RELIABILITY OF HISTORICAL MINARETS IN EGYPT UNDER GROUND MOTION EXCITATIONS.

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ABSTRACT

The reliability of historical minarets in Egypt under ground motion excitation is examined in this study. A simplified formula is developed to determine the fundamental natural period of ancient masonry minarets. The seismic behavior of a model, representing the ancient masonry minarets, when subjected to earthquake excitation is evaluated. The performance of the minaret under the seismic forces required by the Egyptian Codes as well as under lateral forces proportional to the masses is also investigated. A procedure to evaluate the safety of masonry minaret when subjected to ground motion excitation is presented. Equivalent element parameters are chosen in performing the analysis by taking into consideration the effects of the infill material and the body material. The model is based on the experimental results of Naraine and Sinha and Page et al. The study shows that the type of construction material has a significant effect on the natural period of the minaret and the seismic performance of the system. It also shows that the significant reduction in the cross section of the minaret may lead to partial failure in which the system does not use its maximum strength to resist the seismic forces.

keywords: Masonry minarets, Earthquake excitation, Natural period, Seismic performance.

INTRODUCTION

The recent activity of earthquake belts surrounding Egypt shows that the egyptian region is no longer in low active seismic zone. This activity can be realized by reviewing the earthquake excitations that affected the Egyptian region in the past five years. The most effective ground motion excitations had occurred in 1992, 1995, and 1996. Although these excitations are classified as moderate earthquakes, the reliability of ancient masonry structures under seismic forces is still unassessed. This is because masonry structures have low shear strength. Therefore, the seismic behavior of this type of structures needs to be evaluated.

The existence of huge amount of ancient monuments in Egypt highlights the issue of their performance when subjected to ground motion excitations. The recent Egyptian Code for the Calculation of Loads and Forces on Buildings and Structures of 1993 [CLFBS] [1] furnishes design methods in which buildings can be designed to resist earthquake forces. These methods are also presented in the Egyptian Code of Practice and Design of Reinforced Concrete Structures of 1989 [ECPD] [2]. However, the treatment of masonry structures to resist earthquake excitations is not presented in the Egyptian Codes. This is may be explained by the fact that recent structures are built either of reinforced concert or of steel skeletons. Therefore, safety of ancient structures should be determined.

In this research, the seismic behavior of ancient masonry minarets is investigated under several ground motion excitations. A simplified formula to determine the fundamental period of minarets is developed. A procedure that can be used to determine the safety margin of minarets against failure is suggested.

DESIGN CONCEPT

More than one thousand ancient minarets are standing in the metropolitan area of great Cairo. The existing minarets are built with different styles through long period of years. The earliest minaret, which is still existing, is the one of Alhakim, built in the tenth century (1003 A.D) [3]. Starting by the Fatimid era passing through Ayyubid era, Mumluk, Qayt-bay, Algury, to Ottoman era, the design concept is undeviating [3]. The construction idea made in a way that the structural system consists of an outer body and an infill. The outer body serves as a skeleton to resist gravity and shearing forces. On the other hand the infill serves as a heavy mass to insure stability of minarets since many of them as high as seventy meters above the ground level. The stair case, in the part where the infill is not presented, works as a tie for the outer body. Although the design concept is unchanged, the geometric shapes of the minarets were changing to represent the unique style of that epoch. Figure (1) shows the style of construction of different era.

Based on the available materials in each epoch, the body of the minaret was built consequently. In the Fatimid and Ayybid epochs, baked bricks were used as the masonry type of the body. On the other hand, stones were the masonry type used in the thirteen century (the Mamluk era) until the eighteen century (the Ottoman era) [3]. The thickness of masonry varies from 20 cm single leaf to 50 cm double leaf. The infill consists of local materials such as lime, sand, and coarse aggregate mixed with used and fresh mortar. The infill material is usually fill the volume of the minaret extending from the foundation level to the mosque level.

