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SEISMIC EVALUATION AND RETROFIT OF A 7TH CENTURY HISTORICAL BRICK MASONRY DOME IN SEMNAN

A. Mortezaei[1], S.M. Zahrai[2]

ABSTRACT

The restoration and conservation of the built heritage are key issues for highly civilized countries. Historical city buildings are integral parts of the built heritage to be preserved, and their safety is a primary requirement in seismic areas. As many unreinforced masonry domed structures are vulnerable on their domes (even under gravity loads), this study mainly focuses on an investigation of effectiveness of placing steel rings at the dome's support level and CFRP sheets along the tension zone on the inner face to improve the structural behavior. The problem is considered through an example of a real conservation case study of the Abbasi Mosque in Semnan, late 7th century AH and the early 8th century AH. The structure is subjected to gravity and seismically originated forces. FE analysis is conducted and the behavior of the system before and after retrofitting process is compared. Also, the site observations related to the crack patterns are explained in detail. Numerical results show that external confinement or tightening using steel rings reduces the principal stresses and displacements of the structure significantly and a more uniformly distributed stress condition is obtained.

Introduction

Architectural heritage is not only culturally important but also economically vital as it is a great support for tourism and leisure industries bringing in billions of dollars to otherwise ailing economies of many older regions of the world. Protecting these often very heavy masonry structures in high seismic zones is a challenge that is of great concern for authorities, researchers and engineers alike.

Post Islamic monumental buildings of Persia are among the world's most beautiful heritage listed architecture. Abbasi Mosque also called Royal Mosque is one of the finest and the most stunning buildings in the world. The Mosque, begun in 712 during the reign of Shah Abbas I and, despite the Shah's impatience, under construction until 738 represents the culmination of a thousand years of mosque building and a magnificent example of architecture, stone carving, and tile work in Iran, with a majesty and splendor that places it among the world's greatest buildings (Fig. 1).

The outer recessed portal faces north, as required by the placement of the *Maidan,* but since the axis of the mosque itself and that of the *mehrab* must be in the direction of Mecca (hence northeast to southwest), an awkward adjustment was necessary to avoid a serest of

[1] Lecturer, Civil Engineering Dept., Islamic Azad university- Semnan branch, Semnan, Iran
[2] Associate Professor, Center of Excellence for Engineering and Management of Infrastructures, School of Civil Engineering, the University of Tehran, Tehran, Iran

dislocation. The portal, almost a building in itself and understood as an aspect of the *Maidan* rather than of the mosque, forms a welcoming embrace, inviting and guiding the throngs outside into the refuge, security and the renewal the mosque provides. In fact, it is the most thrilling example of human artifice that could be imagined. Its height amounts to 30 m, the flanking minarets are 42 m tall with the sanctuary minarets higher still, 48 m. The two panels which flank the actual entrance within the recess carry the design of a prayer rug, a reminder of the mosque's essential purpose.

Iran's historical buildings, Abbasi mosque of Semnan being one of them, have been particularly susceptible to earthquake damage, and prone to partial or total collapse, sometimes due to non-expert restoration (Ramos and Lourenço 2004). Masonry buildings are generally able to carry the vertical loads in a very safe and stable way, while they are rather sensitive, from a structural point of view, to horizontal loads (Hart and Ekwueme 2004). The high seismic vulnerability of these building is due both to the particular configuration and to the mechanical properties of the masonry material. Prediction of the structural response of monumental buildings while in principal is not different from that of other constructed facilities is a more challenging task for several reasons as mentioned in Carpinteri *et al.* (2005).

In brief, monumental historical buildings can neither be analyzed in a manner similar to the everyday standard buildings nor strengthened by the standard structural schemes because of the uncertainties that affect their structural behavior and mechanical properties. The above considerations explain the need for specific modeling and analysis strategies for these buildings. In this paper, a contribution is made to the issue of modeling and seismic analysis of the brick masonry dome of the Semnan's Abbasi mosque (Fig. 2). This study demonstrates the possibility of utilizing and practicality of employing available numerical tools in investigating issues related to the structural behavior and strengthening of historical buildings. An evaluation of the capacity of the mosque to withstand lateral loads together with the expected demands from seismic actions is also provided. The 7th century dome has several crack patterns. To retrofit the dome, combined steel rings and CFRP sheets were used as the tension members at appropriate dome levels. The effects of the current technique of repair and strengthening on the behavior are then investigated in order to evaluate the effectiveness of this technique in retrofitting historical buildings.

