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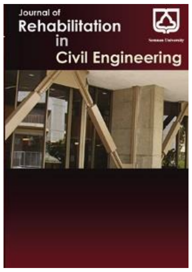

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Seismic Vulnerability and Rehabilitation of One of the World's Oldest Masonry Minaret under the Different Earthquake Frequency Content

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ABSTRACT

Historical sites and remnant monuments from different eras in Iran are the main reasons of tourist attraction. One of the factors that endanger existence of these monuments is earthquakes and it is well known that Iran is located on the Alpide seismicbelt and earthquakes are inevitable. Understanding the structural behavior as well as possible weaknesses and then seismic strengthening under the earthquake are the ways of mitigating hazard in architectural heritage. Minaret of Tarikhanehmosque which is one of the oldest minarets and most precious historical monuments in Islamic world was built between 130 and 170 AH (750-760 AD). In the present study, this minaret is first modeled via ABAQUS finite element software considering geometric details and different seismic analysis such as pushover, modal and nonlinear time history analysis is conducted under the different earthquake frequency contents. After realizing the current state and weaknesses of the minaret, seismic strengthening is done via three different methods including FRP sheets, Ferro-cement (welded wire mesh with micro-concrete/mortar), and fiber reinforced cementitious matrix (FRCM) material. Finally, results of these three strengthening methods were evaluated and the most appropriate method was selected. According to the results, it was observed that Ferro-cement strengthening method is the most effective one among the proposed methods; so that, in comparison to the FRCM strengthening method, this method is effective by up to 100 %.

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1. Introduction

Nowadays Tourism and tourist attraction, which is one of the most important ways to business income and economic prosperity in different societies, relies on geographical, continental and historical location of country. Iran with his chronological background has benefited from these historical aspects. This country with the geographical coordinates of eastern longitudes of 43 to 63 degrees and northern latitude of 25 to 40 degrees is located on the middle of Aliped seismic belt. Large and small earthquakes which occasionally take place are indicative of an active tectonic area in this region [16, 27]. Based on the tectonic setting [31], active fault map [18] and seismicity, the country is divided into three zones including Alborz Mountain Range, Zagros continental collision zone and Eastern and Central Iran, located between Alborz and Zagros (Fig. 1).

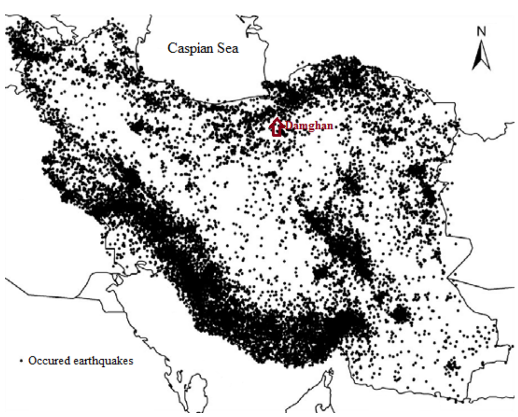


Fig. 1. Seismicity map of Iran.

The Khazar reverse fault is the longest active fault in Alborz and is located at the northern edge of the Alborz Mountains [17]. This is a zone of high seismicity, and strong earthquakes have been recorded in the area. The strongest earthquake which has been occurred is the Damghan earthquake of MS 7.9, which occurred on 856 AD and caused 200000 fatalities [2].

The city of Damghan, which has currently located in the Semnan province, is one of the most ancient urban metropolis in the Iranian plateau, with many historical monuments including Tappeh Hessar which belongs to the Median (728-550 BCE), Parthians (248-224 CE) and Sassanid (224-651 CE) dynastic periods [37].

The Tarikhaneh mosque, which is one of the ancient artifacts, was built as a fire temple during the Sassanid dynasty and converted into a mosque after the advent of Islam. Its construction is referred to second AH century, between 130 and 170 AH (750-760 AD), and its building style is similar to Sassanid era buildings (Fig.2). This historical structure was registered as national cultural heritage with the reference No. 80 [40].

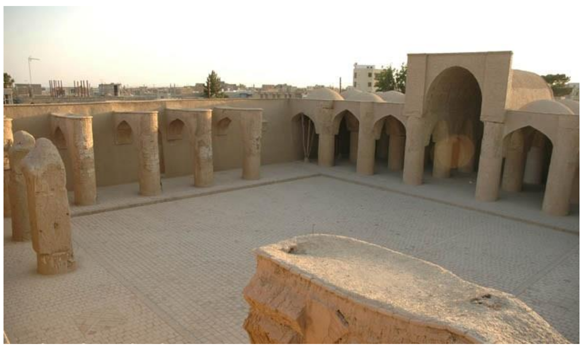
Studying literature review shows that, due to the seismic condition of the site and necessity of preserving the historical monuments as the standing global heritage, which is regarded as a nation's cultural identity, no comprehensive study has been ever carried out in this regard. This paper thus is aimed to investigate the stability of this structure subjected to the earthquakes with different frequency contents and necessity of seismic rehabilitation.

2. Minaret of Tarikhane mosque

2.1. Geometrical features

Tari is the Turkic term for God and Khaneh is a Persian word meaning house. Therefore, the compound word Tarikhaneh, translates into "the house of God". The Tarikhaneh Temple, also called the Tarikhaneh Mosque, is a Sassanid-era monument located on the southern limit of the present day city of Damghan, Iran. This structure was initially used as a Zoroastrian Fire Temple during the Sassanid period; however, after the fall of the

Sassanid Empire it was rebuilt and converted into a mosque in the 8th century. The monument is, thus, known as the oldest mosque in Iran [7]. A square yard including a columned hall built in Qibla side and a row of porches in other three sides are the constituent components of this mosque (Fig. 3).



(a)

(b)

(c)

Fig. 2. Tarikhaneh mosque (a) square courtyard, (b) arcades of barrel vaults supported by circular pillars, (c) cylindrical minaret.

Fig. 3. Bird view of Tarikhaneh mosque.

Columned hall includes seven longitudinal drains toward Qibla and three latitudinal drains in a way that middle drain including altar and pulpit, is wider than other two side drains that expresses initial forming steps of the porch in Iranian Shabestani mosques. This mosque has an open apron with dimensions of 26.72 meters in length and 25.72 meters in width, which is surrounded by an arched space in a way that 22 arch entrances are opened to the mentioned apron. As shown in Fig. 3, it is obvious that great numbers of these arches have been collapsed and just a few of them are survived in recent years.

There is a minaret adjacent to and in north side of Tarikhane mosque, which is built of bricks. According to references, height of the minaret is 26 meters, its perimeter is 13 meters at the bottom and by increasing the height of minaret relative to surface its perimeter decreases so that the perimeter of minaret is 6.8 meters at the top (Fig.4). The minaret, which is strikingly divided into six zones of ornamentation, each rendered in brick with a different geometric pattern, has not any platforms and has been built in circular shape on the floor. Bricks that are used in the structure of this minaret are 4 to 4.5 cm in diameter and 22 cm in both length and width, and bricks that are used for external decorations are 17 or 17.5 cm in both length and width and 3.5 cm in thickness.

Since exact features of the minaret were required for modeling and analyzing, these feature wearer-measured accurately by using a Total Station in four stations and 216 points (Table1). Through this accurate measurement, the perimeters of highest and lowest parts of the structure as well as accuracy of eccentricity of the minaret top were specified. It is remarkable that the minaret top eccentricity is equal to 69 cm in the horizontal direction, thus its incline would be almost 2.89 percent. Having this detailed information could be highly effective in the accuracy of the results.

Fig. 4. The minaret of Tarikhaneh mosque.

Table1. Accurate measurement of the minaret.

Location	Radius (m)	Area (m²)	Perimeter (m)
Upper ring of minaret	1.051	3.471	6.605
Lower ring of minaret	2.118	14.092	13.307
Height of minaret(meter)	23.828		

2.2. Mechanical properties of materials

Knowing the current physical and mechanical properties of the used materials in the monumental structure is another important step in modeling and analyzing of the heritage buildings. Accurate information about the mechanical properties of a structural material needs a set of various tests which some of them are destructive. Nevertheless, because of some principles and protocols in conservation and structural restoration of architectural heritage[20], destructive tests have not been permitted. Therefore, non-destructive methods or moderately destructive methods with a lower level of destruction are more widely used [8]. For this reason, 100 mm diameter cores was used in this study to determine the mechanical properties of the materials whose advantages have been mentioned by Sassoni and Mazzotti (2013). By means of this method, mechanical properties of the minaret materials have been determined considering type and kind of the brick materials and mortar used in the construction.

In determining mechanical properties of materialsit is worth noting that minaret walls has been made of two different kinds of bricks, one of them are bricks with 22.5 cm width that are structural elements and another type with 17 cm width which is used in outer layer for the purpose of decoration. However decorative bricks have no effect on calculating resistance and their resistant effects has been neglected, however mass effects were considered in density value which play a great role in calculating lateral force.The results of testing the samples taken from different parts of the building based on the above mentioned method are presented in Table 2.

