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Seismic vulnerability of a Mamluk style minaret

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ABSTRACT: Seismic assessment and retrofitting of historical structures are challenging task due to the geometrical complexity and lack of knowledge about the inner core material and due to the incapability of masonry material to resist any tensile stresses. A better understanding of resisting system of such structures is the key issue for a comprehensive structural analysis, interpretation of the analysis results and a proper intervention. The main objective of this study is to investigate the seismic vulnerability of the Mamluk style minarets. For such purpose, a Mamluk style minaret constructed in the 14th century, namely, the Qusun minaret was selected and analytically modeled using a three-dimensional finite element model. The model was used to assess the minaret's dynamic characteristics and to analyze its response to different ground motion excitations. Both inelastic static modal pushover analysis and inelastic dynamic time-history analysis are adopted for scaled input motions. The assessment of the seismic performance is based on both global and local criteria. Results indicated that, due to the irregular mass and stiffness distribution along the heights of the studied minaret, this type of minarets is more vulnerable to moderate to strong earthquakes with moderate frequency content.

1 INSTRUCTIONS

A large inventory of historical minarets now exists in the so-called "Old Cairo City". Chronologically, historical Cairene minarets can be categorized into five groups, namely, Tulunid (827 to 904 A.D), Fatimid (969 to 1171A.D), Ayyubid (1171 to 1250 A.D.), Mamluk (1250 to 1517 A.D) and Ottoman Turk (1517 to 1848 A.D) [Aly et al. 1996]. Following the 1992 Dahshur earthquake, large numbers of these minarets were recorded to experience different levels of damage. Examining damage records indicated that minarets built during the Mamluk period were among the most severely affected structures. Irregular mass and stiffness distribution along their heights with large displayed stalactite carving made them more vulnerable to damage during earthquakes compared to other minaret styles [Aly et al. 1996].

To investigate the seismic vulnerability of the Mamluk style minarets, the "Qusun minaret" (1337 A.D.) was selected to represent this type of structures. The minaret considered for this study is shown in Fig. (1). It is located in the Al-Suyuti cemetery on the southern side of the citadel. It has an impressive rectangular stone shaft, carrying an octagonal second story with a stone Mabkharah on top [Abouseif, 1987]. Seismic Vulnerability of the Qusun Minaret is studied numerically. A three dimensional nonlinear finite element model for the minaret is established using the commercial software ANSYS ver. 11.00 based on the experimental study conducted by El-Habbal et al., 2008. The numerical model of the minaret is used to carry out a modal analysis for the minaret. Results of the modal analysis are compared to the experimental results to ensure the reliability of the numerical model.

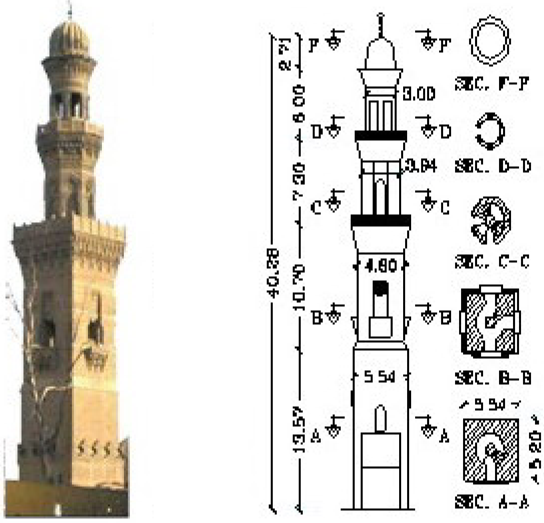


Figure 1. Qusun minaret

Subsequently, two types of analyses are performed. A modal pushover analysis is performed to obtain the capacity-demand curve of such endangered structures. In addition, a time step nonlinear dynamic analysis using three different earthquakes with different frequency contents was held. The latter results are used to ensure the reliability of the modal pushover analysis results, and to study the effect of peak ground acceleration (PGA) and frequency content on the vulnerability of such endangered structures.