Seismicity of Semnan region

The portion of Alpide belt from Iran in the west to Burrma in the east, seismically, is one of the most active intercontinental regions of the world. Semnan region is part of the Iranian plateau that is subjected to many tectonic activities, including active folding and faulting, and volcanic eruptions (Fig. 3). It is also known for its long history of disastrous earthquakes. Not only have these earthquakes killed in thousands but they have also led to waste of valuable natural resources. Since 1900, over 120,000 fatalities have been resulted from earthquakes in Iran.

Semnan is located in the north of Great Kavir. The gravity survey by Dehghani and Makris (1983) indicates that the crust beneath the Great Kavir is in isostatic equilibrium; it is thus unlikely to be undergoing broad uplift or downwrap at present, apart from the northern fringe adjoining the actively rising Alburz Mountains. However, the Kavir basin with the associated Garmsar, Semnan and Damghan basins are areas of considerable active faulting and fault-related seismicity, particularly along the faulted basin margins (Fig. 4). The historical context of earthquakes in this region has been compiled by Ambraseys and Melville (2005). First-motion data indicate that these earthquakes are almost all generated by reverse slip and subsidiary strike-slip movements (Dehghani and Makris 1983). The strike-slip component of deformation probably has a complex origin. Earthquakes are characteristically shallow, of large magnitude but are discontinuous, with long recurrence periods (Berberian 1977). For the central Kavir, the mean return periods of about 22, 170 and 1150 year have been determined for earthquakes of magnitude 5.5, 6.5 and 7.5, respectively. The northern Kavir is more active, with return periods of 5, 30 and 250 year, respectively (Nowroozi and Ahmadi 1986). Historical records show that nearly every larger town near the Kavir border, including Semnan has been severely damaged by the earthquakes in the past. In 1927, an area of 280000 Km^2 was shaken by an earthquake centered at the western side of the Kavir (Ambraseys 2005). Qumes (Ghoomes) city hill is located 35km to the southeast of Semnan. In the old Islamic literature, Semnan, Damghan, Bastam and Gorgan have been named as being part of Ghoomes (Haghighat 1990). Many historians mentioned a high-magnitude earthquake (Io=X, Ms 7.9) on 22 December 856 in this region which wiped off the Qumes civilization from the face of the earth. At least 200000 fatalities were reported (Haghighat 1990). Fig. 5 shows a recent seismicity map for Iran which includes Semnan region. Fig. 6, then shows, the return period of the seismic events with a magnitude more than $M_s = 4$ in the region.

Actual state of conservation

The earthquake of 27 March 1830 caused many damages to the wall of Shabistan which was repaired after the earthquake. The top of minaret was ruined by the earthquake of 22 July 1927 and re-built after the event. The last restoration on the mosque was performed in 1964, when in the area around the apse, a new masonry foundation with lime mortar was built. At the same time, the roof of Shabistan was cleaned of the hash mud mixture which was rubbed on year after year (for decades) to waterproof the roof. After this restoration work along the northern wall of the dome, the mosque exhibited a variegated cracking pattern. Fig. 7 shows these variegated cracks around the dome that is the result, in the authors' hypothesis, of two different mechanisms; the first being the movement and outside rotation of the dome area (confirmed by the presence of full crack along the wall which support the dome) as a result of ground settlement and consolidation following the work around the external area of the dome and the second being the movement of northern and southern walls; which is due, certainly, to the presence of the thrust of the main arch of the dome. The understanding and correct interpretation of the actual cracking path, and knowledge of the state of conservation of the monument, is a crucial undertaking for the assessment of the mosque's vulnerability under future earthquake loads.

Structural Analysis

The analysis performed here covers the dome in which significant cracks are visible. The analysis is based on a nonlinear 3D finite element model in which the modeling is performed on the basis of the concepts of homogenized material and smeared cracking constitutive law (Luciano and Sacco 1997). In this paper a nonlinear smeared macro-model is used for the numerical simulations of the brick masonry dome. A nonlinear finite element analysis program is used to perform the analysis here. The program employs a layered finite element approach and can be used to predict the nonlinear behavior of any masonry structure that is composed of thin plate members. This includes shells, shear walls, or any combination of these structural elements.