Table2. Mechanical properties of material.

Mass density (kg/m³)	Poisson's ratio	Young's modulus (kg/m²)	f_t' (kg/m²)	f_c' (kg/m²)	Dilation angle (degree)
3108	0.18	2200	0.14	4	25

where fc' is compressive strength and ft' is tensile strength of masonry material used in the minaret.

Also, based on the borehole drilling of the soils surrounding the minaret, the soil texture was well-graded gravel which classified as coarse soil.

2.3. Finite element modeling

In order to conduct a non-linear dynamic analysis, the minaret model was simulated using finite element software ABAQUS. Because of large volume of the minaret structure and the fact that numerous bricks have been used in the construction of this monument, microscopic modeling method would be so expensive and time-consuming. As a result, macro modeling method was employed. By using this method detachment of bricks and mortar has been ignored and a uniform element is utilized [9]. Since the foundation of the minaret is sited on the hard soil, soil-structure interaction is not considered in the finite element model [4].

In this regard, a four grid shell element type with reduced integration point, S4R, was selected. The reason of using this element is its low structural thickness relative to the other dimensions. This means that shell elements are used for structural modeling where the ratio of thickness to other dimensions is less than 10 percent. Moreover, using the first order element with linear function (first order) considering employment of a reduced integration point which decreases integrating points to one single point at the middle of the element, decrease the cost and time of analytical procedure along with a proper accuracy. It is noteworthy to say that the minaret model was discretized with 6978 elements and corresponding 28171 nodes (Fig. 5).

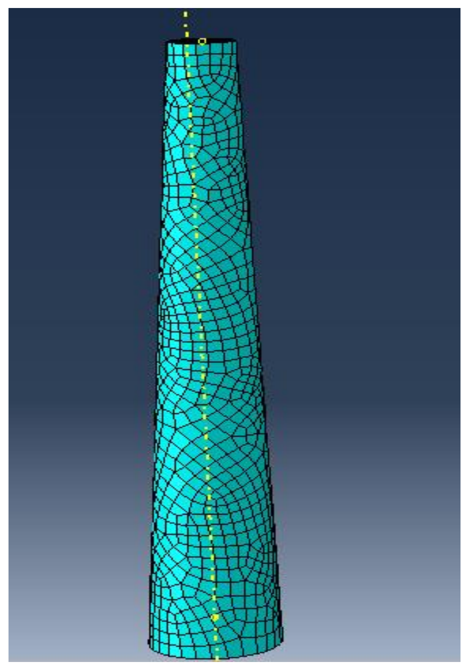


Fig. 5. 3-D modeling and meshing of the minaret in ABAQUS software.

For defining the materials characteristics in the software, Concrete Damaged Plasticity option was used (Fig. 6). This option is a continuous damaged model which is usable for concrete and other brittle and fragile materials [1]. The Drucker-Prager criterion, which is commonly used criteria in FE software for modeling masonry, was employed in this paper [23]. Drucker-Prager yield criterion has been used by many researchers for the analysis of unreinforced masonry structures [10, 39].

The most proper solving method must be selected in a way that leads to the masonry analysis purposes. In this research, dynamic explicit method has been chosen according to the time history and pushover analysis. Explicit procedure calculates the state of a system at a later time from the state of the system at the current time. This method performs the analysis using a large number of inexpensive, small, time increments. For modal analysis, frequency mode in linear perturbation procedure has been selected which is commonly used for modal analysis in ABAQUS [28].

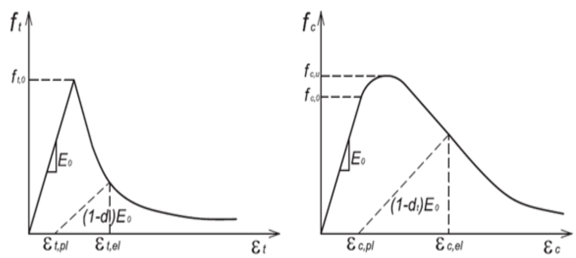


Fig. 6. Mechanical behavior of masonry under uniaxial (a) tension & (b) compression.

3. Seismicity of damghan and selected records

Quaternary fault of Damghan which crosses 10 km away of north of Damghan is studied by Krinsley (1970) for the first time. He defined it as a quaternary fault which its setup is normal with incline to south along withcollapsingof its southern parts (Fig.7).

According to studies of Berberian and Yeats (1999), Damghan fault is 100 km long including two basic western and eastern parts. In western part of fault (from north of Damghan to Dehmolla village in eastern side of Damghan), with a length of 53 km, its direct part rises northern block in north of Damghan and southern block is collapsed that is representative of a steep compressive fault toward north. However in eastern part (from north of Damghan and east of Siyahkouh toward Ahwanou village of Damghan) the northern block is collapsed and southern one is raised up which define a compressive fault toward south. Existence of triangular flat surfaces in southern walls of the fault, indicate strike component presence in addition of vertical component in Damghan fault's movement [30]. Yet, there is no strike movements discovered from investigations of existent water ways on aerial images toward the fault. There is no exact seismicity data about Damghan fault; however, the following earthquakes have been reported by Berberian (1995).

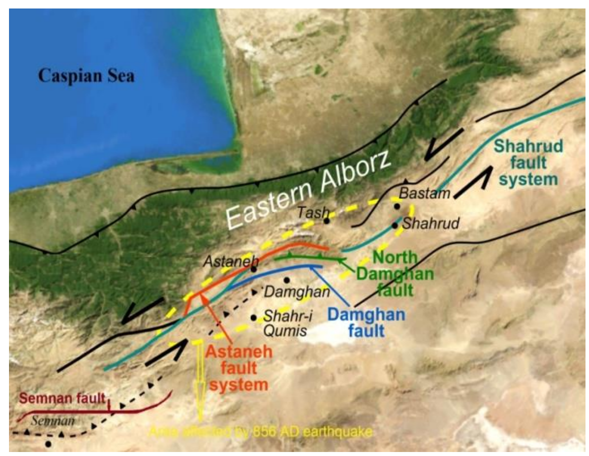


Fig. 7. Main faults of Semnan province and Damghan city.

- Earthquake of 22nd of December of 856 AD in Qomes (Damghan now) with magnitude of Ms=7.4.

- Earthquake of 1102 AD in Damghan with magnitude of Ms=5.5.

- Earthquake of 9th of January of 1982 AD.

- Earthquake of 12th February of 1953 in Toroud next to the Damghan with a magnitude of Ms = 6.5.

- Earthquake of 27th August of 2010 in Damghan with the magnitude of Ms = 5.9.

In this study, According to suggestion of the Iranian Code of Practice for Seismic Resistant Design of Buildings which is known as the Standard No. 2800 [21], seven earthquake records with the magnitude varying between 6.4 to 7.7 and having epicentral distance 20 to 112 km were selected. On the other hand, in order to include the effects of earthquake frequency content, records with different frequency contents were used. Selected earthquake records can be classified into three classes according to the frequency content: (a) high PGA/PGV ratio of more than 1.2; (b)intermediate PGA/PGV ratio with 1.2 ≥ PGA/PGV ≥ 0.8; and (c) low PGA/PGV ratio withPGA/PGV< 0.8 [35]. Accordingly, Loma Prieta and Northridge earthquakes have low frequency content, while Imperial Valley and Manjil earthquakes have intermediate frequency content and San Fernando, Oroville, and Tabas earthquakes have high frequency content. Table 3 presents some information regardingselected records. Since the minaret has been located in the central seismotectonic province of Iran, two records, namely Manjil and Tabas, were used to include the region's seismic parameters in the analysis. According to the Iranian Code of Practice for Seismic Resistant Design of Buildings [21], the level of seismic risk in Damghan region is high; therefore, the selected records were scaled based on the design spectrum in this standard.

Table 3. Characteristics of selected ground motion records

Earthquake	Date	Site	Comp.	Magnitude(Ms)	PGA(g)	PGV(m/s)	A/V
Loma Prieta	1989	Yerba Buena Island	090	6.9	0.68	2.68	0.25
Northridge	1994	Rinaldi Receiving Sta	normal	6.7	0.9	1.67	0.52
Imperial Valley	1940	El Centro	S00E	6.6	0.348	0.334	1.04
Manjil	1990	Tehran-Sharif University	186098	7.3	0.013	0.0123	1.05
San Fernando California	1971	Pacomia Dam	S74W	6.4	1.075	0.577	1.86
Oroville California	1975	Seismogr. Station Oroville	N53W	5.7	0.084	0.044	1.91
Tabas	1978	Ferdows	T1	7.4	0.108	0.0427	2.52

4. Structural analysis and results

The remarkable point that must be considered here is various types of analysis methods that should be performed on the minaret. The more diverse analytical methods are, the more accurate and reliable results would be and stability condition and structural resistance will be more clarified.