2 STRUCTURE IN-SITE DESCRIPTION

The minaret has an impressive rectangular stone shaft, carrying an octagonal second story with a stone Mabkharah on top. From the first glance, it seems that the minaret is a freestanding structure. However, a closer look indicates that it was constructed as a part of the Seif Eldin Qusun Al-Saki monastery (Khanqa) for teaching Islamic rules. After the destruction of the adjacent monastery, the minaret is currently separated and directly resting on the ground. The total height of the minaret is 40.28 meters with the first balcony at 16.80 meters, the second balcony at 24.40 meters, and the third one at 31.85 meters from ground level. The base rectangular shaft is about 5.20×5.54 meters and it extends to the first balcony, as shown in Fig. (1). The minaret body at the base shaft is composed from three different layers starting from the minaret outer surface to the inner core. The outer layer is a 45 cm thick limestone wall, the inner core is a circular limestone column with a 1.50 meters wide diameter, and a weak massive filling material was used to fill the gap between the outer layer and the inner core [El-Habbal et al., 2008]. In 1888, severe deep cracks within the minaret lower body were observed. In response, The Arabic Committee for Restoring Islamic Heritage restored this part of the minaret by using four steel rods installed to tie the minaret four-side walls together. In addition, the committee installed stone parapets to the balconies and repaired the damaged part from the top cap "Mabkhara" [El-Attar and Osman, 2004].

The studied minaret is visually inspected to assess its current structural condition after several past earthquakes. Visual inspection indicated that the lower parts of the minaret (Lower than Mabkharah columns) at present are in a relatively good condition with minor cracks. Deterioration to some stones, especially at the base, was detected. Such stone disintegration is attributed mainly to the environmental conditions and aging process. On the other hand, some remarkable cracks are observed in the stone columns carrying the Mabkharah.

3 PROPOSED ANALYTICAL MODEL

The minaret prototype is numerically studied through a finite element model (FEM). For such purpose, a commercial finite element modeling computer package, "ANSYS ver. 11.00" is used. Eight-node-solid elements are utilized to simulate the external, internal, and fill regions of the minaret body. Shell elements are used to simulate the helical stair. All fine details including openings, recesses in the walls, and changes in wall cross-sections are accurately simulated to create a realistic model that is as close as possible to the real structure. Existing cracks in the minaret body are modeled by defining double nodes at the crack location for the two adjacent elements surrounding the existing crack, to provide free motion for each element separately during the deformation process.

In general, the behavior of the construction material in such historical buildings under severe loading conditions is expected to be nonlinear-inelastic. The inherent heterogeneous nature of stone walls interconnected through weaker mortar layers makes the behavior of such historical minarets during earthquakes be non-linear over the minaret body [El-Attar and Osman, 2004]. However, it is found in literature that stress distribution in such historical buildings is not uniform over the minaret body when they are hit by a random vibration. Hence, a modal analysis was performed to view the stress distribution at each mode shape, in order to specify the most stressed parts in the case of the Qusun minaret.

It was found that modeling all the minaret parts as a nonlinear-inelastic material is time consuming. The most stressed parts and the filling material between the inner and outer stone layers are defined as a nonlinear-inelastic material, with a Drucker-Pragger failure criterion to follow the discrete cracking criterion, which is the most appropriate for stones and weak mortar. The non-stressed parts are defined as a linear-elastic material to overcome the time consuming problem. The elastic material properties are listed in table (1), and the non-linear material properties are listed in table (2).

Table 1. Elastic Material Properties

Zone	Young's modulus	Density	Poisson's ratio	Damping Multiplier
limestone	3350 MPa	2172 Kg/m^3	0.21	0.02
Filling material	50 MPa	2000 Kg/m^3	0.2	0.005

Table 2. Non-linear Material Properties

Material	Shear Coeff.	Tensile strength	Comp. Strength	Tension Cracking factor	Cohesion	Angle of Friction	Flow Angle
Lime-stone	0.30 / 1.00	0.55 MPa	16.70 MPa	0.60	5.0 MPa	85°	85°
Fill	0.20 /0.30	0.05 MPa	0.15 MPa	0.20	0.1 MPa	60°	60°