In this program, a hypo-elastic model using the principle of equivalent uniaxial strains is used. This nonlinear model is based on the biaxial orthotropic hypo-elastic concrete model of Darwin and Pecknold (1977) and has been modified for application to masonry according to Vratsanou (1992). It uses the principle of equivalent uniaxial strains as a simplification of the complex biaxial material behavior.

The constitutive relation is described for each principal stress direction by means of the uniaxial stress-strain relation and the equivalent uniaxial strains are fictitious strains in the principal stress directions. The principal stresses correspond to the stresses of a fictitious uniaxial state. An important advantage is that the uniaxial stress-strain relationships and other required material characteristics can be derived by means of uniaxial tests. The failure criterion used is based on the assumption that the angle between the bed joints and the first principal stress direction is 45°, since the cracks in shell elements subjected to in-plane seismic loading usually arise under this angle.

For analysis of most plane stress problems, masonry is assumed to behave as a stress-induced orthotropic material. In this study, the orthotropic constitutive relationship developed by Bazant et al. (1986) model is used for modeling the masonry using the smeared cracking idealization. The constitutive matrix, D, is given by:

$$D = \frac{1}{(1-\nu^2)} \begin{bmatrix} E_1 & \nu\sqrt{E_1 E_2} & 0 \\ \nu\sqrt{E_1 E_2} & E_2 & 0 \\ 0 & 0 & \frac{1}{4}(E_1 + E_2 - 2\nu\sqrt{E_1 E_2}) \end{bmatrix} \tag{1}$$

in which, E_1 and E_2 are the tangent moduli in the directions of the material orthotropy, and ν is the Poisson's ratio. The orthotropic material directions coincide with the principal stress directions for the uncracked masonry and these directions are parallel and normal to the cracks for the cracked masonry.

Cracking of the masonry is one of the important aspects of material nonlinear behavior of the masonry. In this program, for crack modeling, smeared elasto-plastic continuum model was used. This smeared elasto-plastic continuum model is based on the non-smooth multi-surface plasticity theory and includes anisotropic elastic and inelastic behavior and is assumed to occur when the principal tensile stress at a point (usually a Gauss integration point) exceeds the tensile strength of the masonry. After cracking, the axes of orthotropy are aligned parallel and orthogonal to the crack. The elastic modulus perpendicular to the crack direction is reduced to a very small value close to zero and the Poisson effect is ignored.

Nonlinear analysis is performed using an incremental-iterative tangent stiffness approach and the element stiffness is obtained by adding the stiffness contributions of all layers at each Gauss quadrature point. The change in the material stiffness matrix during loading necessitates an incremental solution procedure with a tangent stiffness scheme.

Structural aspects and methods

The analysis method proposed and adopted in this study is based on a two-step procedure. Firstly, the overall structure is analyzed in the linear range using a complete 3D model, with the aim of characterizing the static and dynamic behavior, defining the internal force distribution among the single elementary parts and identifying the weak points of potential failure in the building. Secondly, the nonlinear model of the dome is used for assessment of the seismic behavior of the building. The comparison between the results delivers an estimate of the seismic safety level of the building, and gives an indication of the types and locations of the required restoration interventions.

Linear static analysis

As-stated previously, a preliminary linear analysis of the masonry building is performed in order to obtain some basic information on the global behavior of the building. Although the hypothesis of elastic behavior of masonry material is not strictly correct, this preliminary step is able, in the authors' opinion, to offer some basic results concerning the internal force distribution among the single elementary parts and would identify the weak points representing potential failure locations in the building. Static and dynamic analyses have been carried out on the 3D model of the mosque structural assembly using the finite element program.
The chosen mechanical properties of wall elements are in agreement with the results of existing tests (Corradi *et al*. 2002) on similar masonry and in-situ testing and are conservative. Values assumed in this study are: Young's modulus, *E*, equal to 20000 MPa, Poisson modulus, ν, equal to 0.25 and self-weight, W, equal to 22 kN/m^3. The structural elements have been analyzed under constant vertical loads, resulted from self-weight and from roof loads. Masonry walls are assumed to be connected reasonably well due to the good quality of the existing connections. The main information which can be derived from the linear analyses of the mosque is the interaction, and in particular the stress resultant distribution within the structural elements in the two principal directions. Furthermore, comparing the results obtained from these different analyses allows identifying the effect of dynamic characteristics of the building on the interaction among elements and on the distribution of internal forces. In Fig. 8, results of the static analyses on the 3D dome, under constant self-weight vertical loads and the lateral loads are reported in terms of stress resultant distribution among the structural elements. This result confirms that mosques were designed by architects who were skilled in attempting very slender schemes; these structural systems, though able to resist vertical (compressive) static loads, are not always adequate to withstand horizontal forces derived from seismic actions. Also, the results of the static analyses on the 3D dome model show, the maximum values of the displacements occur near the big arch of the dome.