4.1. Statics analysis

During static analysis that is in fact a part of pushover analysis, it would be clarified that whether the structure is tolerable enough to stand its own weight or not and what the amount of structural deflection is caused by the minaret weight. Fig. 8 depicts the compressive stresses of the minaret under the gravitational loads. The allowable level of compressive stress is 4 MPa. As it is clear in the stress contour of the minaret, the maximum applying compressive stress do not reach the upper level of allowable stress. The maximum displacement of the minaret under the own weight is less than 4 mm, and this amount of displacement is negligible compared to whole structural dimension and mass. As a result, the structure is sufficiently endurable against its own weight.

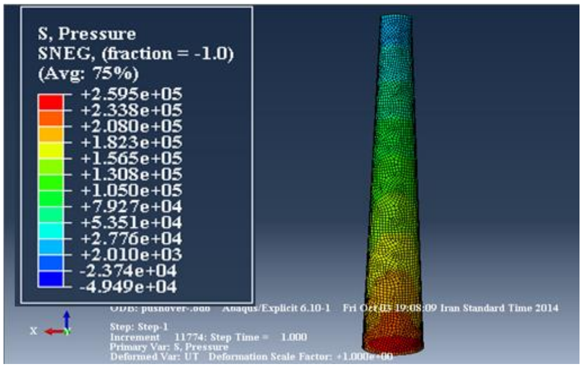
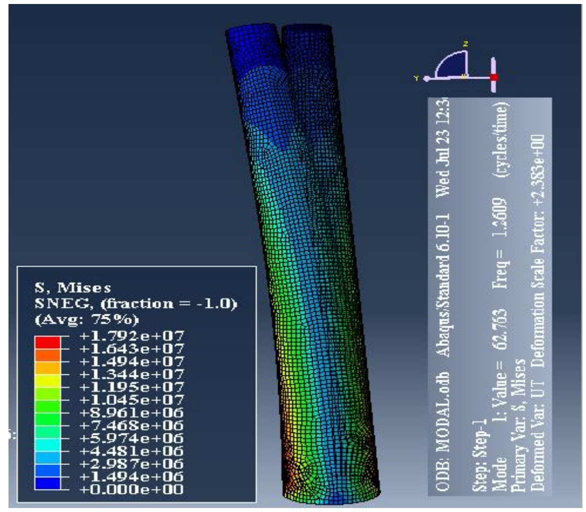


Fig. 8. Stress contour of the minaret under the gravitational loads.

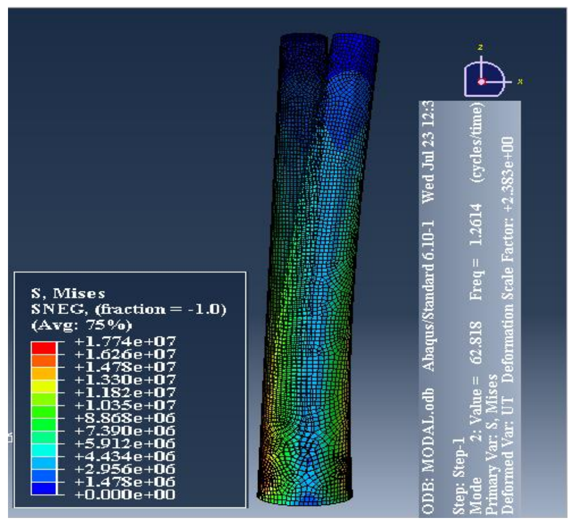
4.2. Modal analysis

Modal analysis is used to determine the vibration characteristics, i.e. natural frequencies and mode shapes, of the minaret while it is being analyzed. The natural frequencies and mode shapes are important parameters in the analysis of the minaret for dynamic loading conditions. It also can be a starting point for another, more detailed, dynamic analysis, such as time history analysis. In the modal analysis of the minaret, number of deformation modeswas limited to 20 modes. In order to realize the structural condition, first 5 modes as well as 8th mode that are in vertical direction have been depicted in Fig.9.

As it is shown in modal shapes, due to the symmetric shape of the minaret, first and second modes and also third and fourth modes are similar in a way that odd modes are in Ydirection and even modes are in X direction.Some pertinent information related to modal analysis are presented in Tables 4 to 6. Examining the structural periods in different vibration modes reveal that the considered structure is a flexible one.



(a)



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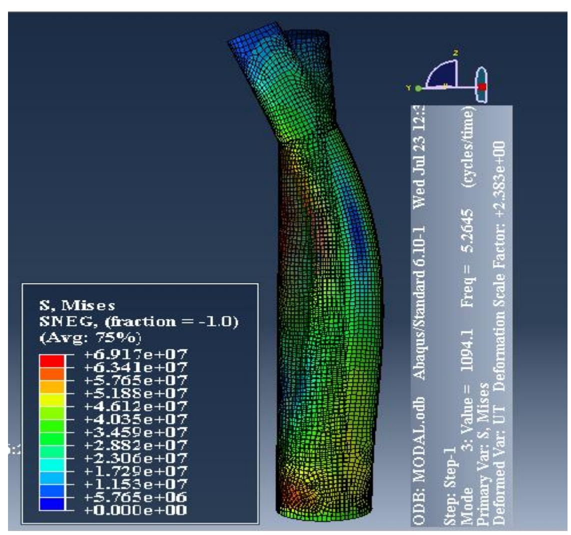

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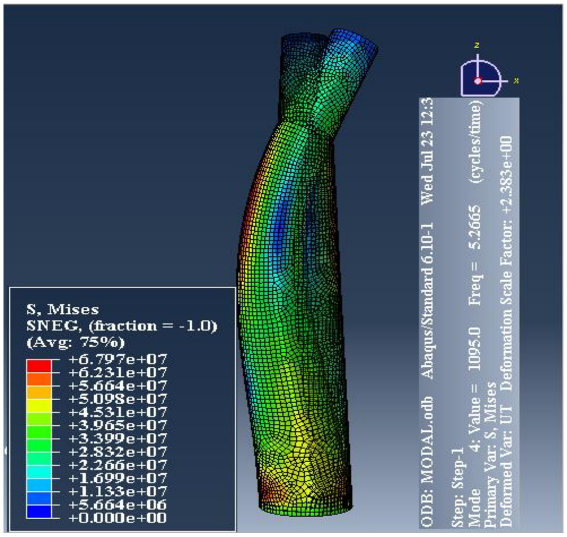

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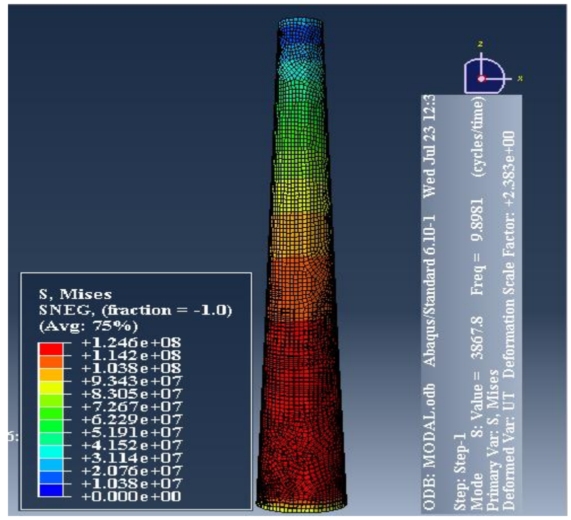

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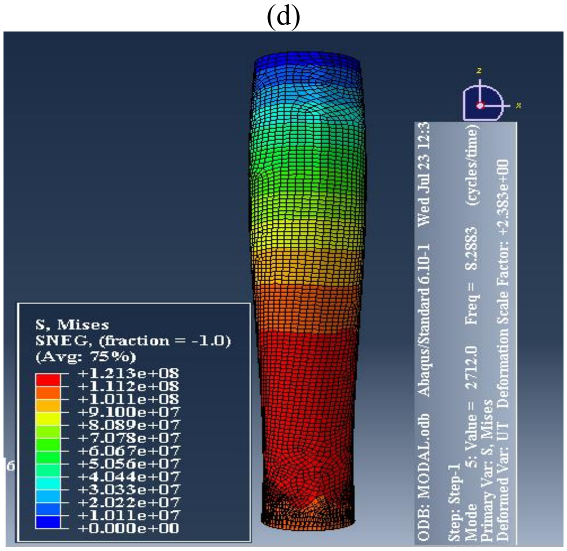


(e)

Fig 9. (a) First mode (cantilever form), (b) Second mode (cantilever form in orthogonal direction of first mode), (c) Third mode (whip form), (d) Fourth mode (whip form in orthogonal direction), (e) Fifth mode, (f) Eighth mode (in vertical direction).

