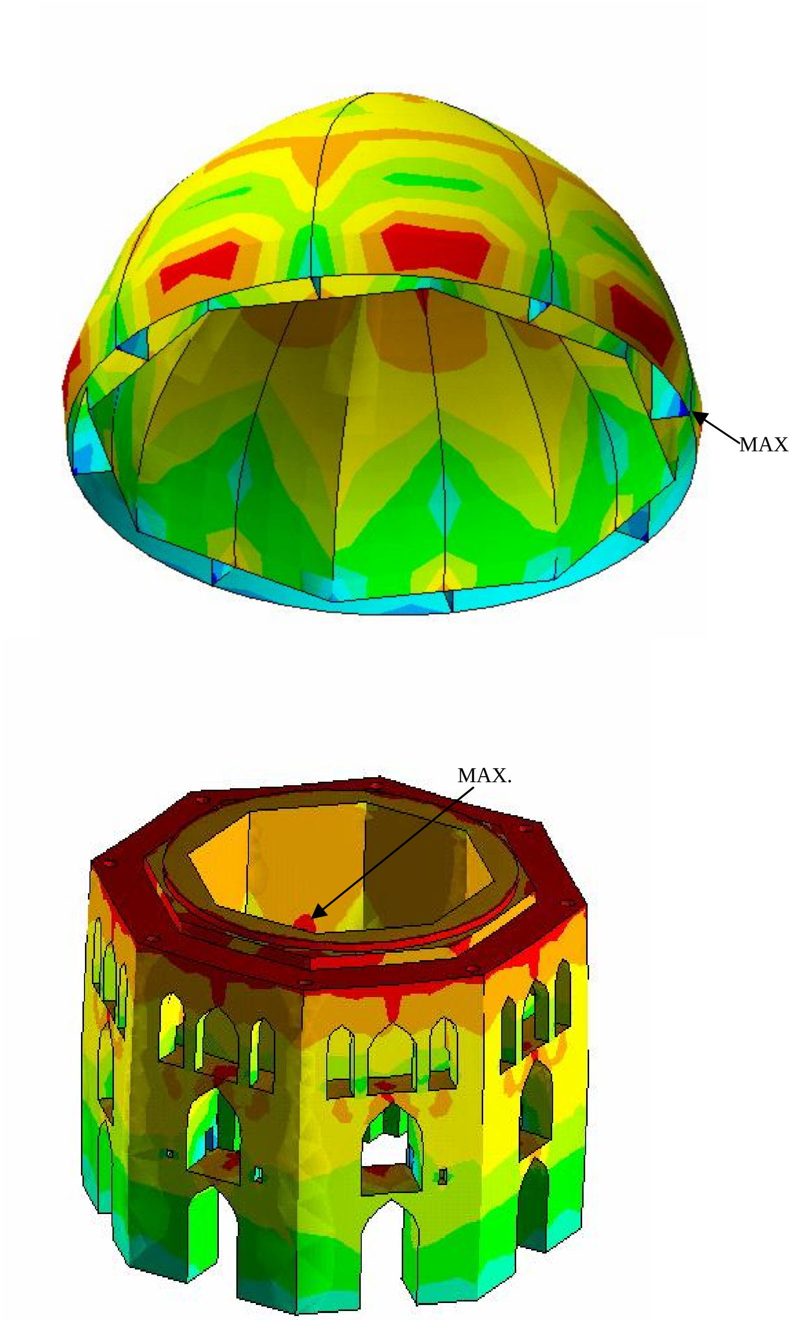

Figure-8 Distribution of maximum compressive stress due to gravity load

The seismic analyses are performed for three levels of seismic hazard with return period of 75 years, 475 years and 2500 years using static push-over analysis. The lateral accelerations for these return periods are found respectively 0.23g, 0.44g and 0.76g [3].

