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A SEISMIC BEHAVIOR AND REHABILITATION OF THE HISTORIC MASONRY MINARET BY EXPERIMENTAL AND NUMERICAL METHODS

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ABSTRACT

Historical masonry structures frequently present an unsatisfactory behavior under exerted seismic loads.Because ofcultural values and vulnerability of these kinds of structures to seismic loads, they must be protected and retrofitted in a way which is both safe and non-destructive. In this paper, Zein-o-din minaret, one of the Iranian historical structures in Kashan built in13th century was selected in order to find a solution which can be applied to other similar historic towers. First, some information on the geometric characteristics of the minaret was collected and afterwards by conducting related experiments, the mechanical properties of the materials were determined. Then, using ambient vibration testing, the structural dynamic behavior such as the main natural frequency of the minaret was obtained. Dynamic analyses of this minaret were implemented through ABAQUS software and the resulted natural frequency from the numerical analysis was compared to the corresponding value from ambient vibration testing. Finally, by utilizing the verified numerical models, various options were proposed for rehabilitation of the Zein-o-din minaret. The outcomes illustrated that using high strength grout for filling the gaps between the bricks and seams would be the best solution for renovation of this historical minaret.

Keywords: Dynamic analysis; earthquake engineering; finite element method; heritage structures and monuments; retrofit/ repair.

1. INTRODUCTION

Growing interest in the preservation of historic structures has stimulated a considerable need for reliable methods in analyzing of unreinforced masonry monuments. Due to the cultural significance and vulnerability against earthquake loads, rehabilitation of these structures has been at the center of academic discussions in recent years.In other words, this field has attracted the great deal of interest among many scholars and researchers.The ambient

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vibration testing has become the most important experimental method available for assessment of the dynamic behavior of full scale structures [1], the main reason would be no need for force vibration equipment and minimum interference with the normal use of the structure.The tests showed to be especially suitable for flexible systems, such as bell-towers [1], and masonries and minarets [2].Basaran et al. [3] investigated the seismic safety of masonry minaret using its dynamic characteristics. Preciado et al. [4] evaluated the seismic vulnerability of historic towers and fundamental aspects of retrofitting techniques. Muvafik [5] conducted the field research on a historical masonry brick minaret during earthquake. Conservation and structural safety assessment of ancient masonry towers have become of increasing concern; the main reason is the consequence of some disastrous eventssuch as the ones recorded in Europe such as bell-tower of St. Magdalena in Goch, Germany.Examples of recent investigations include studying of famousstructures, such as the ‘Blue mosque’ [6], the Civic Tower in Vicenza [7]and the St. Stefano bell-tower in Venice [8]. Structural safety of historical building made of reinforced concrete was evaluated by Mosoarca and Victor [9].Analytical and experimental investigations are considered in following studies: field survey of the “as built” configuration and of the crack pattern and non-destructive and slightly destructive tests (e.g. flat-jack tests or sonic pulse velocity tests).Khodayari et al. [10] investigated the behavior of Kabud Tower under lateral loads by ANSYS finite element software. Modal analysis showed that frequency of with-crack model is %1.5 less than crack free model, this value increases while the depth of crack increases over the time. Several Non-Destructive tests were carried out by different research groups on the structure of the Qotbminaret in Delhi, India. Including the research conducted byRamos et al. [11]. To evaluate its structural behavior, Dogangun et al. [12] present environmental and other factors play an important role in deterioration of historical structures. Koksal et al. [13] developed a practical approach using FRP to strength masonry walls.Altunişik et al. [14] studied the seismic response of masonry minaret and possible strengthening by Fiber Reinforced Cementitious Matrix (FRCM) materials.

Zein-o-din minaret in Kashan was built in the thirteen century AD with its original height of 47 m. this minaret was the symbol of Kashancity and was observable from any point in the city.The height has been changed in different periods as a result of seismic activities and it is continuously reduced to present 20 m height.In this paper, an ambient vibrationtest has been done to assess its structural behaviorsuch as main natural frequency of the minaret.Series of information regarding the geometric properties of the minaret were collected.Afterwards, by conductingseveral experiments, the mechanical properties and strength of the materials wereobtained. By application of these data, frequency analysis of the minaret was performed to determine its dominant natural frequency. Maximum stress and displacements of the structure is obtained through static and dynamic analyses performed by ABAQUS software.Several methods of rehabilitation are proposed, at the end, it was decided that the best solution for the tower can be presented based on the results obtained from moment-axial loadinteraction curves (M-N) of the minaret.

