Structural Study and Evaluation of Previous Restoration Work of Mohammad 'Ali Pasha Mosque at the Citadel in Cairo

Dr. Yaser Yehya Amin Abdel-Aty♦

Abstract

Mohammad 'Ali Pasha Mosque at the Citadel in Cairo is considered one of the main landmarks in Egypt. It majestically stands at a northwestern bend of the Citadel and it is visible from numerous locations in Cairo. It has become the symbol of the Citadel, to the point that its name is given to the whole complex in the colloquial Egyptian parlance .

This paper studies analytically the static and dynamic structural behavior of this great mosque using computer numerical modeling techniques, to reach the main reasons for past cracking and failures in its domed-roof and other structural elements, which occurred by the end of 19th Century. A number of 3D-models are analyzed to study the mosque, in both original and after restoration conditions, under static (i.e. dead and live loads) and dynamic (i.e. Eigenvector modal analysis, response-spectrum and time-history) cases of loading. Besides, structural evaluation of major restoration project, in 1930s, is conducted to determine the current structural safety status of the mosque.

1. Introduction

Mosque of Mohammad 'Ali Pasha at the Citadel in Cairo was built following the architectural style of Turkish (Ottoman) Mosques in Istanbul. This mosque has a unique and unparalleled architectural style in Egypt and all other Arabic Countries (1). Besides, Turkey

---

♦Lecturer at Cairo University, Faculty of Archaeology, Restoration Department

Keywords: Ottoman, Masonry, Structural evaluation, Restoration, Numerical model

(1) El-Bash, H., *Al-Qahira* (History, Arts and Monuments), *Al-Ahram* Pub., Cairo, 1970, p. 486 (in Arabic).

has very few number of mosques that follow the same architectural style.

This unique Turkish-style mosque in Egypt suffered dangerous cracks and structural failures in domes, roofing system, walls and central columns, by the end of 19th Century. These structural deficiencies were unsuccessfully restored in 1899 A.D., since few years later the structural condition of the mosque got worth and many dangerous structural cracks and failures appeared again (2). This required urgent action from the Egyptian government, to rescue one of the most precious Moh. 'Ali's constructions in Cairo. During the reign of King Foad I, in 1931, a complete scheme of restoration for the mosque was started, which was completed during the reign of King Farouk, in 1939 (3).

This paper aims to understand and analyze the structural behavior of this unique and important mosque, with its complicated roofing system, under critical loading conditions, on which the proper restoration work is mainly dependent upon. Also, this paper will assess the last major structural restoration work that substituted domes, arches and columns in the mosque with reinforced concrete structural elements, following their original shape and cladding(4). This evaluation would verify the current structural safety of this historic mosque under possible loading conditions, especially seismic loads, which are considered the most critical actions that affect heritage structures in Egypt. The importance of this research refers to the very few number of previous work that studies the structural behavior of those Ottoman (Turkish-Style) historical mosques, with their complicated domed-roofing system (5). Findings

---

(2) Mahir, S., *Masajid Misr wa Awleya'ha Al-Salehoon*, Supreme Council of Islamic Affairs, Part IV, *Al-Ahram* Pub., Cairo, 1971, pp. 251-255 (in Arabic).

(3) Abdel-Wahab, H., History of Archaeological Mosques (*Tareekh Al-Masajid Al-Athareyah*), *Al-Nahda Al-Masryeh* Pub., Cairo, 1946, Part II, pp.379-380 (in Arabic).

(4) Ibid, pp. 380-381.

(5) Beyen, K., Structural identification for post-earthquake safety analysis of the Fatih mosque after the 17 August 1999 Kocaeli earthquake, www.elsevier.com/locate/engstruct, Engineering Structures 30 (2008), pp. 2165–84.

and conclusions of this research would help conservation and preservation studies of this unique and important mosque of Moh.'Ali in Cairo and its counterparts in Turkey.

2. Historical Background

Mohammad 'Ali Pasha is considered the founder of modern Egypt. He governed Egypt and Sudan from 1805 A.D. till 1848 A.D. (6). During his reign, the Citadel continued to be seat of Government, as all previous Islamic eras (since the Ayyubids until the Ottomans). He started to restore walls of the Citadel and build numerous palaces, schools, and government buildings inside it. Then, he established a great mosque and adjoined a mausoleum inside it, which includes graves for him and his family (7).

The mosque was founded on debris of old Mamluk buildings at the Citadel. Its construction was started during Mohammad 'Ali Pasha reign, in 1830 A.D., whom was later buried inside it in 1848 A.D., and completed during the reign of 'Abbas Pasha I, in 1857 A.D., who achieved its decorations. The Turkish architect of this mosque was Yusuf Bushnak; who chose the Mosque of Sultan Ahmet in Istanbul as a prototype for the design of Moh.'Ali Mosque, with some modifications (8); see Plates (1-a) and (1-b).

Near the end of the 19th Century, the mosque showed many dangerous cracks. It was repaired in 1899 A.D. by reinforcing the four piers and bracing the masonry of the arches at their springing with iron belts. These repairs, however, were not influential for shortly afterwards more cracks began to appear in different parts of the mosque (9). Thus, the structural condition of the mosque became so dangerous. A major scheme for its complete restoration was implemented during the late King Fouad I, in 1931. This scheme

---

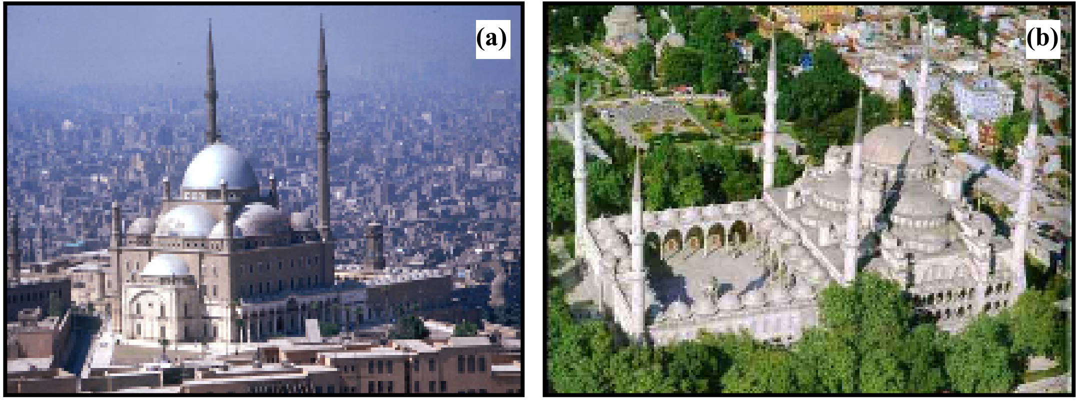
(6) El-Bash, H., Op. Cit., p. 486.

(7) Mubark, A., *Al-Khetat Al-Tawfikiya*, for Cairo, Egypt and other old and famous cities, Part V, *Bolaq* Pub., Cairo, 1888, pp. 110-112 (in Arabic).

(8) Abdel-Wahab, H., Op. Cit., p. 378.

(9) Mahir, S., Op.Cit., pp. 251-255.

comprised demolition, rebuilding, painting and gilding of the entire domed-roof and its supporting elements (i.e arches, columns, etc.). The first part of this scheme was completed during the reign of the late King Fouad I. The second part, which comprised the alabaster lining, painting and gilding, was completed during the reign of King Farouk I[10]. The total expenses amounted to 100,000 EP.



a) Mohammad 'Ali Pasha Mosque in Cairo. b) Sultan Ahmet Mosque in Istanbul

Plates (1: a and b): Moh.'Ali Mosque in Cairo and its architectural prototype in Istanbul of Sutlan Ahmet Mosque (After: ArchNet website, http://archnet.org/library/images, 2005).

3. Architectural Description of the Mosque

Moh. 'Ali Mosque was built following architectural style of Ottoman Mosques in Istanbul and similar to Sultan Ahmet Mosque; see Plates (1-a) and (1-b). The mosque's plan is square (length of each side =41 m); which is adjoined to nearly square courtyard (*sahn*) of dimensions 53x52 m from N-W side; see Figure (1) and Plates (2) and (3).

Roofing system of the mosque is composed of two levels of domes; which provides greater sense of space than horizontal roof, as roof is supported on four piers only. The roof consists of one central dome (diameter =22 m), supported by four arches that rest on four massive square columns (length=2.8 m), see Figures (1 to 3) and Plates (8 to 9). The backside of these arches is covered by four

---

[10] Abdel-Wahab, H., Op. Cit., pp. 379-381.

semi-ellipsoidal domes. This composite domed-roof is surrounded by four smaller domes at the corners of mosque's roof (diam. =10.5 m). Another semi-dome covers the *mihrab* (prayer niche) on the eastern side of the mosque (see Plates: 2, 4 and 8-b). At North and West corners of the mosque rise two elegant cylindrical minarets of Ottoman style, 82.7 m high; see Figures (2) and (3), and Plate (3). Arcades (*Iwans*), which are composed of shallow domes that rest on circular arches and marble cylinder columns; extend along N-E and S-W façades of the mosque, beside the interior four sides of the courtyard. Arches, columns and walls of all arcades; are lined with alabaster (11); see Plate (3).