The results of seismic analysis for a return period of 75 year and PGA= 0.23g indicate a maximum drift of 10 ^{mm} at top of the dome. Figure 9 shows the distribution of maximum compressive stress in the building. It indicates that the maximum compressive stress, S3=1704 kN/m^2, occurs at the corner of one of the main columns is well below the ultimate compressive strength of the material.

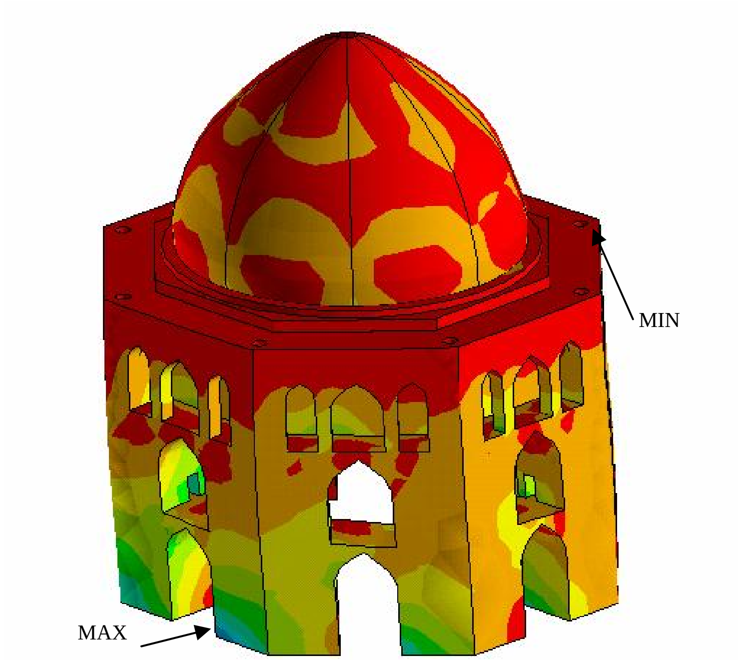

Figure-9 Distribution of maximum compressive stress at PGA= o.23g

Figures 10 through 13 compare the results of the analysis with cracking zones of the failure surface shown in Figure 5. The locations with light color shades indicate cracking of the material. These Figures indicate that some portions the main structure, the dome, and walls in the second story cracks but main portion of the structure remains intact at this seismic level.

