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Condition Assessment and Structural Analysis of a Historic Masonry Minaret in Egypt

Maher A. Adam[1], Tarek S. El-Salakawy[1], Mohamed A. Salama[1]
Alaa A. Mohamed[1]
[1] Civil Engineering Department, Faculty of Engineering at Shoubra, Benha University, Egypt

ملخص البحث
يوجد في مصر عدد كبير من المآذن التى تم بناء معظمها في القرنين التاسع عشر والعشرين. المأذن من الأجزاء المهمة جداّ فى تكوين المساجد والتى غالباّ ما تكون مصنوعة من أحجار مقطوعة أو من الطوب الطفلى العادى، وتمثل ابعاد المأذن من حيث الطول والعرض والارتفاع والنحافه تحديا انشائيا حيث انها تجعل هذه المنشاءات تتعامل وكأنها مبانى عاليه وعليه فإنه يجب أن يكون هناك عناية خاصة لمثل هذه المنشاءات عند التعامل مع الاحمال الديناميكية و خاصة أحمال الرياح والزلازل كما انه يعاني العديد من هذه المآذن من شيخوخة المواد وتدهورها والظروف البيئية السيئة ونقص الصيانة وهناك مخاوف تتعلق بسلامة هذه الهياكل المهمة وإمكانية خدمتها ، وضرورة إجراء تقييم هيكلي لها.
يهدف البحث الحالى إلى دراسة وتقييم الحالة الإنشائية لأحد المأذن التراثية وهى مئذنة الرفاعي التي تمثل نموذجيًا لهذا النوع من المنشأت في مصر. يتم دراسة حالتها الحالية بما في ذلك تحديد مواد البناء وتدهورها مع مرور الزمن والاحمال المتوقعه الواقعة عليها عن طريق عمل نموذج حسابى و التحليل الخطى واللاخطى باستخدام برامج التحليل الانشائى المعروفة (ANSYS v.15 and SAP2000). مع مقارنة بين التحليل الخطى واللاخطى لتقييم كفاءة و سلامة المنشأ الانشائية. وأثبتت النتائج أن المنشأ فى حالة استقرار وقادر على تحمل جميع الاحمال الواقعة عليه.

Abstract

Egypt has a large number of masonry minarets; most of them were constructed in the 19th and 20th centuries. Many of these minarets suffer from material aging, deterioration, adverse environmental conditions and lack of maintenance. Concerns regarding the safety and serviceability of these important structures take place, and the necessity for structural assessment activities currently are going on.
This paper presents the condition assessment and structural analysis of a heritage masonry minaret (Al-Rifa'i minaret), that represents a typical example of these kind of structure in Egypt. Its current condition is studied including identification of the building materials, evaluation of the actual deteriorated material properties and estimation of the current loading conditions. A numerical study is performed to evaluate the structural behavior in order to assess its structural efficiency and safety margin. Numerical modeling using finite elements and nonlinear structural analysis are performed using commercial program ANSYS v.15 under the applied static and dynamic loads and the worse expected loading cases. A comparison between static and dynamic analysis is performed, also linear and non-linear analysis have been compared. The obtained results regarding stresses, deformations and cracking within the structure indicate overall stability and safety of the structure in its current condition.

Keywords: assessment, historic, masonry, minarets, structural analysis, nonlinear, linear, dynamic analysis.

1. Introduction

Masonry is the oldest building material that still finds wide use in today's building industries, Masonry minarets consider one of the most important historical masonry structures in Egypt, Historically, minarets were initially constructed as elevated structures attached to Islamic mosques to be used by the Mu'adhdin to summon people for the prayers, Cairo City is considered one of the oldest cities in the world that possesses a large inventory of historical minarets, so there is an urgent need for evaluation and assessment of existing these structures in terms of existing loads and expected loads such as wind and seismic loads. They have suffered significant damage during past earthquakes in Egypt and elsewhere. The structural mechanical properties of each masonry minaret, depend on many factors including the structural knowledge and applications at the time of construction, experience of the architect or engineer, seismicity of the region, and availability of construction materials in each area. Irregular mass and stiffness distribution along their heights made them more vulnerable to damage during earthquakes. Al-Rifa’i minaret is selected as a case study in this paper to present evaluation of its material properties and structural behavior under different load cases such as own weight, wind load and earthquake loads at zone 3 and zone 5 in Egypt [1].

2. Structure Description

Al-Rifa’i minaret was constructed in 1911, it is a mixed of styles taken from the ottoman and mamluk styles, and it is located in Midan Al-Qalaa, Cairo, Egypt, The minaret’s total height is 42 m, it consists of four main parts, the first part is a square base 4.27 × 4.27 m with height 7.55 m, the second part which is a vertical shaft that changes its cross section from a square to an octagon, it’s dimensions are 4.27 × 4.27 m with height 7.15 m then the third part which is a cylindrical body with diameter 3.70 m and height 9.12 m and finally the forth part, a top cap (Mabkhara) supported on eight columns with height 13.70 m, the general dimensions, plans, elevation and vertical sections of Al-Rifa’i minaret are shown in Figure 1 and 2.

Figure 1: Al-Rifa’I minaret.