The mosque has three entrances, one in the middle of each side expect the prayer-niche (*Qibla*) side. The N-W door opens on the courtyard, which includes other two doors, located near the two minarets. The courtyard has an octagonal fountain, covered by a carved alabaster dome, above which is a larger dome that support on eight columns. This dome has an awning with raised gilt ornament, representing scenes from nature. It is also covered, as the domes of the mosque, with sheets of lead; see Plates (3) and (6).

A brass clock-tower surmounts the middle of the N-W side of the courtyard, which overlooks on the Citadel Square; see Plate (6).

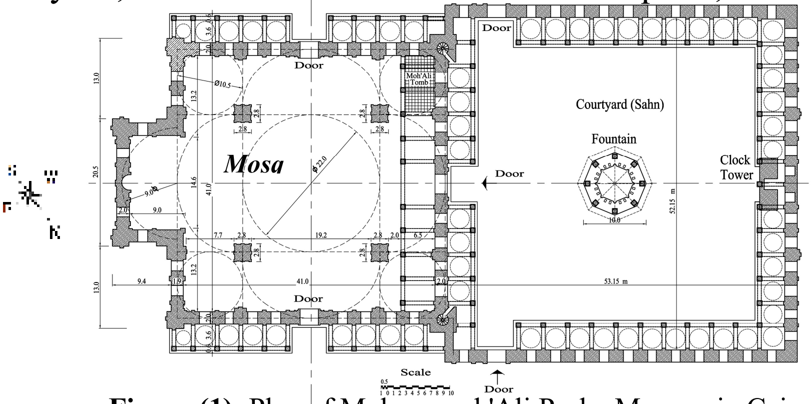


Figure (1): Plan of Mohammad 'Ali Pasha Mosque in Cairo (12).

---

(11) Principles of Architectural Design and Urban Planning During Different Islamic Eras, Organization of Islamic Capitals and Cities Pub., Jeddah, Saudi Arabia, 1992, pp. 403-405.

(12) Mahir, S., Op. Cit., pp. 251-261.

The clock-tower was presented, in 1845, to Moh.'Ali Pasha by King of France, Louis Philippe, in return for the obelisk, which adorns the Place de la Concorde in Paris today (13). This clock-tower, somehow, does not seem at odds with the rest of the mosque.

The interior of the domes and semi-domes is decorated with painted and gilt ornament in relief, executed in a neo-baroque style, while their exterior surfaces are covered with sheets of lead. Walls and columns inside the mosque are lined with alabaster to the height of 11.30 m, with colored ornaments above; see Plates (8), (9) and (10-a). The mosque is lighted by magnificent crystal chandeliers with glass lamps (14); see Plates (7) and (9-b).

The mosque has two minbars; the larger is the original one that made of wood and decorated with gilt ornament. The smaller minbar was built of alabaster and added to the mosque in 1939, during the reign of King Farouk I, see Plate (7). The mosque has a balcony (*dikka*) on its N-W side, which is supported on alabaster arches and columns; see Plate (9-b). The handrails of the dikka and the galleries around the domes are all made of bronze (15).

The mausoleum of Moh.'Ali Pasha and his family lies at the western corner of the mosque. It has a Carrara-marble mounting that carved with beautiful ornament and inscriptions. It is also surrounded by a beautiful decorated bronze grille, made by order of the late 'Abbas Pasha I (16); see Plate (10-b).

---

(13) The Mosques of Egypt (from 641 to 1946 AD), Ministry of Waqfs, The Survey of Egypt Pub., Giza, Vol. II, 1949, p.119, (**re-issued by researcher**).

(14) Mahir, S., Op. Cit., pp. 257-261.

(15) Mahir, S., Op. Cit., pp. 258-261.

(16) Abdel-Wahab, H., Op. Cit., pp. 379-381.

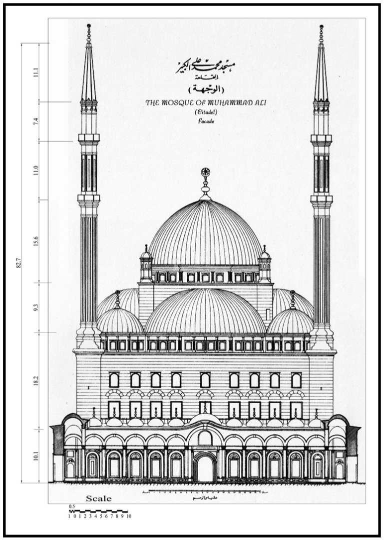


Figure (2): N-W Façade of Mohammad 'Ali Pasha Mosque (16).

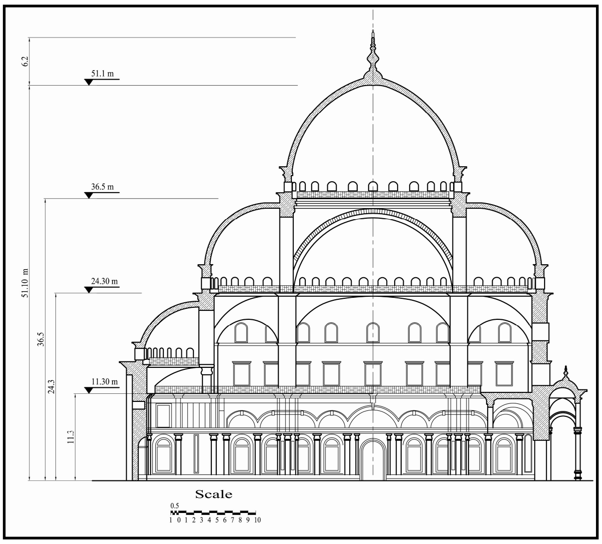


Figure (3): Section Elevation (N-W to S-E) of the Mosque (17).

4. Building Materials and Soil Condition of Moh.'Ali Mosque

The original mosque of Moh.'Ali at the Citadel was built of limestone masonry, for all its structural elements (i.e. walls, piers and domes). Walls, inside and outside the mosque; were clad with alabaster that it was called in some references the 'Alabaster Mosque'. It was constructed over a deep layer of artificial and well-compacted landfill, which covered the ruins of old Mamluk buildings at Mosque's site in the Citadel. Besides, the site was filled up with landfill to raise the Mosque's level to the highest level among all its surrounding structures (18).

The interior decoration and exterior claddings of the mosque were not achieved until the death of Moh.'Ali Pasha. They were altered several times during the reigns of his successors. Before completion of the mosque, the alabaster panels from the upper walls were taken

---

(17) The Mosques of Egypt (from 641 to 1946 AD), Op. Cit., p.118.

(18) Abdel-Wahab, H., Op. Cit., pp. 380-381.

away and used for the palaces of Abbas I. The stripped walls were clad with wood painted to look like marble [19].

Under the major restoration project for the mosque, during the late King Fouad I, in 1931, the entire domed-roof and its supporting members (i.e. arches, beams and columns) were demolished and rebuilt with Reinforced Concrete [20]. The mosque's decoration, with alabaster lining, painting and gilding, was achieved during the reign of King Farouk I; see Plates (4) to (9).

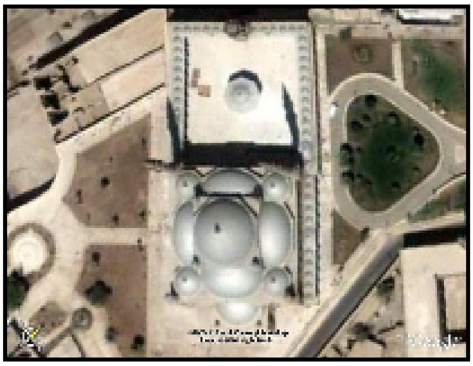


Plate (2): Aerial-View of Moh. 'Ali Mosque; shows the compound domed roof (After: Google Earth Website).

Plate (3): Wide-angle View of Moh. 'Ali Mosque; shows *Sahn*, fountain and *Iwans* (After: www.alhamdon.org).

Plate (4): S-E Façade of Moh. 'Ali Mosque; shows alabaster cladding and the semi-dome over the mihrab.

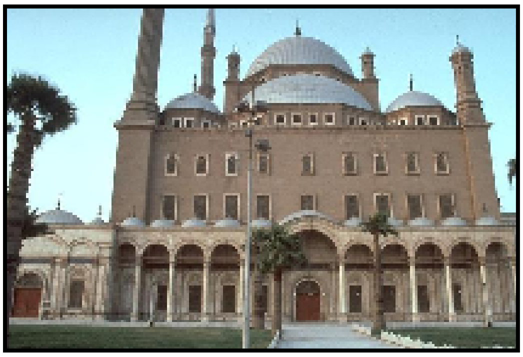


Plate (5): N-W Façade of Moh. 'Ali Mosque; shows the external arcade topped by shallow domes and covered with alabaster clad.

