Journal of Ferdowsi Civil Engineering, Vol.27, No.1, 2016

Seismic Analysis of Persian Historical Brick Masonry Minarets

Mehrdad Hejazi[1], Sayed Mohammad Moayedian[2],
Maryam Daei

1-Introduction

Minarets play a key role in classical Persian architecture. The art of minaret construction reached its peak in the eleventh and twelfth centuries A.D., during which a large number of minarets were built in Isfahan, Central Iran, the capital of the country in that era. Barsian, Chehel-Dukhtaran, Ghar, Sin, Ali, Sariban, Ziar, Rahravan, and Bagh-i-Qush-Khana minarets are the most famous ones in Isfahan (Fig 1.). In this paper, the structural behavior of these nine minarets, which are made of brick masonry materials, is studied.


(a) (b) (c) (d)

Fig.1 A number of studied minarets in Isfahan: (a) Bagh-i-Qush-Khana; (b) Sariban; (c) Ali; (d) Chehel-Dukhtaran

In general, a minaret comprises of the basement, body and crown. The basement is constructed inside the earth on a rocky or firm soil layer. The body of the minaret consists of the central column, the spiral staircase and the outer shell. The outer shell may have different shapes with a constant or varying thickness. The crown is placed on the top of the body.

There are few works dedicated to the seismic analysis of historical minarets. The work of Hejazi that investigated Persian minarets from both architectural and structural engineering viewpoints was the first one. In his work, he gave comprehensive information based on his broad literature review. He also presented the results of structural analysis of a Persian historical brick masonry minaret.

2- Loading and method of analysis

The non-linear three-dimensional finite element method using the ANSYS code is used for analysis. The eight-node brick element SOLID 65, which incorporates both the William-Wranke and Drucker-Prager criteria, is used for modelling.

All nine minarets are analyzed under weight and seismic loads. In order to study the effect of structural elements, i.e. the outer shell, the central column and the spiral staircase, the analysis has been performed for two cases: 1) the complete minaret (outer shell + central column + staircase), and 2) only the outer shell.

Non-linear time history dynamic analysis of the minarets due to earthquakes has been performed based on the Iranian Seismic Code. Seven pairs of appropriate horizontal ground motion time history components, satisfying the characteristics mentioned in the Iranian Seismic Code, have been selected. Selected acceleration time histories representing the ground motion effects reflect the expected earthquake acceleration at the sites of the minarets.

Peak ground acceleration with a 10% probability of occurrence in 50 years in Isfahan varies from 0.18g to 0.32g, and 0.25g is suggested by the Iranian Seismic Code. Soil type in Isfahan may be compacted or semi-compacted. In this study, the soil type is assumed semi-compacted to be conservative.

Since the accelerogram data for the occurred earthquakes in Isfahan is not available, accessible time histories that belong to other sites with geologic, tectonic, seismologic and in particular soil characteristics similar to Isfahan are considered. For this reason, the strong motion database collected by the University of California at Berkeley is used. Seven earthquakes with magnitudes between 4 and 6.5 Richter, a distance less than 100 km, and soil shear wave velocity between 180 m/s and 360 m/s are chosen. The peak ground acceleration of the selected earthquakes is between 0.18g and 0.32g. The characteristics of the selected earthquakes are shown in Table 1.

Non-linear time history analysis is performed for each of the nine minarets under the seven selected earthquake scenarios.

The analysis of the results obtained indicate that all nine minarets in both cases of the complete model and only the outer shell model collapse during the early stages of the earthquake. It is due to the accumulation of cracks at the junctions of the staircase and the central column. Maximum tensile and compressive stresses occur at these points.

[1*] Corresponding Author: Associate Professor, Department of Civil Engineering, Faculty of Engineering, University of Isfahan.
Email Address : m.hejazi@eng.ui.ac.ir

[2] PhD Candidate, Department of Civil Engineering, Faculty of Engineering, University of Isfahan.

[3] Assistant Professor, Department of Civil Engineering, Faculty of Engineering, University of Isfahan.