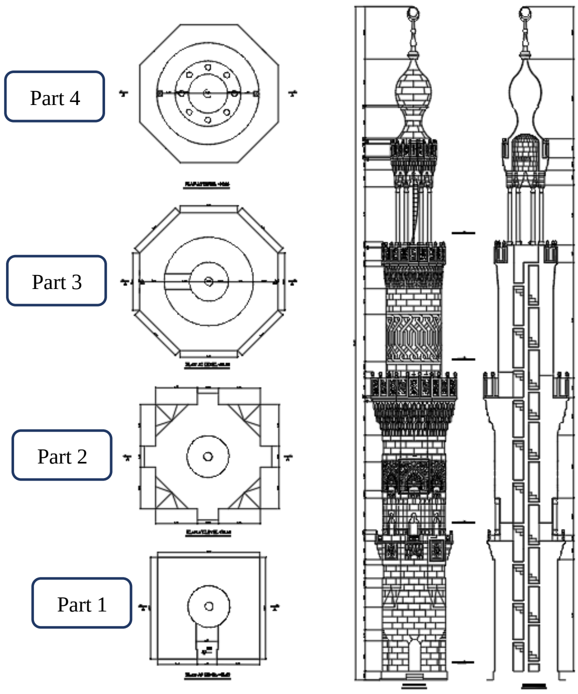


Figure 2: Geometry of the minaret, Elevation, Plans and Vertical section.

3. Structural Analysis

3.1.Numerical Modeling and Nonlinear Analysis Approach

In order to study the structural behavior of the minaret under the acting loads, the whole structure was numerically analyzed by means of refined numerical models based on the finite element method. The complex irregular nature of masonry construction makes accurate structural analysis a challenge. Masonry material is characterized by nonlinear mechanical behavior, even for low deformation levels, with anisotropy both in the linear and nonlinear range. Furthermore, masonry structures often require 2D or 3D modeling approaches [2].

To represent the heterogeneous and anisotropic nature of masonry construction using finite elements, different modeling strategies may be followed that are reviewed by Roca et al [3].

Discretization of the structure can be performed using the following three approaches:

(i) Detailed micro-modelling - units and mortar in the joints are represented by continuum elements whereas the unit-mortar interface is represented by discontinuous elements.

(ii) Simplified micro-modelling - expanded units are represented by continuum elements whereas the behaviour of the mortar joints and unit-mortar interface is lumped in discontinuous elements.

(iii) Macro-modelling - units, mortar and unit-mortar interface are smeared out in the continuum [4].

Comparison of the three main modeling strategies for masonry conclude that although detailed micro-models are capable of addressing some of the complexities, their application is primarily restricted to small-scale structures with regular geometric forms [3].

The macro modeling (smeared, continuum or homogenized) is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation, especially for such complicated geometry of these structures and the selected modeling strategies describes the structural behavior with acceptable accuracy [5],and it was used in the present study.

3.2. Finite Element Mesh

A three-dimensional finite element model was made for the whole minaret structure using the commercial software ANSYS v.15 [6]. In the three-dimensional model, the masonry components are represented by macro-meshing strategies using solid elements SOLID 65 (Figure 3) to define the individual blocks and zero thickness joint elements at their interfaces (stone-to-stone joint type), as shown in (Figure 4).

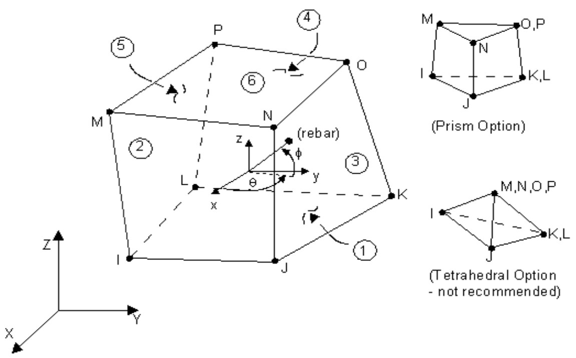
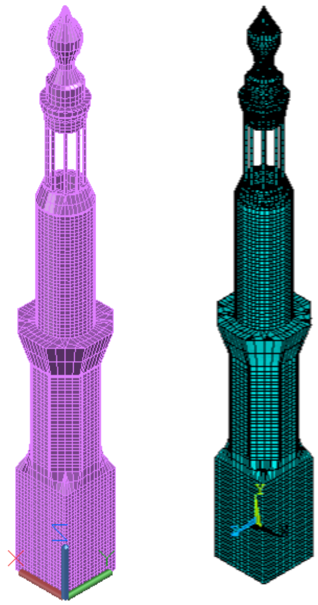


Figure 3: Solid65 geometry



(a) (b)

Figure 4: The 3D meshing of Al-Rifa'i minaret. (a) Autocad meshing, (b) Ansys meshing.

3.3. Material Properties

The material properties of the minaret are taken from the similar study of Al-Attar [7] and are listed in (Table 1).

Table 1: Masonry mechanical properties.

Masonry Compressive Strength (f'm)	4.25 MPa
Modulus of Elasticity (Em)	297.5 MPa
Weight Density	20.9 KN/m^3
Major Passion's Ratio	0.2
Tensile Strength	0.96 MPa
Shear coefficient along opening cracks (ShrCf-pO)	0.2
Shear coefficient along closed cracks (ShCf-Cl)	0.8
Tension limit, cracking limit (UnTensSt)	0.96 MPa
Compression limit, crushing limit (UnCompSt)	4.25 MPa

3.4. Loads and Load Cases

The loads acting on the minaret structure were calculated according to Egyptian code [1], and can be listed as follows.

1. Dead load: the own weight of the structural element.
2. Wind load: the wind speed is considered 33 m/s (Cairo zone).

Wind loads is considered for one direction only (x-direction) because of the symmetry of the minaret. The total base shear is 116 KN.