2. DESCRIPTION OF ZEIN-O-DIN MINARET

There are several historical documents available for Zein-o-din minaret, the most important of which is Jane Dieulafoy's itinerary. According to her description of the minaret, it was one of the tallest minarets in Iran with height of 47 m which was built in 13th century. The tower suffered severe damage as a result of major earthquakes occurred in the district of Kashan. The damage was extensive to the point that caused major crack into the main structure almost at the middle section of the minaret. Also, the two degree deviation from the straight line was developed (tilted slightly about 2°). For this reason, in the 19th century, the minaret height was reduced to about 27 m of the remaining structure and finally reduced to its current height of 20 m. Fig. 1(a) illustrates the Zein-o-din minaret with the original height of 47 m as it was built in the 13th century.Under relatively destructive earthquake in Kashan(most likely during Zand era empire), the high altitude of the minaret resulted in the loss of static equilibrium. As it was mentioned the minaret tilted slightly (about 2°) andthe deformation of the present height configuration of the minaret can be easily seen in Fig. 1(b).The minaret is shapedin the form of a cone and its diameter is reduced from the bottom upwards in such a way that the diameter is 4.3 m and 3.75 m at the lowest and highest points, respectively. The shell thickness of the minaret is 80 cm. It also has a mast of 75 cm thickness, with the tower spiral staircase going upwards around the mast. The number of stairs is 116 steps which are made of brick material. The dimensions of the stairs change according to their location at any height. The length of the stairs varies from the bottom which the step has a length of 92 cm to the last step which has smallest length of 68 cm. Fig. 2 presents the geometric characteristics of the minaret at its current form. Staircases are not fully connected to the main structure, therefore the contribution of stiffness of staircase is not modelled. However, the effect of its mass is considered to obtain fundamental frequency.

(a)

(b)

Figure 1. The Zein-o-din minaret (a) with a height of 47 meters in the thirteen century (b) the deformed configuration

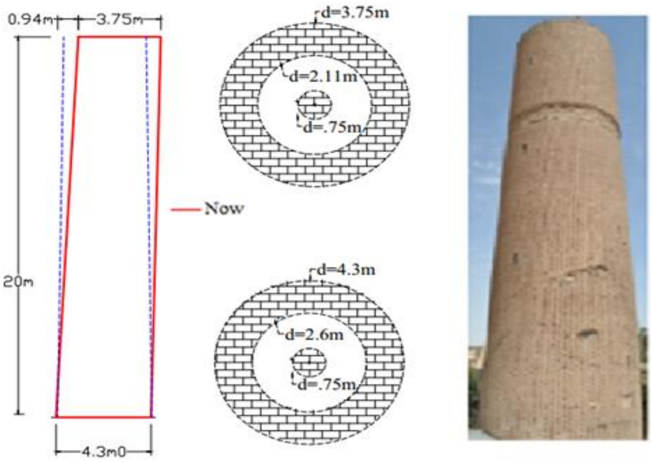


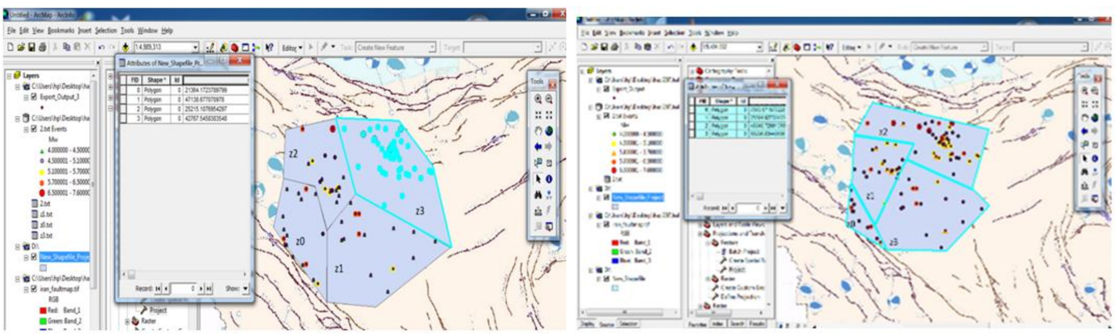
Figure 2. The geometric properties of the minaret at its current form

3. RISK ANALYSIS OF KASHAN CITY

In this section, the tectonic faults of the Kashan cityin the radius of 200 km areinvestigated. The historical and instrumentalearthquakes from 1900 to 2014 in Kashanareconsidered and Gutenberg-Richter relationships are determined through Arc-GIS software with a scaled magnitude and in text format. Finally, the site spectrum and the risk curve for the Kashan city are acquired using MATLAB computing language.

3.1 Zoning of seismic sources

In order to increase the accuracy and reliability of the results, the risk analysis and classification of seismic sources were carried out in two ways. Figs. 3(a)-(b) indicate these different classifications.After determination of Gutenberg-Richter relationships, seismicity parameters of the region and Boer’s attenuation relations, the sources are meshed and divided to smaller sections. The conducted meshing through Arc GIS software with the format of (ascii) is used as the input data for MATLAB.



(a) (b)

Figure 3. Seismic sources (a) zone 1, (b) zone 2

3.1.1 Risk analysis for the two categories

Figs. 4(a)-(b) illustrate the 475, 975 and 2475 years-old risk analysis curve for the first and second categories.