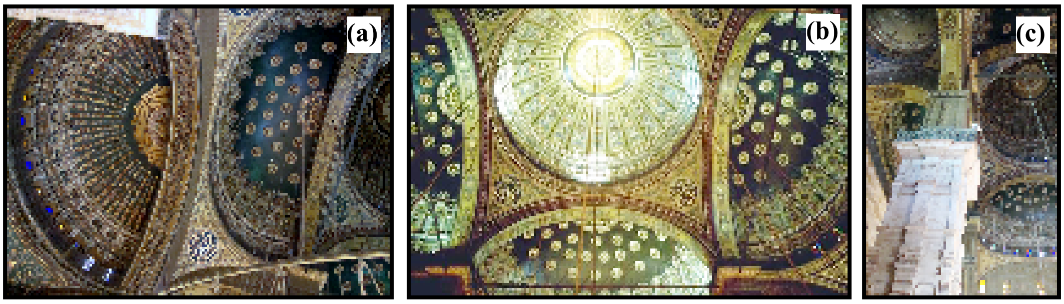
---

[19] Principles of Architectural Design and Urban Planning During Different Islamic Eras, Op. Cit., pp. 403-405.

[20] Abdel-Wahab, H., Op. Cit., pp. 380-381.

Plate (6): Brass clock-tower above the middle of the N-W side of the courtyard and the fountain.

Plate (7): Interior of Moh. 'Ali Mosque; shows alabaster cladding, miharb and the two minbars.



a- Semi-dome over prayer-niche.

b- The central dome and the surround semi-domes.

c- Central Column and roof.

Plates (8: a, b and c): Details of bottom views for the doomed-roof from inside the mosque, showing their supports of arches and piers, and their ornamentation.

5. The Major Structural Failures of the Mosque in the Past

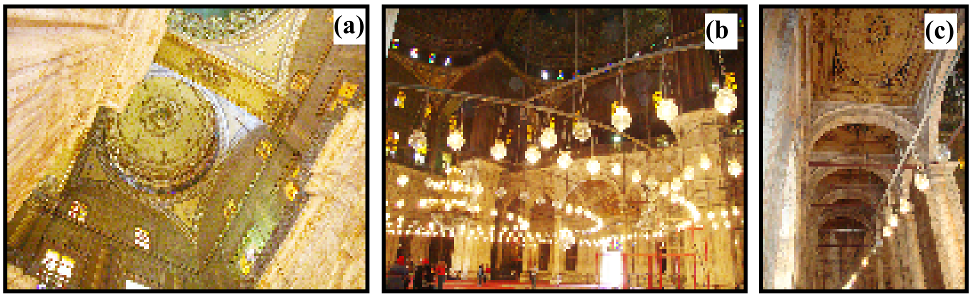
Architectural style of Turkish mosques, during Ottoman era; is considered evolution of Byzantine architecture of churches in Turkey and Greece (21). Turkish architects seek for more vast space of prayer area, with minimum interruption with columns. To achieve this aim, domed-roofs were utilized. Consequently, structural system of the roof of Moh.'Ali Mosque at the Citadel was complicated and innovative at its time. Besides, the domes and semi-domes were not shallow as the domes of Sultan Ahmet

---

(21) Principles of Architectural Design and Urban Planning During Different Islamic Eras, Op. Cit., pp. 403-405.

Mosque in Istanbul. The entire mosque, including its complicated doomed-roof; were originally constructed of limestone masonry work. This unprecedented structural system for mosques in Egypt showed serious failures and deficiencies after short period of time (in about 40 years). Serious cracks, separations and inclination were recorded in many structural elements of the mosque (i.e. domes, columns and walls) (22). The dangerous structural condition of this important royal mosque made the government of the late King Fouad I, in 1931; to conduct a complete restoration project to rescue and preserve this mosque from demolition. Documents did not record the main reasons for these structural problems; whether inadequate structural design (e.g. poor thickness or strength for structural elements) or strong earthquake.

This research analyzes the structural system of Moh.'Ali Mosque at the Citadel, under the various loading condition (i.e. static and dynamic loads); to study the structural behavior of its complicated domed-roof and determine expected failure mechanism of its original construction. This aims to reach the main forces that caused the 19th Century failures. Besides, the research will conduct structural evaluation of the major structural restoration work of the domed-roof and columns of the mosque; which were carried out during the reign of King Foad I, in 1931.



a- Corner (smaller) domes from inside.
b- Balcony (Dikka) over N-W entrance.
c- Roof of the dikka.

Plates (9: a, b and c): One of the small domes of the mosque from inside and the N-W Iwan inside the mosque; showing the decoration and alabaster cladding.

---

(22) Abdel-Wahab, H., Op. Cit., pp. 379-381.

a- The interior of N-E side of the mosque.

b- The mausoleum of Moh.'Ali and his family.

c- Courtyard's S-W arcade.

Plates (10: a, b and c): Interior and exterior parts of the mosque; show the alabaster cladding of walls.

6. Structural Restoration Project of the Mosque in 1931-39 A.D.

The serious cracks and failures in many structural elements of Moh.'Ali Mosque, beside the unsuccessful restoration work; which did not last for more than few years, made the Egyptian authorities to carry out a major restoration project for the mosque, in 1931. Engineers decided to pull down all the roofing system of the mosque, after completing the full documentation of the building, including its decoration. Then, the four piers, arches, domes and semi-domes were reconstructed using reinforced concrete (R.C.), as a more robust and efficient building material than limestone masonry (23). The substituting R.C. structural elements were designed and constructed to resist internal forces and thrust of complicated domed-roof.

Since available documents of the mosque were carried out by archaeological inspectors, which recorded general notes about work, materials and costs (without specialized engineering information); the details of structural restoration work will be deduced from the available records and photographs. The presume properties of building materials, which were used in substitution work of unsafe masonry structural elements with R.C. similar members; are expected as follows:

---

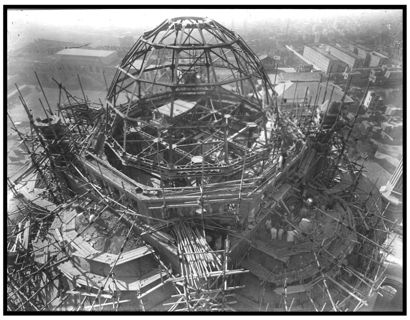
(23) Abdel-Wahab, H., Op. Cit., pp. 378-381.

- Characteristic strength of reinforced concrete work, by that time; is expected (f_{cu}) =150-200 kg/cm^2 and Mild steel is used in reinforcement; of yield strength (f_y)= 2400 kg/cm^2.
- Original masonry work (i.e. walls, columns, arches and domes) were built from limestone, which was quarried from *Muqattam* hill and constructed using multiple-leaf system (two outer layers of ashlars' stones with rubble infill in-between). Alabaster lining for internal and external walls were brought from *Bani-Swif* quarry (24).

Plates (11: a to f) show the main restoration work carried out in the mosque at the first phase, in 1931. Plate (10-a) shows all the domes and semi-domes after they were dismantled and the steel scaffold for the new R.C. domes. Plate (11-b) shows two main arches after they were rebuilt with R.C. and their steel scaffolds. The apparent section-dimensions are 1.2x1.5m. Plate (11-c) shows a top view of the roof after dismantling original roof and the steel framework of the new R.C. domes. Plate (11-d) shows the steel reinforcement of domes and their supporting girders. Plate (11-e) shows steel reinforcement mesh of the S-E semi-dome and the framework of the other domes. Plate (10-f) shows the smaller corner domes after casting concrete. Plate (12-a) shows the tryout of the assembly operation for lead plates which would cover one of the domes.

a) Steel scaffoldings for all domes, after pull down roof of mosque.

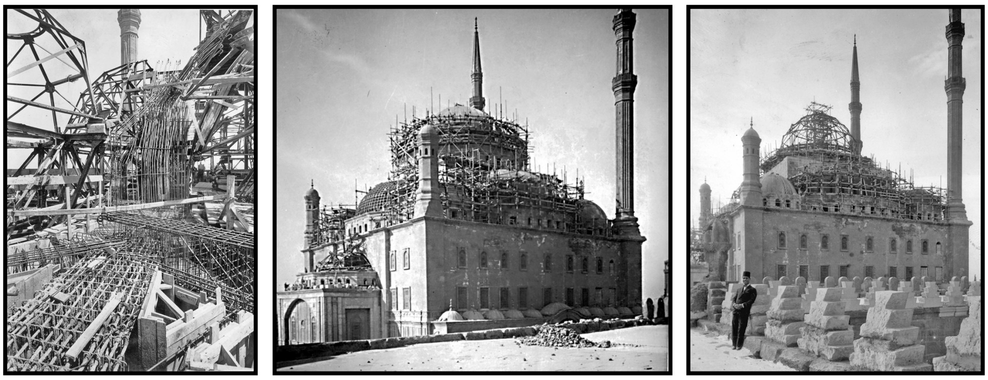
b) Reconstruction of main-arches with R.C.



c) Reconstruction of R.C. domes on the stone-masonry original walls.

---

(24) Ibid., pp. 380-381.



d) Steel reinforcement for substituting beams and domes.

e) Reinforcement and frameworks of domes before casting concrete.

f) The small domes after casting concrete and the scaffold of the main dome and semi-domes.

Plate (11): Details of reconstruction of the Mosque's roof with substituting R.C. elements (25).

a) Trying the cutting out of lead plates for covering dome surfaces.

b) Domes and semi-domes are composed of R.C. ribs, on which later the R.C. domes were casted above.

c) After casting the domes and semi-domes and before casting the central dome.