STRUCTURAL MODEL

The finite element technique is utilized to investigate the dynamic characteristics and seismic performance of ancient masonry minarets [4]. In this technique, the structure is subdivided into an assembly of a finite number of discrete elements where continuity and equilibrium conditions must be satisfied at their nodes. A large enough number of elements is chosen in modeling the minaret to insure the accuracy of the results. A especial care was given in defining the nodes in which the cross section of the minaret is changing. Figure (2) shows a typical example of two dimensional model for a minaret. For tall slender masonry minarets, a vertical cantilever 2-D beam element can be used for modelling [5]. This assumption gives accurate results since the slenderness ratio lays with tall slender structures [5]. In this model, the mass of the minaret is considered lumped at the nodes. It is recognized in the model that the body materials and the infill materials play significant roles in identifying the properties of the elements. Therefore, a especial care was given in estimating the cross section characteristics.

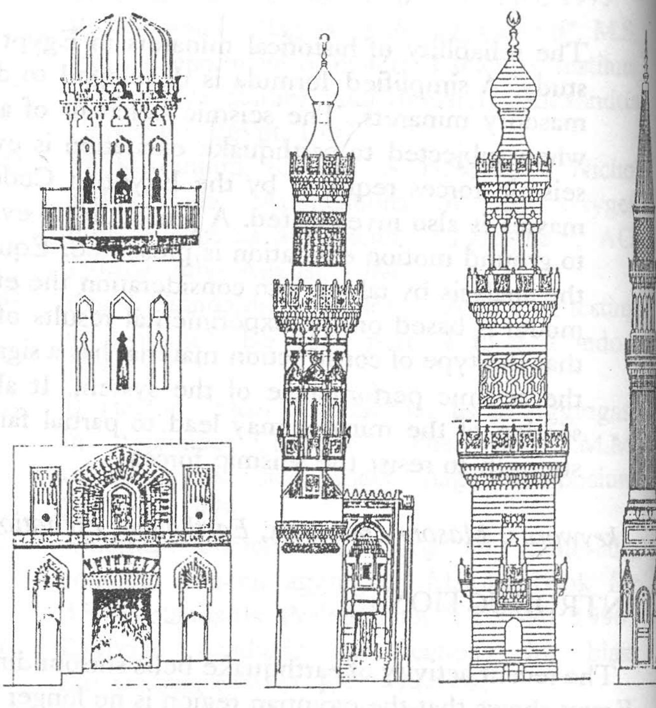


Figure 1. Style of Construction of Different Eras

Many factors may affect masonry properties such as; type of block, mortar, dimensions of units, joints width, and arrangement of bed. The non homogeneity of the body and the infill are also major factors that affect the model of the structure. The strength and resistance criteria which play significant roles in the analysis of minarets, can not easily adopted for ancient minarets. Adding to all these factors, the existing cracks in each individual case can not be modeled. Considering all these uncertainties, it seems that it is not reasonable to include all these factors in the analysis. This is because some of these factors may exist and the others may not in many cases. Therefore, the model should represent a simplified and a realistic case while the sophisticated effects can be considered in a specific case [6,7,8]. Based on that, the material should be treated as homogeneous, continuous and isotropic. Masonry is treated as an ideal nonlinear homogeneous material. It should be mentioned that for a specific case, experimental investigation including laboratory tests and site tests should be done in order to determine the material characteristics of that construction.