$F = C_f\ K\ q\ A$ Where C_f : Total wind force coefficient. K = 1.

A: Total Area.

q: ($q = 0.5\times10^{-3}\ \rho\ v^2\ c_t\ c_s$) $\rho = 1.25$ Kg/m^3, v = 33 m/s, $c_t = 1$, $c_s = 1$.

3. Earthquake load (zone 3): The spectral acceleration is 0.15g, earthquake loads is considered for one direction only (x-direction). The total working base shear of the

minaret due to the earthquake zone 3 equal 558 kN, the effect of earthquake loads is derived from the following equations:

$T = C_t\, H^{0.75}$ Where $T = 0.822$ sec $C_t = 0.05$ $H = 42$ m.

$T_C \leq T \leq T_D$: $S_d(T) = a_g\, \gamma_1\, S\, (2.5/R)\, (T_c / T)$

Where $T_C = 0.25$ sec $T_D = 1.2$ sec $R = 2.$ $S = 1.$

$S_d(T)$: Horizontal design spectrum for elastic analysis. $a_g = 0.15g.$ $\gamma_1 = 1.$

$F_b = S_d(T)\, \lambda\, W / g$ Where F_b : Ultimate base shear force (kN). $\lambda = 1.$

W : Weight of the minaret (kN). $g = 9.81$ m/sec^2.

4. Earthquake load (zone 5): This zone is considered to evaluate the structural safety of the minaret in a high seismicity location even if it is located in zone 3.

Zone 5 spectral acceleration is 0.3g, earthquake loads is considered for one direction only (x-direction). The total working base shear of the minaret due to the earthquake zone 5 equal 1115 KN, the effect of earthquake loads is derived from the previous equations.

The minaret structures are usually subjected to different load cases during its life time, this study considered five load cases that represent most of the effective load cases subjected to these kind of structure.

Case A: Construction case: where minaret is subjected to its own weight only.

Case B: Wind case: where minaret is subjected to its own weight and wind load.

Case C: Seismic case: where minaret is subjected to its own weight and earthquake loads zone 3, this loading case has been developed using ANSYS v.15 and SAP2000 (non-linear and linear model respectively).

Case D: Seismic case: where minaret is subjected to its own weight and earthquake loads zone 5.

4. Numerical Results

4.1. Case A: Gravity Load Case Results

As a first step towards examining the level of stress within the minaret body, the considered minaret was analyzed for gravity loads. The load in this case is the minaret self-weight 7948 kN (total vertical reaction). stresses have maximum value in compression in y-direction equal 1807 kPa and tension equal 45 kPa, minaret stresses and deformation shape are shown in Figure 6 and 7.

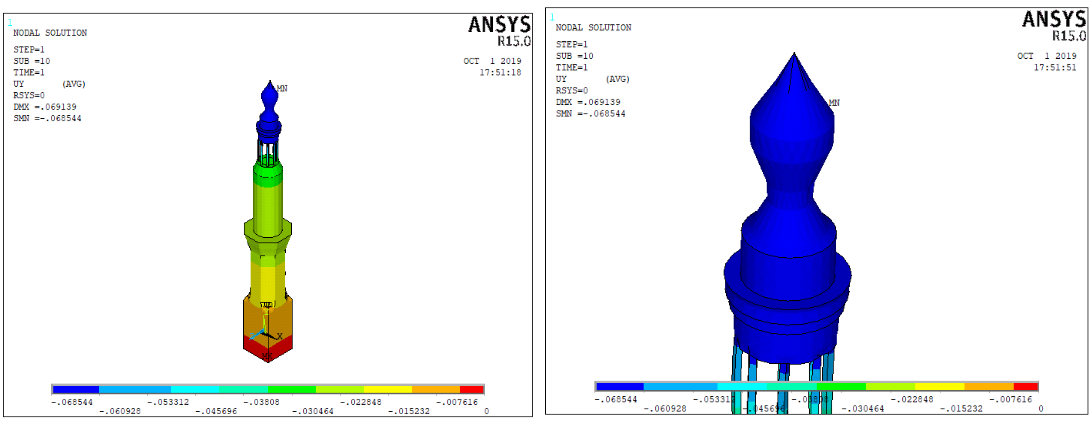


Figure 6: Deformed shape in y-direction of El-Rifa'i minaret (gravity case).

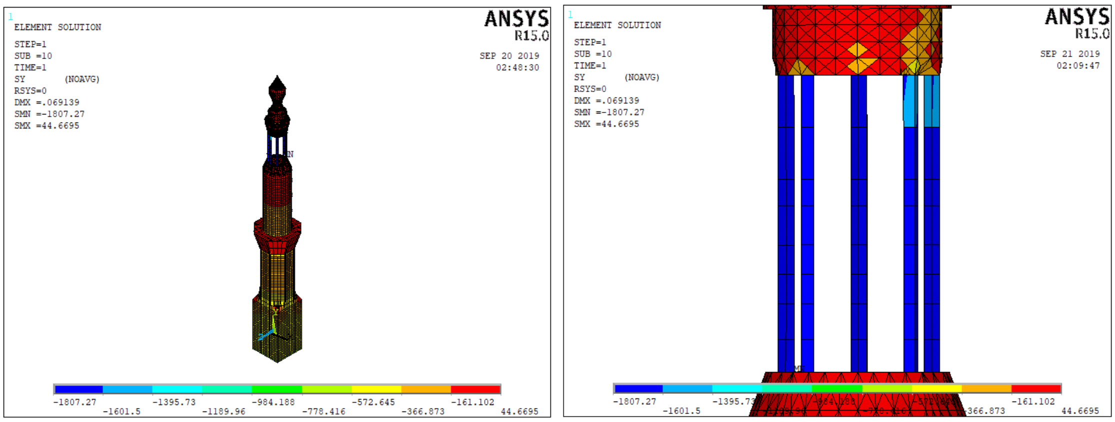


Figure 7: Stresses in y-direction of El-Rifa’i minaret (gravity case).