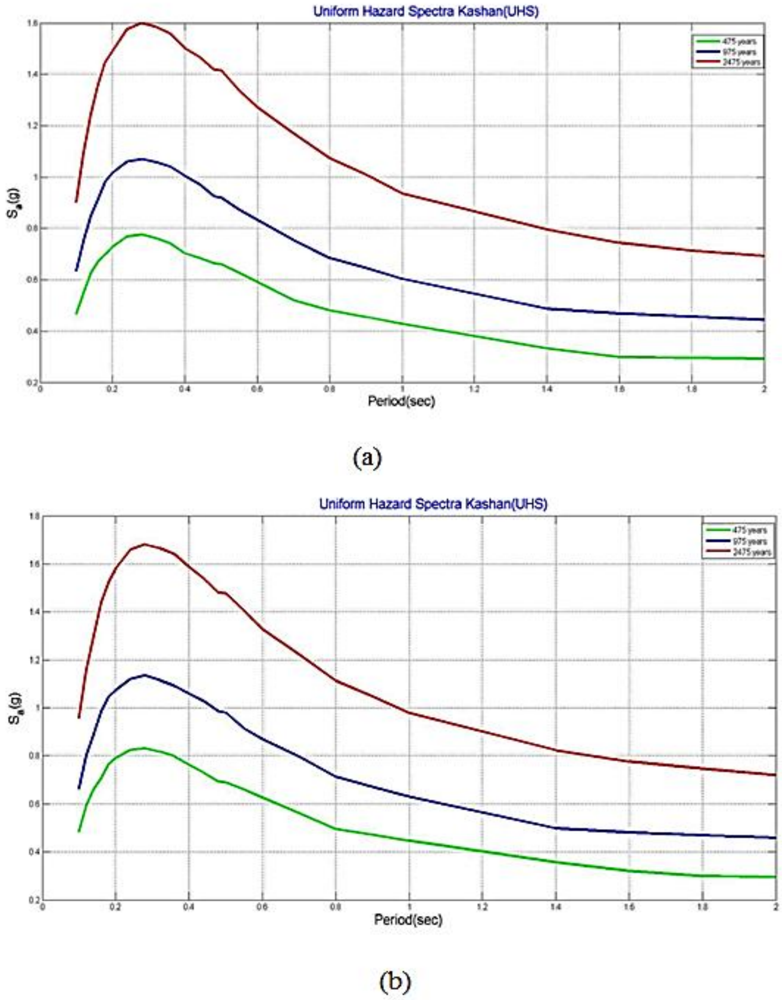


Figure 4. Risk analysis curves of acceleration (a) zone 1, (b) zone 2

3.1.2 Risk curves for the two categories

Risk curves of the first zoning are depicted in Fig. 5(a).For the first and second risk levels, the occurrence probability of 2% and 10% in 50 years (return period of 475 and 2475 years-old, respectively) can be obtained as follows:

$$T = 475\,year \quad => N_y = \frac{1}{T} = \frac{1}{475} \approx 0.002 \quad => \text{Acceleration} = 0.252g \tag{1}$$

$$T = 2475\,year \quad => N_y = \frac{1}{T} = \frac{1}{2475} \approx 0.0004 \quad => \text{Acceleration} = 0.37g \tag{2}$$

Risk curves of the first zoning are depicted in Fig. 5(b).

