IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 17, Issue 3 Ser. III (May - June 2020), PP 21-30
www.iosrjournals.org

Numerical Study of the Seismic Behavior of a Historic Stone MasonryTower

Amr M. Abdel-Halim[1], Mohamed N. Fayed [2], Gehan A. Hamdy[3], Mohamed A. Abdel-Wahab[4]
[1, 2, 4]*Faculty of Engineering, Ain-Shams University, Egypt*
[3]*Faculty of Engineering at Shoubra, Benha University, Egypt*

Abstract:
Background*:Unreinforced masonry towers are especially vulnerable to damage during earthquakes.A historic stone masonry minaret in Cairo (1468 A.D.) showed signs of damage and obvious inclination after occurrence of strong earthquakes in 1992 and 2015. Investigating the dynamic behavior of this historical tower is of primary importance to assure its structural safety and seismic vulnerability and enable conservation of thisheritagemonument.*
Materials and Methods*: Numerical modeling and seismic analysis are performed for the minaret in its current condition using finite element commercial software in order to investigate its seismic behavior and to assess its structural efficiency. Several numerical models are made for the minaret to study the influence of openings and of the spiral stairs to the dynamic behavior.*
Results*: The obtained numerical results regarding stresses and deformations are analyzed and correlatedto the observed damages and inclination. The results indicate overall stability of the structure in its current condition while high stresses occur at several locations.*
Conclusion:*The numerical results demonstrated the need for retrofit actions for the minaret in order to improveits seismic behavior.*
Key Word*: Masonry; Tower; Historic;Finite Elements; Dynamic Analysis; Seismic; Assessment.*

Date of Submission: 04-06-2020 Date of Acceptance: 20-06-2020

I. Introduction

Unreinforced masonry towersare highly vulnerable to damage due to dynamic action occurring during earthquake ground motions. This is attributed tothe anisotropy, heterogeneity and poor tensile strength of masonry and other factorssuch as the distribution of masses and inertia forces along the structure[1, 2]. Additionally, many of the historic towers suffer from long harsh environmental exposure and different levels of deterioration and damage, whichplaces these structuresat significant risk inearthquakes events. A destructive earthquake struck Egypt in October 1992 (Mw 5.9) and caused damage or collapse of many of the monumental minarets; the most severely damaged minarets were the stone minarets constructed from 1250 to 1520 A.D.[3]. Numerical investigation of four masonry minarets in Cairo representing different historical eras showed that stress concentrations occurred at locations of abrupt change of cross-section or variation of materials[4, 5].

The monumental stone minaret of the Mosque of Fatma El-Shaqra(1468 A.D.) is located in a very crowded residential and commercial district in the center of Cairo, Egypt. Following the destructive 1992 earthquake, several stone walls of the mosque were cracked and damaged. The slender minaret showed observed inclination which increased after another strong earthquake in 2015;the deviation at the top reached 300 mm from the central position.In-situ survey showed degradation of material due to weathering conditions and physical attack and cracks at almost several locations of the minaret body, especially in the lower part, as well as wide cracks and displacements of stones near the door opening. The threat to its structural safety imposed closure of the mosque and scaffolding the minaret,as shown in Figure 1, to avoid failure or collapse in case of another earthquake event.

Numerical modeling and analysis of historic masonry structures is a difficult task because the mechanical behavior of masonry exhibits non-homogeneity, low shear and tensile strength and brittleness of mortar joints[6]. Different modeling strategies and analysis methods can be adopted to represent masonry behavior with different levels of accuracy[7]. Finite element (FE) method have been used to represent masonrystructures usingeither planar elements (plates or shells) or three-dimensional (3D) elementssuch as brick or solid elements; FE macro-models were reported to provide accurate simulation of the response of masonry structures [8, 9].Zaki et al.[10]studied the dynamic behavior of two 20 m high historical stone minarets in Cairo using 3D FE modeling and linear elastic analysis using SAP2000 program; the dynamic characteristics obtained from ambient vibration tests were used to update the FE model. Finite element modelingby shell elements was made using SAP2000 software for historic stone minarets in Istanbul; results showed that the highest damage occurs at the base and the lower part of the minarets[11, 12]. Esmail and Essa[13]assessed the seismic behavior of a historic stone minaret in Cairo by 3D FE model using response spectrum analysis.

II. Material And Methods

The seismic behavior of the minaret is investigated through modelingof the whole minaret by three-dimensional finite elements (FE) using commercial software SAP2000 v.18.2 (2017)[14]. Macro-modeling approach was adopted considering the stone blocks and mortar layers as a homogenous isotropic continuum. Previous research studies showed that assuming average mechanical properties for wall assemblages based on experimentally determined values can give a reasonable estimate of the real behavior [15, 16]. Several FE models are created to explore the influence of different geometrical and modeling parameters. The vibration modes are determined; the seismic response was performedthrough time-history dynamic analysis under three ground acceleration records as well asresponse spectrum analysis.