4.2. Case B: Wind Load Case Results

In this case, the applied loads on the minaret are its own weight and wind load with total base shear of 114 kN, the resulted deformed shape in x-direction indicate the maximum value for lateral displacement of 222 mm as shown in Figure 8.

This equation below gives limits of earthquake specifications under an earthquake or high wind case ($\Delta_{max}/H_{minaret} < 0.02$) ($292 \div 42000 = 0.0069 < 0.02$) [8]. Maximum stresses in z-direction due to the horizontal load of the wind occurring in the columns as tension equal 550 kPa and compression equal 920 kPa (Figure 9) , in y-direction stresses in columns tension equal 418 kPa and compression equal 2612 kPa (Figure 10), the maximum tensile and compressive stresses occur at a height of 29 m in the columns immediately above the transition zone (part 4 of the minaret). Crack pattern shows no cracking for wind load case.

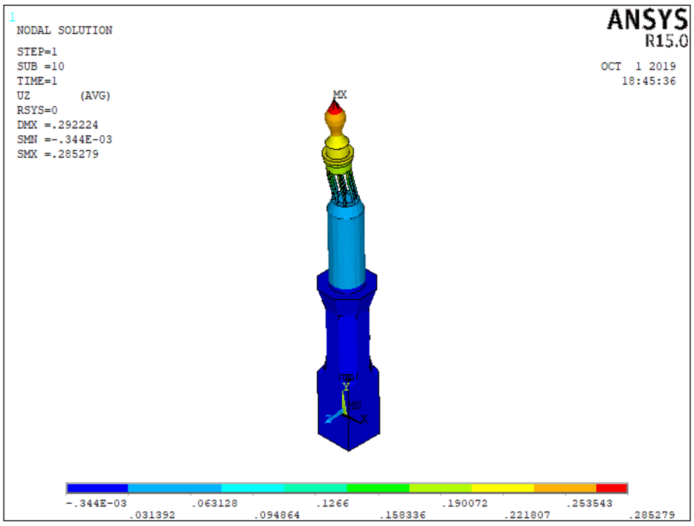


Figure 8: Deformed shape in x-direction of El-Rifa’i minaret (wind case).

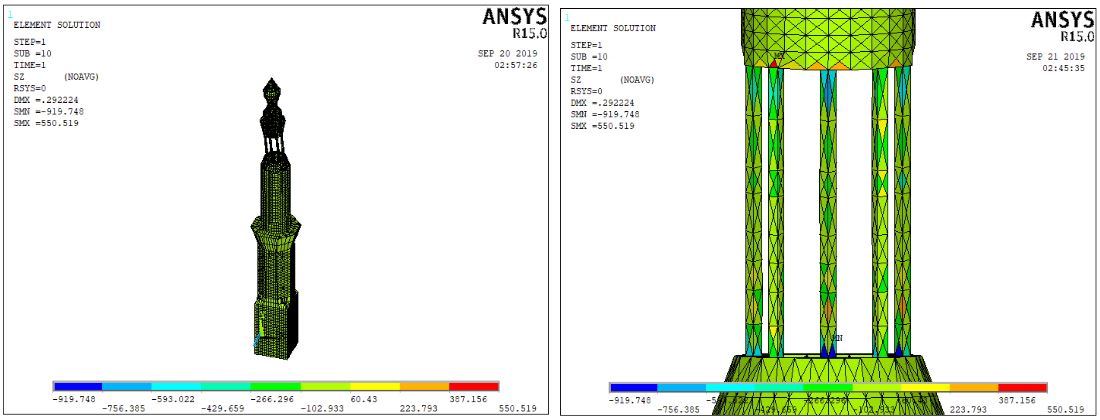


Figure 9: Stresses in z-direction of El-Rifa’i minaret (wind case).

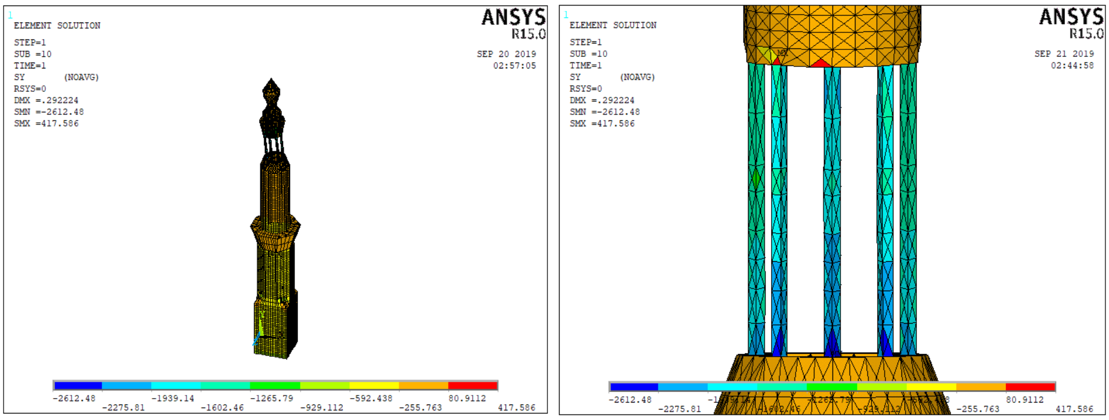


Figure 10: Stresses in y-direction of El-Rifa’i minaret (wind case).