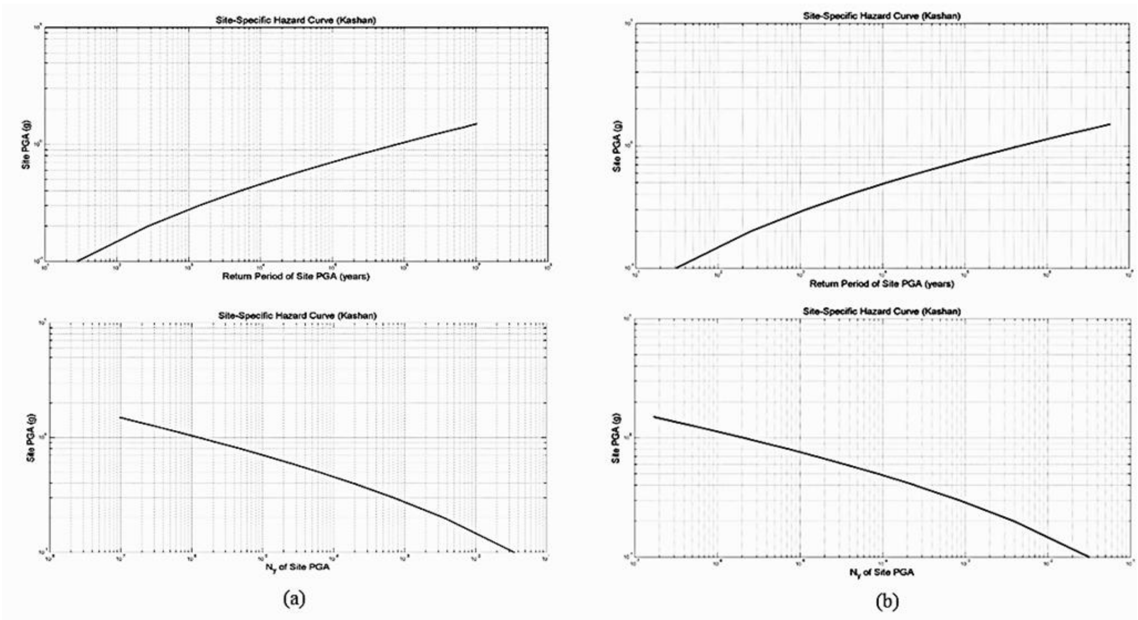


Figure 5. Risk curves (a) first zone (b) second zone

4. EXPERIMENTAL PROCEDURE

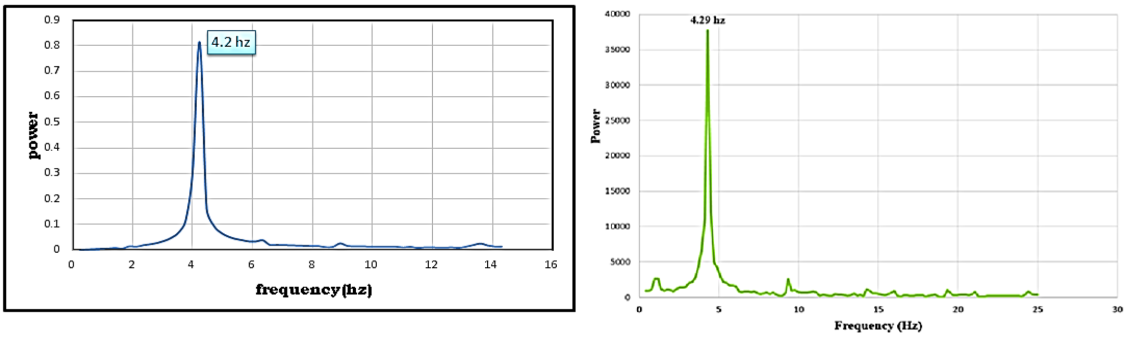
Dynamic characteristics of structures such as natural periods of vibration, the vibration modes and damping ratioare the most important factors that define the behavior of structures under seismic condition. Because of the usual simplification assumptions that have been made into the mathematical and theoretical models of these types of structures which usually ignores the effect of non-structural elements,the use of experimental techniques of such structures are even more needed. Since the actual dynamic testing of these structures reveals the true dynamic behavior of these important historical structures.In this section, the main natural frequency of the Zein-o-din minaretis obtained through ambient vibration testand then it is compared to the corresponding value resulted from the numerical analysis of the structure.

4.1 Ambient vibration test

Two methods of measurement can be utilized to obtain the dynamic characteristics of structures; one is the force vibration and the other is the ambient vibration.In these tests, a small-scale model is built and loading under different conditions are applied to the structure. Due to the fact that the scale of the model is more complicated as compared to thefull scale model, the necessity of considering the precise boundary and support conditions, the amount and intensity of the loadunder testing condition would be more highlighted.The benefit of full-scale measurements is that it requires rather inexpensive measurement devices to conduct the test.

4.2 Calibration of theaccelerometer module

The accelerometer was precisely calibrated through shaking table test. As can be observed in Figs. 6, the fundamental period resulted from force vibration test of two data loggers is 0.23s which is in good agreement with the value of 0.233s obtained from accelerometer test. They have negligible difference with numerical analysis equals 0.24s. It should be mentioned that the minaret has circular cross-section and it is well known that ambient vibration testing is not an easy task. In this case, at least two series of measurement had been performed: one in the plane where the tilt is maximum and the other in the orthogonal plane and the results are the same.

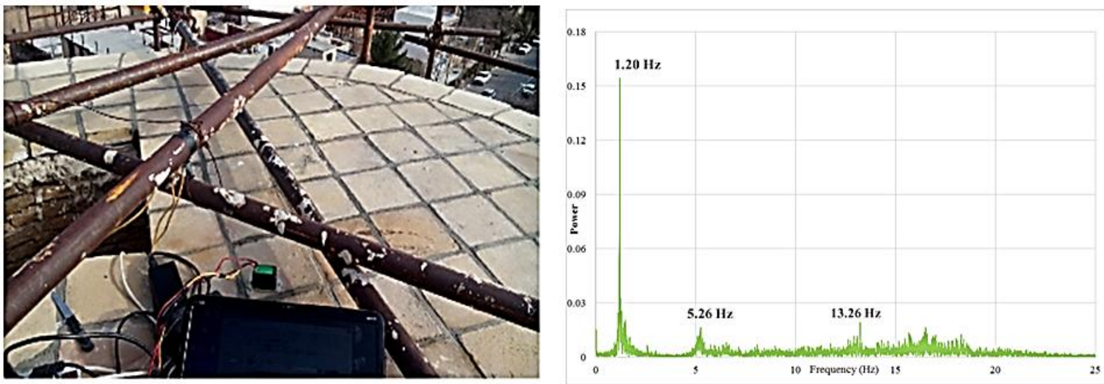


(a) (b)

Figure 6. The response spectrum obtained from experimental model using (a) centronics data logger (b) accelerometer

4.3 Recording of zein-o-din minaret

Fig. 7(a) shows the recording of Zein-o-din minaret in which the data will be stored in a text file after installation of accelerometer to the mentioned board. The recording time took place between 5 to 6 minutes. Fig. 7(b) shows the dominant natural frequency of the first mode to be 1.2 Hz, this is the fundamental frequency of the structure which is obtained using the highest mass participation factor (90 %).



(a) (b)

Figure 7. (a) Recording of Zein-o-din minaret (b) dominant natural frequency of the first mode

4.4 Properties of materials

Regarding lack of information about the quality of applied materials in Zein-o-din historic minaret in Kashan, in this section it is tried to provide necessary information for numerical modeling through performing material testing, the results can be utilized toproposerehabilitation methods in the following sections.