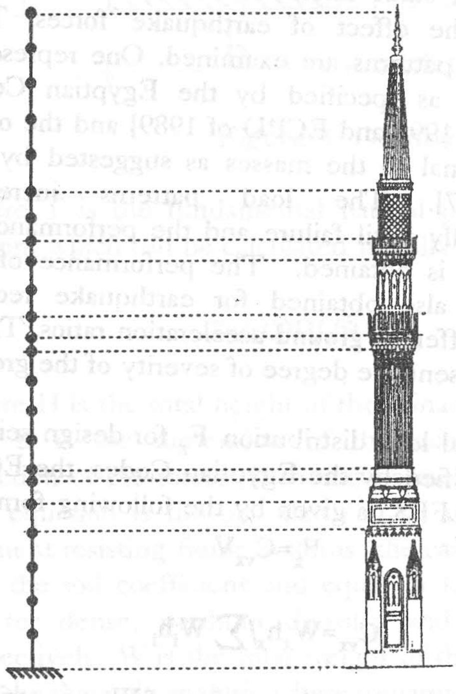


Figure 2. Two Dimensional Model For A Minaret

MASONRY CHARACTERISTICS

Several empirical formulas were found in the literature that can be used to determine masonry characteristics [9,10]. The mean values of the compressive strength can be obtained as follows:

$$f_{cw}=10[(\frac{2}{3}\sqrt{f_{cb}}-\alpha)+\beta f_{cm}](kg/cm^2) \quad (1)$$

where:

f_{cw} compressive strength of masonry respectively

f_{cb}, f_{tb} compressive and tensile strength of block (f_{tb} = 1/15 f_{cb})

f_{cm}, f_{tm} compressive and tensile strength of mortar (f_{tm} = 1/10 f_{cm})

α, β correction factors for masonry

The modules of elasticity of uncracked masonry, E_w, is related to the mean compressive strength by approximate relationship as:

$$E_w=(12000-8200)f_{cw}[\text{stone masonry}] \quad (2)$$

$$E_w=6200f_{cw}[\text{brick masonry}] \quad (3)$$

poisson's ratio, ν, of original masonry is assumed to be equal 0.2.

Several parametric study were conducted to verify these approximate equations. Bernardini et al. [11] operated an experimental model for masonry. The results were compared with those computed numerically by Vratsanou [12] and a good agreement was obtained. Tomazeviv and Zarnic [13] obtained experimental results and compared these results with numerical ones and the agreement was good. This concludes that the empirical formulas are good enough to be used.

On the other hand, the filling materials are in reality nonhomogeneous. Based on the type of filling (sand, lime, coarse aggregate, ...etc.), their compressive strength varies from 5 to 70 kg/cm^2 and the tensile strength varies from 2 to 5 kg/cm^2 [14].

Equivalent Element Characteristics

Several studies were carried out in order to investigate the actual distribution of stresses on masonry cross section [15]. Linear and non linear behavior were studied. In the linear stage, it was found that deformation characteristics of the composite section can be obtained by assuming perfect bond between masonry and infill. The equivalent cross section area (A_{eq}) and the equivalent moment of inertia (I_{eq}) can be determined from the following equations:

$$A_{eq}=A_w+nA_{inf} \quad (4)$$

$$I_{eq}=I_w+nI_{inf} \quad (5)$$

in which A_w and A_{inf} are the cross section area of the body and the infill respectively. I_w and I_{inf} are the moment of inertia of the body and the infill respectively. n is the ratio between the modules of elasticity of the infill (E_{inf}) and that of the body (E_w).

On the other hand, in the nonlinear stage when the compressive strength of the infill reaches its maximum, yielding starts to take place. As the forces increases, the stresses is further distributed on the masonry while stresses on the infill remain constant. Failure occurs when the compressive strength of the demand increases that of the masonry (the supply strength). It should be mentioned that for conservative results, the tensile strengths of the masonry and the infill are neglected. This assumption was made based on the reality that degradation and deterioration had been occurred in stone mortar and infill mortar of old built masonry structures [16]. Figure (3) shows the distribution of actual stress and the equivalent masonry and infill stresses. The values of k_1 and k_2 were determined experimentally to be 1.0 and 0.95 respectively [15].