Plate (12): More details of reconstruction of the substituting R.C. domes of the mosque (26).

Plate (12-b) shows the R.C. ribs, which the main dome is composed of, with shear anchors of steel-bars to connect dome that is casted later with its supporting ribs. This plate demonstrates the main system of R.C. domes and semi-domes of the mosque. They are composed of R.C. ribs, of cross section (approx.) =0.4x1.0m, with cross-ribs (every 3.0m) to connect them in the lateral direction. Ribs

---

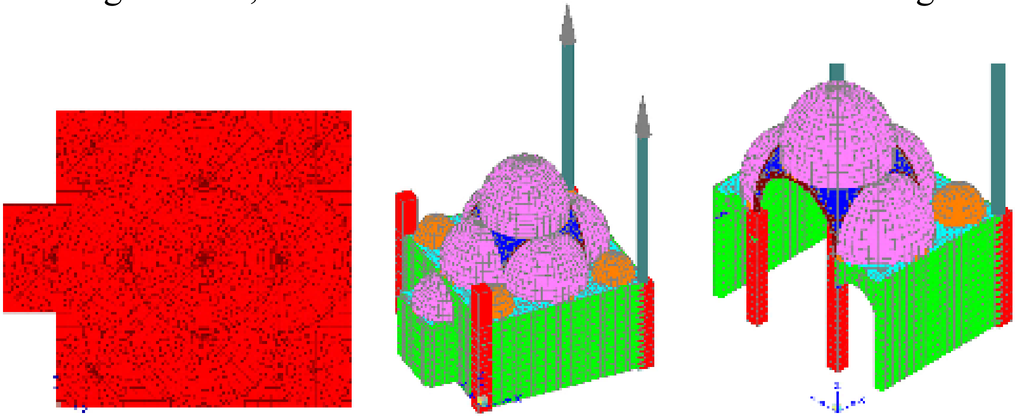
(25) Center for documentation of Egyptian Antiquities at Al-Zamalik, Supreme Council of Antiquities (SCA), Cairo, Egypt.

(26) Center for documentation of Egyptian Antiquities at Al-Zamalik, Op. Cit.

are covered with two R.C. slabs from top and bottom sides. Expected slab thickness equals 0.15 m. External surface of upper-domes are covered with lead plates, while surface of bottom-domes are plastered and painted. Plate (12-c) shows the corner domes and semi-domes after casting concrete and before putting lead plates.

7. Structural Analysis of Moh.'Ali Mosque

To understand the structural behavior and determine the failure mechanism of Moh.'Ali Mosque; structural analysis of 3D-numerical model of the mosque is conducted under static and dynamic load cases, utilizing Finite Element Method (F.E.M.). The full mosque is modeled in 3D, using one of the well known computer package utilized in the field of structural engineering (27); see Figures 4: a, b and c. Walls and domes are modeled using Shell-elements, while other structural elements (i.e. columns, arches and minarets) are modeled using 3D-frame-elements.



a) Plan

b) 3D-Extruded View

c) 3D-Section View (More zoom)

Figure (4): Details of the 3D Numerical Model of Moh.'Ali Mosque using F.E.M. (**not equal scale**).

A number of 3D-numerical models are prepared to represent the mosque in different cases. The first 3D-model studies the original mosque; which was fully constructed from masonry work, for

---

(27) SAP2000, Version 10.1.0, CSi Analysis Reference Manual for SAP2000, Berkeley, California, USA: Computers and Structures Inc., 2006, pp. 269-281.

domes, columns and walls. The second 3D-model studies the mosque after the major restoration project in 1931; which domes and columns were dismantled and reconstructed using reinforced concrete (R.C.) instead of stone masonry. The following structural analysis cases (28) are conducted to each 3D-numerical model:

- Case (1): Linear static analysis under dead and live loads (DL+LL).
- Case (2): Modal analysis for vibration modes, using Eigen-vector analysis.
- Case (3): Response-spectrum analysis for seismic response.
- Case (4): Linear Time-History Analysis.

According to results of dynamic analysis, and the need to analyze and understand the static and dynamic behavior of the complicated domed-roof; only the mosque building, without the adjoined courtyard and *Iwans*, will be studied. This is due to *Iwans* of the adjoined courtyard will attract mass and affect the results of Eigen-modal analysis, beside the main scope is to analyze the structural behavior of the domed-roof and the mosque, where the failure occurred during 19th Century.

7.1. Input Data for Structural Analysis of Numerical 3D-Models

Structural analysis work of 3D-models of the mosque are conducted using input-data for properties of its historical masonry materials, derived from preliminary inspection of different building materials in the mosque, beside the previous available data of equivalent building materials in similar historical structures from Ottoman and Mamluk periods. Reasons for this are summarized as follows:

- The good structural condition of all mosques' elements (walls, columns, etc.), with no cracks or failures, which does not allow extracting samples through or from.
- At present, authorities of SCA (Supreme Council of Antiquities) do not give permission for sampling from the mosque;

---

(28) SAP2000, Op. Cit., p.73.

as the last phase of restoration project is to end, and the sound structural condition gives no reason for study.

- The current fine-restoration work in all surfaces prohibits extraction of samples of stones from surfaces, beside the ashlars' limestone are not accessible (stones lie above ground by about 11.3m, which need scaffolds to climb and reach them).
- The thick alabaster cladding that covers all internal and external walls (to about 11.3m above ground), to a high level and with no cracks or openings through, which prevent exploring the internal construction of masonry work behind.
- Difficulty to take samples from internal infill layer of masonry walls due to all pervious reasons.
- The abundance of experimental data available for similar historical building materials conducted during the last decade in the restoration projects of mosques in Historical Cairo.
- Properties of reinforced concrete materials, used in the restoration project (in 1931) were not documented by engineers. Consequently, technical and specialized details needed for structural analysis work are not documented.
- The scope of present structural analysis of the mosque is to understand the structural behavior of the complicated system of the domed-roof and to evaluate the safety of the R.C. substituting structural elements of the last restoration project. These aims will be satisfied by using these data for building materials; which provide reliable and efficient analysis results.

Visual inspection and available archaeological documents showed that the original mosque was fully constructed from limestone masonry work, which stones were from *Muqattam* quarry (29). Walls were constructed following multiple-leaf system (i.e. two outer layers of ashlars' stones with rubble infill in-between). Lime mortars with regular additives (e.g. powder of crushed red-brick or fly-ash "*Qusrmil*") are expected to be used in construction of

---

(29) Abdel-Wahab, H., Op. Cit., pp. 380-381.

masonry work. Alabaster lining over internal and external walls were brought from *Bani-Swif* quarry (30). The construction technology is similar to other historical buildings from previous periods in Cairo. The researcher will use the following mechanical properties for stonemasonry work in Moh'Ali mosque; which are the average values of results of wide range of experimental work on similar masonry building materials in historical mosques in Cairo, and a number of other researches on historical buildings abroad of similar masonry materials. Details of mechanical tests, its results and various calculation methods for estimating the equivalent values of masonry work from values of its constituent materials; are all given in previous research work of the researcher (31), and out of scope of this paper.

A research by Soliman, A. *et. al.* (32) studied various properties of limestone samples, from different location in Egypt, and found compressive strength of limestone samples from *Muqattam* hill ranges between 183 to 415 kg/cm^2, with average value = 298 kg/cm^2. Another study by the researcher (33) on limestone samples, which were taken from a historical mosque in Cairo, and originally extracted from *Muqattam* hill; showed compressive strength ranges between 190 to 326 kg/cm^2, with average value = 249 kg/cm^2.

Accordingly and from previous research work by the researcher (34), expected and presumed mechanical properties of historical stonemasonry work in Moh'Ali Mosque are as follows:

---

(30) Ibid., pp. 380-381.

(31) Amin, Y., Analysis and Assessment of Structural Deficiencies in Historical Islamic Religious Buildings from Bahri Mamluk Period and the Possible Scientific Methods for Conservation and Restoration with Application on the Madrasa of Umm Al-Sultan Sha'ban in Cairo, Ph.D. Thesis, Cairo University, Faculty of Archaeology, Conservation Dept., 2004, pp.237-245, (Unpublished).

(32) Soliman,A.,Tahlawi, M. and Goma'a, W., Data Book of Egyptian Limestones, Geotechnical Specifications, Mining and Metallurgical Dept ., Assiut Univ., Assiut, 1972, pp. 6-8.

(33) Amin, Y., Op. Cit., Appendix (4), p. A-82.

(34) Ibid., pp.237-245.