4.4.1 Description of grout quality control test

According to the criteria of rehabilitation codes (FEMA 357), grout of masonry walls should be tested for shear strength.Grout shear strength (V_t) should be determined on the basis of the experiments which is 80% of test values (V_{to}). Walls that their grout shear strength is less than 2 kg/cm^2 are not met the minimum grout quality requirements and they are vulnerable in terms of shear strength. To do the grout quality control test, an enerpac 104 jack has been utilized. Fig. 8(a) shows the schematic of the conducted test.

4.4.2 Moisture content of brick

The brick which is chosen to determine its moisture percent is weighted (W_1) and it is put in the oven at 110 °C, and exited it after 24 hours, then it is weighted (W_2). The moisture content can be determined as $\frac{100(W_1 - W_2)}{W_1}$. Therefore, the moisture content for the bricks of the minaret using W_1=390.88 and W_2=387.53 is 0.86%.

4.4.3 Water absorption test of brick

The brick that had chosen to determine its moisture percent is weighted (W_d). It is completely soaked in the plastic container consist of clean water, and waitedfor 24 hours, its surrounding should be cleaned with a moistened cloth, then it is weighted as W_s.The water absorption of the brick used in the minaret with W_d=387.53 and W_s=442.21 is 14.11%.

4.4.4 Determination of brick density

The brick density can be determined as follow:

$$W=390.88\ g \tag{3}$$

$$V = L*B*H \Rightarrow V = 13.271*5.918*2.788 = 218.96 \tag{4}$$

$$Density = \frac{390.88}{218.96} = 1785.2 kg/m^3 \tag{5}$$

In which L, B and H are denoting the length, width and height of the brick, respectively.

4.4.5 Determination of elasticmodulus with stm-600

Elastic modulusof brick is obtained as 1080 MPa from the test using equipment (STM-600),

Fig. 8(b) Indicates the test condition.

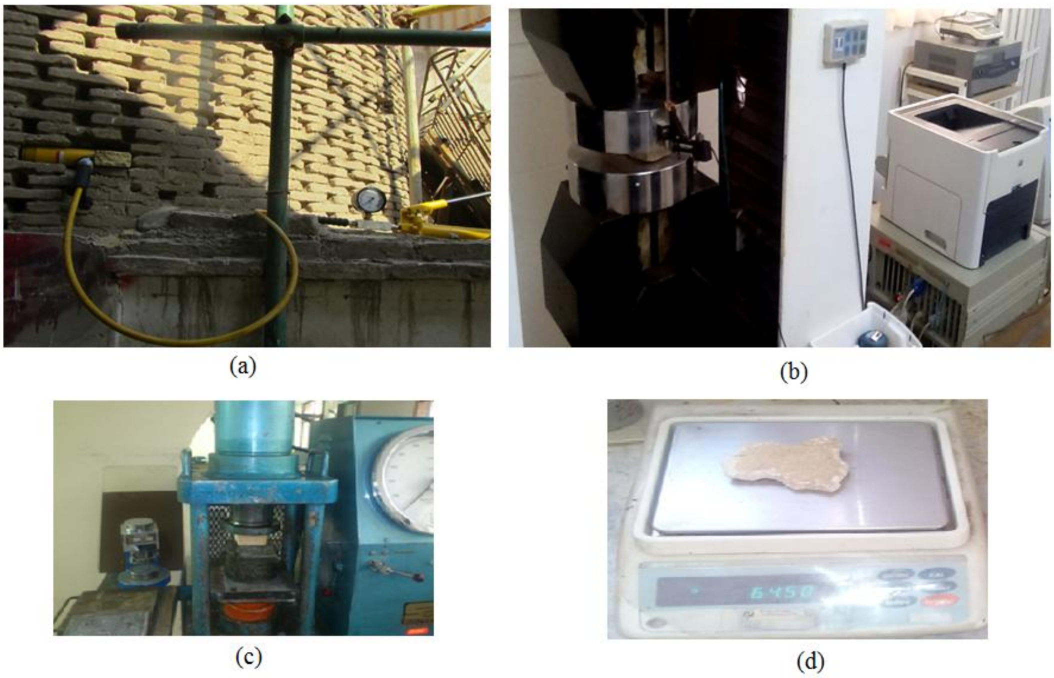


Figure 8. (a) Grout quality control test (b) determination of elastic modulus (c) determination the compressive strength of brick (d) determination of grout weight

4.4.6 The compressive strength of kashan traditional brick (for the purpose of rehabilitation)

Brick compressive strength can be obtained from the following equation:

$$C = \frac{W}{A} = \frac{8100}{85.56} = 94.67 kg / cm^2 \tag{6}$$

In which, *C*, *W* and *A* are denoting the compressive strength of the brick, maximum applied load and under loading surface, respectively. Fig. 8(c)shows the test for determining the compressive strength of brick.