Table 4. Eigen value output of the minaret

Mode No.	Frequency		Generalized mass	Time period
	(rad/time)	(cycles/time)		
1	7.9223	1.2609	36594	0.79
2	7.29258	1.2614	36432	0.79
3	33.078	5.2645	42027	0.19
4	33.091	5.2665	41580	0.19
5	52.077	8.2883	93505	0.12
8	62.191	9.8981	69670	0.1

Table 5. Participation factors of the minaret modal analysis

Mode No.	X-component	Y- component	Z- component	X-rotation	Y- rotation	Z- rotation
1	-0.14611	1.6295	-4.66214E-02	-28.060	-1.0399	51.597
2	1.6337	0.14651	-8.38268E-04	-2.5244	28.186	5.5299
3	0.18847	-0.98293	2.21596E-02	5.6565	0.38572	-31.030
4	-0.98844	-0.18948	2.84014E-03	1.0914	-5.7990	-6.8900
5	3.67604E-04	1.20256E-04	-3.26126E-05	-3.8887E-03	4.94435E-2	1.8727
8	-3.23314E-03	4.31603E-02	1.4185	-1.4720	4.94435E-2	1.3670

Table 6. Effective mass in modal analysis of the minaret

Mode No.	X-component	Y- component	Z- component	X-rotation	Y- rotation	Z- rotation
1	781.17	97163	79.539	2.88127E+07	39573	9.74229E+07
2	97237	781.97	2.56003E-02	2.32172E+05	2.89422E+07	1.11406E+06
3	1492.9	40604	20.637	1.34472E+06	6252.7	4.04658E+07
4	40624	1492.9	0.33540	49528	1.39826E+06	1.97386E+06
5	1.26357E-02	1.35224E-03	9.94507E-05	1.4140	228.59	3.27939E+05
8	0.72827	129.78	1.40194E+05	1.50964E+05	1.41320E+08	1.30193E+05

4.3. Pushover analysis

By means of pushover analysis, the minaret was subjected to gravity loading and a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behavior until target displacement is reached. In this research, nonlinear static analysis is used by employing dynamic explicit analysis in ABAQUS finite element software. This analysis method that is used in recent studies with acceptable resultsis authorized in some guidelines like FEMA273(1997). Results provide insight into the ductile capacity of the structural system, and indicate the mechanism, load leveland deflection at which failure occurs.

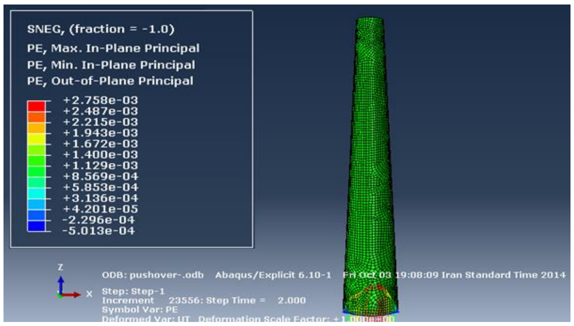
It is worth mentioning that due to the eccentricity of minaret top relative to its foundation, $P-\Delta$ effect plays an important role in the structural behavior. Since the most critical time state happens when the lateral force is applied in a direction which the largest amount of eccentricity occurs, in this research body force is applied in the same direction of eccentricity. In the other hand, NLgeom option is on, in Step module of the software which is provided for large displacements. Therefore, geometrical nonlinearity effects are considered.

In the pushover analysis procedure of the minaret, the analysis time would not come to an end due to large strains in small periods of time, thus the analysis is interrupted. Although it is possible to diagnose this problem and continue the analysis, however, since large displacements and plastic strains in the structure ensure failure of the structure, analysis would be finished in this point.

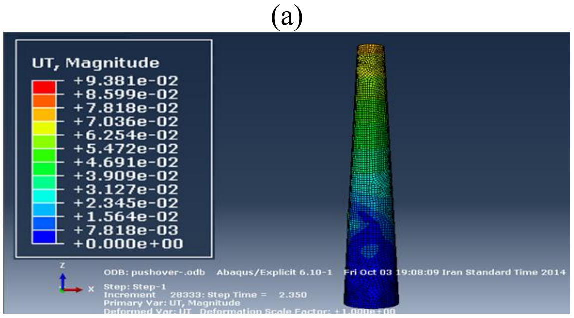
According to the results, the minaret can withstanda lateral force up to 0.17 of its own weight in the most critical state. This amount is equal to 0.34 of total lateral force which is considered to be applied to the minaret structure. As can be seen in Fig. 10, beginning of the failure under considered lateralforce would be in minaret foundation and its failure would be entirely catastrophic according to the fact that analysis is force control. Because the cracks are located in the half tensile part of the structure, these cracks are tensile cracks and are not considered as shear cracks (Fig. 10a). The minaret begins to fall against this force from the zone that is specified in the Figure. As it is obvious in Fig. 10b, support reaction under the lateral force is equal to 394.5 kN.

4.4. Nonlinear time history analysis

Nonlinear time history analysis utilizes the combination of ground motion records with a detailed structural model hence is capable of producing results with relatively low uncertainty. In nonlinear time history analyses, the detailed structural model subjected to a ground-motion record produces estimates of component deformations for each degree of freedom in the model [19]. In this study, seven records having different frequency contents along with weight loads were used for dynamic analysis of the minaret. In the following for brevity, the results of the nonlinear dynamic analysis of the minaret have been presented under the three records.



(a)



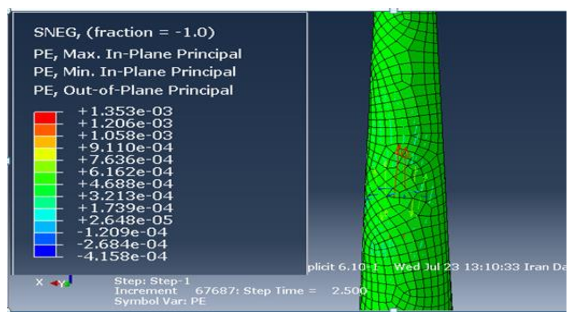
(b)

Fig. 10. (a) Plastic strains in the location where the failure begins from the minaret foundation, (b) The contour of minaret displacement at the last moment of pushover analysis.

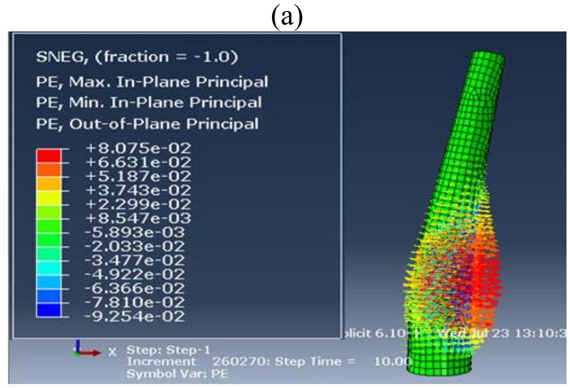
4.4.1. Tabas record

As can be seen in Fig.11a, under the Tabas record, the first cracks appear at the middle of minaret. According to the normal vector of cracks,the cracksare peripheral and tensile type, and they alsohave been formed in tensile phase of the minaret. This incident occurs because of material weakness in tension.Following some times after appearing the cracks on the minaret, the tension cracks grow rapidly in this phase and encompass larger area.After this moment, with reciprocal movements of base, tensile and compressive phases would be replaced in the minaret.

A remarkable point at these moments is that despite of being in compression zone, maximum plastic strainoccurs in tensile. The reason would be clarified with observation of crack's normal vectors at these moments. Dominant cracks are in vertical radial cracks, and this is due tothe fact that structural material of the minaret has not sufficiently strength under the tension resulting fromcompression. Of course, as can be seen from Fig. 11a, peripheral compressive cracks also exist in the minaret at the same moments which arenominated as crushing cracks. Following this time on, there will be no more changes in tensile and compressive phases of the structure, bypassage of analysis time and occurrence of further momentums, extent and magnitude of existence cracks will increase, until the time that aggregative tensile and compressive cracks becomevisible in the minaret and it is obvious which the structure would collapse finally in this direction (Fig. 11b).