- Range of compressive strength of lime-stones (f_b) = 200-300 kg/cm^2
- Range of compressive strength of mortar (f_m) = 15-25 kg/cm^2
- Characteristic compressive strength of stonemasonry work (f_k) = 60 kg/cm^2 (0.6 KN/m^2)
- Young's Modulus of Elasticity of stonemasonry work ($\mathbf{E_m}$) = 6.0 x10^4 kg/cm^2
- Specific weight of stonemasonry work (γ) = 2.40 ton/m^3
- Shear Modulus of stonemasonry work ($\mathbf{G_m}$) = 2.4 x10^4 kg/cm^2
- Poisson's ratio of stonemasonry work ($\boldsymbol{\nu}$) = 0.25

Expected mechanical properties for reinforced concrete (R.C.) work, which is used in the 1930s restoration project of the mosque and considered in structural analysis of second 3D-model; are (35):

- Characteristic compressive strength of concrete (f_{cu}) =150-200 kg/cm^2 (1.5-2.0 KN/m^2).
- Mild-steel type 24/35 Yield Strength (f_s) of reinforcing bars = 2400 kg/cm^2 (24 KN/m^2).
- Young's Modulus of Elasticity of reinforced concrete (36) ($\mathbf{E_c}$) = 1.84 x10^5 kg/cm^2 .
- Specific weight of reinforced concrete (γ_c)=2.50 ton/m^3
- Shear Modulus of reinforced concrete ($\mathbf{G_c}$)= 0.767 x10^5 kg/cm^2
- Poisson's ratio of reinforced concrete ($\boldsymbol{\nu}$) = 0.20

7.2. Loads and Forces affect the Mosque

Structural analysis work for 3D-models that represents both original and after-restoration conditions of the mosque; are conducted under

---

(35) ECRC, Egyptian Code of Practice for Design and Execution of Reinforced Concrete Buildings, Ministry of Housing, Public Utilities and Building Development, **Code No. 203**, Cairo, 2007, p. 5-2 (in Arabic).

(36) Ibid., p. 2-13.

static and dynamic loads, which values are estimated in accordance to ECL Code (37).

Static case No.1 considers the following main data, for estimating service dead loads (**Working Loads**) that affect roofs of the mosque (before restoration and after restoration):

- Thickness of masonry central dome and semi-domes = 0.40 m
- Thickness of small masonry dome at corners = 0.25 m
- Average thickness of all multiple-leaf masonry walls = 2.0 m
- Load of lead sheets over domes' surfaces (thick.=3mm) =350kg/m^2 (3.5 KN/m^2)

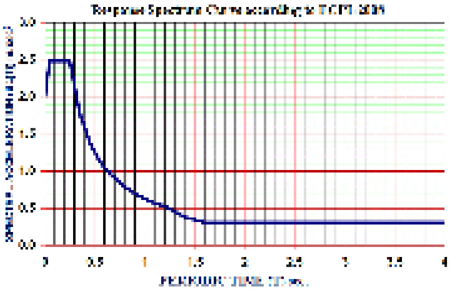


Figure (5): Response spectrum curve according to ECL 2008.

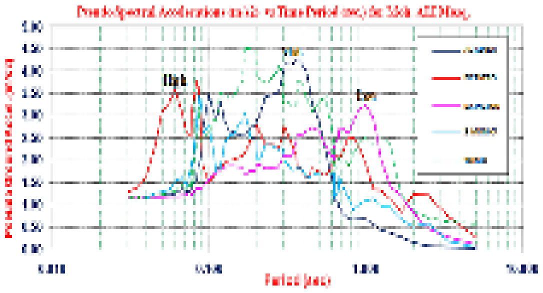


Figure (6): Pseudo spectral accel. vs period (damping = 5%), showing low, medium and high frequencies (Graph in Logarithmic Scale).

- Load of domes' flooring layers under lead sheets = 100 kg/m^2
- Live load over domes and semi-domes = 50 kg/m^2

Response spectrum curve in Figure (5) that is needed for dynamic analysis relevant case; considers the following loading data, for substituting of parameters in article 8-4-2-2 (38):

- From Table 8-1 (39); soil class is B-type.

---

(37) ECL, Egyptian Code of Practice for Loads in Structural and Masonry Works, Ministry of Housing, Public Utilities and Building Development, **Code No. 201**, Cairo, Sept. 2008, pp. 107-122, (in Arabic).

(38) ECL, Op. Cit., pp. 118-122.

(39) Ibid., p.114.

- From Table 8-2 (40); Peak Ground Acceleration (PGA); a_g=0.125g (Seismic Zone II).
- From Table 8-3-A (41); S =1.35, T_B =0.05, T_C =0.25, and T_D =1.2
- From Table 8-4 (42); ή =1
- From Table A , of Appendix (A-8) (43); R = 2

For Time-History analysis and due to scarcity of accelerogram records of the earthquakes in Egypt (until the present time); a number of earthquake acceleration records (which are available in the data library of the SAP2000 program) are examined to finally select three records that cover a wide spectrum of frequencies and (a/v) ratios. Figure (6) shows response spectra curves for Pseudo Spectral ground acceleration vs Time), to select three earthquake records, which provide low (Lexington record), medium (Altadena record) and high (Elcentro record) frequencies. All these records are scaled to peak ground acceleration (PGA) of 0.125g; which corresponds to the maximum PGA expected in Cairo. Resulting forces for each analysis cases are modified according to ECRC Code (44); to apply Working or Ultimate design methods in the structural evaluation of the mosque elements.

7.3. Criteria of Structural Evaluation and Safety of the Mosque

Historical masonry work in Moh.'Ali Mosque, before and after restoration, will be will be structurally evaluated using Working Stress Design Method (WSDM) and ECM Code (45). Whilst, reinforced concrete elements, of the 1930s restoration work in the mosque; will be structurally evaluated using Ultimate Limit Design

---

(40) Ibid., p.115.

(41) Ibid., p.120.

(42) Ibid., p.151.

(43) Ibid., p.114.

(44) ECRC, Op. Cit. pp. 3-1 to 3-5. (e.g. U = 1.12 D + α L + S :where "U" is Ultimate loads, "D" is Dead loads, "L" is Live loads, "S" is seismic loads, and "α" is a multiplier)

(45) ECM, Egyptian Code of Practice for Design and Execution of Masonry Buildings, Ministry of Housing, Public Utilities and Building Development, **Code No. 204**, Cairo, 2006, pp. 31-35 (in Arabic).

Method (ULDM) and the ECRC Code (46). The reasons for this can be summarized as follows:

- All codes of masonry work, in the United States, Europe and Australia (47), until 1990s, beside the present Egyptian Code of Masonry Buildings (48) (ECM); are all based only on Working Stress Design Method (WSDM). The increasing number of research programs on contemporary masonry work, in the last decades (49), which study mechanical properties and structural behavior, enabled to convert design codes into Ultimate Limit Design Method (ULDM).
- Ultimate Limit Design Method recommends reliable building materials, in both properties and construction, which suits modern masonry work and reinforced concrete structures, with reliable quality control in manufacturing and erection. This method reduces factor of safety than Working Stress approach (WSDM), with more limitations to serviceability and cracking(50).
- Consequently, Working Stress Design Method (WSDM) is more convenient to historical masonry work than Ultimate approaches, due to lack in reliability and consistency of mechanical properties caused by limited number of samples allowed, multiple materials used in its construction and poor quality control applied.

The following **allowable working stresses** for **stonemasonry work** are considered according to Egyptian Code of Practice (51) for Masonry Work (ECM), and based on material properties, in section (7.1). They are utilized for evaluation of structural safety of various masonry elements in the mosque, which are as follows:

---

(46) ECRC, Op. Cit. pp. 4-1 to 4-51.

(47) Drysdale, G., Hamid, A. and Baker, R., Masonry Structures Behavior and Design 2nd Edition, The Masonry Society (TMS) Pub., Boulder, Colorado, USA, 1999, pp. 59-62.

(48) ECM, Op. Cit., pp. 31-35 (in Arabic).

(49) Drysdale, G., *et. al.*, Op. Cit., p. 60.

(50) Drysdale, G., *et. al.*, Op. Cit., p. 61.

(51) ECM., Op. Cit., pp. 31-35.

- Allowable axial compression stress in masonry (**f_{ca}**) = 12 kg/cm^2 (0.12 KN/m^2)
- Allowable flexure compression stress in masonry (**f_{cb}**)=15 kg/cm^2 (0.15 KN/m^2)
- Allowable flexure tensile stress in masonry (**f_{tb}**)= 0.5 kg/cm^2
- Allowable shear stress in masonry (**q**) = 2 kg/cm^2

To utilize Working Stress Design Method (WSDM) for the evaluation of structural safety of **masonry** elements, ultimate forces resulting from response spectrum and time-history analyses' cases (i.e. cases No. 3 and 4) should be divided (52) by **1.40** before adding to static forces resulting from case No.1 (i.e. from D.L.+L.L. only), to modify them to working forces. When checking the safety of the resulting working stresses due to seismic forces, it is allowed to raise (53) the previous allowable stresses by 20%.

Characteristic compressive strength of R.C. elements in the mosque will be considered (f_{cu}) =200 kg/cm^2.