4.3. Case C: Seismic Load Case Results (Zone 3)

In non-linear model, the applied loads on the minaret are its own weight and earthquake load with total base shear 400 KN, the deformed shape in x-direction, the maximum value for displacement is 1200 mm as shown in figure 11, these plots reveal one of the main dynamic characteristics of the minaret, namely, the relatively flexible upper part and the stiff lower body, The figures indicate a larger tendency of the upper part to sway relative to its stiff support, columns stresses in z-direction are shown in Figure 12.

The tension stresses equal 704 kPa and compression equal 1858 kPa because of the horizontal load of the earthquake, in y-direction stresses in columns, tension equal 998 kPa and compression equal 5486 kPa (Figure 13). As can be noted, analyses indicated that stresses in y-direction exceeding both the tensile and compressive allowable strengths. These stresses are located at the connection between the minaret cap and the minaret body (at the bottom of the columns carrying the cap-part 4 of the minaret). The weakest point in the minaret body was identified as the columns supporting the top cap. At the same time the cracks appear in the columns as the stiffness decrease so the material cracked (Figure 14).

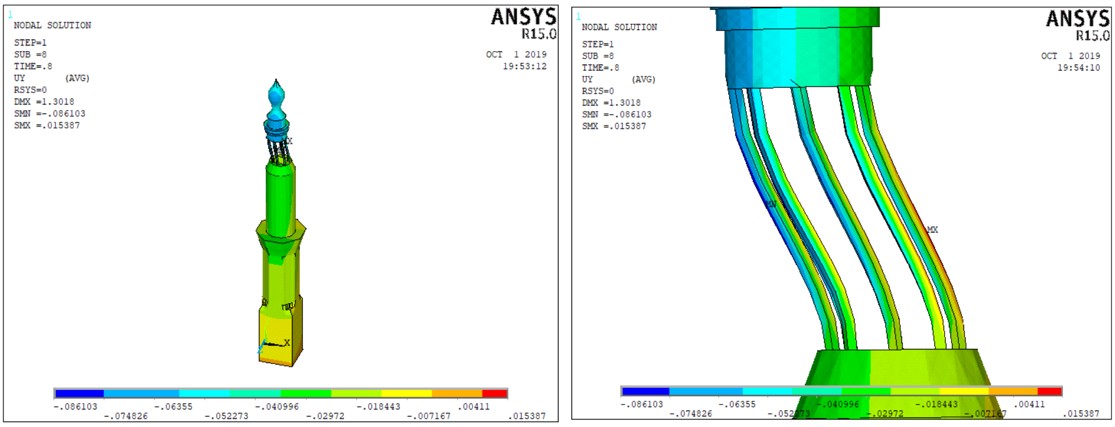


Figure 11: Deformed shape in x-direction of El-Rifa'i minaret (zone 3 case).

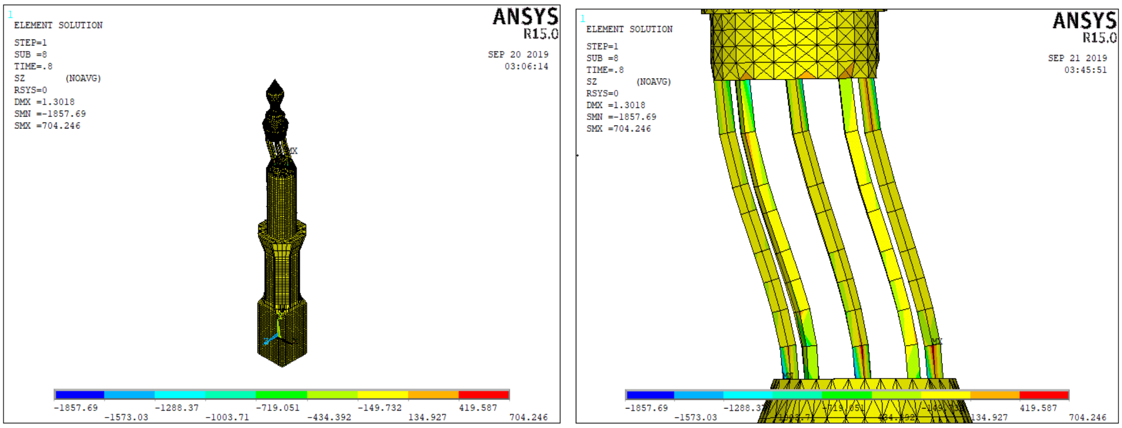


Figure 12: Stresses in z-direction of El-Rifa'i minaret (zone 3 case).