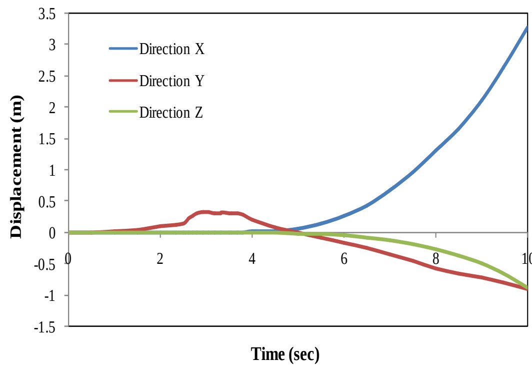
(a)



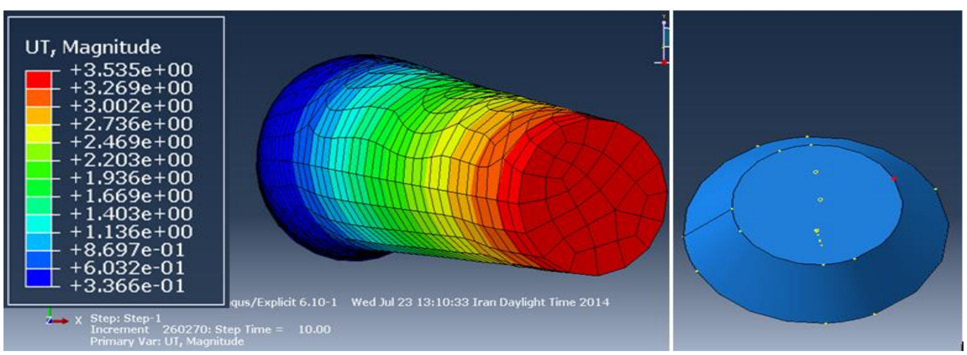
(b)

Fig. 11. Plastic strains and normal vectors of cracks in the minaret during time history analysis under the Tabas record (a) in 2.5th second, (b) at the end of analysis.

The structure collapses after some movements in a direction perpendicular to the direction of applied record (Fig. 12a). As it is specified in Fig. 12b, the maximum displacement is occurred in X direction and the structure would collapse in this direction. The remarkable point is that the monitoring (control) point is located somewhere that the maximum displacement occurs. This issue is clear in Fig. 12b which shows the minaret displacement at the last time of analysis and also illustrates the displacement monitoring point.



(a)



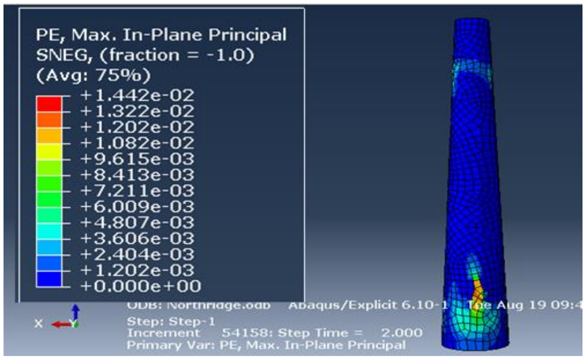
(b)

Fig 12. (a) Displacement diagram in three principle direction and, (b) contour displacement of the minaret under the Tabas record.

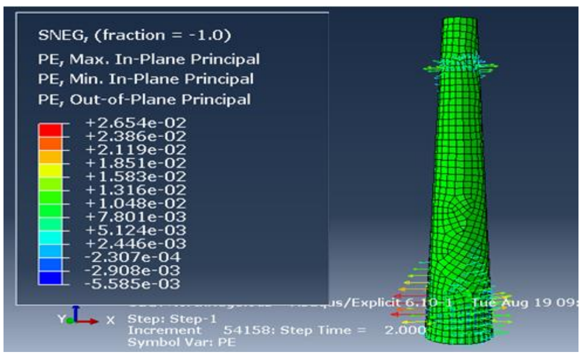
4.4.2. Northridge record

As soon as the record is applied to the foundation of the minaret, the plastic strains will be formed and distributed immediately in the structure. It is obvious in Fig. 13a that initial strains are entirely tensile, thus initial cracks are tensile too. Over time, amount of developing stresses increase in the lower half of the structure gradually and after five seconds from the beginning, strains at a height of three meters from foundation will increase to a magnitude that there is no possibility of the minaret stability (Fig. 13b). Aggregation of different tensile and compressive cracks appearing on the minaretindicates that structural materials have not enough strength against different type of tensile and compressive forces (Fig. 13c).

Under this record, the maximum displacement is occurred in Y direction in a way that it is observable in 6thsecond of analysis, with a displacement equal to 1.75 m at minaret top.



(a)



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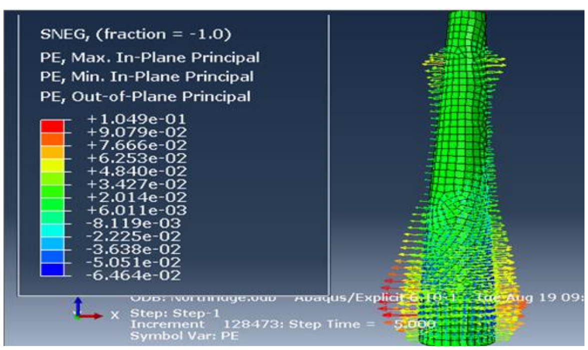


(c)

Fig 13. (a) Plastic strains at 2nd second, (b) Normal vector of cracks at 2nd second, (c) Normal vector of cracks at 5nd second in time history analysis of minaret under the Northridge record.

4.4.3. Imperial valley record

Because of frequency content of this earthquake, stresses would abruptly appear in two parts which are at 2m away from minaret foundation and 3m away from its top. As can be seen in Fig. 14a, produced strains in these zones are initially large and this is because of extremely large displacements which are equal to 60cm at the beginning of this record. It is noteworthy to mention about structural stresses at these moments that, developed stresses at the minaret foundation are compressive and tensile at top of minaret. It is also obvious in Fig. 14b that top of the minaret is exposed to direct tension while orthogonal cracks and thus tensions caused by compression are appeared at minaret foundation, crushing isalso appeared in this zone. According to Fig. 14c it is clear that, stress concentration quickly shifts to foundation of minaret in a way that plastic strains grow rapidly in this region and are developed over time. In the 4thsecond of time history analysis, strain magnitude and its distribution area grow to the extent that there is no possibility for minaretstability. Density of cracksand crushing at minaret foundation are completely obvious in Fig. 14d. It is obvious from normal vector of minaret cracks that the maximum amount of stresses and strains occur in compressive phase of minaret. However this does not mean that dominant cracks are compressive too. Major displacement is occurred in Y axis direction so that in 5th second of analysis, displacement of minaret top is almost 2.75m.

The results showed that the records with low frequency contents produced the higher displacements and stresses in the minaret. Stress contours resulted from the earthquake records in all cases exceeded the compressive and tensile strengths of the minaret's materials. As a result, since magnitudes of the actual stress are larger than the allowable values, seismic rehabilitation seems to be necessary.

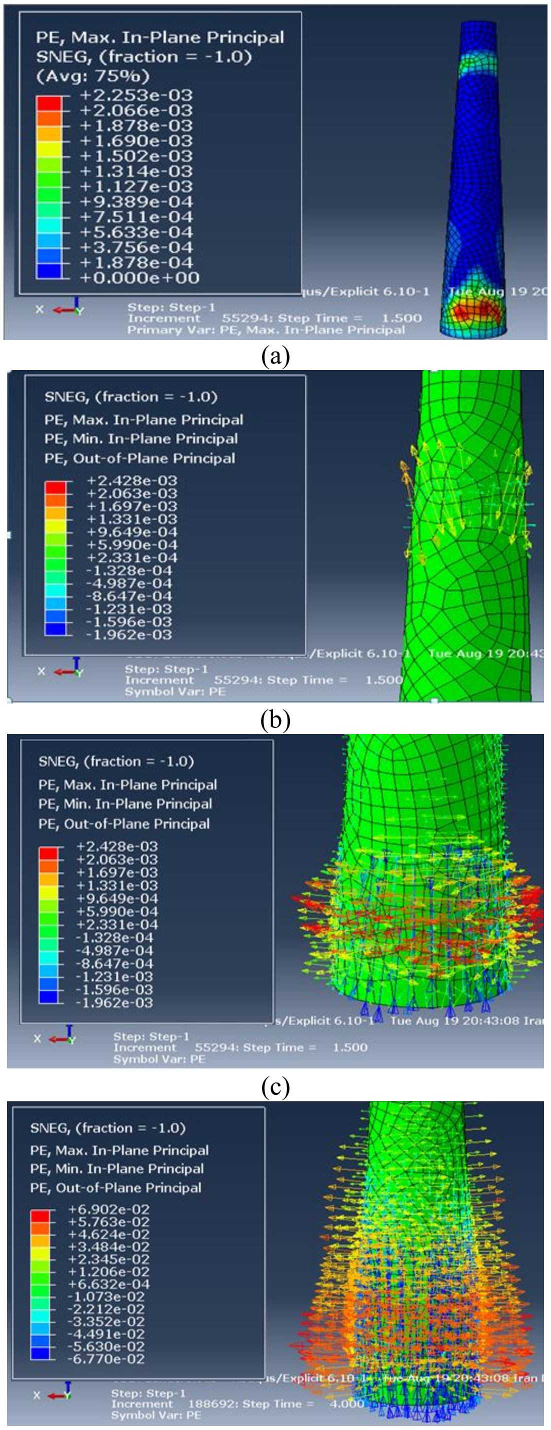


Fig 14. Results of time history analysis of the minaret under the Imperial Valley record: (a) Plastic strains in 1.5th second, (b) Normal vector of cracks at top of minaret at the time of 1.5th second, (c) Normal vector of cracks at base of minaret at the time of 1.5th second. (d) Normal vector of cracks at lower parts of the minaret at the time of 3ed second.