4 MODAL ANALYSIS

A modal analysis is performed to extract the minaret's dynamic characteristics and to identify the most stressed parts over the minaret's body. Within ANSYS, the Power dynamics analysis method (Which is suitable for very large models with +100000 DOF) with no mass lumping is utilized for this purpose. Modal Stresses are also extracted and plotted. As shown in Fig. (2), the most stressed parts for all mode shapes are the top stone columns carrying the top bulb and sections at large openings such as doors and windows. Therefore, these zones are defined as nonlinear-inelastic solid elements, and the other parts are defined as linear-elastic solid elements. In the literature, this approximation is accepted when the resulting stresses due to modal analysis in the linearly modeled parts are very small compared to the modal stresses in the non-linear parts.

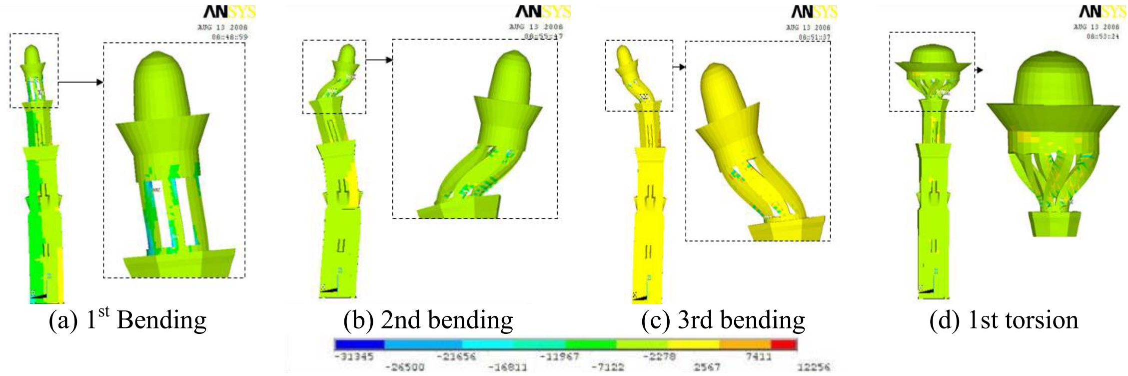


Figure 2. Stress Distribution in Different Mode Shapes

5 MODAL PUSHOVER ANALYSIS

Pushover analysis has been the preferred method for seismic performance evaluation of structures by the major rehabilitation guidelines and codes because it is conceptually and computationally simple. Pushover analysis allows tracing the sequence of yielding and failure on a member and structural level as well as the progress of the overall capacity curve of the structure. Although pushover analysis has advantages over inelastic analysis procedures, the accuracy of pushover predictions and the limitations of current pushover procedures must be identified. The estimate of target displacement, selection of lateral load patterns and identification of failure mechanisms due to higher modes of vibration are important issues that affect the accuracy of pushover results. The main objective of this section is to identify the reliability level of inelastic pushover analysis for such endangered structures. For such purpose, the inelastic seismic performance of the minaret is determined using the Modal Pushover Analysis (MPO), to be compared later on to the inelastic seismic performance of the minaret obtained from nonlinear dynamic analysis.

The pushover loads are applied at several levels along the height of the minaret. Pushover loads are applied at the levels of the 1st and 2nd balconies and the Mabkhara top point. These loads are applied in proportion to the mode shape displacement at each level. MPO analysis was repeated three times to take into account the modal displacements corresponding to the first, second, and third bending mode shapes. The total base shear resulting in each analysis case is plotted versus the maximum top point displacement computed from the MPO analysis at each mode (Fig. 3)