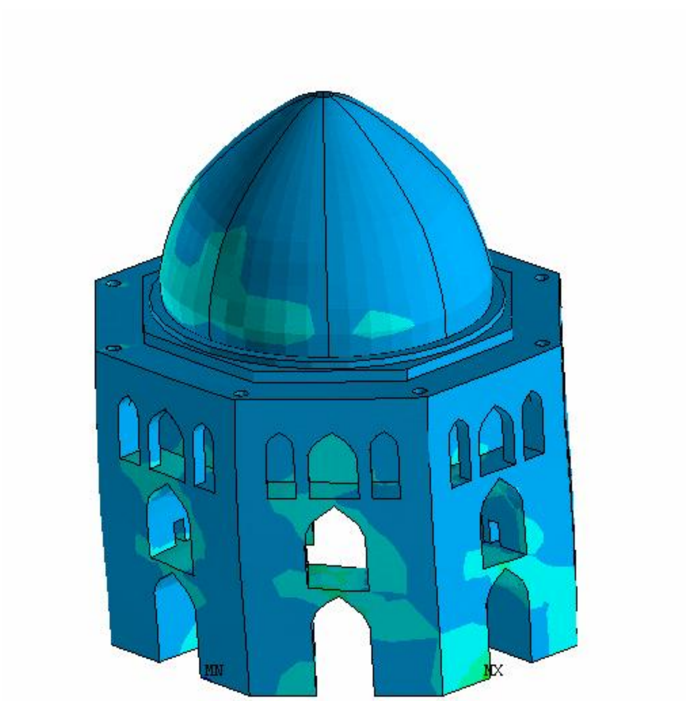

Figure-10 Cracking of the main structure and the dome

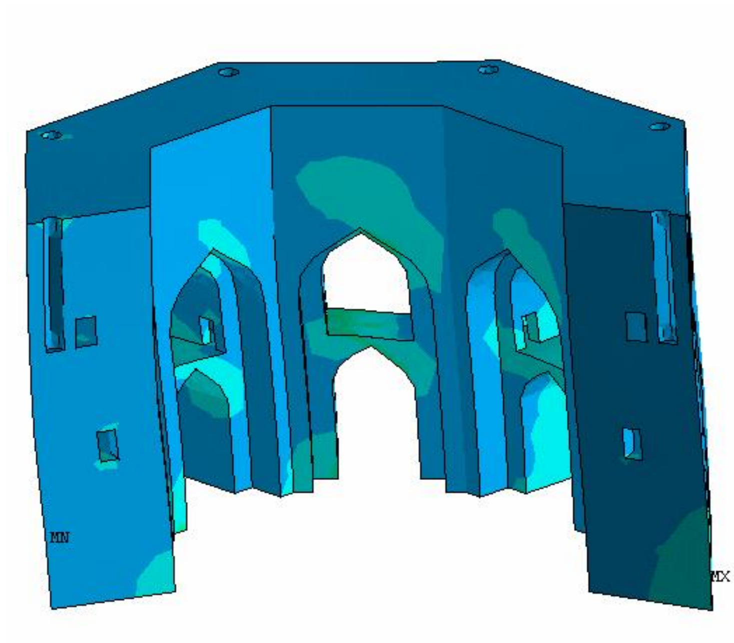

Figure-11 Cracking at a cross section of the main structure

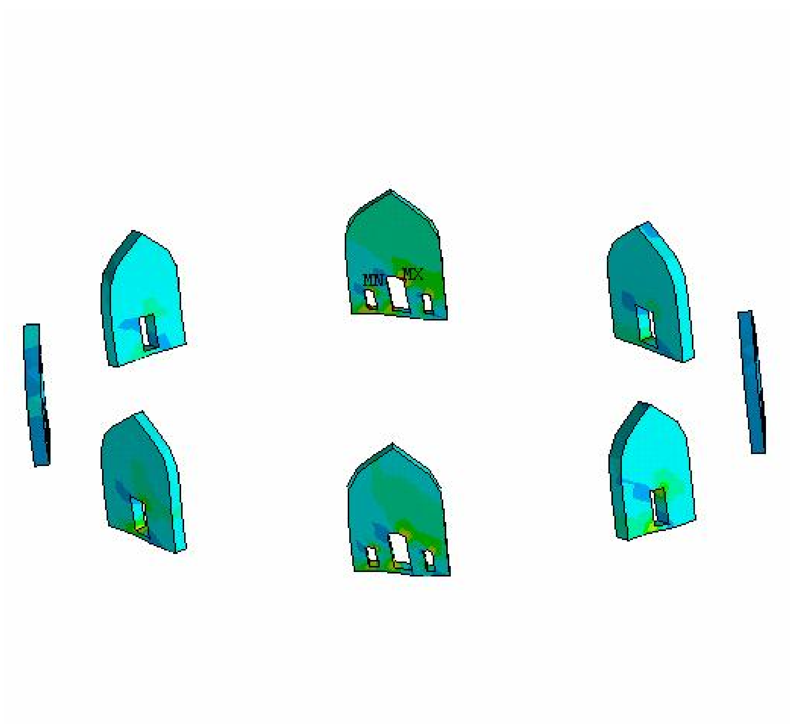

Figure-12 Cracking of the exterior walls on the second story

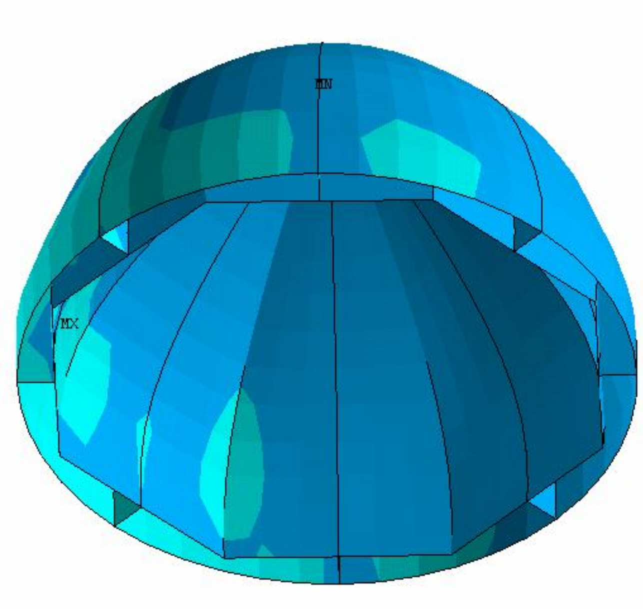

Figure-13 Cracking of the dome structure

The results of seismic analysis for a return period of 475 year and PGA= 0.44g indicate a maximum drift of 19.6 ^{mm} at top of the dome. Figure 14 shows the distribution of maximum compressive stress in the main building. It indicates that the maximum compressive stress, S3=2480 kN/m^2, occurs at the corner of one of the main columns. This stress is about 20% below the ultimate compressive strength of the material, f_c= 3000 kN/m^2. Figure 15 shows the maximum compressive stress in the exterior