5. Seismic strengthening of the minaret

As it is defined from analysis results, minaret structure in all sections of its bottom to its top is weak in different resistant factor like tensile, compressive and shear factors. Considering the minaret conditions, level of vulnerability, and level of compressive and tensile stresses, three seismic strengthening methods are proposed for the internal body of the minaret, including fiber reinforced polymer (FRP) sheets, fiber reinforced cementitious matrix (FRCM), and Ferro-cement (welded wire mesh with micro-concrete/mortar).

Initially, the idea of using FRCM material as the first material for retrofitting was formed because of large amount of tensile and compressive cracks or tensile meridional cracks. Before further analysis, it was assumed that by using this material and full containment of these types of cracks, stability situation of minaret would be desirable against lateral forces. However after observing results of using FRCM material which had less improvement for strengthening, the Ferro-cement and FRP were considered for rehabilitation plan.

5.1. Strengthening using FRCM and ferro-cement

One of the effective methods for seismic strengthening is to provide concrete coating on the masonry walls. This strengthening method usually is done by two techniques including Ferro-cement and FRCM [41-42]. The Ferro-cement strips comprising of welded wire-mesh reinforcement embedded incement-sand mortar or micro-concrete have a composite action with the masonry resulting in significantly enhanced strength and ductility [22]. In this method, either a network of horizontal and vertical bars is installed on the wall surface or then the wall is coated with concrete. Concrete coating on the wall can completely fill the gaps and seams on the wall surface and provide a favorable adhesion and connection. FRCM materials are combined of a fiber mesh which may be either polyparaphenylene benzobisoxazole (PBO) fiber mesh or carbon fiber meshand a cementitious mortar matrix which is stabilized by dry organic fibers [38].

(a)

(b)

Fig. 15. (a) FRCM reinforcement fabric examples. Left: carbon fabric, Right: PBO fabric, and **(b)** Application of FRCM on a masonry wall [32].

It can be said briefly that, FRCMs are made of reinforced combined cement materials along with carbon continuous and resistant fibers, in order to remove or reduce FRP fibers disadvantages, in addition to compensation of concrete element flaws [33]. Actually FRCM is significantly thermal resistant in addition to containing FRP advantages, and it can be used in humid surfaces. In the other hand it is practicable in lower temperatures.Various kinds of FRCM which were common in Iran before PBO introductioninclude: textile reinforced mortar (TRM), textile reinforced concrete (TRC), mineral based compound (MBC), and fiber reinforced cement (FRC) [3, 34].

(a)

(b)

Fig. 16. (a) Typical FRP application. **(b)** Examples of strengthening of historical & modern masonry with FRP [32].

Fig. 17. Ferrocement Layers on masonry wall. Left: Wire mesh and Right: Concrete coating. [13].

In this paper PBO features are as follows:tensile strength of PBO fiber net was assumed as 5000 MPa in both directions (longitudinal and transversal), and elastic modulus and failure strain were taken as 270000 MPa and 0.02, respectively.

Thickness of a single ply of PBO net is 0.045.

It is necessary to mention that, in strengthening design modeling, FRCM network thickness in longitudinal and transverse directions is same. Since the minaret has been made of two layers of bricks which the outer layer is for the purpose of decoration and its role is over looked in analysis, decorative bricks can be temporarily removed from statue precisely to implement the seismic retrofitting, and after implementation of FRCM on the case, removed, named and replaced bricks must be reinstalled on their own locations carefully [29].

In definition of mechanical properties and behavior of FRCM material in ABAQUS software, since different properties are considered for this material in vertical directions, Lamina option is used in order to define elastic propertywhich is common for similar materials like FRP. The property of this option is that, strains are planar and material propertiesare considered different in orthotropic directions.

According to the properties of FRCMwhich the most important one is its high resistance against tension despite its low thickness, in present research this material is assumed as rings wrapped around the minaret which are coating surface of minaret from bottom tohalf-height of the minaret. Thus, the main direction against tension is horizontal direction in ring shapes around the minaret. Because of cracks and bricks failure types in initial analysis, this direction has been chosen to define FRCM material properties. As further explanations, it should be said that most of the failure in minaret structure is happened in compressive phase due to tension caused by compression in vertical direction, and since FRCM plays a significant role in tension naturally, therefore horizontal direction is reasonable direction in order to avoid tensile cracks caused by compression which are produced in perpendicular direction by confining the minaret.

Mechanical properties of the materials in Ferro-cement and FRCM are presented in Table 7 and 8, respectively. Total thickness of the FRCM material was chosen as 50mm with 4 plies of PBO fiber net. Thickness of a single ply of PBO net is 0.045 and 0.010 mm for longitudinal and transversal direction.

Table 7. Material properties of welded wire mesh with micro-concrete

Material	Density (kg/m3)	Poisson's ratio	Young's modulus (MPa)	Tensile strength (MPa)	Diameter (mm)
Micro-concrete	2100	0.2	10.6	---	----
Wire	7850	0.3	150000	750	2.5

Table 8. Mechanical properties of the FRCM material

Material	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)	Failure strain
PBO fiber net	----	5000	270000	0.02
Cementitious matrix	27	2.4	----	----

5.2. FRP strengthening

The FRP sheets are composed of unidirectional fibers, thus assumption of isotropic properties is unrealistic for FRP [43-45]. In other words, mechanical properties of this material are different in every direction [12]. Generally, multiple layers of this fiber are stuck to the structural element with epoxy resin in an orthogonal way so that the mechanical properties became the same in two orthogonal directions [15]. Mechanical properties of the FRP sheets used in this study are presented in Table 9.

Table 9. Mechanical properties of the selected FRP sheets

FRP type	Young's modulus (MPa)	Poisson's ratio	Tensile strength (MPa)	Shear modulus (MPa)	Thickness (mm)	Density (kg/m3)
CFRP	Ex=62000 Ey=4800 Ez=4800	νxy=0.22 νxz=0.22 νyz=0.30	958	Gxy=3270 Gxz=3270 Gyz=1860	1.0	1800

In order to find the appropriate geometry and sufficient number of layers for FRP, the minaret is strengthened using 5 different cases. In the first case, the sheets cover the entire minaret by 10 layers with the thickness of 1, 2, and 10 mm and width of 1.4 m. In the second case, the sheets cover the entire minaret in a complete geometry with layers of thickness 1 and 10 mm. Thickness of 10 mm means that 10 FRP layers with thickness 1 mm are used. All cases are compared under the selected earthquake records.

FRP is simulated using 4-node shell elements (with 6 six degrees of freedom at each node). For calculating element stiffness matrix, reduced integrating method is used, as shown in Figure 18. This element is recognized as S4R element in the software which is able to include in-plane large strains and considered as an element with appropriate convergence in different solid mechanics problems including thick plate problems, plate with non-linear behavior of geometry, and materials and plate buckling analysis. Furthermore, this element can simulate different shells on an isotropic and orthotropic basis for multi-layered or reinforced cases. It must be noted that the components reinforced by FRP show two kinds of failure including a) FRP rupture, and b) FRP debonding; thesecond failure mostly occurs at bending elements such as beams, while the first failuremostly occurs at compressive elements such as columns where FRP is wrapped and the main focus is placed on the confinement property. To achieve higher accuracy, both of aforementioned failures were considered in the modelling. The interaction between bricks and FRP was also considered to be adhesive, or "tie" connection based on the terms used in ABAQUS software.

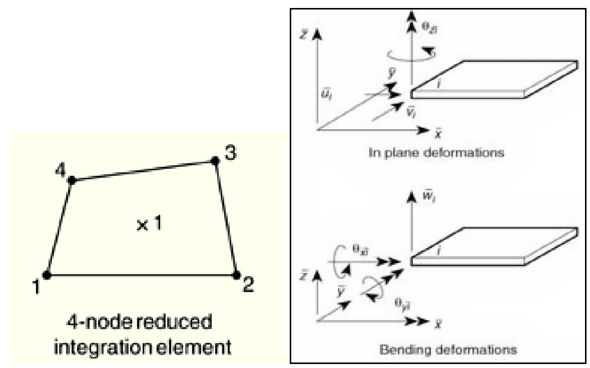


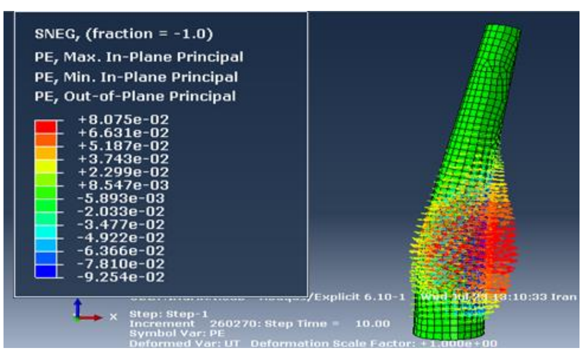
Fig. 18. 4-node shell elements.