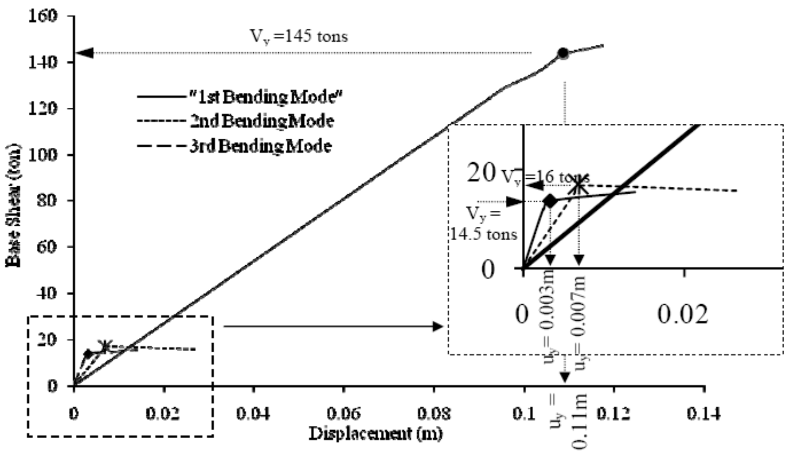


Figure 3. Base shear versus top point displacement due to pushover analysis

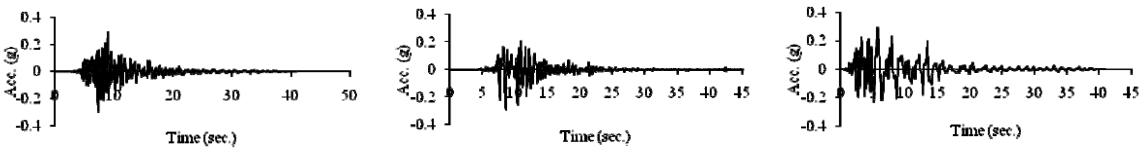
Figure (3) shows the change of the highest point's displacement in conjunction with the change in the total base shear applied in each mode shape obtained from the MPO analysis. It is found from the latter relationship that the structure behaves in the first bending mode shape linearly elastic most of the time and yield occurs just before the complete structural failure in this mode. The post yield length of the P-Δ curve in the first bending mode shape is very short until complete failure in that mode occurs. In the second and third bending mode shapes, the yielding point has a great role in changing the structural behavior in the post yield region, and it is noticed that the structural yielding point occurs at small values of the TPD in the second and third mode shapes. In addition to the significant increase of the initial global structural stiffness in the second and third bending mode shapes, this leads to a ductility disorder compared to the stiffness value corresponding to the first bending mode shape.

6 PERFORMANCE ANALYSIS

To evaluate the performance of the minaret during earthquakes, three different earthquakes are utilized. In selecting these earthquake records, three main aspects are considered, namely, the frequency content of the record, and the peak ground acceleration (PGA) to peak ground velocity (PGV) ratio (a/v). The selected records were picked up to cover a wide spectrum of frequencies and a/v ratios. The three selected earthquakes are from the same ground excitation (Kobe 1995) at three different recording stations, as listed in table (3). All three records are scaled down to three different values of PGA: 0.10g, 0.15g, 0.30g that corresponds to the maximum expected earthquake accelerations within Cairo city for a return period of 475 years. Figure 4 shows the earthquake records after being scaled to a PGA of 0.3g.

Table 3. Selected Earthquake Records

Station\component	PGA (g)	PGV (cm/sec)	PGD (cm)	Distance to fault	A/V	Frequency content category
Nishi-Akashi\ NIS000	0.51	37.28	9.529	11.1 km	1.37	high
KJMA\ Kjm000	0.82	81.30	17.695	0.6 km	1.00	medium
Takatori\ Tak000	0.61	127.1	35.788	0.3 km	0.48	low



