



Ain Shams University
Faculty of Engineering

Assessment of Seismic Behavior of Monumental Minarets in Egypt

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE IN
CIVIL ENGINEERING (STRUCTURAL ENGINEERING)

By

Amr Mansour Mohamed Abdel-Halim

B.Sc. Civil Engineering - The British University in Egypt

Supervised by:

Prof. Dr. Mohamed Nour-El-Din Fayed

Professor of Structural Analysis
Faculty of Engineering
Ain Shams University

Prof. Dr. Gehan Abdel-Rahman Hamdy

Professor of Structural Analysis
Faculty of Engineering at Shoubra
Benha University

Dr. Mohamed Ahmed Abdel-Wahab

Assistant Professor - Structural Engineering Department
Faculty of Engineering - Ain Shams University

Cairo, Egypt

2020



Ain Shams University
Faculty of Engineering

Assessment of Seismic Behavior of Monumental Minarets in Egypt

By

Amr Mansour Mohamed Abdel-Halim

B.Sc. Civil Engineering - The British University in Egypt

EXAMINERS COMMITTEE

Name	Signature
Prof. Dr. Osama Omar El-Mahdy Professor of Structural Analysis Faculty of Engineering at Shoubra - Benha Univ.	
Prof. Dr. Abd-El-Salam Ahmed Mokhtar Professor of Structural Analysis Faculty of Engineering- Ain Shams Univ.	
Prof. Dr. Mohamed Noor-El-Din Fayed Professor of Structural Analysis Faculty of Engineering- Ain Shams Univ.	
Prof. Dr. Gehan Abdel-Rahman Hamdy Professor of Structural Analysis Faculty of Engineering at Shoubra - Benha Univ.	

Date: .../.../...

Cairo, Egypt - 2020

STATEMENT

This thesis is submitted to the Faculty of Engineering at Ain Shams University in partial fulfillment of the requirement of the M.Sc. Degree in Civil Engineering (Structural Engineering).

Any kind of work included in this thesis has been done by the author. No part of the thesis has been submitted for a degree or a qualification at other university or institute.

Signature

Amr Mansour Mohamed

Researcher's Data

Name of Researcher	Amr Mansour Mohamed
Date of Birth	March 13, 1992
Place of Birth	Egypt
Nationality	Egyptian
First University degree	B.Sc. Civil Engineering
Department	Civil Engineering
University	The British University in Egypt
Date of Degree	July 2014
Current Job	Design Engineer – Structural Engineering at the Arab Contractors (Osman Ahmed Osman & Co.)

Acknowledgement

First of all, I am so grateful to Allah for giving me the guidance, strength, patience, and hope to finish my research. It is the mercy of God, and my trust in him that have made such a dream to become reality.

I give many thanks for my advisor, **Prof. Dr. Mohamed Noor-El-Din Fayed** for his advices along the research period, his smart suggestions, his ideas and patience have been great assets, and for facilitating the work in our faculty to be easier.

I wish to express my deep gratitude to my advisor, **Prof. Dr. Gehan Abdel-Rahman Hamdy**, for her inspiring guidance, valuable advice and encouragement throughout the progress of this research.

Finally, I'd like to express my very deep appreciation to my parents and to my sister for providing me with reliable support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

I also place on record, my sense of appreciation to all who have contributed or have been helpful in making my dream become real.

Really "Thank You" and may Almighty God richly bless you.

Signature

Amr Mansour Mohamed

Abstract

Ancient masonry minarets have a historic and social significance and are considered as architectural heritage. One of the most important problems facing these structures is the dynamic response under lateral loads, especially under the effect of earthquake excitation. Previous seismic activity verified that especially old stone masonry minarets suffered severe damages, because of the poor seismic resistance. The 1992 & 2015 earthquake in Egypt has caused damage and even failure loss of several monumental masonry minarets in Cairo.

These study was carried out in main stages: overview the published literature in the field and numerical modeling and dynamic analysis are performed for the minaret in its current condition using linear and nonlinear finite element commercial software in order to investigate its seismic behavior and to assess its structural efficiency. The contribution of openings and spiral stairs on the dynamic behavior are examined, in addition to the influence of other modeling parameters. The obtained results regarding stresses and deformations within the structure are analyzed and related to the observed damages. The results indicate overall stability of the structure in its current condition while high stresses occur at several locations. The actions made for restoration and stabilization of the minaret are presented. After retrofit intervention, the seismic analysis has shown improvement of the seismic behavior of the minaret and demonstrated the effectiveness of the retrofit actions.