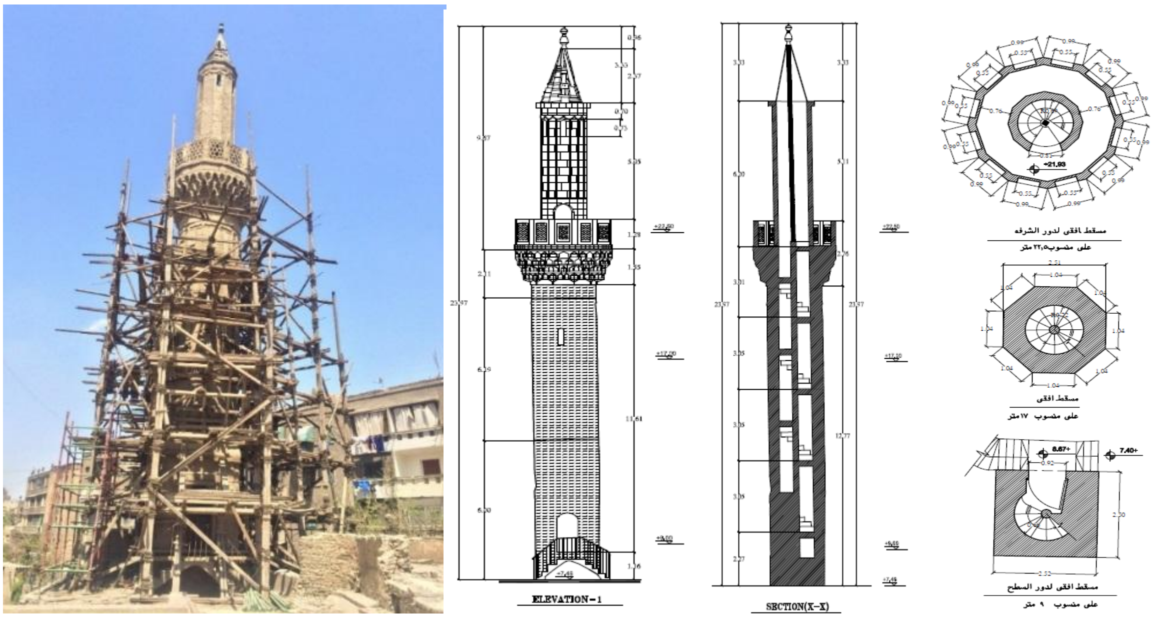


Figure 1: The minaret of Fatma El-Shaqra mosque: external view, elevation, longitudinal section and cross-sections.

Structure description:

The minaret is constructed of limestone blocks of average dimensions 500x300x250 mm bonded by slag ash. It is about 32 m. high and consists of three parts of different cross-sections, as shown in Figure 1. The lower part (pulpit) extends 9.0 m above the ground and has a square plan of outer dimensions 2500x2500 mm. and inner cylindrical shaft of constant diameter 1500mm containing helical staircase constructed from stones interlocked with the stones of the cylindrical shaft and attached at the center to a solid cylindrical lead core (column) of diameter 300 mm. The second part has octagonal cross section with outer dimensions of 2500 mm and extends for 15 m height, a balcony and the roof are at the top of the helical staircase about 21 m above the ground level. There are openings in the outer wall of the minaret and one door at the entrance of the minaret at the top of pulpit at height 9m above the road level.

Material properties:

The adopted masonry material properties are based on the results of experimental testing of stones and core samples. Masonry compressive stress is considered to be 4.225 N/mm^2, weight density = 19 kN/m^3; major Poisson's ratio = 0.2, tensile strength = 0.5 MPa; modulus of elasticity (Em) = 2400 MPa. The stress-strain relation for masonry is adopted from the literature.

Finite elementmodeling:

In order to study the influence of the minaret geometrical aspects on its seismic performance, three different models were created for the minaret (M-1, M-2 and M-3). Additionally, for each model in SAP2000, the minaret was represented by two modeling types: by shell elements and by solid elements for comparison. In

Model M-1, the body of the minaret is considered without window or door openings;the cylindrical shaft has diameter 1500 mm and wall thickness 500 mm; the core of diameter 300 mm and the helical staircase having thickness of stairs 200 mm are included.Model M-2 includes the body of the minaret with openings of the door and window,as well as core and stairs, as shown in Figure 2. In Model M-3, the core and stairs are removed to illustrate the role of the stone stairs and core in providing seismic stability to the minaret.

Boundary conditions:

The minaret supporting condition was modelled as springs representing the soil; the spring stiffness was calculated using Winkler equation. A preliminary linear analysis was made for model M-1 where the soil bearing capacity was assigned a low value (0.04 MPa) and the deformations at the minaret base due to vertical and lateral loading were estimated. Based on these results, the stiffness of springs used to simulate the soil was recalculated according to the settlement of the minaret in each part.

Loads:

The considered loads are the minaret own weight and service loads. Seismic analysis is made through response spectrum analysis according to Egyptian Code for loads on Structures ECP201-2012 [17]. Dynamic time-history analysis was made forall six models of the minaret was performed using three scaled ground acceleration-time records: N-S components of El-Centro, Altadena and Pomona Earthquakes, shown in Figure3[14].Eigenvalue analysis was also performed to determine the modes of vibration for the minaret using the six modeling approaches.