walls on the second story. It indicates that at the corner of openings the maximum compressive stress exceeds the ultimate compressive strength of 3000 kN/m^2. The cracking of the structure is similar to those shown in Figures 10-13. However due to higher tensile stresses, the crack widths are expected to higher than the previous case.

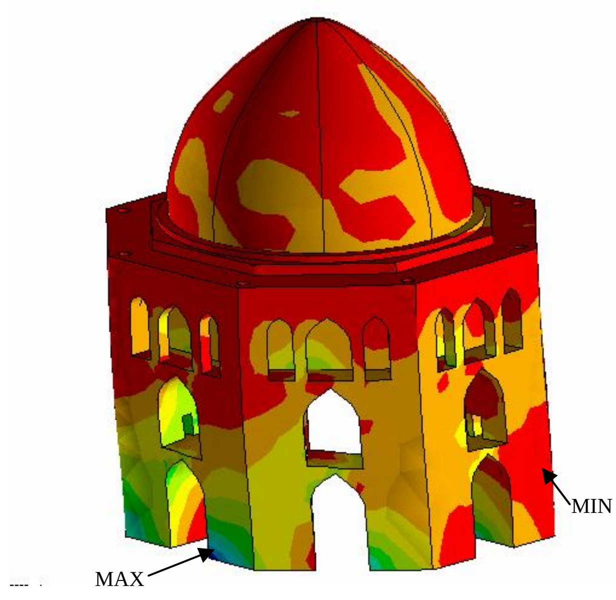

Figure-14 Distribution of maximum compressive stress at PGA= o.44g

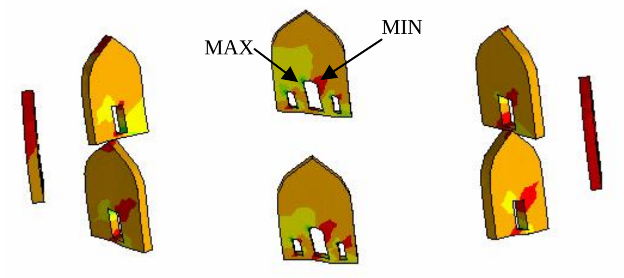

Figure-15 Distribution of maximum compressive stress in the exterior walls

The results of seismic analysis for a return period of 2500 year and PGA=0.76g indicate a maximum drift of 33.9^{mm} at top of the dome. The cracking of the structure is similar to those shown in Figures 10-13. However due to higher tensile stresses, the crack widths are expected to higher than the previous cases.