Seismic analysis

Earthquake codes and regulations are not valid for the assessment of the seismic vulnerability of historical buildings which are made of materials that have aged and which have already suffered damage. To obtain the dynamic response of the structure, four different types of earthquakes (El-Centro, Bam, Tabas and Manjil) with a maximum input acceleration of 0.35g are applied. The selected sets of earthquake records are chosen in order to investigate the nonlinear structural response to an excitation with different frequency content and duration.

In order to reduce the computational effort, the previously described FE model of the mosque has been updated posing gap elements around the areas where cracks are present. The seismic analyses carried out on the nonlinear 3D FE model have allowed evaluation of the ultimate strength capacity of the mosque. Some load combinations that were used in transversal and longitudinal seismic directions allowed a direct, though approximate, assessment of the seismic safety level of the mosque. Square root of sum of squares (SRSS) technique has been used for the load combination. The most severe load combination for the building turns out to be the seismic load acting to the lower level of the dome which has low integrity and stiffness. For this load combination, the demand vs. capacity (about 11 % of seismic load) confirms the susceptibility of this type of buildings to extensive damage and possibly to collapse, as has frequently been observed during earthquakes. As a matter of fact, building collapses for a seismic load equal to about 7.5 % of external load would be due to the failure of the dome of the mosque in which the first mode takes place. Comparing the effects of different loads used in the seismic analyses, shows that the mosque is especially vulnerable at the support level, due to low integrity and stiffness and the presence of cracks in this level.

Strengthening proposal

The analysis of the static and seismic behavior of the dome has permitted us to point out two main weaknesses of the building. The state of cracking patterns at the mosque consists of two different types of cracks. The ones that pass through the masonry dome's entire height of the lower part; a second type of cracks, which are limited to the surface of the dome.

With respect to this weakness, it's then possible to suggest a strengthening retrofitting technique respectful of the architectural aspects. Regarding the second type of cracks on masonry walls, injections of aerial mortar (grout) can be used. The aim of this technique is to close the cracks and to improve the connections of the dome.

Regarding the first type of cracks, since the crack pattern was growing to the tension stress zone it was decided to apply additional CFRP sheets to the inner surface of the dome. Four layers are applied. The mechanical properties of the CFRP sheets include a density of fiber 1820 kg/m3, an effective thickness 0.165 mm, a tensile strength 4000 MPa, and a tensile modulus of elasticity of 230 GPa (Mortezaei *et al*. 2009).

At the support level of dome sub-vertical compressive stresses are highest. For increasing of dome stability and help to stiffen the entire dome with respect to tensile stresses arranged in the tangential direction, two steel plate rings are placed at this level. The results (Fig. 9) show that stresses are significantly reduced by up to 46%. Furthermore, a more uniform stress distribution over the dome is obtained after retrofitting. Also, comparing of the mode shapes of original and retrofitted dome shows increasing of mode shapes period in retrofitted dome (Fig. 10).

Conclusions

In order to assess the structural behavior and evaluate the seismic vulnerability of the Abbasi mosque of Semnan, which is a historical building dating back to the Safavi dynasty period, a finite element model of the mosque is analysed under earthquake loading. For this purpose a 3D numerical model of the mosque has been constructed firstly. A preliminary linear elastic analysis has allowed obtaining some basic information about the structural behavior of the building. Then, the mosque is subjected to a seismic analysis through the application of horizontal forces perpendicular to one another not acting simultaneously.

Comparing the demand (seismic loads) vs. capacity (material and topology strength) confirms the susceptibility of this type of building to extensive damage and possibly to collapse, as is frequently observed. It was observed that the mosque is especially vulnerable in the lower level of dome, due to low stiffness and the presence of cracks in the wall. When external steel rings and CFRP sheets are used in the dome, numerical analyses reveal that stresses are significantly reduced up to 46%. Effectiveness of the retrofit system under gravity loading is significant. On the other hand, although the effectiveness of the retrofit system seems less in case of earthquake loading, the distribution of stresses over the entire dome is more preferable when compared to the unretrofitted dome. Furthermore, a more uniform stress distribution over the dome is obtained after retrofitting.