5.3. Comparison of the results

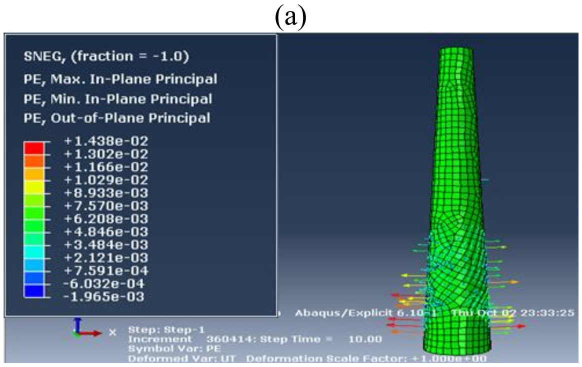
Before strengthening of the minaret, push over analysis was interrupted because of large strains appeared in the structure in a very short moment. After strengthening scheme using FRCM, condition of produced strains was improved a little bit, and analysis was continued to the end without errors. Howeverstrains werestill large and completely affect the structure, and cause itto fail. Nevertheless after strengthening of the minaret using Ferro-cement, strains are significantly reduced so that even up to the last moments of the analysis there is no strain in the structure. The structural condition is acceptable after FRP strengthening, and just a few insignificant strains are formed in tensile region in foundation of the minaret

At last moments of time history analysis under the sevenselected records, significant values of plastic strains are appeared in a large area of minaret foundation, and as it is observable again from cracks normal vectors, various types of cracks are produced due to severe strains in minaret structure.

By surface investigating which is affected by strains and also crack normal vectors, it is clear that strengthening using FRCM has been successful only in controlling specific types of cracks. FRCM material surrounds minaret perimeter like a belt, and does not allow bricks to be taken apart due to the tensions caused by compression, and thus, meridional tensile cracks do not appear anymore. But this method is not a proper method to control tensile and compressive cracks which appear perpendicular to bricks common surface and these cracks normal vector is perpendicular to the minaret face (Fig. 19).



(a)

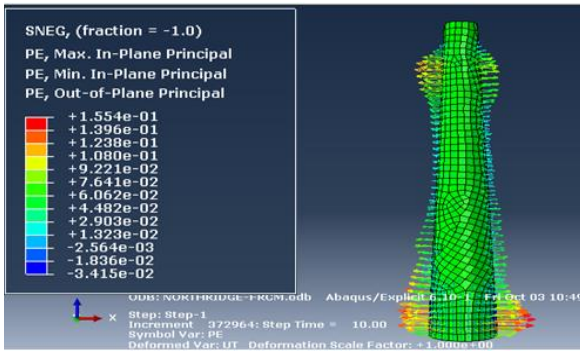


(b)

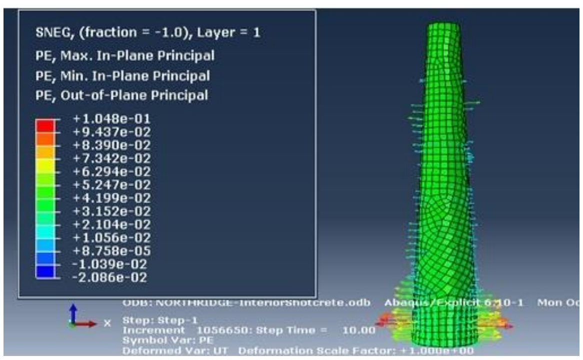
Fig 19. Normal vector of cracks and plastic strains at the last moment of time history analysis under the Tabas record (a) before strengthening, (b) after strengthening using FRCM.

Methods based on development of Ferro-cement, are the most effective methods to control cracks which are caused by compression or crushing. Also, despite the fact that concrete do not have desirable performance in tension, it has a significant superior performance compared with structural materials, and thus lots of cracks of this type are controlled and disappeared after applying Ferro-cement strengthening plan. Therefore, it can be realized from the results thatstrengthening method using FRCM is successful in controlling some types of cracks, however generally it cannot be used as a practical method to control cracks and strains on its own. But Ferro-cement and FRP strengthening methodhave generally better performances in controlling strains and cracks in terms of surfaces affected by cracks, and extent of regions affected by strains, and also in terms of numerical values and strain magnitudes relative to FRCM using (Fig. 20).

As it obvious in Fig. 21a, before strengthening pushover analysis is interrupted because of error emergence in 2.35th second, and during this short period, displacement would be about 9.3 cm. This amount of displacement is significant relative to applied load.After strengthening using FRCM, although analysis is not interrupted in mentioned moment and continues to the end, amount of displacement at the end of analysis is low. However displacements level in the minaret are small and acceptable after strengthening using FRP and Ferro-cement. Also, by comparing displacement at last moment of strengthening using FRP and Ferro-cement, it is obvious that, although displacement is more reduced in second method compared to first method, but it is not significant. Thus it has been determined that both FRP and Ferro-cement strengthening methods are successful in controlling displacement, but the method of FRCM strengthening has not shown a good performance in controlling displacements, in pushover and time history analysis (Figs. 21 and 22).



(a)



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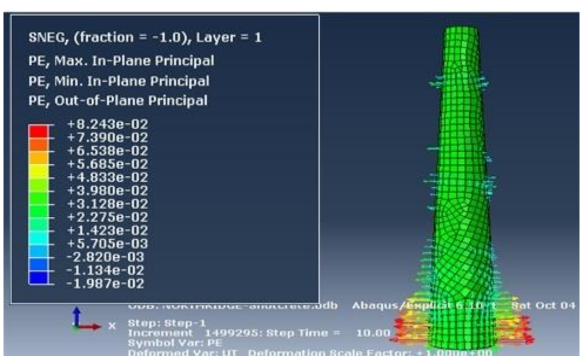
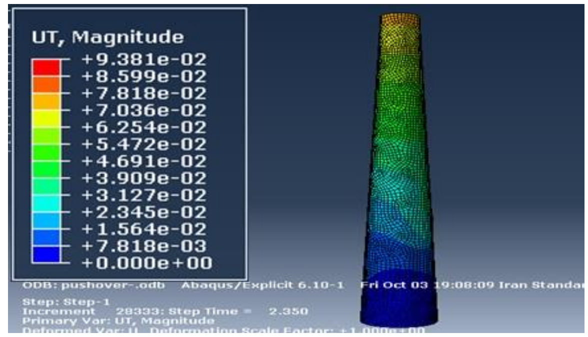
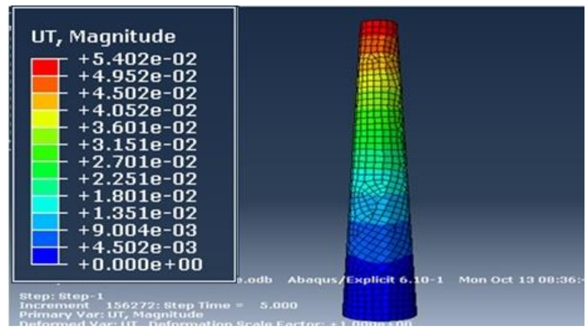


(c)

Fig 20. Normal vector of cracks and plastic strains at the last moment of time history analysis under Northridge record after strengthening method using (a) FRCM, (b) FRP, and (c) Ferro-cement.



(a)



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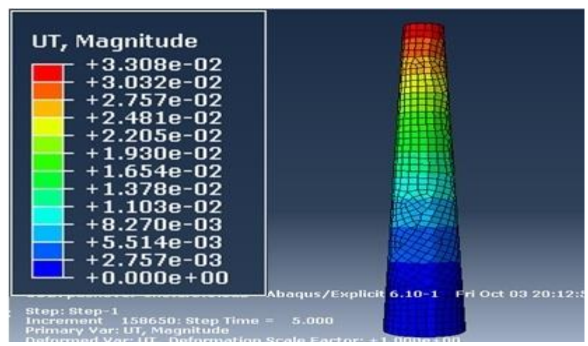
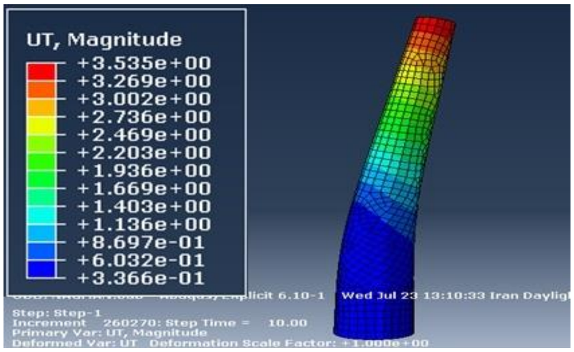


(c)

Fig 21. Displacement contour of the minaret at the last moment of pushover analysis (a) before strengthening, (b) after FRP strengthening, (c) after strengthening using Ferro-cement.