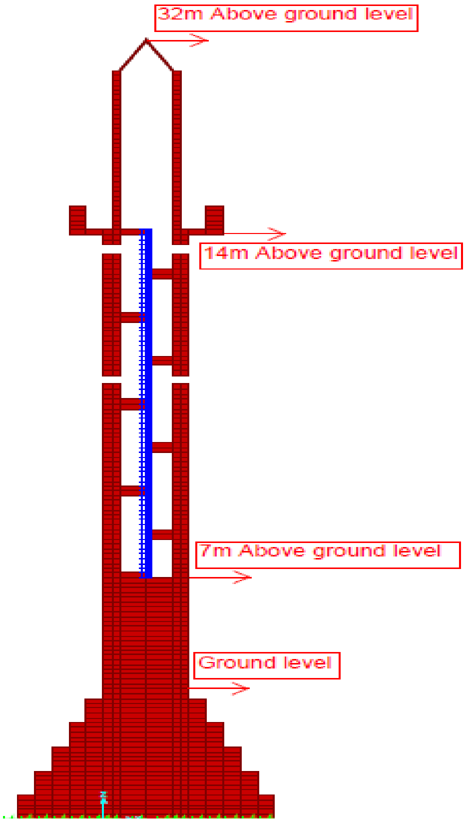
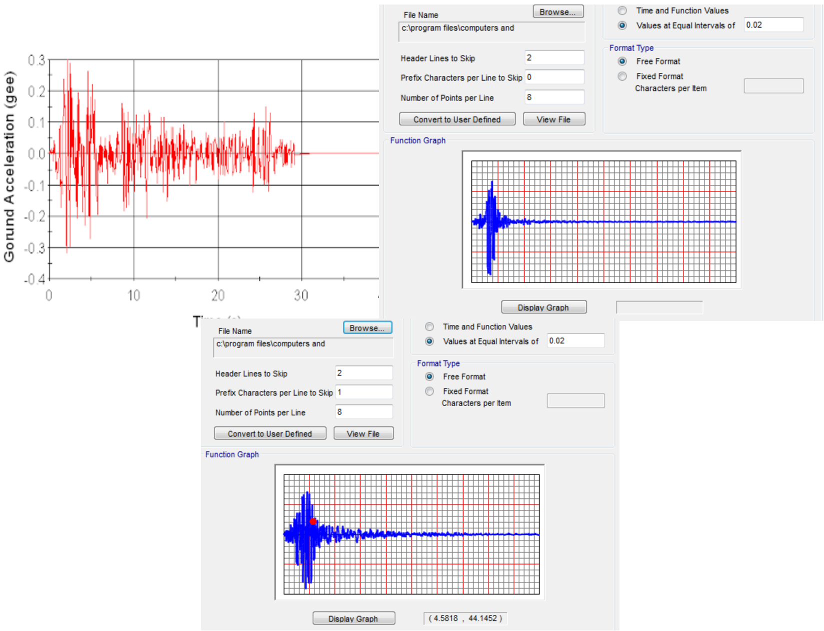


Figure 2: Finite element mesh of the minaret for model M2



File Name: c:\program files\computers and
Header Lines to Skip: 2
Prefix Characters per Line to Skip: 0
Number of Points per Line: 8
○ Time and Function Values
● Values at Equal Intervals of: 0.02
Format Type
● Free Format
○ Fixed Format
Characters per Item

File Name: c:\program files\computers and
Header Lines to Skip: 2
Prefix Characters per Line to Skip: 1
Number of Points per Line: 8
○ Time and Function Values
● Values at Equal Intervals of: 0.02
Format Type
● Free Format
○ Fixed Format
Characters per Item
(4.5818 , 44.1452)

Figure 3: Time history of N-S component of El-Centro, Altadena and Pomona earthquakes

III. Numerical Results

Dynamic response:

The numerical results of displacement of the minaret top with time during the three studied earthquake records are shown in Figs. 4-6 for the minaret models M1, M2 and M3 using shell and solid element models.

Table 1 shows the maximum displacement at top of the minaret obtained from time-history dynamic analysis under the three studied earthquake records and from response spectrum analysis for the different models. Figure 7 shows the deformed shapes of the minaret at maximum displacement obtained from time history and response spectrum analyses for the different models.

Stresses:

The obtained maximum and minimum stresses obtained under combined gravitational and earthquake loading for the minaret model M2 using solid elements are shown in Figure 8.

Modeshapes:

Table 2 shows the periods corresponding to the first six modes for the different models. Figures9 and 10 show the mode shapes for models M2 using shell and solid elements, respectively.

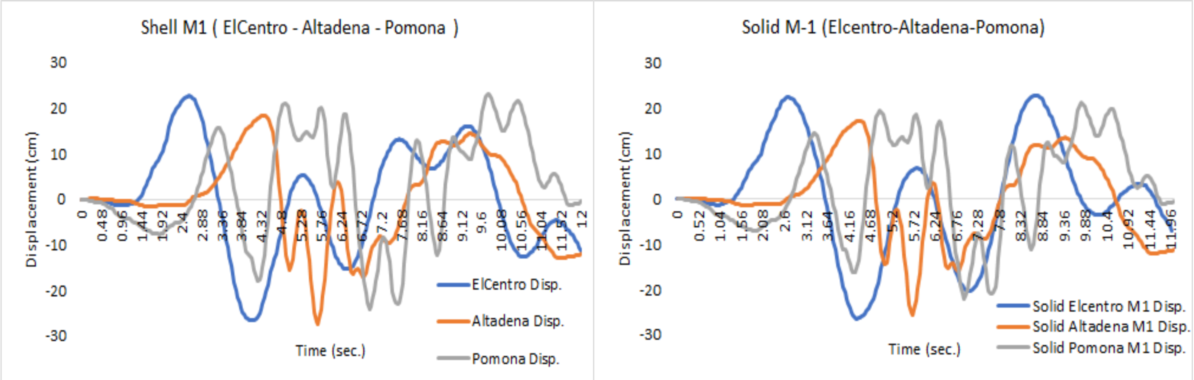


Figure 4: Displacement with time due to different earthquake recordsfor model M-1 using shell and solid elements