The analysis of repair and strengthening techniques shows the effectiveness of the usual structural reinforcements in terms of increased seismic capacity. It is believed that the results and the conclusions obtained with respect to the seismic assessment of this case study can be extrapolated to the wide variety of historical mosques, and generalized for other masonry buildings.

Figure 1. Bird view of Abbasi Mosque

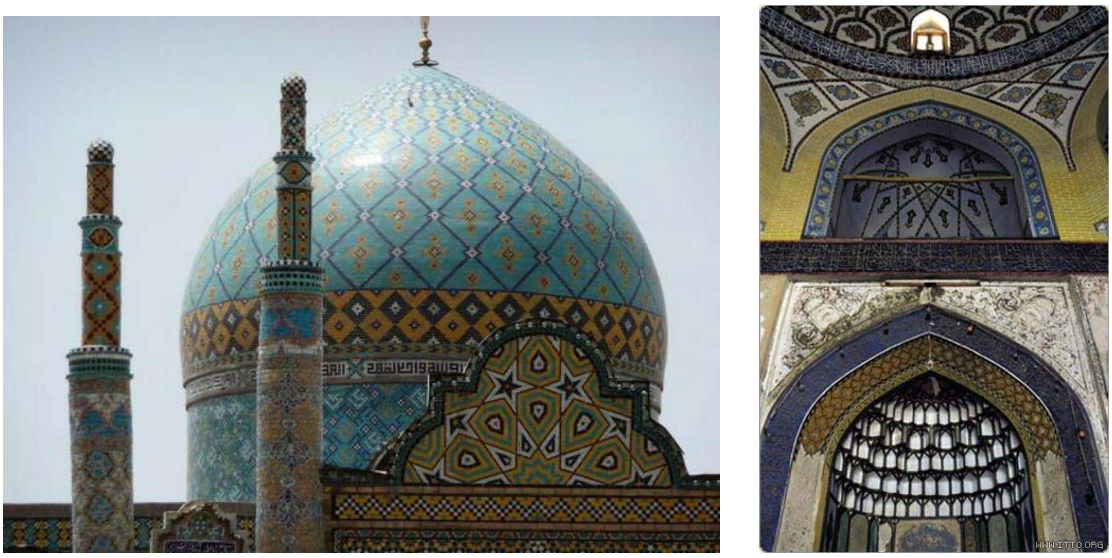


Figure 2. Arial and inner view of Abbasi Mosque's dome

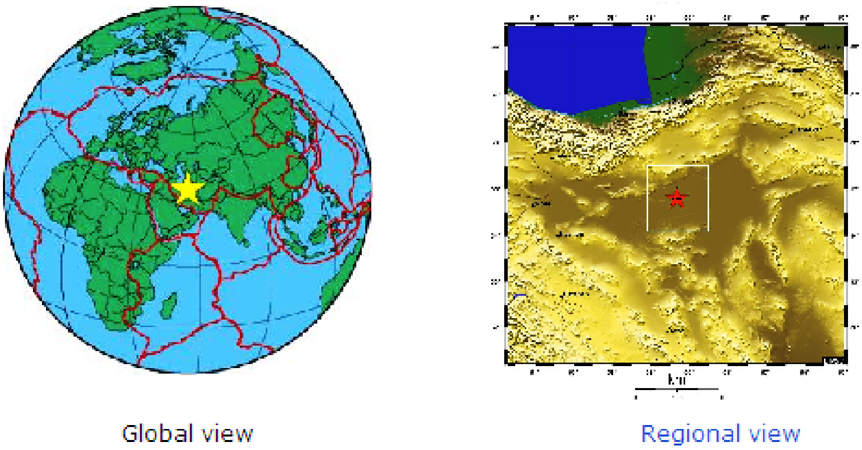


Figure 3. Global and regional view of Semnan city

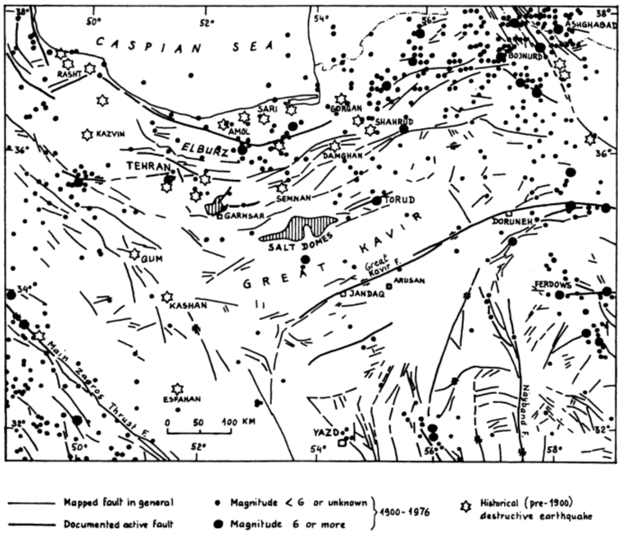


Figure 4. Map of major fault traces and earthquake epicentres in northern and central Iran