STRUCTURAL ANALYSIS

Minarets can be modeled as two dimensional structural systems without any significant error as mentioned before. The finite element method is used in modeling the minarets. The equation of motion of multi-degree of freedom system when subjected to earthquake excitation can be written as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{1\}\ddot{x}_g \qquad (6)$$

where [M], [C], and [K] represent the mass, damping, and stiffness matrices respectively. The vectors $\{u\}$, $\{\dot{u}\}$, and $\{\ddot{u}\}$ are the relative displacement, velocity, and acceleration of the system respectively [18]. The ground motion acceleration is represented by the symbol $\ddot{x}_g$. When gravity effect considered in the equation of motion, Eq. (6) can be rewritten as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K-K_g]\{u\}=-[M]\{1\}\ddot{x}_g \qquad (7)$$

where $[K_g]$ represents the geometric stiffness matrix. It should be mentioned that gravity effect plays significant role only when the structure is near failure [17].

The step-by-step method is considered to determine the linear and non linear response of the minaret [19]. Dynamic characteristics as well as the dynamic response of the minaret are obtained. The fundamental natural period of the model is determined for several types of block and different infill materials. The effect of the type of block is evaluated. The structural behavior of the model is obtained for static lateral load distributions which represent the effect of earthquake forces. Two lateral load patterns are examined. One represents the pattern as specified by the Egyptian Codes [CLFBS of 1993 and ECPD of 1989] and the other is proportional to the masses as suggested by the author [17]. The load patterns increases monotonically until failure and the performance of the system is obtained. The performance of the minaret is also obtained for earthquake records scaled to different ground acceleration ratios. These ratios represent the degree of severity of the ground motions.

The lateral load distribution F_x for design seismic forces specified by the Egyptian Codes, the ECPD and the CLFBS, is given by the following formula:

$$F_x=C_{vx}V \qquad (8)$$

where

$$C_{vx}=W_x h_x/\sum W_i h_i \qquad (9)$$

where W_x and W_i are the portion of W at or assigned to level i or x. h_i and h_x are the height above the base to level i or x.

V is the minimum seismic lateral force and can be calculated by using the following equation:

$$V=ZIKCSW \qquad (10)$$

where Z is the seismic intensity coefficient and equal to 0.1, 0.2, and 0.3 for seismic zones 1, 2, and 3, respectively. I is the important factor and equal to 1.25 for emergency and post-disaster structures and 1.0 for others. K is the structural system coefficient accounting for the ductility of the system and equal to 0.67, 0.8, 1.0, and 1.33 for ductile moment resisting space frames, non ductile frames, box system, and dual system of moment resisting frames plus reinforced concrete walls respectively. C is determined according to the following formula:

$$C=1/(15\sqrt{T})\leq 0.12 \qquad (11)$$

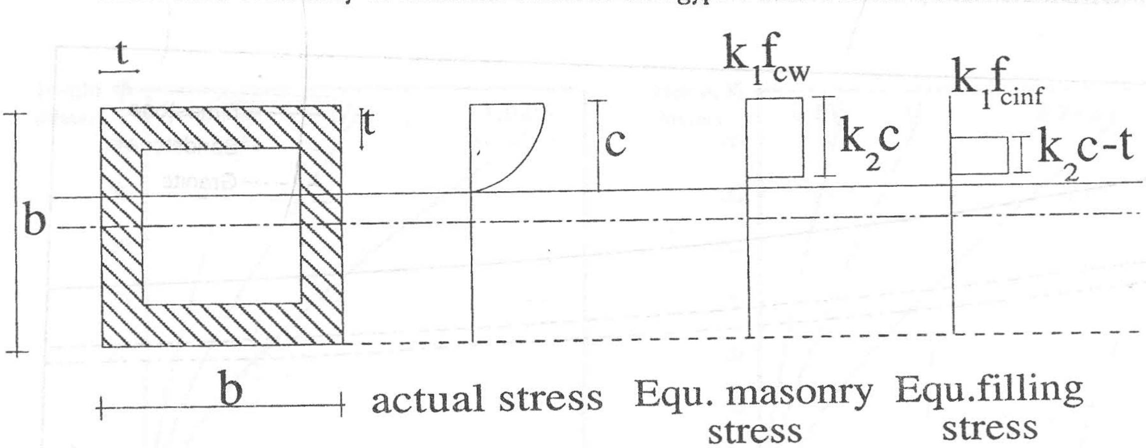


Figure 3. Distribution of Actual Stress and The Equivalent Ones.