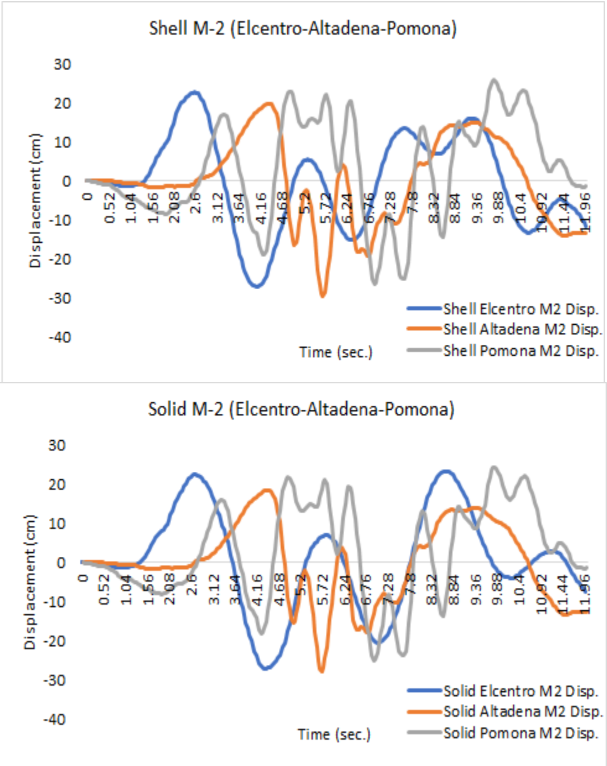


Figure 5: Displacement with time due to different earthquake records for model M-2 using shell and solid elements

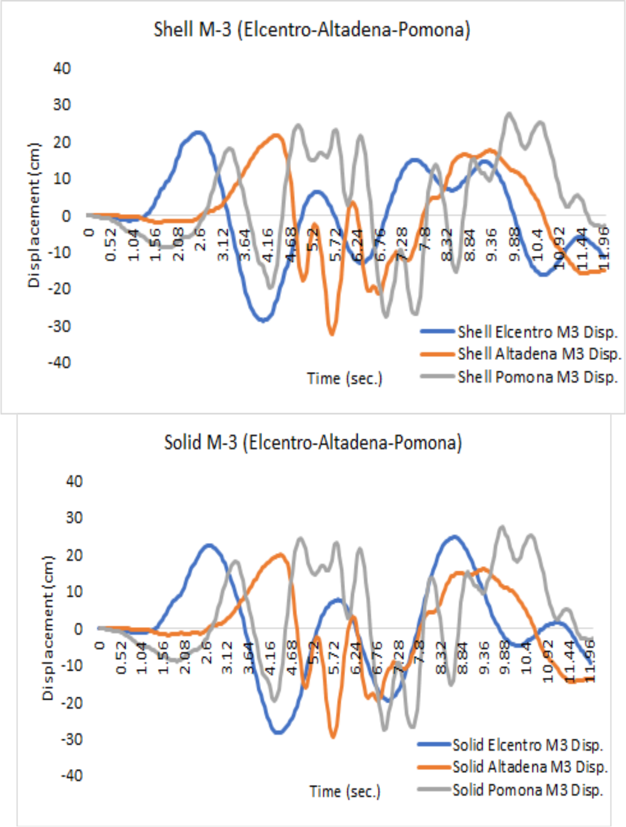
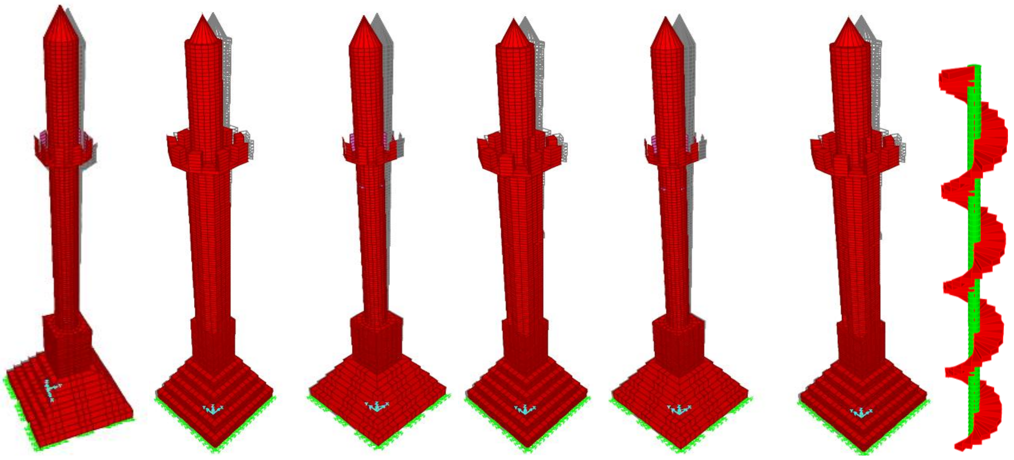