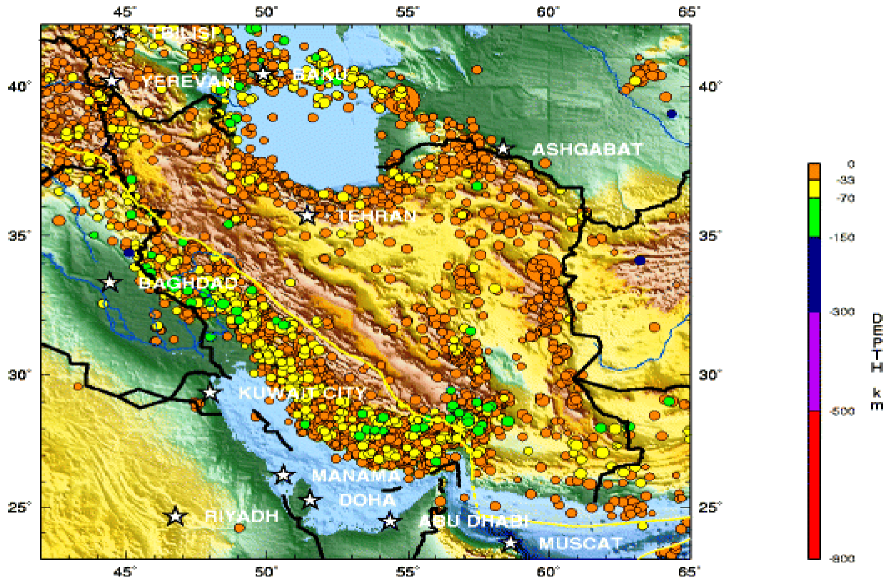


Figure 5. Seismicity of Iran, 1990-2006

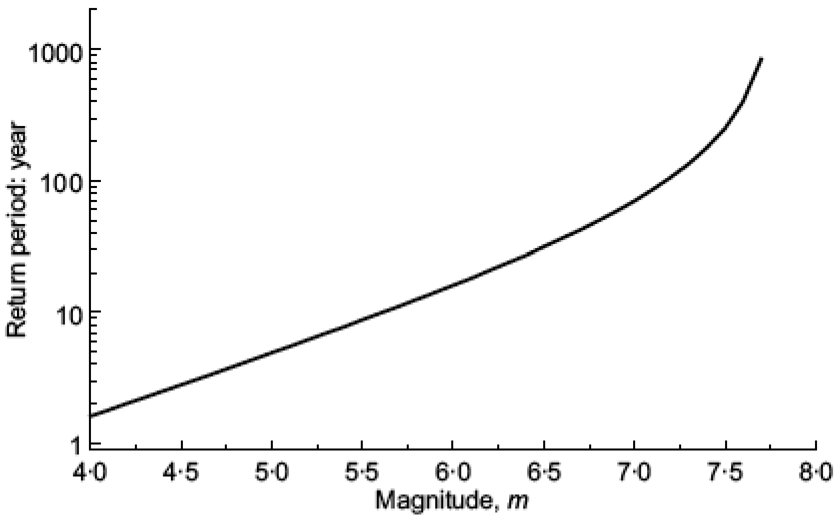


Figure 6. Return period versus