Nishi-Akashi\ NIS000 KJMA\ Kjm000 Takatori\ Tak000

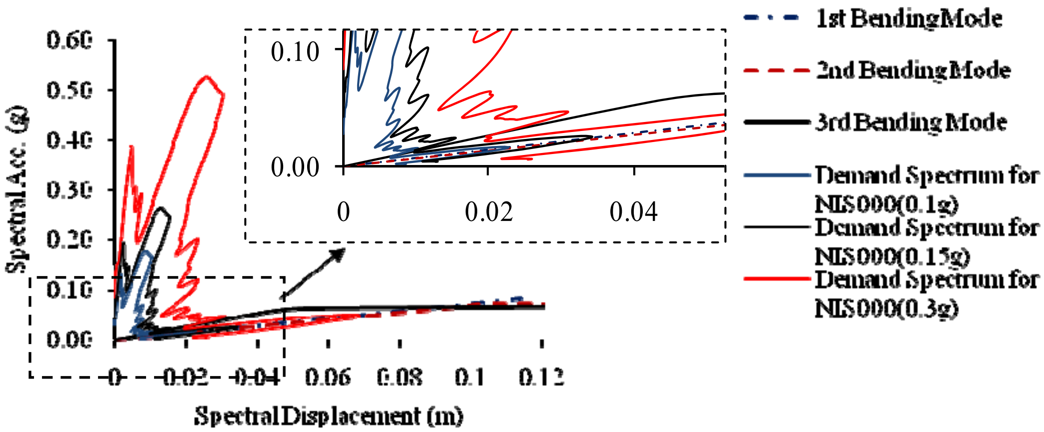
Figure 4. Used ground excitations scaled to a PGA of 0.30g

Structural seismic performance is determined by defining the structural performance point. According to FEMA 274 [FEMA 2000]. the performance point is defined as the intersection between the seismic demand curve and the capacity spectrum curve, which defines the displacement demand imposed on the structure [Saleh and Zaghw]. For such purpose, the total base shear (V) resulting in each analysis case is plotted versus the maximum top point displacement computed from the MPO analysis at each mode, as shown in Fig. (4), then, equations (1 through 3) are used to determine the capacity spectrum curves for each mode, as shown in Fig. (5). The inelastic response spectrum is then converted into spectral displacement versus spectral acceleration to be known as the demand curve. Conversion of the inelastic response spectrum was achieved using the Raleigh-Ritz procedure which is given by the following equations. Both, the demand curve and capacity curve are drawn on the same axis in order to facilitate the comparison between the seismic demand and the structural capacity. The latter discussed steps are repeated for each of the examined earthquakes. Table (4) summarizes the pushover analysis results.

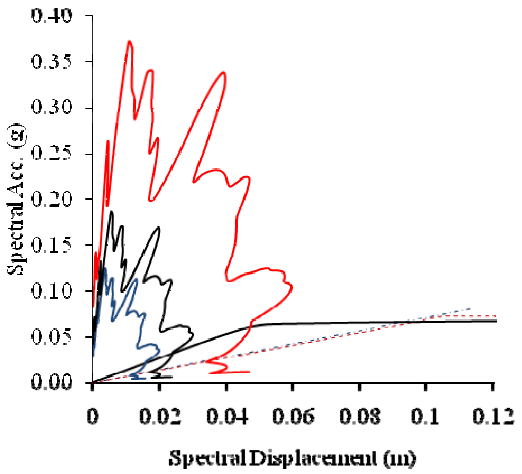
$$S_a = \frac{V}{W_{em}} \times g \qquad W_{em} = \frac{\left(\sum_{i=1}^{N} w_i \varphi_{im}\right)^2}{\sum_{i=1}^{N} w_i \varphi_{im}^2} \mathrm{W}$$

$$S_d = \frac{\delta_t}{\varphi_{rm} \Gamma_m} \qquad S_a = \frac{T^2}{4\pi^2} S_d$$

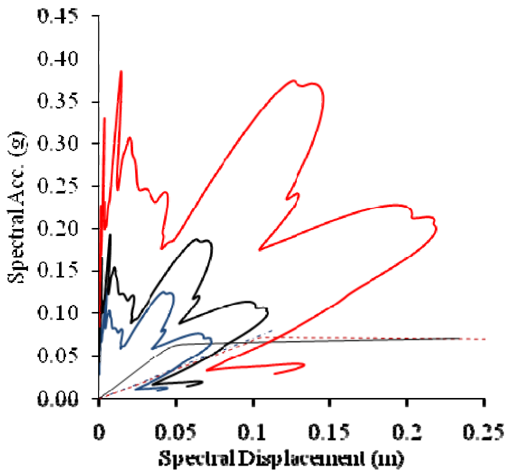
where, Γ_m : is the modal participation factor , W: is the total building weight, φ_{rm} : is the amplitude of the mode shape at the roof, and δ_t: is the roof displacement computed from the Pushover analysis.