Figure 6: Displacement with time due to different earthquake records for model M-3 using shell and solid elements

Table 1: Dynamic analysis results: maximum lateral displacement at minaret top for the different models

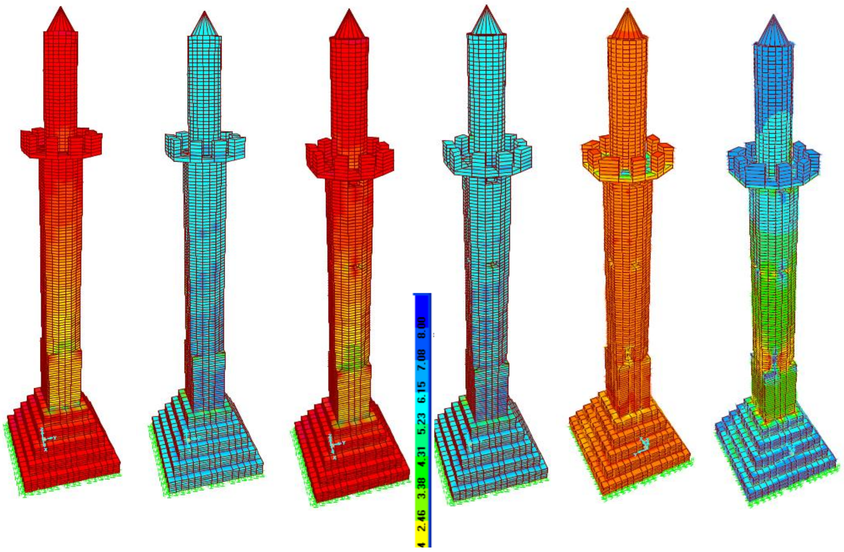
Model	El Centro	Altadena	Pomona	Resp. Spec.

		Time (sec.)	Max. disp. (mm)	Time (sec.)	Max. disp. (mm)	Time (sec.)	Max. disp. (mm)	Max. disp. (mm)
M1	shell	4.12	266.80	2.84	273.11	6.86	241.10	165
	solid	4.32	263.70	2.90	254.96	6.98	220.50	155
M2	shell	4.12	269.80	2.84	293.71	6.86	263	167
	solid	4.32	268.40	2.90	275.35	6.98	249.17	158
M3	shell	4.12	285.80	2.84	333	6.86	282.70	170
	solid	4.32	283.60	2.90	296.22	6.98	268.57	161



M-1-shell M1-solid M-2 shell M2-solid M-3 shell M-3 solid Stairs

Figure 7: Deformed shape of minaret at maximum dispalacement using shell and solid elements



M-1 M-2 M-3

Figure 8: Maximum and minimum stresses corresponding to maximum displacement for solid models

Table 2: Mode shapes and period for the different minaret models

Mode	Period (sec.)					
	Model M-1		Model M-2		Model M-3	
	Shell element	Solid element	Shell element	Solid element	Shell element	Solid element
Mode 1	2.271	2.179	2.386	2.164	2.271	2.081
Mode 2	2.261	2.168	2.259	2.151	2.148	2.068
Mode 3	1.263	0.701	0.798	0.402	0.786	0.701
Mode 4	1.264	0.699	0.791	0.70	0.780	0.696
Mode 5	0.608	0.560	0.608	0.560	0.607	0.560
Mode 6	0.453	0.325	0.433	0.335	0.438	0.327

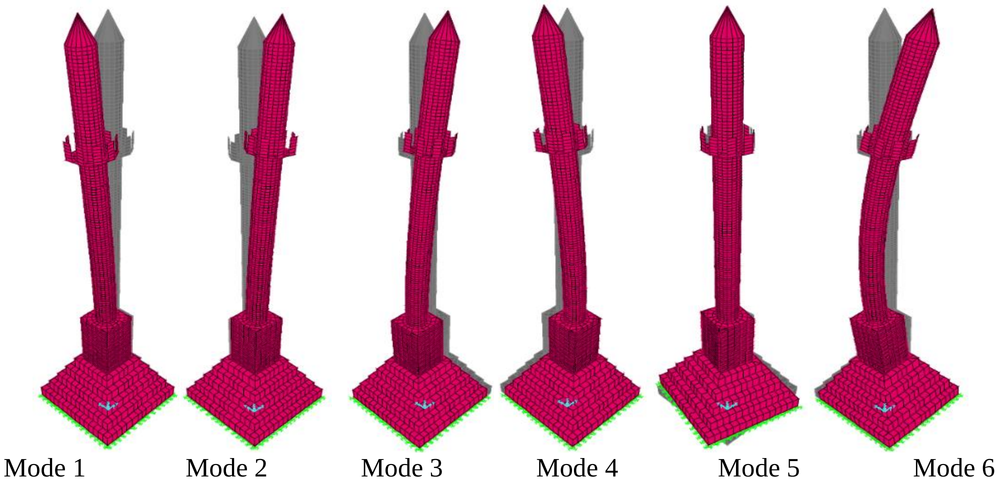

Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6

Figure 9: Deformed shape of minaret for the first six modes - Model M2- shell elements