where T is the fundamental natural period of the system which can be calculated initially for minarets as:

$$T = 0.09H/\sqrt{B} \qquad (12)$$

where H is the total height of the minaret in meters and B is the dimension of the minaret in the direction of the forces. It should be mentioned that this equation is the one that can be used for non moment resisting frame systems (the case of study). S is the soil coefficient and equal to 1.0, 1.15, and 1.3 for dense, medium density, and week soils respectively. W is the total weight of the minaret.

In the dynamic analysis where minaret is subjected to earthquake excitations, the damping matrix can be considered proportional to the stiffness or the masses or both according to the following equation:

$$[C] = \alpha_1[M] + \alpha_2[K] \qquad (13)$$

in which α_1 and α_2 are constant and can be determined by assumed damping ratios to the most effective two modes. It was recognized during the course of this study that when the damping ratio is assumed to be a function of [M] and [K], the failure occurred at a section different from that when the damping is assumed to be a function of [K] only or [M] only. This may conclude that the behavior of masonry systems are very sensitive to the damping function and needs to be considered in further research. However, in this case of study it is assumed that damping is proportional to the stiffness only. This assumption is made in which the failure pattern was the same as in the two cases of static lateral loads. The damping ratio is chosen to be 5% of the critical.

Figure (4) shows the effect of the type of block and that of the infill on the fundamental natural period of the minaret. As can be seen, for the same type of block, the natural period decreases as the ratio between the modules of elasticity of the infill, E_f, and the body, E_w, increases. The results indicate that the percentage reduction in the natural period when the ratio changes from 0.0 to 1.0 is about 30%. It can also be recognized from the figure that for a certain ratio of E_f/E_w, as the modules of elasticity of the body increases, the natural period of the minaret decreases. This notable reduction may conclude that the materials of the body and the infill have a significant effect on the natural period of the minaret. Table (1) shows the values of the parameters used in this analysis.

Statistical analysis is performed by using the modules of elasticity of the block of the body as a normalized parameter [17]. Then, regression analysis is made to determine the best fitting line that fits the normalized curves. This is done in order to determine a formula that can be used to estimate the natural period of tall slender masonry minarets. In performing these analyses, it was taken into consideration that the equation should be formulated using the code parameters. The developed formula can be written as follows:

$$T = 0.087\frac{H}{\sqrt{B}}\left(1 - 0.3\frac{E_f}{E_w}\right)\left(1 - \frac{E_b}{15 \times 10^4}\right) \qquad (14)$$