(a) Capacity and demand curves for NIS000 earthquake (high frequency content)



(b) Capacity and demand curves for Kjm000 earthquake (medium frequency content)



(c) Capacity and demand curves for Tak000 earthquake (low frequency content)

Figure 5. Capacity and demand curves for the examined earthquakes with different PGA

7 NON-LINEAR TIME HISTORY ANALYSIS

The non-linear time-history analysis (NLTH) is an accurate tool for evaluating the exact performance of buildings during earthquakes. In this investigation, Time step analysis was performed using the same pre-analyzed model utilizing pushover analysis, with the same positions of material non-linearity. Time history for displacement and acceleration are recorded at the minaret top point under the effect of each selected earthquake. Figure (6) shows the displacement history of the top point of the minaret during the NLTH analysis using each of the selected earthquakes. As shown in the figure, the structural behavior is more ductile in the case of earthquakes having low frequency contents. Moreover, for low and high values of a/v ratios there is no observed failure in the minaret body at PGA of 0.1g during the ground excitation period. However, failure occurs at PGA of 0.1g in the free vibration stage after the ground excitation having vanished. On the other hand, for the same values of the a/v ratio PGA values between 0.15g and 0.3g cause severe damage for the minaret structure with all used earthquakes in the early stages of the earthquake. For moderate values of the a/v ratio, convergence of the results could not be achieved at early times of all earthquake records and the program indicates the presence of resonance, which is the cause of severe damage in the structure. It is noticed also from the stress history recorded at each load step that failure always occurs at the slender stone columns carrying the top bulb. In fact, there is historical evidence of such a behavior, where it is reported that the original Mabkharah collapsed during an earlier earthquake and the existing one was restored around the beginning of the twentieth century [Saleh and Zaghw, 2001]. The results are also summarized and listed in table 6.

Table 4. Results of pushover analysis

Eq. record	PGA (g)	Performance Point						SRSS	
		1st Bending mode		2nd Bending mode		3rd Bending mode			
		S_d (m)	S_a (g)	S_d (m)	S_a (g)	S_d (m)	S_a (g)	S_d (m)	S_a (g)
NIS000	0.10	0.022	0.017	0.022	0.0076	0.005	0.015	0.032	0.024
	0.15	0.034	0.025	0.033	0.032	0.010	0.0216	0.048	0.046
	0.30	0.067	0.050	0.067	0.051	0.023	0.032	0.098	0.078
Kjm000	0.10	0.013	0.011	0.013	0.010	0.016	0.025	0.024	0.029
	0.15	0.088	0.014	0.018	0.013	0.024	0.034	0.093	0.039
	0.30	0.038	0.029	0.035	0.025	0.047	0.066	0.070	0.076
Tak000	0.10	0.053	0.032	0.046	0.026	0.071	0.070	0.100	0.081
	0.15	0.077	0.057	0.072	0.051	0.080	0.071	0.132	0.104
	0.30	0.150	0.100	0.12	0.073	0.110	0.072	0.221	0.143

Table (6): Results of Time Step Non-linear Analysis

Eq. Record	Frequency content	PGA = 0.10g			PGA = 0.15g			PGA = 0.30g		
		TPD§ (m)	TPA** (g)	Failure Time	TPD§ (m)	TPA** (g)	Failure Time	TPD§ (m)	TPA** (g)	Failure Time
NIS000	High	0.08	1.29	N/A	0.09	1.92	8.14 s	0.14	1.37	6.93
Kjm000	Medium	0.07	0.95	2.14 s	0.084	1.10	1.93 s	0.10	0.75	7.83
Tak000	Low	0.24	0.95	N/A	0.17	2.48	4.05 s	0.20	2.14	3.47