Table 6. The characteristics of selected earthquakes used in time history dynamic analysis

No.	Earthquake name	date	Magnitude (M)	Maximum ground motion acceleration (g)
1	Coyote Lake	1979/6/8	5.7	0.248
2	Morgan Hill	1984/4/24	6.2	0.212
3	Northridge	1994/1/17	6.7	0.245
4	Parkfield	1966/6/28	6.1	0.246
5	San Fernando	1971/9/2	6.6	0.210
6	Superstition Hills	1987/11/24	6.7	0.247
7	Whittier Narrows	1987/1/10	6	0.243

3- Parametric study of seismic behavior

In order to find conditions which the minarets can withstand, a parametric study of the imposed earthquakes has been done. The parameters that were studied are the height of the minaret, tensile and compressive strengths of materials, failure criterion, and damping ratio.

In order to study the effect of height, in the finite element model the height of each minaret was gradually reduced from the top and non-linear time history analysis was performed for different assumed heights. It can be seen that the failure time is delayed by decreasing the height and the minaret does not fail at all for a specific height; i.e. 7 m or 25% of the real height for the Rahravan minaret.

By increasing the strengths of materials up to 50 times, the minarets still fail under the earthquake. An increase of 100 times, which is not possible in the real world makes the minarets strong enough against earthquakes. Therefore, it can be concluded that in practice increasing the strength of the materials cannot resolve the seismic vulnerability of minarets.

In addition to the William-Warnke failure criterion, the Drucker-Prager yield criterion was applied to a number of minarets to study the effect of failure criteria on seismic behavior. Despite changing the failure criterion, the minarets still collapse due to the earthquake during the early stages of analysis.

A number of researchers have reported that changes in damping ratio can have a significant effect on the seismic behavior of masonry structures. To evaluate this effect, damping ratio was increased from 5% to 20%, but the minarets collapsed again during the early stages of earthquakes, while they experienced more displacements.

4- Limited applicability of modern seismic codes for historical minarets

The results obtained from seismic analysis indicate that all of the minarets fail under imposed earthquakes even if the strength of the materials increases by 50 times or the height of the minarets is reduced by 50%. This is in contrast with the actual fact that all of the minarets are still standing intact after about a millennium. Similar results have been reported by other researchers (Hejazi 1997; Hejazi and Mehdizadeh Saradj 2014; EU 2006). It must be recognized that modern codes including seismic ones based on which the present study has been performed, are prepared for the design of modern structures and they can lead to unrealistic conclusions about the safety of historical structures. Only recently a limited number of regulations and guidelines, such as Italian code OPCM. 3431 and ISCARSAH Recommendations, provide recommendations for structural assessment of heritage structures.

5- Conclusions

The seismic behavior of nine Persian historical brick masonry minarets has been studied in this paper. Concluding remarks are as follows for the earthquake load.

1. The analysis shows that all the studied minarets fail during the early stages of earthquakes. Cracks are distributed from the bottom to the 10% of the height of the minaret for the complete minaret and for the outer shell model. In some cases cracks extend to 30% and 50% of the height for the complete and outer shell models, respectively. Sometimes the complete minaret model fails earlier than the outer shell model. This is due to the concentration of stresses at the junctions of the spiral staircase and central column and outer shell.
2. Shorter minarets fail later than taller ones.
3. Increasing tensile and compressive strengths, even up to 50 times, does not prevent the failure; it only postpones the failure.
4. The results obtained from the Drucker-Prager yield criterion are close to those obtained from the William-Warnke failure criterion. Only displacements at failure obtained from the former criterion are always less than those from the latter one; for the Rahravan minaret there is a reduction of 91.54% in displacements. Therefore, the Drucker-Prager yield criterion has led to a relatively good approximation for the studied minarets.
5. By increasing the damping ratio from 5% to 20% the minarets still fail during the early stages of the earthquake, but they experience larger displacements. For example, the Rahravan minaret (only the outer shell model), which fails at 1.06 s in both cases, experiences displacements of 0.065 m and 0.152 m for damping ratios of 5% and 20%, respectively.