7.4. Structural Analysis of First 3D-Model of the Mosque (The Original Condition Before Restoration)

The 3D-model, which represents the original condition of Moh.'Ali Mosque (before restoration); is analyzed under both static and dynamic loading conditions. Discussion of structural analysis' results is summarized as follows (54):

- Maximum compression working stress in the main four columns, at zero level, under static load case only (DL+LL) equals -14.9 kg/cm^2. It is unsafe since it is 124% of the safe stress value (**f_{ca}**).
- At top level of columns (at base of main arches), under static load case only (DL+LL); working bending moment (M_{33}) = 88 m.t. and associate normal force (N)= -790 t. Resulting working normal

---

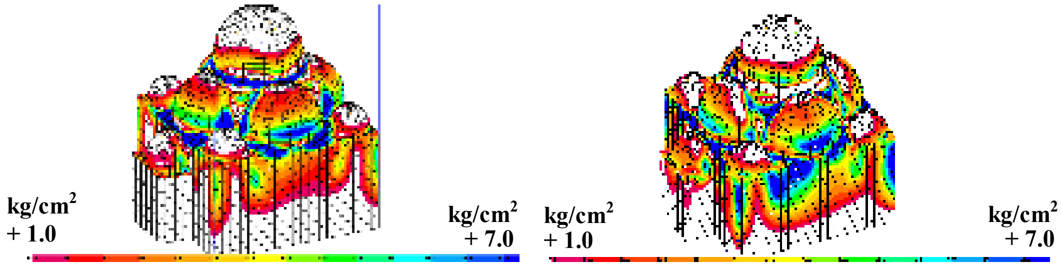
(52) ECL, Op. Cit., p.116.

(53) ECL, Op. Cit., p.3-4.

(54) Concrete section dimensions are given by: breadth x depth (in meters), and reinforcement is given by number of bars and the bars diameter (in mm.) after (φ) symbol."M" stands for bending moments, "N" or "P" stands for normal forces, and "S" stands for stresses.

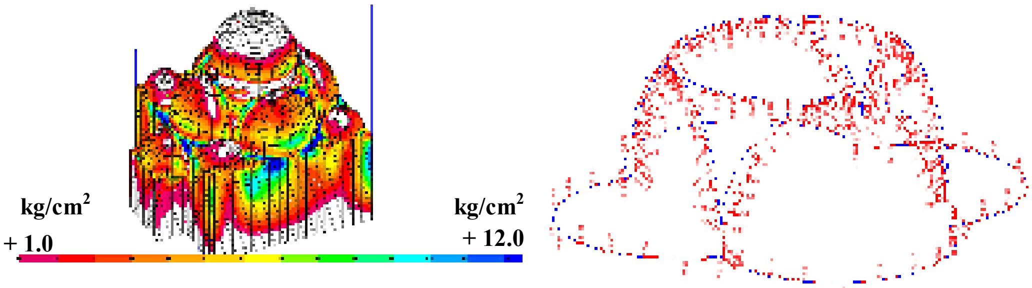
stresses range between -7.76 to -12.48 kg/cm^2; which are both structurally safe.

– Figure (7-a) shows the color code of maximum principle tensile-stress distribution (S_{max}) in walls and domed-roof of the mosque; due to static load only (DL+LL). Resulting working stresses range between +1.0 and +7.0 kg/cm^2, which both are unsafe. The maximum value is 14 times more than allowable flexure tensile stress of masonry (f_{tb}). These tensile stresses, under static load only; spread out over the lower half of the main dome, in all area of remaining semi-domes and small domes, and in the upper half of the mosque walls, which are nearly most of mosque elements.



a) Maximum principle tensile stresses due to static load only (DL+LL): +1.0 to +7.0 kg/cm^2.

b) Maximum horizontal tensile stresses (S_{11}) due to DL+LL+ Resp. Spec. X: +1.0 to +7.0 kg/cm^2.



c) Maximum horizontal tensile stresses (S_{11}) due to DL+LL+ Time_H. ALT.: +1.0 to +12.0 kg/cm^2.

d) Normal force diagram in arches under static load only (DL+LL): $N_{max.}$ = - 156 tons.

Figure (7): Selected results of structural analysis of original condition of the mosque under static and dynamic load cases; showing the most critical **working** stress values.

– Figure (7-b) shows distribution of maximum horizontal tensile stresses (S_{11}) in the mosque; due to summation of static load-case and response-spectrum case in X-direction. More blue color zones indicate higher tensile-stress concentrations than in the previous Figure (7-a).

– Figure (7-c) shows distribution of maximum horizontal working tensile stresses (S_{11}) in the mosque; due to summation of static load-case and time-history case of Altadena record. Stresses range between +1.0 and +12.0 kg/cm^2. Tensile stresses that exceed safe value; cover most of mosque elements.

– Figure (7-d) shows normal force diagram in main arches and ring beams under static load only (DL+LL). At critical section; N = -145 t. and M=42 m.t. Maximum expected arch cross-section, from similar Islamic mosques in Cairo; is 0.7x1.2 m. Resulting normal stresses range between -7.74 to -42.26 kg/cm^2 (comp.). Maximum stress exceeds allowable values by 2.82 times (282%).

– Figure (8) shows the main eight deformed shapes of Eigenvector modal analysis. Only the two minarets respond in the first four modes (#1 to#4); with first bending. The mosque responses in the following four modes; with first bending in modes #5 and #6, and bending with torsion in modes #7 and #8.

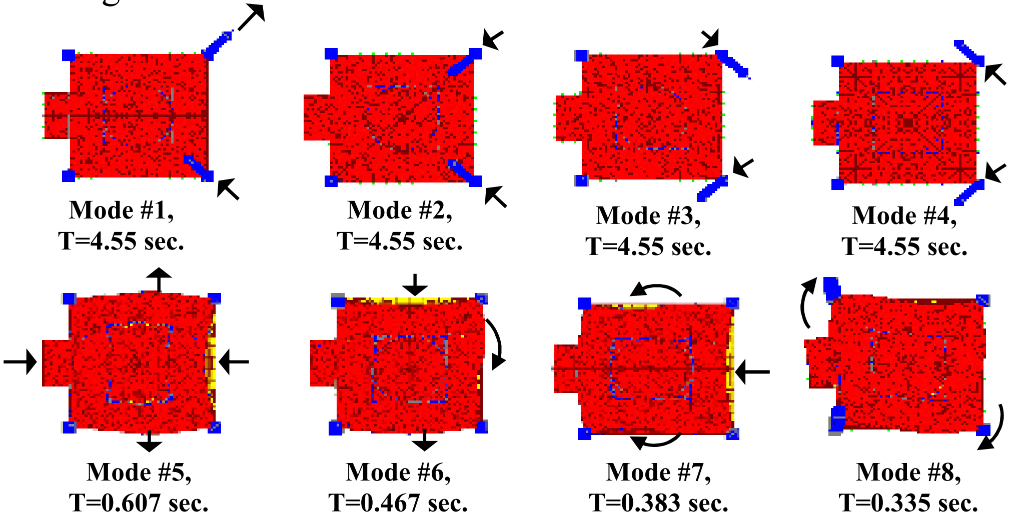
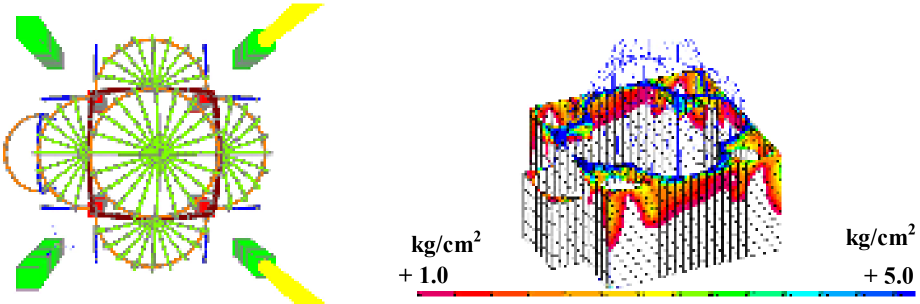

Mode #1, T=4.55 sec.
Mode #2, T=4.55 sec.
Mode #3, T=4.55 sec.
Mode #4, T=4.55 sec.
Mode #5, T=0.607 sec.
Mode #6, T=0.467 sec.
Mode #7, T=0.383 sec.
Mode #8, T=0.335 sec.

Figure (8): The first eight Eigenvector modal shapes of the mosque (original condition).

7.5. Structural Analysis of Second 3D-Model of the Mosque (Condition After 1930s Restoration Project)

Another 3D-model is prepared to represent the mosque of Moh.'Ali after the major restoration project in 1931. All roof-domes and their supporting elements (i.e. ring beams, arches and columns) were substituted with reinforced concrete (R.C.) elements. Cladding and surface finishing of these new counterpart structural elements make them appear similar to the original elements. This 3D-model is also analyzed under the same load cases of the first 3D-model of the original condition.



a) Perspective extruded top view of frame-elements in 2nd model, showing R.C. arches, ribs and ring-beams.

b) Maximum horizontal tensile working stresses (S_{11}) due to static load case only: +1.0 to +5.0 kg/cm^2.

Figure (9): Second numerical 3D-model (frame-elements) and tensile stress distribution in masonry-walls under static load case only.

Discussion of results of structural analysis' work of second numerical model is summarized as follows:

– Most critical deflection of doomed-roof lies at peak of the central dome, which decreased to 69% of the original case, under static load case-1 only. This caused by the increase of rigidity of R.C. domed roof from masonry one, although the total working base reaction of the two models are nearly the same.

– Compressive working stresses in all masonry walls, under all analysis cases, are less than -8.0 kg/cm^2, which are safe.