Key Words: Masonry; Tower; Historic; Finite Elements; Dynamic Analysis; Seismic; Assessment

Table of Contents

Acknowledgement.....	I
Abstract.....	II
Table of Contents	III
List of Tables.....	VII
List of Figures.....	VIII
CHAPTER 1	1
INTRODUCTION	1
1.1 Background.....	1
1.2 Research Significance	1
1.3 Scope and Objectives	2
1.4 Thesis Outline	2
CHAPTER 2	4
BACKGROUND AND LITERATURE REVIEW	4
2.1 General.....	4
2.2 Existing Historical Masonry Minarets in Egypt	4
2.2.1 First towers and minarets until Tulunid Period: (827-904).....	4
2.2.2 Fatimid Period: (969- 1171) and Ayyubid Period :(1171 to 1250)	6
2.2.3 Medieval minarets from Mamluk period: (1250-1517)	9
2.2.4 Historic minarets from Ottoman era till 19th century.....	11
2.3 Causes of Deterioration and Damage of Historic Masonry Structures	11
2.3.1 Material aging due to climatic factors.....	11
2.3.2 Biological degrading factors	13
2.3.3 Human abuse, misuse, overloading and lack of maintenance	13
2.3.4 Hazards, earthquakes and fires	13
2.4 Mechanical Behavior of Masonry Constructions.....	14
2.5 Previous Research on Numerical Modeling of Masonry Towers	15

2.6 Previous Research on Seismic Behavior of Masonry Minarets.....	19
CHAPTER 3.....	25
DESCRIPTION AND NUMERICAL MODELING OF STUDIED MINARET	25
3.1 General.....	25
3.2 Studied Minaret Description.....	25
3.2.1 Location and historical data of minaret.....	25
3.2.2 Architecture and dimensions	26
3.2.3 Material of construction	31
3.3 Condition Survey and Observed Damage	32
3.4 Finite Element Method	34
3.5. Numerical Modeling of Minaret Using Linear FE Analysis Software SAP 2000.....	35
3.5.1 Elements types.....	35
3.5.2 Finite element modeling parameters.....	35
3.5.3 Finite element mesh	37
3.5.4 Material properties.....	38
3.5.5 Load cases	39
3.5.5.1 Time history analysis	39
3.5.5.2 Response spectrum analysis	39
3.5.6 Boundary conditions	40
3.6 Numerical Modeling of Minaret Using Nonlinear FE Analysis Software “ANSYS 19.0 “	40
3.6.1 Used elements.....	40
3.6.2 Finite element mesh	41
3.6.3 Assumptions material for non-linear behavior	42
3.6.4 Nonlinear analysis parameters.....	42
3.6.5 Element output data	43
Fig. 3.17 Output stresses for the element SOLID65.	43

3.6.6 Boundary conditions	43
CHAPTER 4	44
SEISMIC ANALYSIS OF THE UNSTRENGTHENED MINARET	44
4.1 General.....	44
4.2 Performed Seismic Analysis of Minaret.....	44
4.2.1 Time history dynamic analysis	44
4.2.2 Response spectrum analysis	46
4.3 Numerical Results and Discussion for Seismic Behavior	46
4.3.1 Natural frequencies and mode shapes.....	46
4.3.2 Displacement-time relations.....	48
4.3.3 Deformed shapes and maximum displacements.....	49
4.3.5 Stresses	64
CHAPTER 5	75
RESTORATION AND SEISMIC ANALYSIS OF RETROFITTED MINARET	75
5.1 General.....	75
5.2 Methodology for Minaret Conservation and Restoration.....	75
5.3 Executed Restoration Measures for Minaret	75
5.3.1 Crack repair, repointing and grouting.	76
5.3.2 Soil stabilization using micropiles.....	81
5.3.3 Dismantling and reconstruction of the minaret upper part.....	82
5.4 Numerical Modeling of the Minaret after Strengthening	91
5.5 Numerical Results for Seismic Behavior of the Strengthened Minaret	91
5.5.1 Natural frequencies and mode shapes.....	91
5.5.2 Displacement-time response.....	93
5.5.3 Stresses	94
5.5.4 Effect of strengthening on the seismic behavior of the minaret.....	97
CHAPTER 6	99

SUMMARY AND CONCLUSIONS	99
6.1 Summary.....	99
6.2 Conclusions.....	100
6.3 Suggestions for Future Research Work.....	101
REFERENCES	102