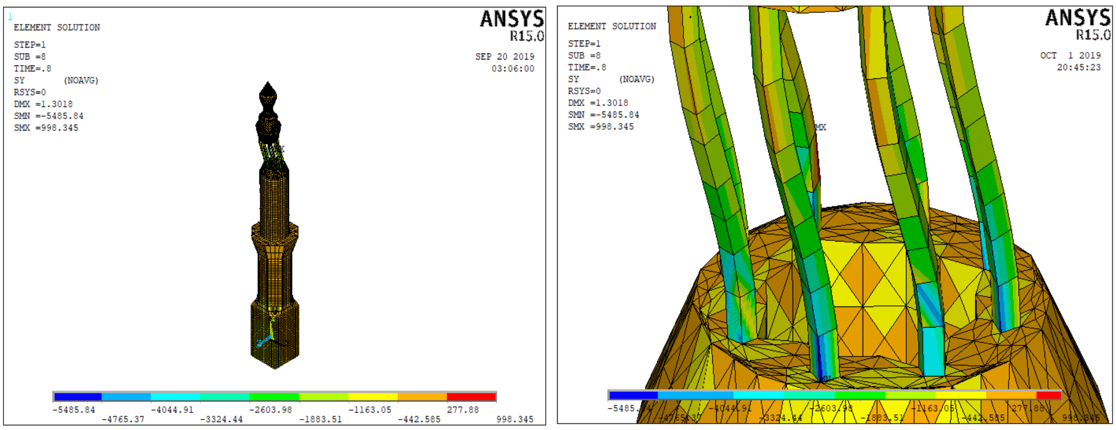


Figure 13: Stresses in y-direction of El-Rifa'i minaret (zone 3 case).

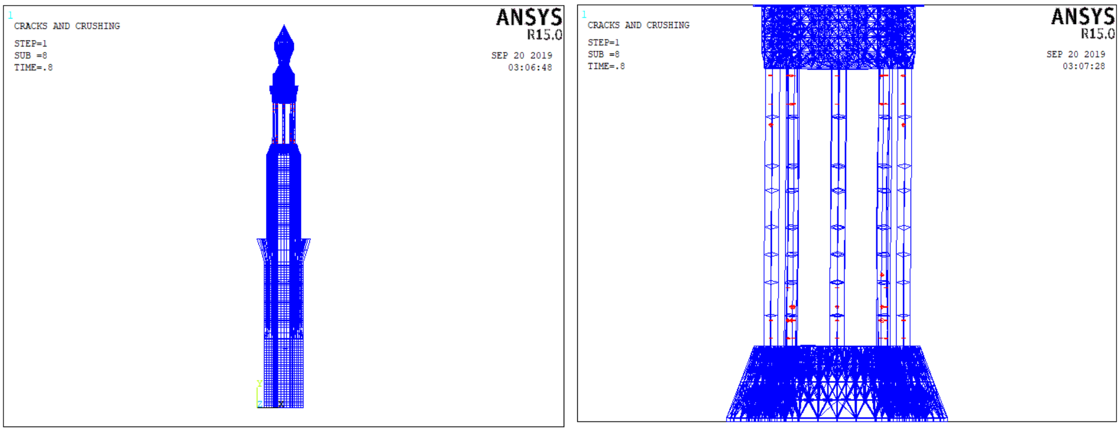
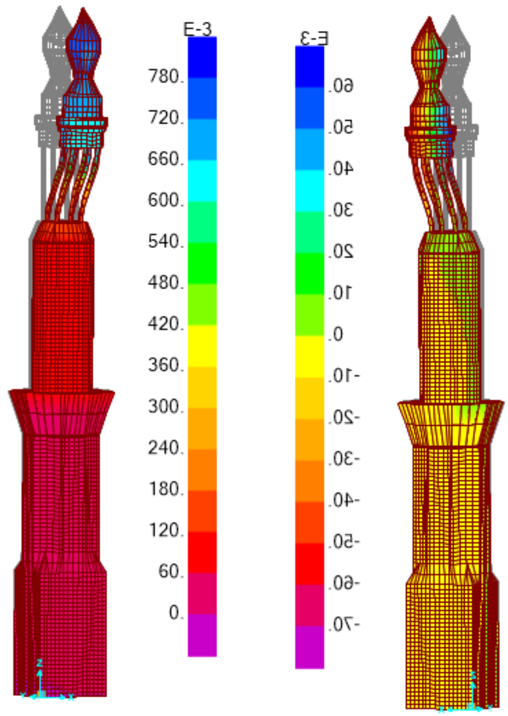


Figure 14: Cracking pattern of Al-Rifa'i minaret (zone 3 case).

In linear model, the applied loads on the minaret are its own weight and earthquake load with total base shear 400 KN, the maximum displacement is 821 mm (Figure 15). In z-direction compression stress equal 4289 kPa and tension stress equal 1008 kPa as shown in (Figure 16), in y-direction compression stress equal 2080 kPa and tension stress equal 777 kPa (Figure 16), the maximum tensile and compressive stresses occur at a height of 29 m in columns (part 4 of the minaret) as it is the weakest part of the minaret.