– Maximum principle tensile working stress (S_{max}) in all masonry walls, under static load case-1 only, decreased to less than +2.0 kg/cm^2, while it exceeded +5.0 kg/cm^2 in the original condition.

– Tensile working stresses in all masonry walls, in horizontal (S_{11}) and vertical (S_{22}) directions, and due to combination of static loads and either time-history loads (i.e. Altadena record) or spectrum load; exceed +5.0 kg/cm^2. Figure (10-a) shows stress contours; ranges between +1.0 and +7.0 kg/cm^2. Tensile stresses, above safe value; cover wide area of mosque's masonry walls.

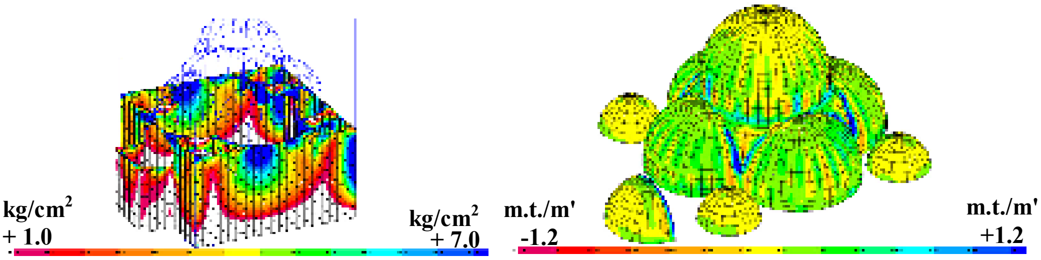
– For R.C. main dome and four semi-domes, the most critical loading condition is the combination of static loads (case-1) with time-history (case-4) of Altadena record. Under this load combination; radial and tangential ultimate bending moments (M_u) are less than ±1.2 m.t./m'; see Figure (10-b). Also, the most critical membrane forces (N_u) in these domes are the ultimate radial forces (F_{11}) that range between -28 (comp.) to +26 (tension) tons/m'. Using ultimate design, chart-D (55), it is found that required radial reinforcement ($As_{req.}$) should not be less than 7φ13/m' for thickness of 15 cm; due to high tensile forces. Tangential reinforcement is the minimum, which is 5φ10/m'. Reinforcement required for the rest of R.C. domes, with 15 cm thickness; is 5φ10/m'.

– The most critical loading combination that provides maximum ultimate compressive normal stresses in the main four columns is found under the combination of static loads (case-1) with time-history (case-4) of Altadena record. Resulting forces are: Pu_{max} = -1638 tons (with zero moments) at bottom level of columns, whilst at top level, the resulting forces are; Pu_{max} = -1301 t., Mu_2= 571 m.t., and Mu_3= 758 m.t. Since columns' concrete dimensions are 2.8x2.8m, and minimum reinforcement (according to ECRC) equals 0.6% (56); the ultimate load capacity,

---

(55) El-Behairy, S., Reinforced Concrete Design Handbook, Vol.2, 4th Edition, Ain Shams Univ., 1990, p.393.

(56) ECRC, Op. Cit., p.6-63.



a) Maximum horizontal working tensile stresses (S_{11}) in masonry walls, due to DL+LL+Time-hist. (ALT.): +1.0 to +7.0 kg/cm^2.

b) Maximum horizontal ultimate bending moments (M_{11}) in R.C. domes, due to: DL+LL+ Time-hist. (ALT.); ±1.20 m.t./m'.

Figure (10): Most critical load condition for tensile stresses in masonry walls, and radial bending moments of R.C. domes of the mosque after restoration.

as a short column (57), is $Pu_{cap.}$ = 6245 tons. Checking column safety, using interaction diagram under bi-axial bending, it showed columns are all structurally **safe**.

– Internal ultimate forces in the four main R.C. arches that carries the central dome, under static load case only; are: normal force ($Nu_{max.}$) = -298 t. with corresponding bending moment (Mu) = -144 m.t. at arch foots, and: Nu= -116 t. with corresponding bending $Mu_{max.}$=168 m.t. around arch's key. The most critical values of these internal forces occurred also under combination of static loads (case-1) with time-history (case-4) of Altadena record; see Figures (11-a and 11-b), which are: $Nu_{max.}$= -411 t. with Mu=-208 m.t. at arch foots, and Nu=-150t. with $Mu_{max.}$=158 m.t. near arch-key. Accordingly, concrete section of the main arches, of observed dimensions 1.2x1.5 m, is proved to be structurally safe under internal forces of the most critical loading condition and using ultimate design, chart-D (58), which requires minimum reinforcement.

– Most critical ultimate forces in ring-beam of the central dome are: $Nu_{max.}$= -199 t. (comp.) with Mu= 5.4 m.t. under static load only (case-1), and $Nu_{max.}$=-260 t. with Mu=20 m.t. under the

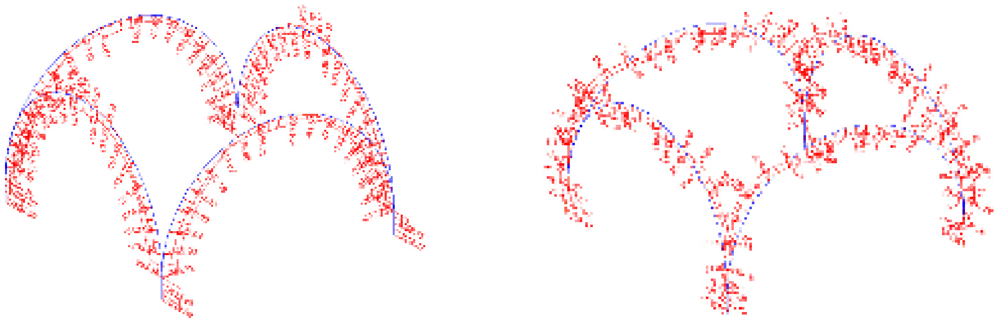
---

(57) ECRC, Op. Cit., (Equation 4-12-a), p.4-10 .

(58) El-Behairy, S., Op. Cit., p.393.

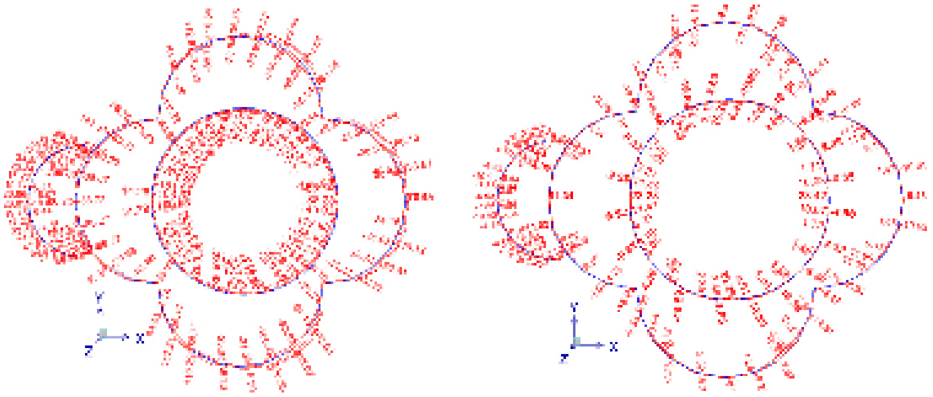
combination of static loads (case-1) with time-history (case-4) of Altadena record; see Figure (11-c and 11-d). Similar load combination results in forces, at ring-beams of other semi-domes, of critical values of: Nu_{max}= +265 t. (tension) with Mu= 22.1 m.t. Visual inspection of roof, from inside the mosque; showed concrete dimensions of these beams (approx.)=0.6x1.0 m., which are also safe, according to ultimate design method (ULDM).

– Most critical internal ultimate forces in domes' ribs occurred also under the combination of static loads (case-1) with time-history (case-4) of Altadena record. Their values are: $Nu_{max.}$= -145 tons



a) Ultimate normal force diagram in main arches, due to DL+LL+Time-hist. (ALT.), in tons.

b) Ultimate bending moment diagram in main arches, due to DL+LL+ Time-hist. (ALT.); in m.t.



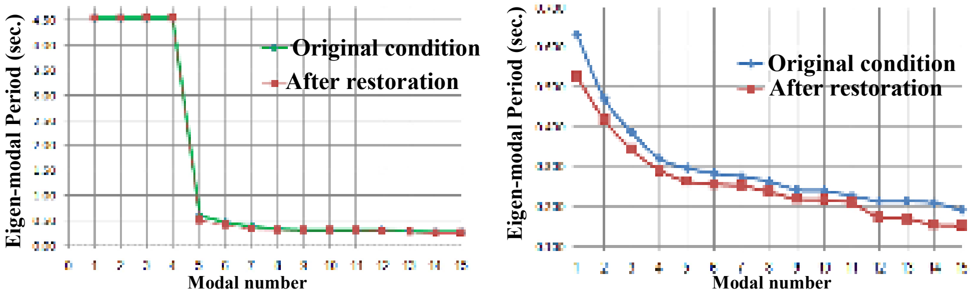
c) Ultimate normal force diagram in main arches, due to DL+LL+ Time-hist. (ALT.), in tons.

d) Ultimate bending moment diagram in main arches, due to: DL+LL+ Time-hist. (ALT.), in m.t.