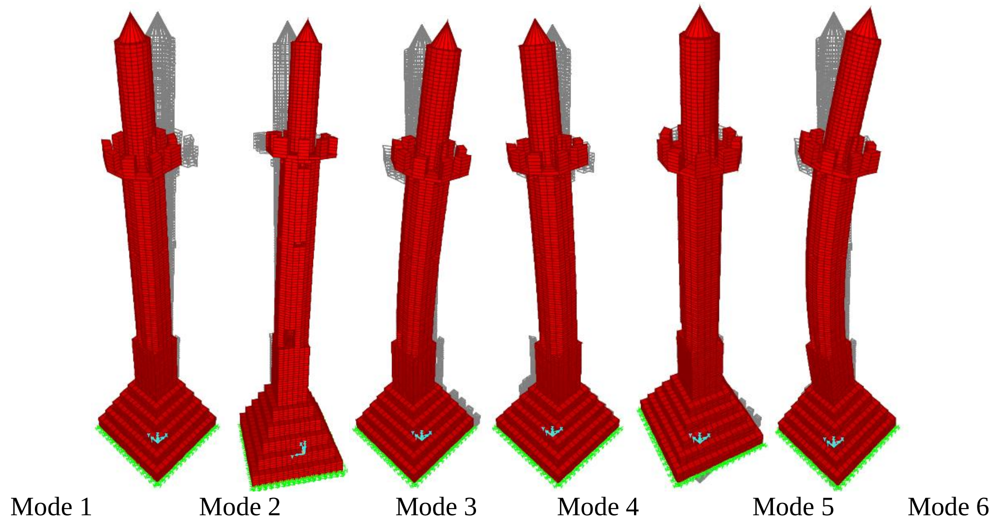

Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6

Figure 10: Deformed shape of minaret for the first six modes - Model M2- solid elements

IV. Discussion

Maximum displacements:

From the results given in Table 2, it is given that for El Centro Earthquake: using shell elements, the maximum displacement occurs at 4.12 sec. for all models, and its value for M-1, M-2 and M-3 models is 266.80mm, 269.80mm and 285.80mm, respectively, while using solid elements, the maximum displacement occurred at 4.32 sec. for all models, and its value for M-1, M-2 and M-3 is 263.70mm, 268.40mm and 283.60mm respectively. For Altadena Earthquake: using shell elements, the maximum displacement occurs at 2.84 sec. for all models, and its value for M-1, M-2 and M-3 is 273.11mm, 293.71mm and 333.00mm, respectively, while using solid elements, the maximum displacement occurred at 2.90 sec. for all models, and its value for M-1, M-2 and M-3 is 254.96mm, 275.35mm and 296.22mm, respectively. For Pomona earthquake: using shell elements the maximum displacement at the minaret top occurs at 6.86 sec. for all models, and its value for M-1, M-2 and M-3 is 241.10mm, 263mm and 282.70mm, respectively, while using solid elements, the maximum displacement occurred at 6.98 sec. for all models, and its value for M-1, M-2 and M-3 is 220.50mm, 249.17mm and 268.57mm, respectively. For response spectrum analysis, using shell elements, the maximum displacement at the minaret top for M-1, M-2 and M-3 is 165mm, 167mm and 170mm, respectively, while using solid elements, the maximum displacement for M-1, M-2 and M-3 is 155mm, 158mm and 161mm, respectively. The maximum displacement of minaret top obtained by response spectrum analysis are compared to dynamic time-history analysis in Table 3. Itis observed that for all models, the maximum displacement of the top of the minaret calculated using response spectrum analysis is considerably less 50-70% of the values obtained by dynamic analysis using time-history earthquake records.

Stresses:

Higher stresses are caused by Altadena earthquake record than by El Centro and Pomona earthquakes.It is observed from Figure 8 that the massive solid pulpit in the lower part of the minaret seems to reduce the stress but compressive stress at the top of the pulpit increased due to the sudden change in the cross-section. Higher stresses were observed at the transitional segments of the minaret and extra stresses were obtained for models M-2 and M-3 at the window and door openings at the lower transition segment.The average maximum stress values determined through FE shell model in the lower transition segment around window and door opening are about 4.0 N/mm^2 in compression and 0.7 N/mm^2 in tension. The maximum stress for masonry assemblage considered to be 4.225 N/mm^2 in addition to the low tensile strength, brittleness and aging of the mortar joints, necessitates measures for strengthening to avoid tensile stresses which would result in cracking and local failure. These locations match with the observations and results reported in published research. Maximum stresses were shown to occur at transition segment and connection region between minaret stool and polygonal body, and this transition region between the square minaret boot and the cylindrical bodywas concluded to be themost vulnerable section under seismic loading [1]. Numerical results showed stress concentrations at locations of abrupt change of cross-section or variation of materials[4].Damage survey conducted for masonry minarets after major earthquake events showed that the most common structural failure was near the bottom of the cylindrical body of the minaret[18]. Field investigation and structural analysis revealed thathigh stresses are observed at the transitional segments of a historic brick minaret and at window and door openings[19].

Comparison between shell and solid element models:

Table 4 lists the maximum displacement at top of minaret and the corresponding timedue to El-Centro earthquake record. It is observed from Table 4 that the maximum displacements obtained using solid (brick) element model are slightly lower than for shell elements. The maximum displacements obtained for solid element models are approximately 99%, 92%, 93% and 94% of those of the shell elements for El-Centro, Altadena, Pomona earthquakes records and response spectrum analysis, respectively, as given in Table 5.