List of Tables

Table 3.1 Structure models and the elements included in each model	36
Table 3.2 SOLID65 concrete material data.....	42
Table 4.1 Results for mode shapes of minaret and corresponding time and frequency using shell elements.....	47
Table 4.2 Results for mode shapes of minaret and corresponding time and frequency using solid elements	47
Table 4.3 Maximum displacement at top of minaret for time history analysis of the different earthquakes using shell element	62
Table 4.4 Maximum displacement at top of minaret for time history analysis of different earthquakes using solid element	62
Table 4.5 Maximum displacement of the minaret top by response spectrum analysis using the different models	63
Table 4.6 Maximum stresses in minaret body due to earthquake for linear dynamic analysis shell element	73
Table 4.7 Maximum stresses in minaret body due to earthquake for linear dynamic analysis solid element.....	73
Table 5.1 Results for mode shapes of minaret M-2 model after strengthening.....	91
Table 5.2 Results of maximum displacement of retrofitted minaret due to earthquakes.....	93

List of Figures

Fig. 2.1 Central courtyard of Ahmed ibn Tulun minaret [2]	5
Fig. 2.2 Elevation of Ahmed ibn Tulun minaret [3]	5
Fig. 2.3 Courtyard and surrounding halls of the mosque of Al-Hakim [4]	6
Fig. 2.4 Al-Hakim minaret [6]	7
Fig. 2.5 Details of Al-Hakim minaret [5]	7
Fig. 2.6 Al-Azhar minaret [7]	8
Fig. 2.7 Al Saleh Najmuddin Ayoub minaret [8]	9
Fig. 2.8 Sultan Hassan Ibn – al – Nasir Muhammad ibn Qalawn minaret [9]	10
Fig. 2.9 Sultan al-Ghuri minaret [10]	10
Fig. 2.10 Mohamed Ali minaret [11]	11
Fig. 2.11 Compressive strength of masonry prisms and the individual components [13]	14
Fig. 2.12 Building materials and construction techniques of corbels in medieval Cairo [17]	16
Fig. 2.13 Section showing masonry columns supporting arches and tied by timber [18]	17
Fig. 2.14 The URM perforated brick wall with two windows (a) wall after cyclic test, (b) 3D finite element model of wall, (c) numerical results [21]	18
Fig. 2.15 Stress contours showing stress concentration and cracks in tower [22]	18
Fig. 2.16 Stress contours showing stress concentration at change of section of minaret [23]	19
Fig. 2.17 Photos of the used instruments [27]	21
Fig. 3.1 Location of mosque of Fatma el Shaqra [35]	25
Fig. 3.2 Monuments number and name of Fatma el Shaqra Mosque [36]	26
Fig. 3.3 Elevation of Fatma el Shaqra minaret	27
Fig. 3.4 Front elevation of upper part of the Fatma el Shaqra minaret	28
Fig. 3.5 Rear elevation of upper part of the Fatma el Shaqra minaret	28
Fig. 3.6 Longitudinal section of the Fatma el Shaqra minaret	29
Fig. 3.7 Section plan at level 9 m above ground level	30
Fig. 3.8 Section plan at level 17m above ground level	30
Fig. 3.9 Section plan at level 22m above ground level	31
Fig. 3.10 Lime stones of the minaret wall and the stone staircase	31
Fig. 3.11 Elevation of minaret of Fatma el Shaqra and minaret heavily scaffolded since the 1992 earthquake	32
Fig. 3.12 Cracks of stones at the lower part of the minaret	32
Fig. 3.13 Surveying data show the displacement of the top of the minaret 320mm	33