(a) (b)

Figure 15: Deformed shape (Earthquake Zone 3). (a) X-direction, (b) Y-direction

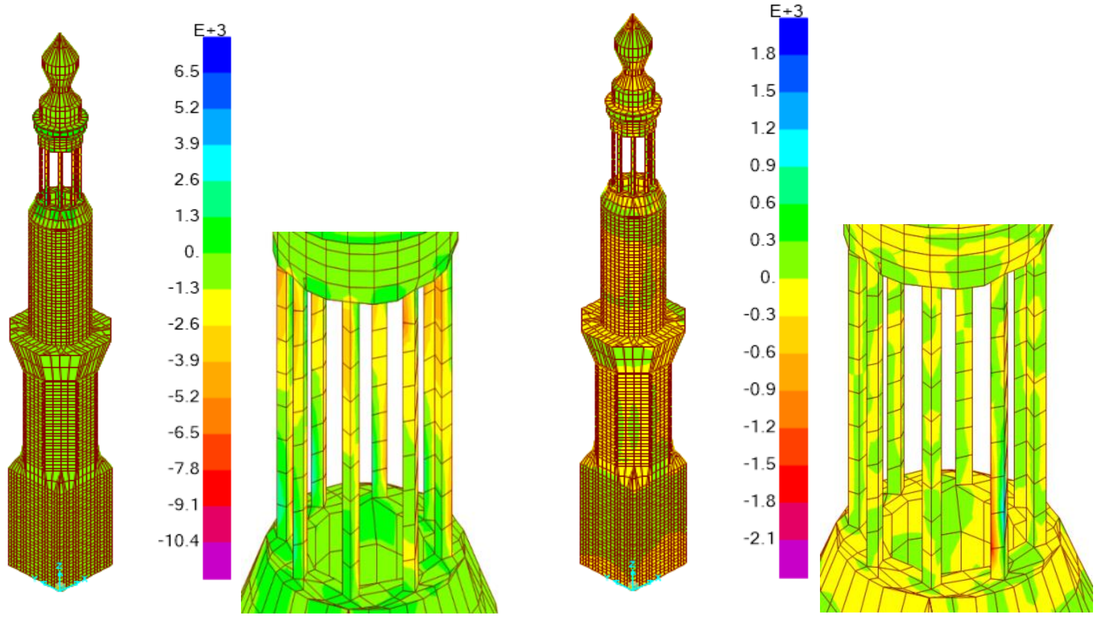


Figure 16: Stresses of El-Rifa'i minaret (Earthquake Zone 3). (a) Z-direction, (b) Y-direction.

4.4. Case D: Seismic Load Case Results (Zone 5)

The applied loads on the minaret are its own weight and earthquake load with total base shear of 800 KN, However the minaret model fail to complete the numerical solution of this load cases, the following results represent the numerical solution at half the considered ultimate load and substep (0.5), the resulted deformed shape in x-direction is shown in (Figure 17), the maximum value for displacement is 1700 mm. Columns stresses in z-direction (Figure 18), tension equal 747 kPa and compression equal 2410 kPa because of the horizontal load of the earthquake, in y-direction columns stresses in tension equal 955 kPa and compression equal 5884 kPa (Figure 19). Analyses results indicates that compressive stresses in y-direction exceeding the allowable stresses of the minaret, the crack pattern is shown in Figure 20.

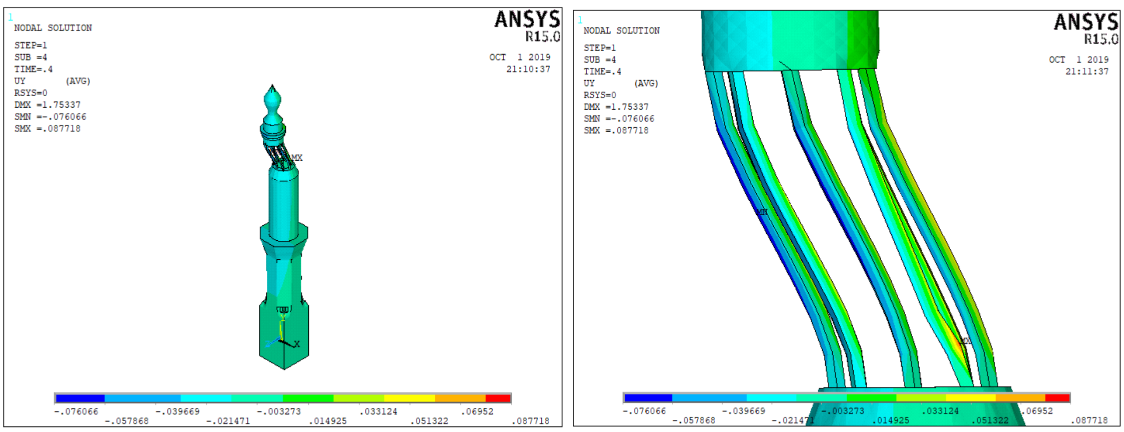


Figure 17: Deformed shape in x-direction of El-Rifa'i minaret (zone 5 case).

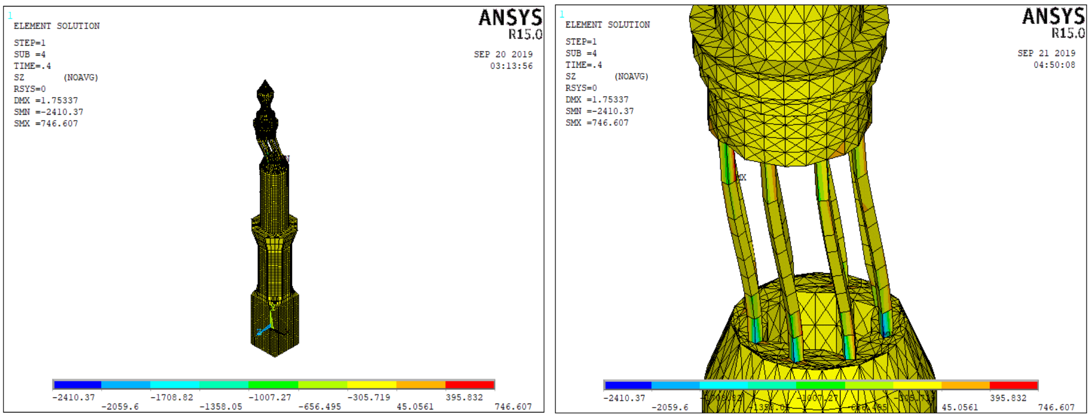


Figure 18: Stresses in z-direction of El-Rifa’i minaret (zone 5 case).