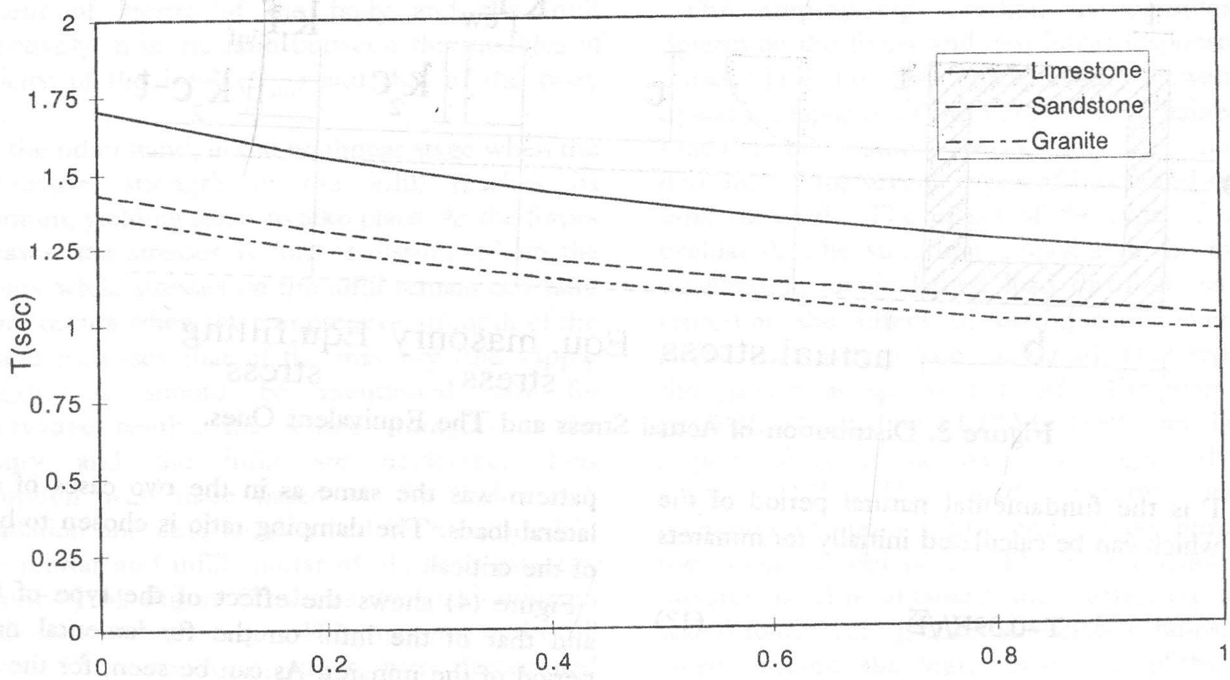


Figure 4. Effect of Type of Block and Infill on The Period

Table 1. Values of Minaret Parameters Used in This Study.

Type	E_b	ν	f_{cb}	f_{cw}	E_w	γ
	kg/cm^2 x 10^4		kg/cm^2 x 10^4	kg/cm^2	kg/cm^2	t/m^3
Lime stone	12	0.2	126.5	28	3.3	1.8
Sand stone	20	0.22	200	33	4.0	2.3
Granite	40	0.0	400	45	5.4	2.7

in which H is the total height of the minaret in meters and B is the width of the minaret in the direction of the excitation. E_f, E_w, and E_b are the modules of elasticity of the infill, the body, and the block of the body respectively. This equation can be used to determine the natural period of minarets in the code.

Figure (5-a) shows the performance of the minaret when subjected to the lateral force distribution of the Egyptian Code. Figure (5-b) shows the performance of the minaret under lateral force distribution proportional to the masses. The material of the body is chosen as lime stone. The distributions of both figures are scaled to different factors representing several degrees of severity of earthquake ground motions until failure. As can be seen, the deformations are almost proportional to the load factor which can be explained by the fact that masonry is a brittle material and failure occurs suddenly. Failure occurs when the load patterns scaled to almost twice the Code requirements.