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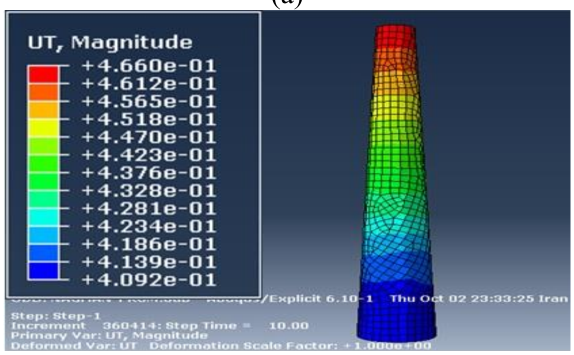

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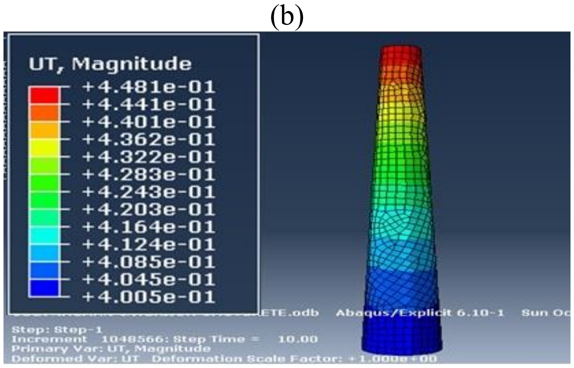

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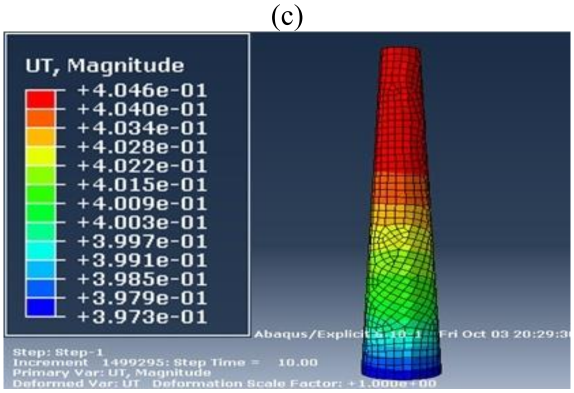

(d)

Fig 22. Displacement contour of the minaret at the last moment of time history analysis under the Tabas record (a) before strengthening, (b)after strengthening using FRCM, (c) after FRP strengthening, (d) after strengthening using Ferro-cement.

6. Discussion

Since there are no clear and codified regulations regarding historical monument strengthening in Iran and also the allowable level of displacement in this structure has not been mentioned in Iranian National Building Code (INBC), it is inevitable to use the other codes and research works. There are some cases that can be used only as a relative criterion to compare that how different strengthening methods work in controlling displacements. As an example, the Ref. used following expression for displacement controlling in monumental building [11]:

$$\Delta_{i\ \max} \leq \frac{0.02 \cdot h_i}{R} \tag{1}$$

Where $\Delta_{i\,.\max}$ is relative displacement, h_i is structural height and R is reduction factor which is determined proportional to the structural plasticity. Moreover, according to FEMA273, relative displacement is also considered equal to 2% of story height for usual structures.

$$\Delta_{i\,.\max} \leq 0.02\times \text{(story height)} \tag{2}$$

In this paper, the allowable level of displacement is as bellow:

$$\Delta_{i\,.\max} \leq 0.02\times 2383/\ 1.5 = 31.77\ \text{cm} \tag{3}$$

The maximum of relative displacements which are obtained for every strengthening plan is specified in Fig. 23.

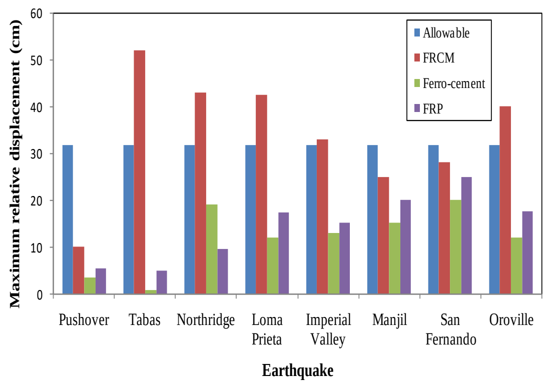

Fig. 23. Maximum relative displacement of different strengthening plans under theselected records.

As it was mentioned before, the minaret is deviated from vertical condition over years of its life, so that top of minaret is deviated with 69 cm of eccentricity. Eccentricity is a factor that increases vulnerability against exertion of lateral forces, and the most critical state takes place when the eccentricity and lateral force are in the same direction. Thus to consider most critical situation in analysis, the lateral force direction was assumed to be aligned with existing eccentricity direction.

By investigating the results of different analysis and displacements of the minaret which wereformerly presented, it is realized thatstrengthening plan using FRCM is accompanied with contradictory results. In a way that, the results are completely acceptable in time history analysisand FRCM is also successful in lateral displacement control, same as the other two strengthening methods. However in pushover analysis, results are extremely poor, and FRCM is not effective in the control of lateral displacement at all.

The results for two other methods were good and generally acceptable. The strengthening method using Ferro-cement is significantly successful compared to the other methods, so that, recorded displacement of this method at last moment of the time history analysis is half the amount of FRP strengthening (Fig. 24).

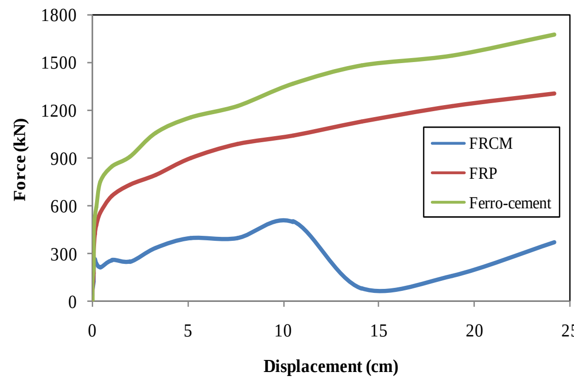

Fig. 24. Force-displacement relationship of different strengthening method.

From the engineering perspective, nowadays applied force on structures which is caused by earthquake is important in constructions design, according to this point; structure is designed in a way that it is sufficiently resistant against these forces. But the structure equilibrium investigation against single resistant parameter, cannot interpret structure behavior during severe movements, and in most cases it doesn't help designers to determine the structural reaction after elastic limit and damage distribution in structural components. It seems that, there is a need to other parameters like seismic energy to control structures behavior. Energy (generally defined as the area confined to force-displacement diagram) expresses the seismic effects during loading. Actually, the structure stands against earthquake when it is capable of absorbing or dissipating energy applied during earthquake, in order to prevent catastrophic failure or yielding with an undesirable mechanism. As a result, earthquake energy investigation in the structure can exactly express the structural behavior and clarify design weak points [25].

In this research, according to the force-displacement curves, the following points are remarkable about the amount of energy dissipation by structural system, before and after strengthening. The curve is not available to the end of event because of analysis interruption after error emergence in 2.35th second. At the same time, maximum resistance of unreinforced structure is about 300kN which is not significant.

In the strengthened minaret using FRCM material, although the area under force-displacement curve is high but the structural maximum resistant is about 500 kN which is negligible against applied load.

7. Conclusion

In this study, using finite element analysis and non-linear dynamic analysis and utilizing field experimental tests for determining the mechanical properties of the materials and the surrounding soil, stability and necessity of seismic rehabilitation of one of the world's oldest masonry minaret was explored under the some selected earthquakes with different frequency contents.

The results showed that records with low frequency contents produced the highest displacement and damage. Stresses resulted from the application of earthquake records in all the cases exceeded the compressive and tensile strength of the minaret materials, which showed the necessity of seismic rehabilitation.

Strengthening method using FRCM, although relatively improves resistant condition of minaret under the lateral forces, it cannot be sufficient enough to stand against dynamic lateral forces, hence, this method is not suggested as a proper method to seismic strengthening of the minaret. Using Ferro-cement strengthening plan to control strains, cracks and displacements, result in a desirable performance. Therefore, strengthening method using Ferro-cement is the most effective one among the proposed methods; so that, in comparison to the FRCM strengthening method, this method is effective by up to 100 %.

Rather acceptable analysis results, easy procedure, no requirement to experts, low costs of procedure implementation and finally ease of gaining required authorization permissions to apply reinforced concrete jacketing on inner wall of minaret, are cases that make Ferro-cement strengthening plan reasonable to prefer this method to the other existing investigated methods in spite of its defects.

Based on mentioned considerations, it seems like this method of seismic rehabilitation is appropriate and beneficial method for historical slender structures.

Finally, however, the assumption of fixed base structure has been commonly used in seismic assessment of historical monuments particularly built on rigid soil media; it will be considered by the present authors for the effect of soil properties on the seismic damage assessment of historical masonry minaret–soil interaction systems.

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