earthquake magnitude for Semnan

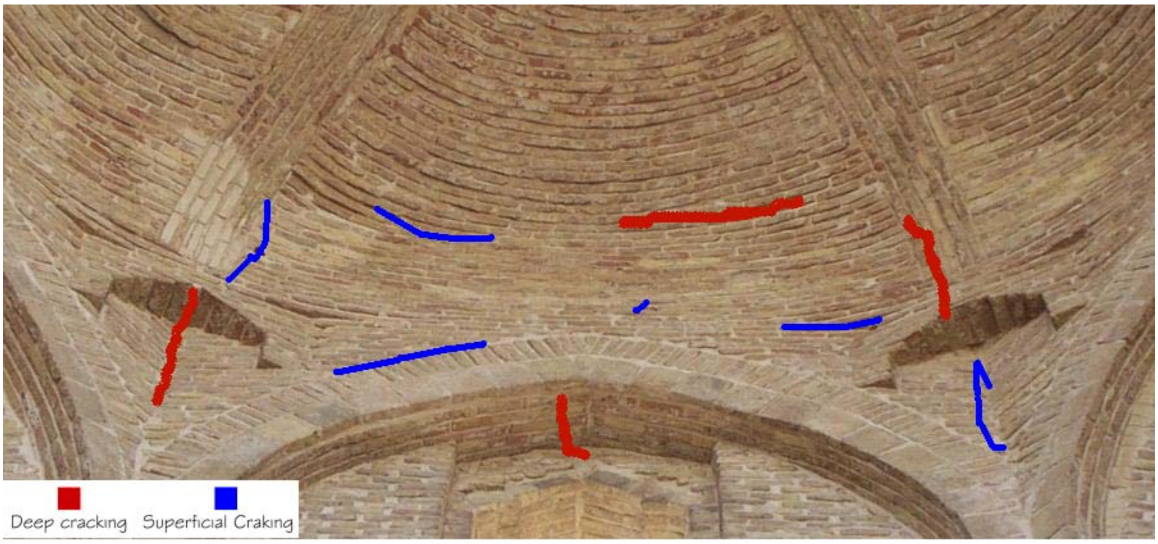
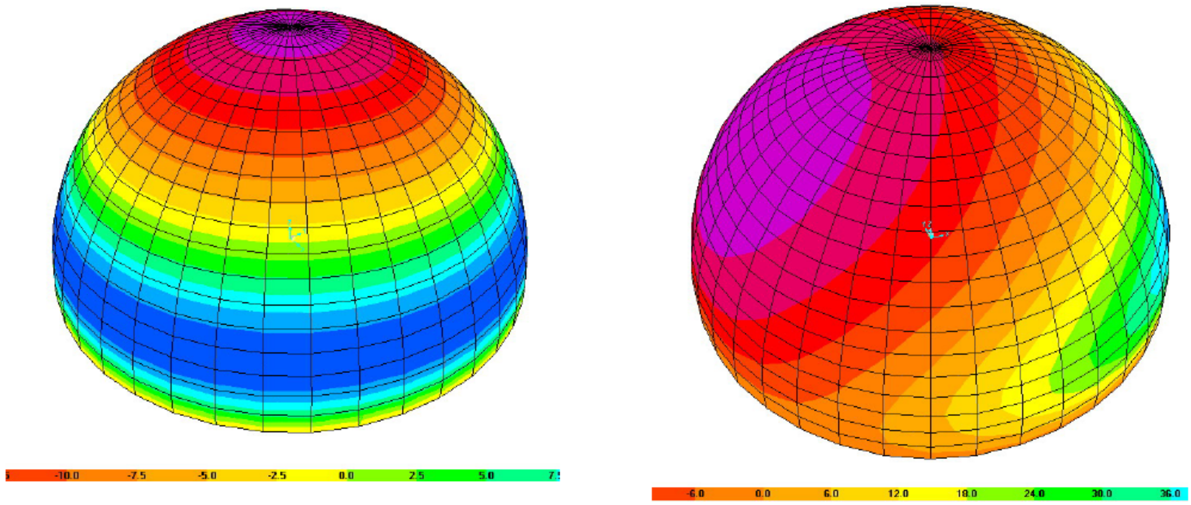
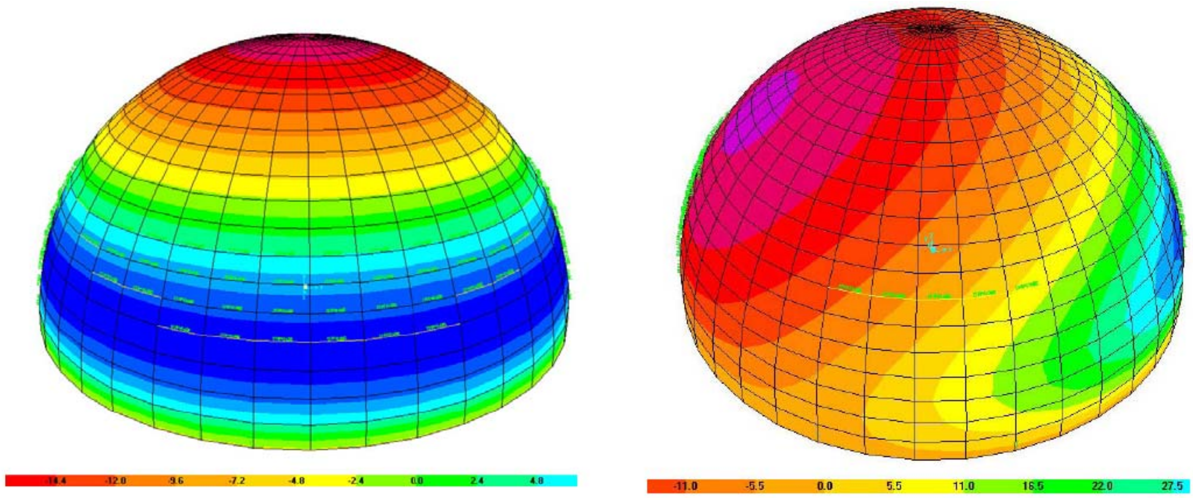