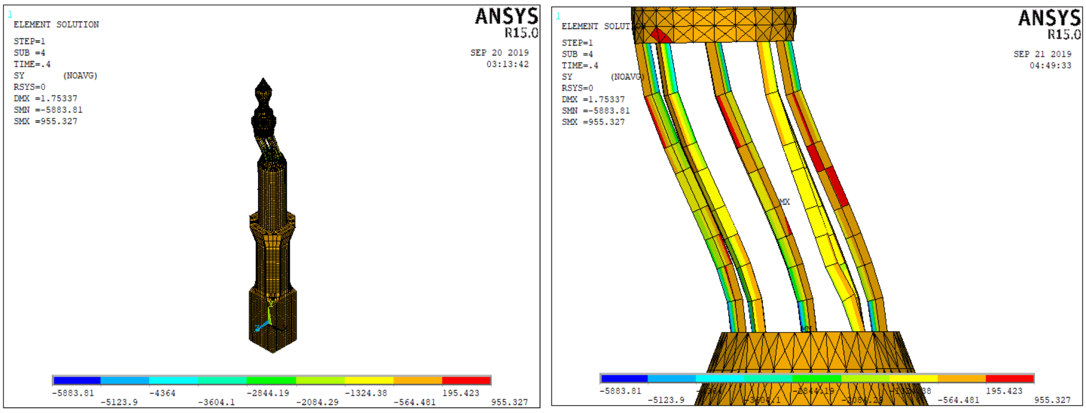


Figure 19: Stresses in y-direction of El-Rifa’i minaret (zone 5 case).

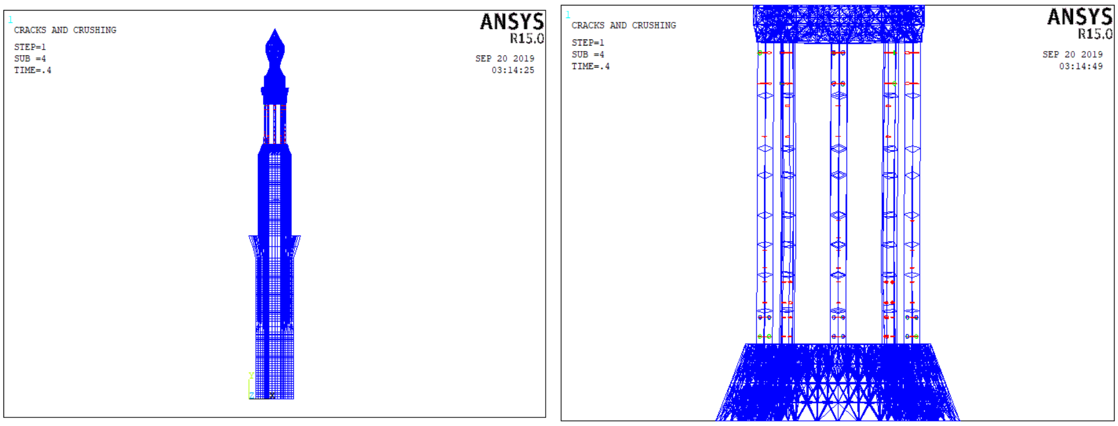


Figure 20: Cracking pattern of Al-Rifa’i minaret (zone 5 case).

5. Conclusion

Based on the nonlinear and linear analysis results obtained and the stresses of Al-Rifa’I minaret, the following conclusion are drawn:

1- In gravity case, the minaret exposed to compression stress equal 1807 kPa due to vertical load (own-weight of the minaret) and the displacement equal 70 mm.
2- In wind case, the minaret exerted tension and compression stresses of 418 kPa and 2612 kPa respectively and the maximum tensile and compression stresses occur at a height of 29 m in the columns and the maximum displacement occurred at the top of the minaret equal 292 mm.
3- In seismic case (zone 3), the non-linear model, A large tendency of the upper part of the minaret to sway relative to its stiff support as the displacement equal 1300

mm, the connection between the minaret cap and the minaret body (at the bottom of the columns) exposed to maximum tension equal 998 kPa and maximum compression equal 5486 kPa, however the linear model, the displacement equal 821 mm and the tension stress equal 1008 kPa and compression stress equal 4289 kPa, these stresses slightly exceeding tension and compression value range of the allowable 960 kPa for tension and 4250 kPa for compression.

4- Linear displacement is smaller than non-linear displacement which is well known and verify the importance of non-linear analysis which gives the real behavior of the minaret.
5- Linear compression and tension stresses are greater than non-linear stresses due to the redistribution of the stresses.
6- In seismic case (zone 5), the minaret has been damaged and failed due to the earthquake as the stresses exceeding tension and compression allowable range of the minaret.
7- Static stresses and displacement are smaller than dynamic stresses and displacement.
8- The weakest point in the minaret body was identified as the columns supporting the top cap.
9- Finally, it was concluded the minaret is able to sustain all the vertical loads in addition to all lateral loads especially wind and seismic loads located at zone 3 which is the real location of the minaret and it can’t sustain the seismic loads located in high seismicity zone (zone 5).

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