Figure (11): Normal force and bending moment diagrams in the main four arches and ring-beams under most critical load condition (static + time-history load cases) for the mosque after with corresponding moment $Mu_{3\text{-}3}$= 84.1 m.t. Ribs' cross section dimensions of 0.4x1.0m, are safe under static loads case-1 and unsafe under most critical load combination (case-1+case-4).

– Modal analysis shows that both 3D-models (i.e. before and after restoration) give almost the same results of modal shapes and Eigen-values; see Figure (12-a). The first four modes belong to the two minarets only (t=4.55 sec.). From mode #5 to #8; the building responds in four bending modes. From mode #9 to #11; the two minarets responds in double bending. From mode #12 to #15 the mass back to the main building and the two short minarets, as they respond in double bending; see Figure (8).

– The two 3D-models were re-analyzed without the tall minarets, to reveal the dynamic response of the mosque. Figure (12-b) shows the enhancement in the seismic resistance of the mosque after restoration of roof, in 1931, as modal-periods decreased to 87% (in the average).



a) Eigen-modal periods of the two models of the mosque, including the two minarets.

b) Eigen-modal periods of the two models of the mosque, without the two minarets.

Figure (12): Comparison between modal participating mass ratios of the two modals represented in modal's periods for the two 3D-models (before and after restoration).

8. Structural Evaluation of Moh.'Ali Mosque for Original and Restored Conditions

Studying various results of structural analysis work for all numerical 3D-models, which represent both the original and the restored conditions of Moh.'Ali Mosque, and verifying forces and stresses of different structural elements of the mosque with safe criteria in masonry and reinforced concrete Egyptian Codes, which was summarized in article 7.3 of this paper; the following conclusions can be drawn up:

i. Exceeding the safe limits of stresses, allowed in design specifications of Codes and Norms, does not always mean that building should fall-down at present. However, the unsafe structural elements will shortly encounter excessive deformations and cracks, which will cause them in anytime to fall partially or totally (59). Also, structural safety should consider serviceability limits (i.e. deflection, deformation and crack width) of structural elements in buildings, when applying ultimate design method.

ii. Domes and minarets are considered among the most vulnerable structural elements, in historical masonry Islamic buildings in Cairo, under seismic forces (60). Consequently, the sophisticated style of Ottoman domed-mosques, which Moh.'Ali Mosque follows, is expected to experience cracks and failures throughout its entire masonry roof, which is fully built of domes, under seismic actions that affect the mosque along its history.

iii. The original design and construction of Moh.'Ali Mosque suffered from serious structural problems. Structural analysis and calculation prove that stresses in masonry domes, arches, piers and walls under static load case only, which is the least of loads affect the mosque, exceed the safe values. Consequently the original construction of the mosque is structurally unsafe under static (permanent) loads only. High compressive stresses in columns exceed safe limits by about 25%. Tensile stresses in masonry walls, arches and domes are unsafe by more than 500% on the average. Also, these unsafe stresses cover most of structural elements' area of the mosque.

iv. Seismic cases of loads (i.e. response spectrum and time-history), when combine with static cases; result in more higher and unsafe

---

(59) Drysdale, G., *et. al.*, Op. Cit., pp. 59-61.

(60) Amin, Y., Op. Cit., pp.42-57.

stresses in all structural elements of the mosque, which even exceed the raised safe stress limits, which is 20% more than values in article 7.3.

v. Structural analysis of first 3D-model shows that innovative structural system of Moh.'Ali Mosque cannot be achieved using traditional masonry work during the period of construction (19th Century), especially for these compound domes and semi-domes that support on each other and carried on the four main columns and peripheral masonry walls. This system needs means to resist the higher thrust and tensile forces result in domes, arches and walls, such as reinforcement with steel bars or sections.

vi. The original mosque was structurally unsafe under static loads (i.e.: D.L.+L.L. only), and its condition got worse under seismic actions, which took place by the end of 19th Century.

vii. The substitution of structurally failed domed-roof with similar elements using reinforced concrete (R.C.) was a traditional solution, implemented by Egyptian Council of Antiquities for restoration of many historical Islamic buildings in Cairo, such as dome over the *Qibla Iwan* of *Madrasa* of *Amir Sarghatmash*, and roofs of North *Zolah* of Mosque of *'Amr*.

viii. Results of structural analysis and calculation check of the second numerical 3D-model, which represent the restoration work of the mosque (in 1930s), prove that all stresses in substituting R.C. elements (i.e. domes, beams, arches and the four central columns) are structurally safe, following the safe criteria in article (7.3) of this paper, under static and dynamic load cases. Although, small zones near middle of semi-domes and its supporting ribs are unsafe under seismic loads only.

ix. The structural condition of Moh.'Ali Mosque, after 1930s restoration project; does not record any structural problems (e.g. leaning, cracking, etc.), even after the seismic actions that hit Cairo in the last two decades, especially the most powerful earthquake in October 1992.

x. Tensile stresses in masonry walls of the mosque, after restoration project, and under static load case only; decreased to safe levels. Although, these stresses still unsafe under seismic loads, which means that masonry walls may face structural problems under future earthquakes.

9. Conclusions and Recommendations

The general conclusions and recommendations of this paper can be summarized as follows:

1) This research analyzes the structural behavior of Moh.'Ali Pasha Mosque at the Citadel, under static and dynamic cases of loading, for both original and after restoration conditions. Explanation and evaluation of structural failures in domes and columns of the mosque, which occurred by the end of 19th Century, are established. Findings and conclusions will help the preservation of this mosque and its counterparts in Turkey.

2) Study and evaluation of structural restoration work for the doomed-roof and columns of the mosque, which was achieved in 1930s, are provided.

3) The original design of the building, using traditional masonry work in construction; was not structurally safe, since the mosque suffered from serious cracks in domes and other structural elements, shortly after construction, which required urgent intervention. This was proved by structural analysis of the first numerical 3D-model of the mosque.

4) The second numerical 3D-model shows the restoration work of the mosque, which was achieved in 1930s, are structurally safe. It also shows the structural vulnerability of the original stone-masonry walls under seismic forces.

5) Historical Ottoman style mosques, such as Moh.'Ali Mosque at the Citadel; should include certain measures and precautions to resist high tensile stresses in domes and arches, such as steel reinforcing bars or sections, since traditional masonry work and materials cannot resist these internal stresses safely. At present,

composite structural domed-roofs can be achieved, safely and efficiently, using modern building materials.

6) Time has proved the structural safety of the current construction of Moh.'Ali Mosque, as no cracks or leaning are recorded or found in any structural elements of the mosque, since the finish of restoration project till the present time.

7) Current R.C. domes and semi-domes in Moh.'Ali Mosque are constructed from R.C. ribs, which are covered from upper side by R.C. slabs,to achieve more robust structural system; see Plate(12-b).

8) According to historical resources(61), the mosque is constructed over deep landfill of sand and gravel, beside the ruins of the previous old structures in the site. This deep layer of landfill rest over *Muqattam* hill at the Citadel, which is composed of lime rock. The long history of the building proved the good condition of the soil and foundation, since no soil problem was recorded, such as settlement with subsequent cracks.

9) The most critical dynamic case of loading, in structural analysis' work of the mosque; is the time-history of Altadena record, which provides intermediate frequency and high Pseudo Ground Acceleration (PGA). Response-spectrum and other time-history analyses' cases provide less internal stresses that cause the mosque, after restoration case, to be safe under combination of some of them with static load case-1. This can be the reason for the structural safety of the current construction of the mosque, after the famous 12th October 1992 Earthquake in Cairo, under which no structural damages were recorded at the mosque (62).

10) High Eigen-modal periods of minarets of the mosque, which are expected due to their height, designate the high seismic vulnerability of the minarets. Since the visual observation prove the good structural condition of the minarets, their foundation maybe

---

(61) Abdel-Wahab, Op. Cit., pp. 379-81.

(62) Center for documentation of Egyptian Antiquities at Al-Zamalik, Op. Cit.

rest on piles. Also, this demonstrates the more stability of slender minarets than massive ones.

11) Structural analysis of historical masonry buildings, using numerical modeling techniques (e.g. using Finite Element Method) is essential and valuable for studying the sophisticated and unusual historical structures. It also helps to establish and reach accurate evaluation for various structural failures and deficiencies, which may take place in historical buildings.

12) Substitution of failed masonry elements with analogous ones using reinforced concrete material, is a controversial alternative of restoration, although international charters and national lows that regulate its application.

13) Restoration of historical building should always aims to overcome the original defaults in design or construction, to reach structural safe buildings, and not always reconstruct failed elements alike to its original construction, without evaluating the problems first.

14) This research highlights the essential role of full and technical documentation of restoration project work, achieved for historical buildings, to cover all details of its phases. This will help in future evaluation of these buildings and reduce experimental and testing works to the minimum.

15) It is recommended to continuously evaluate the structural safety of Moh.'Ali Mosque and other historical structures, especially whenever achieving new restoration projects, after catastrophic events (i.e. earthquake) and when new techniques of evaluation and retrofit are approved from SCA (Supreme Council of Antiquities) and other worldwide Organizations.