§TPD: Top Point Displacement **TPA: Top Point Acceleration

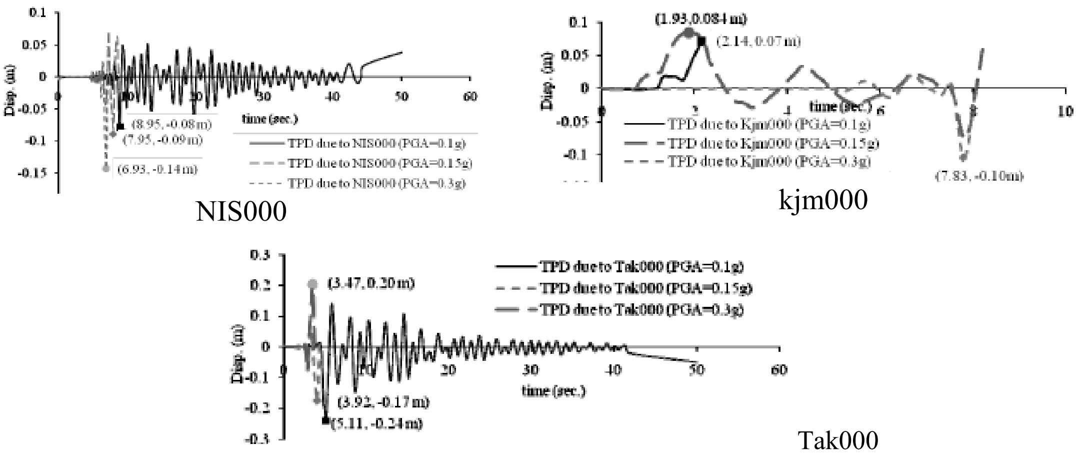


Figure 6. Top point Displacement due to different earthquake hazards

8 CONCLUSIONS

This research investigates the seismic performance of historical minarets with the objective of defining a criterion for their seismic retrofit/repair aiming at reducing the risk of their prohibitive damage or catastrophic failure. From the above detailed study, the following concluding remarks can be stated:

1) Mamluk style minarets are highly rigid structures. Their particular geometry makes them vulnerable to moderate earthquakes.
2) Structural ductility of such historical buildings changes according to the earthquake frequency content.
3) The most vulnerable part in Mamluk style minarets is the top bulb structure.
4) Modal analysis can be used to define the most stressed regions of such structures to be modeled using non-linear material models.
5) Since Modal pushover analysis underestimates the seismic behavior of such structures, it is not the most suitable procedure to use non-linear modal pushover analysis to estimate the seismic behavior of such historical buildings
6) Rather than using non-linear modal pushover analysis procedure, the validity of adaptive pushover analysis should be examined as a simple tool for studying the seismic performance of such historical structures.

References

A. Aly, E. Kordi, S. Elwan, Seismic response of Al-Gharry minaret. Proceedings of the 7th International Colloquium on Structural And Geotechnical Engineering, Ain Shams University, Cairo, Egypt, 1996.

D. B. Abouseif, The Minarets of Cairo. The American University in Cairo Press, 1987.

I. M. El-Habbal, A. H. Al-Zanaty, A. G. El-Attar, A. M. Saleh, The Use of SMA wire dampers to enhance the seismic performance of historical islamic minarets. Ph.D. Thesis, Department of Structural Engineering, Cairo University, Cairo, 2008.

A. G. El-Attar, A. Osman, Seismic response of two islamic minarets. Proceedings of the 3rd European conference on structural control, Vienna university of Technology, Vienna, Austria, 12 July, 2004.

S. Mourad, and A. Osman, Seismic risk appraisal for islamic minarets. Proceeding of the 1st Cairo Symposium on Earthquake Engineering, 3-5 December, 1994.

FEMA, Seismic Isolation and Energy Dissipation. Publ. No. 274, prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C., 2000.

A. Saleh and A. Zaghw, Effectiveness of base isolation of historical minarets using HDRB. Journal of the society of Egyptian Engineers,2001.