Figure 16 shows the distribution of maximum compressive stress in the main building. It indicates that the maximum compressive stress, S3=3725 kN/m^2, occurs at the corner of one of the main columns. This stress is exceeds the ultimate compressive strength of the material and indicates crushing at that location. Crushing zone is expected to expand significantly in an earthquake due to stress redistribution caused by cracking and crushing of material.

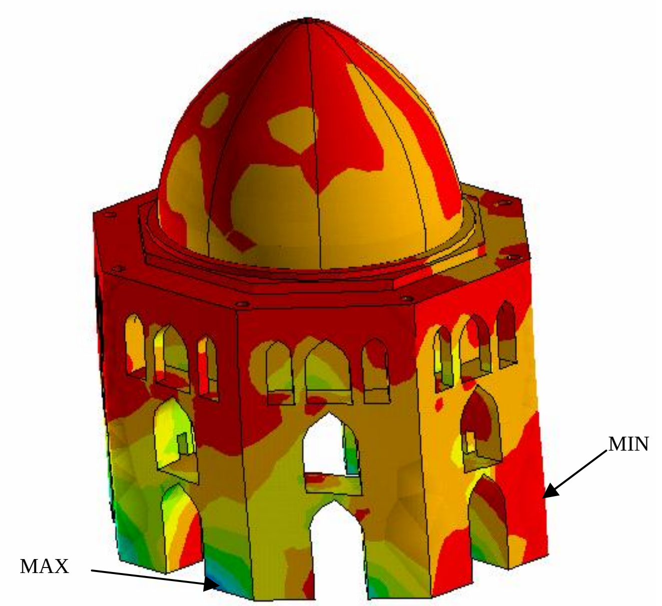

Figure-16 Distribution of maximum compressive stress at PGA= o.76g

DISCUSSION OF THE RESULTS

The results of analyses indicate for an earthquake with return period of 75 years the structures remains intact while some cracking occurs on some part of the structure. But the extent of cracking will not cause collapse of the structure.

For an earthquake with a return period of 475 years the cracking intensifies especially within the dome and the walls on the second story. But the major portion of the octagonal supporting structure remains intact while the maximum elastic compressive stress at base of one of the main columns reaches to about 80% of the crushing strength of the material. Due to cracking of other portions of the structure, this stress is expected to increase significantly and some crushing of portions of the cross sections of large column may occur. For short and normal duration of earthquakes, the intact portion of the columns are expected to be able to prevent collapse of the structure because only about 20% of column area is required to carry the weight of the structure after the earthquake. However, for an earthquake with long duration the damage may be so extensive that part of the structure may collapse at this earthquake level.

For an earthquake with a return period of 2500 years the cracking intensifies further while the maximum elastic compressive stress at base of one of the main columns exceeds the crushing strength of the material. Due to cracking of other portions of the structure, the compressive stress is expected to increase significantly and crushing of major portions of the cross sections of large column may occur. The damage will be so extensive that would cause collapse the structure at this earthquake level.

CONCLUSION

The results of seismic vulnerability analysis of the historic sultaniya dome constructed about 700 years ago are presented. This is the largest dome type building in Iran and before construction of the famous Cathedral of Santa Maria del Fiore in Florence and the aya Sofia mosque in turkey was the largest dome type structure in the world. This monumental building is 47 meter high brick masonry structure with a dome type roof. The roof is a two layer shell structure with a base diameter of 25.5 meters.

The seismic analyses are performed for three levels of seismic hazard with return period of 75 years, 475 years and 2500 years using static push-over analysis. The results of analyses indicate for an earthquake with return period of 75 years the structures remains intact while some cracking occurs on some part of the structure. For an earthquake with a return period of 475 years the cracking intensifies especially within the dome and the walls on the second story. But the major portion of the octagonal supporting structure remains intact. For short and normal duration of earthquakes, the intact portion of the columns are expected to be able to prevent collapse of the structure but for an earthquake with long duration the damage may be so extensive that part of the structure may collapse at this earthquake level. For an earthquake with a return period of 2500 years the damage will be so extensive that would cause collapse the structure at this earthquake level.

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