4.4.7 The density of kashan traditional brick (for the purpose of rehabilitation)

According to the test of brick density:

$$\text{W} = 609.2 \text{ g} \tag{7}$$

$$V = L * B * H \Rightarrow V = 10.32 * 8.29 * 4.18 = 357.61 cm^3 \tag{8}$$

$$\text{The density of brick } = \frac{609.2}{357.61} = 1703.5 kg / m^3 \tag{9}$$

4.4.8 Determining the percentage of grout moisture

The grout that has chosen to determine its moisture percent is weighted (W_1), and put in the oven at 110 °C, and waitedfor 24 hours, then it weighted as (W_2). Fig. 8(d)shows the method of weighing the grout. According to the $\frac{100(W_1 - W_2)}{W_1}$, the moisture percentage would be 1.09%.

4.4.9 The grout water absorption test

The process is similar to the brick water absorption test and the grout water absorption percentage can be determined. The water absorption of the brick used in the minaret with W_d=63.87 and W_s=74.59 is 16.87%.

$$\text{And the grout water absorption percentage} = \frac{100(74.59 - 63.87)}{63.87} = 16.87\% \tag{10}$$

4.4.10 Determination of the grout density

The grout is weighted in the scales as W, and then it is put in a glass jar containing water for 24 hours until it becomes saturated. After addition of some water in a beaker, the volume of water can be recorded as V_1. After putting saturated grouts in the beaker, the volume is recorded as V_2 and the grout density achieved the following equation:

$$\text{Grout density} = \frac{W}{V_2 - V_1} = \frac{64.49}{418 - 384} = 1896 kg / m^3 \tag{11}$$

5. FINITE ELEMENT MODELING AND ANALYSIS

5.1 Modeling by abaqus software

Material with density of 1850 kg/m^3, elasticity modulus of 1.1 GPa and Poisson ratio of 0.17 was definedthrough finite element software of ABAQUS [15]. All the nodes of the support of structure are considered to be constrained from moving and rotating in all directions. Regarding to the conducted analysis, the frequency value of minaret equals 1.27 Hz which is in good agreement with the test result. Once again, the effect of mass due to staircases is modeled, however since the staircase is not fully attached to the minaret, the stiffness effect of staircase is not modeled.

5.2 Dynamic analysis of zein-o-dinminaret

Complexity in the study of seismic behavior of historical masonry structures will be possible with the combination of different models assessment. In order to attain a better and more comprehensive interpretation of seismic behavior of model, dynamic analysis can be used.

Analysis Hypotheses

1. The interaction effect of soil and minaret has been disregarded.

2. Materials behave homogeneously and linearly elastic.
   In the following, linear dynamic analysis stepsof Zein-o-din minaret are defined.

5.2.1 Record selection

By plotting the spectrum of a local earthquake occurred in Kashanand its comparison to the spectrum of 475 year-old for the site in the time period of 0.2T to 1.5T, the earthquake record has been modified.

5.2.2 Dynamic analysis results

Fig. 9 shows the von Mises stress, deformation and horizontal displacement of the minaret. According to the resulted diagrams from dynamic analysis, the displacement of top of the minaret equals to 12.5 cm.considering the fact that the near faults have located in distance of less than 20 km from the Kashan, the selected record is a near-fault earthquake with strong motion duration of 17.4s. Besides, the maximum induced stress in minaret is 32 kg/cm^2.In spite of the compressive strength about 66 kg/cm^{2}and tensile strength of 6.6 kg/cm^2, the required tensile strength of the minaret cannot be satisfied and the minaretexperiences the nonlinear behavior. Therefore, it is essential that the minaret be retrofitted for at most half of its height (about 10 meters). It should be mentioned that the minaret has the required compressive strength against the exerted record.

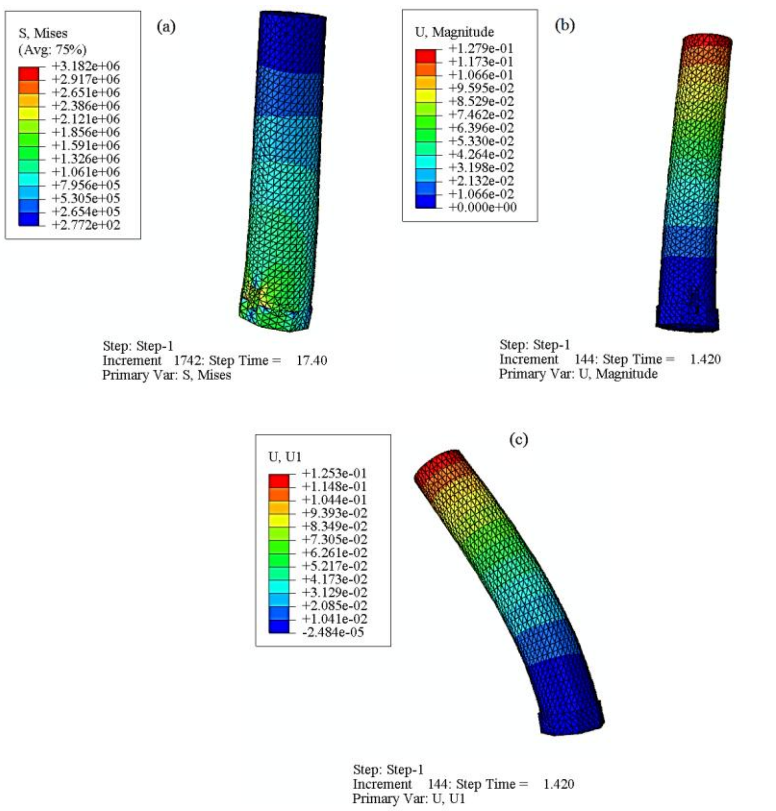


Figure 9. (a) The von Mises stress, (b) deformation of the minaret, (c) horizontal displacement