The results of modal analysis given in Table 2 show that for the first two modes there is slight difference 3-10% in the period between using shell and solid elements; for higher modes 3, 4 and 6, the difference is more exaggerated.

Effect of openings and staircase:

The effect of openings on the dynamic response of the minaret is studied by comparing the results of models M1 and M2 in Table 2.It is observed that the effect of openings is slight (less than 4%) due to the small area of openings. The contribution of stairs and core, deduced by comparing M2 to M3, is more obvious; the difference reaches 15% on the maximum displacement. The model M2including stairs experienced slightly longer vibration periods than models M1 and M3, as observed from Table 2. It is observed that considering window and door openings in models M-2 and M-3, results in localized compressive stress around the openings. The location of extra stresses are found to be consistent with the cracks observed on the minaret during field investigation. Further diagonal cracks from the window to the pulpit (top part of the minaret) are highly possible.Staircase and the core present in models in M1and M2slightly affect the distribution of stresses.

Table 3: Maximum displacement of minaret top by response spectrum compared to dynamic time-history analysis

Model		Maximum displacement using response spectrum analysis			
		Max. disp. (mm)	% El Centro	% Altadena	% Pomona
M1	shell	165	61.84%	60.42%	68.44%
	solid	155	58.78%	60.79%	70.29%
M2	shell	167	61.90%	56.86%	63.50%
	solid	158	58.87%	57.38%	63.41%
M3	shell	170	59.48%	51.05%	60.13%
	solid	161	56.77%	54.35%	59.95%

Table 4: Maximum displacement at top of minaret and the corresponding timedue to El-Centro earthquake record

Model	Maximum displacement for El-Centro earthquake record			
	Shell element		Solid element	
	Time (sec.)	Max. disp. (mm)	Time (sec.)	Max. disp. (mm)
M-1	4.12	266.80	4.32	263.70
M-2	4.12	269.80	4.32	268.40
M-3	4.12	285.80	4.32	283.60

Table 5: Comparison of maximum displacement of minaret top using solid and shell elements for all earthquakes

Model	% Max displacement solid / shell			
	El-Centro	Altadena	Pomona	Response spectrum
M-1	98.84%	93.35%	91.46%	93.94%
M-2	99.48%	93.75%	94.74%	94.61%
M-3	99.23%	88.95%	95.00%	94.71%
Average	99.18%	92.02%	93.73%	94.42%

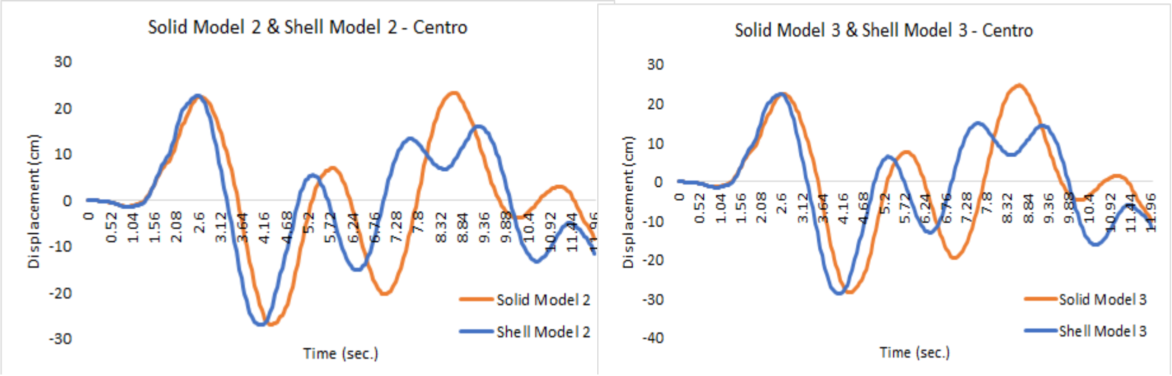


Figure 11: Displacement with time for El-Centro earthquake record:comparing solid and shell elements results

V. Conclusion

In this paper, numerical modeling by 3D finite elements and dynamic analysis were made for the stone minaretof Fatma El-Shakra Mosque in Cairo, constructed 1468 A.D. and having height of 32 m, which showed deviation of its top from verticality reaching 300 mm, in addition to several cracks in the walls after the occurrence of two strong earthquakes. Several numerical models were created and analyzed in order to represent and investigate the effect of several geometrical and structural parameters on the seismic behavior of the minaret.

Based on the obtained numerical results, the main conclusions canbe summarized in the following points.