Fig. 3.14 Finite element mesh for minaret body and stair using SAP2000.....	38
Fig. 3.15 The coordinate system for SOLID65 element	41
Fig. 3.16 Finite element mesh for minaret, elevation, section and stairs using ANSYS	41
Fig. 4.1 Time history of N-S component of El-Centro Earthquake [37]	45
Fig. 4.2 Time history of N-S component of Altadena Earthquake [37].....	45
Fig. 4.3 Time history of N-S component of Pomona Earthquake [37].....	45
Fig. 4.4. Response spectrum of earthquakes	46
Fig. 4.5 Results for mode shapes of unstrengthen minaret using shell elements	48
Fig. 4.6 Results for mode shapes of unstrengthen minaret using solid elements	48
Fig. 4.7 Displacement with time for dynamic analysis for model M-1-shell.....	49
Fig. 4.8 Displacement with time for dynamic analysis for model M-2-shell.....	49
Fig. 4.9 Displacement with time for dynamic analysis for model M-3-shell.....	50
Fig. 4.10 Displacement with time for dynamic analysis for model M-1-solid.....	50
Fig. 4.11 Displacement with time for dynamic analysis for model M-2-solid.....	51
Fig. 4.12 Displacement with time for dynamic analysis for model M-3-solid.....	51
Fig. 4.13 Response spectrum results for maximum deformed shape using shell elements	52
Fig. 4.14 Response spectrum results for maximum deformed shape using solid elements	52
Fig. 4.15 Maximum deformed shape for (M-1 Shell element).....	53
Fig. 4.16 Maximum deformed shape for (M-2 Shell element).....	54
Fig. 4.17 Maximum deformed shape for (M-3 Shell) element)	55
Fig. 4.18 Maximum deformed shape for (M-1 Solid element).....	56
Fig. 4.19 Maximum deformed shape for (M-2 Solid element).....	57
Fig. 4.20 Maximum deformed shape for (M-3 Solid element).....	58
Fig. 4.21 Maximum deformed shape for (M-2 Shell element).....	59
Fig. 4.22 Maximum deformed shape for (M-2 Solid element).....	60
Fig. 4.23 Maximum deformed shape due to earthquake ANSYS	61
Fig. 4.24 Maximum dead load stresses for Shell element Element element)	65
Fig. 4.25 Maximum dead load stresses for Solid element Element element).....	66
Fig. 4.26 Maximum (DL +0.7 El Centro) stresses for Shell element).....	67
Fig. 4.27 Maximum (DL +0.7 Altadena) stresses for Shell element).....	68
Fig. 4.28 Maximum (DL +0.7 Pomona) stresses for Shell element)	69
Fig. 4.29 Maximum (DL +0.7 Elcentro) stresses for Solid element)	70
Fig. 4.30 Maximum (DL +0.7 Altadena) stresses for Solid element).....	71
Fig. 4.31 Maximum (DL +0.7 Pomona) stresses for Solid element).....	72

Fig. 4.32 Maximum stresses due to earthquake using ANSYS.....	73
Fig. 4.33 Stresses concentrated around doors and windows: a) stresses obtained numerically and (b) location of observed cracks	74
Fig. 5.1 Cracks of stones at the lower part of the minaret.....	76
Fig. 5.2 Stitching of cracks [40]	77
Fig.5.3 Some zones required to be injected (a) at the base of the minaret and (b) wide open slots between masonry	78
Fig. 5.4 Modern injection installation with the necessary components [41].....	78
Fig. 5.5 Tests report showing the details of the tested samples.....	79
Fig. 5.6 Core sample take from height 4 meters above ground level	80
Fig. 5.7 Samples before compression testing for cores taken from height 1.5 & 4 meters above ground level	80
Fig. 5.8 Samples after compression testing for cores take from height 1.5 & 4 meters above ground level	80
Fig. 5.9 Test results of two core samples showing failure load and stresses	81
Fig. 5.10 Scheme of a hollow pipe micro-pile [42]	82
Fig. 5.11 Erection of formwork (shuttering)	83
Fig. 5.12 Labelling the cone of wood material.....	83
Fig. 5.13 Storage of labeled wood materials	83
Fig. 5.14 Labelling of masonry stone units	84
Fig. 5.15 Labelling of the masonry of the minaret body.....	84
Fig. 5.16 The minaret after completion of labelling the masonry stones.....	85
Fig. 5.17 Dismantling the crescent and top part of the minaret.....	85
Fig. 5.18 Dismantling of the stones of the minaret body	86
Fig. 5.19 The minaret after dismantling its upper part.....	86
Fig. 5.20 Storing of stones of the minaret	87
Fig. 5.21 After dismantling the stone at the pulpit level	88
Fig. 5.22 Façade of Fatma el Shakra mosque with the minaret dismantled till the pulpit level 7m above the ground.....	88
Fig. 5.23 Fatma el Shaqra minaret after reconstruction and strengthening.....	89
Fig. 5.24 Fatma el Shaqra minaret and mosque façade after completion of restoration works	90
Fig. 5.25 Results for mode shapes of minaret after strengthening	92
Fig. 5.26. Displacement with time for strengthened minaret due to different earthquakes.	93

Fig. 5.27. Results for deformed shape at maximum displacement for minaret after retrofit ..	94
Fig. 5.28 Maximum stresses (kg/cm ²) due to earthquakes before retrofit – shell model.....	95
Fig. 5.29 Maximum stresses (kg/cm ²) due to earthquakes after retrofit – shell model	95
Fig. 5.30 Maximum stresses (kg/cm ²) due to earthquakes before retrofit – solid model	96
Fig. 5.31 Maximum stresses (kg/cm ²) due to earthquakes after retrofit – solid model	96
Fig. 5.32 Levels used to compare minaret displacement before and after strengthening	97