5.3 Comparison of mode shapes of numerical modelwith cantilever beam

This section deals with the comparison of mode shapes obtained from finite element method to a simplified model of a cantilever beam with distributed load under bending. Regarding the fact that the mode shape would be a flexural beam, with the comparison of mode shapes of software which considers the whole energies such as bending and shear to the cantilever beam, it can be concluded that the mode shape of Zein-o-din minaret is approximately flexural. The mode shape of the illustrated beam is determined based on the following equations:

$$\Phi(x) = A1 \cos ax + A2 \sin ax + A3 \cosh ax + A4 \sinh ax \quad (12)$$

$$\Phi(0) = 0 \text{ و } \Phi'(0) = 0 \quad (13)$$

$$M(L) = EI\,\Phi''(L) = 0 \text{ و } V(L) = EI\,\Phi'''(L) = 0 \quad (14)$$

$$\Phi(0) = (A1 \cos 0 + A2 \sin 0 + A3 \cosh 0 + A4 \sinh 0) = 0 \quad (15)$$

$$\Phi'(0) = a(-A1 \sin 0 + A2 \cos 0 + A3 \sinh 0 + A4 \cosh 0) = 0 \quad (16)$$

$$\Phi''(L) = a2(-A1 \cos aL - A2 \sin aL + A3 \cosh aL + A4 \sinh aL) = 0 \quad (17)$$

$$\Phi'''(L) = a3(A1 \sin aL - A2 \cos aL + A3 \sinh aL + A4 \cosh aL) = 0 \quad (18)$$

$$(aL)_1=1.875,\ (aL)_2=4.694,\ (aL)_3=7.855,\ (aL)_4=10.996)$$

$$\Phi(x) = A_1\left[\cos ax - \cosh ax - \frac{(\cos aL + \cosh aL)}{(\sin aL + \sinh aL)}(\sin ax - \sinh ax)\right] \quad (19$$

Fig. 10 depicts the comparison between first mode shape obtained from ABAQUS software and the cantilever beam. As can be seen, there is a good agreement between these mode shapes.

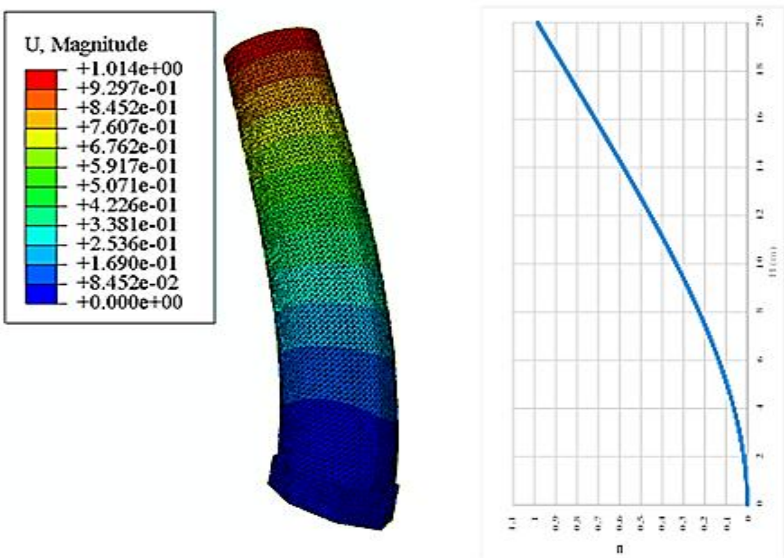


Figure 10. Comparison between first mode shapes obtained from ABAQUS and the cantilever beam

6. MINARET REHABILITATION

The mechanical properties of traditional materials are much lower than concrete and steel. For example, the compressive strength of concrete is 23 times more than a clay brick. For this reason, the low resistance of the constituent materials and fatigue in historic structures are their major weakness against earthquake loading.

6.1 N-M interaction curve for zein-o-din minaret

After determination of material propertieswhich are presented in Table 1, the (N-M) interaction curve was obtained, based on the weight of the minaret equals to 356.33 ton, the moment capacity of 1098 ton.m can be determined.

Table 1: Properties of material

Compressive strength	66 kg/cm^2
Tensile strength	6.6 kg/cm^2
Compressive strain	0.003
Tensile strain	0.002
Density	1850 kg/m^3

6.2 Various rehabilitation methods of the minaret

6.2.1 Filling joints between the bricks by resistant grout

According to the grout quality test which was previously mentioned, the shear strength was lower than the minimum level of shear strength and it is required to retrofit the grout in order to enhance its properties. One of the best approaches for this purpose is utilizing resistant grout which contains epoxy material. In the following section,its properties and implementationof this non-destructive method will be explained.

6.2.1.1 Properties of resistant grout

Positive properties of resistant grout include itshigh-strength, low permeability,easy usage, being economical, durable andcompatible with masonry materials and cement.By filling the outer seams of the minaret with resistant grout, the minaret is surrounded by this grout and the disruption and protrusion of minaret's wall due to the compressive forces can be prevented.