Fig. 7. Cracking pattern on the roof of Ivan



(a) (b)

Fig. 8. Vertical stresses of dome before retrofitting under the (a) vertical loads; (b) lateral loads



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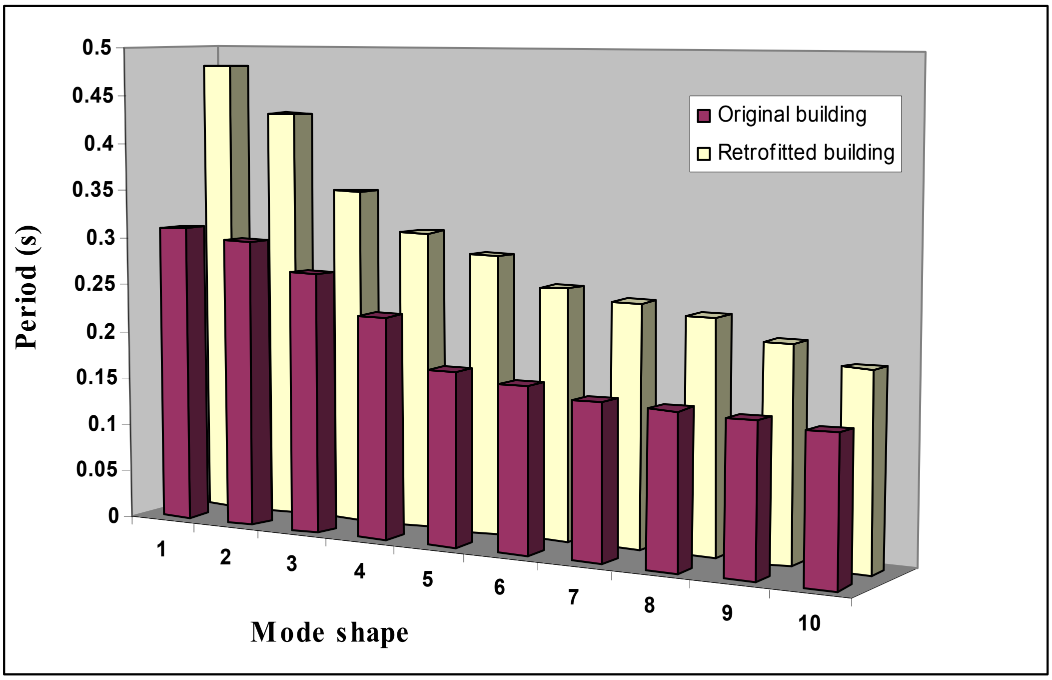

Fig. 10. Comparison of the mode shapes period for original building and retrofitted one

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