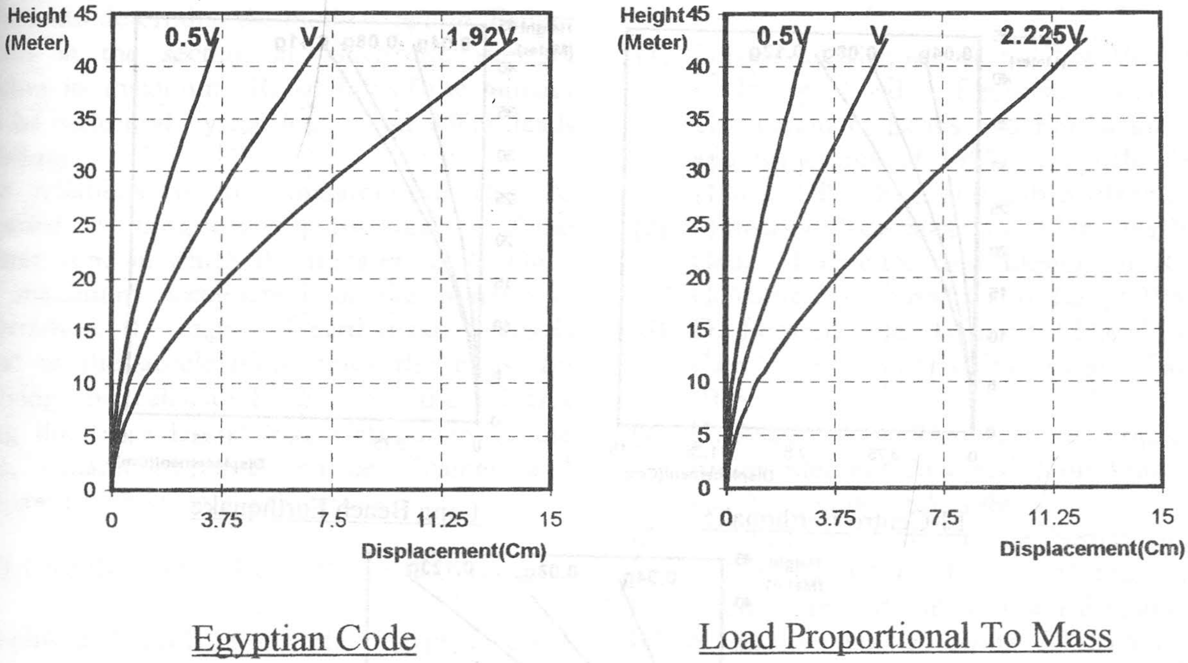


Figure 5. Deformation Due to Different Distributions.

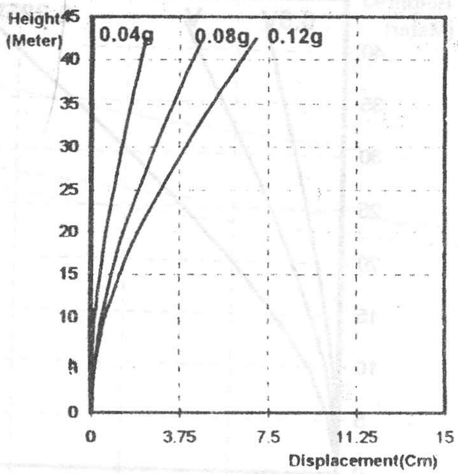
Figure (6) shows the seismic behavior of the minaret under earthquake excitations. The records are scaled to different peak ground accelerations representing several degrees of severity of ground motions. The earthquake records used in this study are the El Centro (S00E comp.), Long Beach (N90W comp.), and IVC2 (S40E Comp.) as of Table (2). As can be seen, the response of the minaret increases as the scale factor increases. The analysis shows that the failure is partial and the mechanism is local. This behavior can be explained as the reduction in the cross section of the minaret from one section to another is significant, the likelihood of occurring a local failure is imminent.

Failure occurs when El Centro record scaled to 0.12g, Long Beach record scaled to 0.11g, and IVC2 scaled to 0.123g. As can be seen, the three peak ground accelerations which cause failure are almost identical. This may conclude that the peak ground acceleration has a significant effect on the response of the minaret. It may also indicate that minarets are not safe against collapse when subjected to an expected severe earthquake with peak ground acceleration greater than 0.12g. Finally, the results conclude that when the reduction in the cross section is notable and the failure is partial, the base shear at failure can be significantly less than the base shear capacity of the minaret [17]. Therefore, the structural system does not use its maximum strength to resist earthquake forces. It should be mentioned that the base shear at failure is maximum and equal to the base shear capacity when the mechanism is global [17].