6.2.1.2 Quality control of resistantgrout

Rehabilitation by resistant grout was conducted and the results are as follow. The values of V_{test}=2150 kg, A_b=2*19.2*18.6=712.4 cm^{2,} σc=0.05 kg/cm ^{2,} V_{to}=2.96 kg/cm ^{2} are selected.

$$Shear\ strength=0.8*2.96=2.37kg/cm^2 \qquad (20)$$

According to the obtained data, the shear strength is higher than minimum level of shear strength which is equal to 2 kg/cm^2.

6.3 Hydrophobic surfaces using nanotechnology

Insulating the surface of historic structures is one of the most common ways to deal with waterproofing of structural materials. Nowadays, there isa wide range ofcommon insulation methods utilizing traditional materials such as thatch and various polymer and resin insulators. The difference between using these common insulators and nano insulator is that in nano insulator the air molecules are easily exchanged in and out of the surface.According to field surveying, it was observed that this non-destructive method can be easily done with minimal intervention.

6.3.1 Core seismic retrofitting

In order to operate the core retrofitting, a column is divided into equal or unequal (according to the current situation) sections and the holes are created. Doing this with grouting concrete in the bottom of the structure significantly increase its seismic strength.

6.3.1.1 Replacingthe core of themasonry structurewith reinforced concrete core

The mast of the minaret is considered as its central core, the inner core can be completely removed and replaced with concrete with minimal intervention. In general, this approach leads to a lot of damages to the architecture and appearance of structure and it is too complicated to be implemented. In addition, this method is less confident than other methods of reinforcement because of its more complex performance with the outer wall. The replaced concrete core has diameter of 75 cm and reinforced by 20 rebars of 18 cm diameter and 5 cm cover.

6.3.1.2 Replacingthe core of the masonry structurewith steel core

Due to the higher modulus of elasticity and strength, using steel instead of reinforced concrete in rehabilitation causes lower damages to historic structures. Also, the appearance of the structure often preserved its original form.In this method, a part of brick core is removed and it will be replaced by steel materials. The diameter of the hole is 20 cm, therefore the diameter of inner core will be 20 cm. This method of rehabilitation is taken on the entire height of the minaret. The implementation of this method would be too complicated and expensive due to the height of the minaret.

6.3.2 Rehabilitation with frp

According to the previous sections, FRP has high tensile strength. Because of low damages to the minaret, utilizing of FRP is a practical approach with minimal intervention. In this method, a layer of FRP is wrapped around the inner wall of the core in the lower half of minaret height. It should be noted that, in retrofitting by this method, the corner of the stairs is needed to be demolished in order to passing FRP and it will be reconstructed after implementation. The disadvantage of this method would be its high cost of implementation.

6.3.3 Injection

Another way to rehabilitate the cracked components of the structure is to filling gaps and holes between the different components by injecting grout or different resins. In this way, the injected materials fill the holes of masonry materials and lead to more uniform distribution of the tensions between the different components and therefore increases loading capacity.

7. CONCLUSION

In this study, the Zein-o-din minaret of Kashan as one of the historic structures of Iran (more than 700 years old) was investigated by performing the ambient vibration measurement, grout cutting test, mechanical tests on the bricks and grout, as well as and numerical analysis and risk analysis of so called minaret.The results of this study are as follow:

1. The fundamental natural frequency of the minaret was measured to be 1.2 Hz based on the results of ambient vibration test. The numerical model was developed which incorporates the properties of the existing grout. The fundamental natural frequency obtained from numerical model indicates that there is a good agreement with experimental results.
2. The maximum acceleration in Kashan city achieved by risk analysis studies is 0.372g (for risk second level, the occurrence probability of 2% in 50 years of useful life or the return period of 2475 years)
3. According to the quality control test of the grout, the shear strength obtained from grout control test was equal to 1.1 kg/cm^2. Since the minimum shear strength of grouts should be 2 kg/cm^2 based on existing instructions of seismic rehabilitation, its shear strength is inadequate and should be replaced with reinforced grouts.
4. Utilizing the verified numerical model, the dynamic analyses of the tower was performed. According to the dynamic analysis, maximum stress on the Zein-o-din minaret under the earthquake with return period of 475 years is equal to 32 kg/cm^2. The minaret does not have required tensile strength with the compressive strength of 66 kg/cm^2 and tensile strength of 6.6 kg/cm^2 and goes to non-linear area. Therefore, it required to retrofitting up to its half highest (about 10 m). In addition, the shape of the first mode is in accordance with bending behavior.
5. By comparing the mode shape of the Zein-o-din minaret with under bending beam, it can be found that the mode shape of minaret is flexural.
6. One of the non-destructive rehabilitation methods with minimal intervention is to substitute the present grout with the higher strength property grout. The numerical results show a great deal of improvement in terms of lowering the stresses within acceptable range.

The following recommendations are suggested to further studies which include micro-scale modeling of the minaret, nonlinear dynamic analysis of the model, the effect of any crack initiation and propagation in the grout and brick elements, additional soil mechanic tests in order to obtain the bearing capacity of the soil surrounding the minaret and a model which includes soil-structure interaction.

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