- Numerical modeling by 3D finite elements and dynamic analysis were made for the minaret; several numerical models were created and analyzed in order to represent and investigate the effect of several geometrical and structural parameters.
- Dynamic time-history analysis under three scaled earthquake records resulted in lateral displacement of the top reaching 260-320 mm for the different studied numerical models, which is close to the observed deviation 300mm. This verifies the efficiency of the modeling and analysis approach.
- Response spectrum analysis was shown to underestimate the maximum displacement of the minaret top.
- The numerical results showed slightly difference between modeling the minaret body by shell and solid elements; differences were in the range of 2-8%.
- The existence of internal core and spiral stairs integrated with the minaret walls was found to enhance the dynamic behavior of the minaret.
- The end constraints of stairs or the nature of connections between the individual steps and the minaret body strongly affect the structural performance of minarets when subjected to lateral loads such as wind or earthquakes.
- The existence of balcony (21 m above ground level) creates mass concentration along the minaret height that and affects its dynamic structural response. Noting also decrease of the minaret cross section and opening at this level, this abrupt change has influence on the dynamic behavior and was shown to cause increased stresses at this transition zone.
- The disintegration and cracks in the stone minaret walls at different locations observed from field inspection were not totally justified structurally. These cracks may be attributed to other factors such as localized damage, local material deterioration, misuse, long environmental exposure, lack of maintenance, etc.
- The soil properties were recalculated several times and the numerical model was adjusted accordingly, in order to yield the correct inclination value. Thus, it is recommended to perform proper actions to enhance the foundation conditions, since it significantly affects the seismic behavior.
- It is recommended to conduct continuous monitoring of the minaret after completion of the restoration work, in order to detect any signs of excessive deformation.

- Conservation measures should be taken for this heritage minaret to preserve its strength and structural efficiency for the next generations.

References

[1]. Dogangun, A.; Acar, R.; Sezen, H.; Livaoglu, R. (2008) "Investigation of dynamic response of masonry minaret structures", Bull Earthquake Eng, 5, 505-517.

[2]. Preciado, A., Bartoli, G. and Budelmann, H. (2015) "Fundamental aspects on the seismic vulnerability of ancient masonry towers and retrofitting techniques", Earthq. Struct, 9(2):339–52.

[3]. Sykora, D., Look, D., Croci, G., Karaesmen, E. and Kraraesmen, E. (1993), "Reconnaissance report of damage to historical monuments in Cairo, Egypt following the October 12, 1992 Dahshur Earthquake", Technical Report NCEER93-0016, National Center for Earthquake Engineering Research, State University of New York at Buffalo, U.S.A.

[4]. Higazy, E.M. (2004), "Vulnerability of historical minarets, investigation of their seismic assessment and retrofitting", Emirates Journal for Engineering Research, 9 (2), 59-64.

[5]. Corbi, O., Zaghw, A., Elattar, A. and Saleh, A. (2013) "Preservation provisions for the environmental protection of Egyptian monuments subject to structural vibrations", International Journal of Mechanics, 3 (7), 172-179.

[6]. Giordano, A., Mele, E. and De Luca, A. (2002), "Modeling of historical masonry structures: comparison of different approaches through a case study", Engineering Structures, 24(8), 1057-1069.

[7]. Lourenço, P.B., Milani, G., Tralli, A. and Zucchini, A. (2007), "Analysis of masonry structures: Review of and recent trends of homogenization techniques", Canadian Journal of Civil Engineering, 34, 1443–1457.

[8]. Ghosh A.K., Amde A.M., Colville J. (1994), "Finite element modeling of unreinforced masonry", 10th International Brick/Block Masonry Conference, Calgary, Canada, July.

[9]. Roca, P., Cervera, M., Pelà, L., Clemente, R. and Chiumenti, M. (2013), "Continuum FE models for the analysis of Mallorca Cathedral", Engineering Structures, 46, 653–670.

[10]. Zaki. M.A., Hassan, A.F., Mourad, S.A. and Osman, A.M. (2008), "Evaluation of the structural integrity of historical stone minarets", in the 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.

[11]. Oğuzmert, M. (2002), Dynamic behaviour of masonry minarets, M.Sc. Thesis, Istanbul Technical University, Turkey.

[12]. Turk, A. M. and Cosgun, C. (2010), "Determination of Seismic Behavior and Retrofit of Historical Masonry Minaret with FRP", 8th International Masonry Conference, Dresden, 148, 2029-2038.

[13]. Ismail M. and Essa A.M. (2014) "Seismic behavior of heritage masonry structures", Int. J. Struct. & Civil Engg. Res., Vol. 3, No. 4, November.

[14]. Peña, F., Lourenço, P.B., Mendes, N., Oliveira, D.V. (2010), "Numerical models for the seismic assessment of an old masonry tower", Engineering Structures, 32 (5), 1466–1478.

[15]. Computers and Structures Inc. (CSI) SAP2000 (2017), "Linear and Nonlinear Static and Dynamic Analysis and Design of Three-Dimensional Structures", Version 18.2, Berkeley, CA, USA.

[16]. El-Attar, A.G., Saleh, A.M. and Osman, A. (2001), "Seismic response of a historical Mamluk style minaret", in: Earthquake Resistant Engineering Structures III, WIT Press, 745–754, www.witpress.com, ISSN 1743-3509.

[17]. ECP 201-2012 (2012), "Code of Practice for Calculating Loads and Forces on Buildings and Structures", Housing and Building Research Center, Ministry of Housing and Urban Communities, Cairo, Egypt.

[18]. Sezen, H., Fırat, G.Y. and Sozen, M.A. (2003), "Investigation of the performance of monumental structures during the 1999 Kocaeli and Duzce earthquakes", in: Fifth National Conference on Earthquake Engineering, Paper no. AE-020.

[19]. Muvafık, M. (2014), "Field investigation and seismic analysis of a historical brick masonry minaret damaged during the Van Earthquakes in 2011". Earthquakes and Structures, 6(5), pp. 457–472.

Amr M. Abdel-Halim, et. al. "Numerical Study of the Seismic Behavior of a Historic Stone MasonryTower." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 17(3), 2020, pp. 21-30.