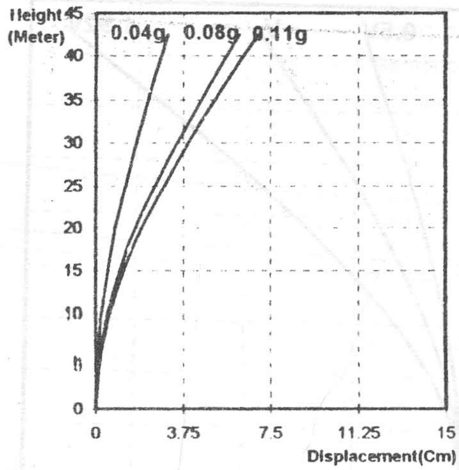
Comparing the performance of the minaret under the static lateral load distributions and under earthquake excitations, it was found that earthquake excitation with peak ground acceleration equal to 0.12g has an equivalent effect on minarets as twice as the effect of the code lateral load pattern [CLFBS].

Based on the preceding analysis, a procedure can be suggested to evaluate the reliability of minarets when subjected to earthquake ground motion. The procedure can be summarized as follows:

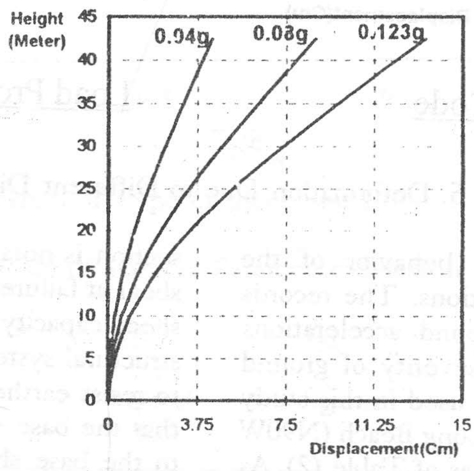
1) Determine the fundamental natural period of the minaret by using Eq. 14.
2) Obtain the lateral load force and its pattern by using the code formula.



El-Centro Earthquake



Long Beach Earthquake



LVC2 Earthquake

Figure 6. Seismic Behavior of Minaret Under Earthquake Excitations.

Table 2. Earthquake Characteristics Used in This Study.

Earthquake Record	Date of	Peak Ground Motions			Duration
		Acc. (g)	Vel. cm/sec	Dis. cm	sec.
El Centro (ELC) S00E Comp	5/18/1940	0.348	33.4	12.4	55.76
Imperial Valley College (IVC2) S40E Comp	10/15/1979	0.333	44.68	19.5	38.26
Long Beach (LOB) N90W Comp	3/10/1933	0.154	17.32	19.2	100.4

3) Increase the lateral load monotonically until failure and determine the mode of failure. Failure occurs at the section in which the strength reaches its maximum. Reliability of the minaret can be measured by the load factor which leads to failure.
4) The reliability of the minaret can also be obtained by using the response spectra of the seismic zone in which the minarets built. Once the maximum acceleration of the minaret is determined, the expected earthquake forces is equal to the acceleration times the mass. By applying the calculated forces on the minaret using the same lateral load distribution of the code, minaret response can be obtained and compared with its strength capacity.

CONCLUSION AND RECOMMENDATION

A simplified formula, using the Egyptian Code parameters, is developed in this study to determine the natural period of masonry minarets. This formula can be used for any type of blocks and infill. The performance of minarets under monotonically and cyclic loadings are studied in this paper. A comparison between the behavior of a minaret when subjected to earthquake excitations and monotonically lateral load patterns is performed. A procedure to evaluate the reliability of a minaret under seismic forces is presented.

The analysis shows that minarets are more likely to fail locally and therefore their systems do not use their maximum strength to resist earthquake forces. This is because the significant reduction in the cross section of the minaret along its height. The analysis shows that the damping function has a significant effect on the minaret behavior at failure. It shows that failure pattern can vary significant as the damping function changes. The results shows that for masonry minarets, the failure pattern developed from earthquake excitation is in a good agreement with the static lateral load pattern when damping is assumed to be a function of the stiffness matrix only. Therefore, it is recommended that damping issue in masonry minarets needs to be considered in further research.

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