Structural Study of Different Proposals for Reconstruction Methodology of Ottoman Citadel of Al-Faqeer at Al-ULA Governorate in KSA to Enhance its Structural Response and Safety Factor Against Earthquake

Dr. Abdulnaser A. Al-Zahrani

Associated Professor, Department of Heritage Management and Tour Guidance, College of Tourism and Archaeology, King Saud University, Riyadh, Kingdom of Saudi Arabia.

Dr. Yaser Yehya Amin Abdel-Aty

Assistant Professor, Department of Heritage Management and Tour Guidance, College of Tourism and Archaeology, King Saud University, Riyadh, Kingdom of Saudi Arabia.

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ABSTRACT

This paper studies a number of alternatives for reconstruction methodology of Ottoman Citadel of *Al-Faqeer* at *Al-ULA* Governorate in Kingdom of Saudi Arabia. The preferable reconstruction methodology is the one that provides the citadel building with sufficient structural safety factor against seismic forces, which are considered the main destructive action that affected most of deficiencies and collapse in the building. This citadel is considered one the invaluable architectural heritage in KSA, which is located in one of its most fames governorates for cultural tourism. The citadel represents with other Ottoman citadels that lies along the Hajj route; part of Ottoman era in KSA. This building is currently abounded by the authorities. Full excavation works of its site and ruins still have not been carried out. Thus, this study is considered preliminary.

The assessment among reconstruction methodologies will be based on the results of structural analysis works (static and dynamic), using computer numerical modeling technique that applies Finite Element Method (FEM).

Three main methodologies are studied in this paper through five case studies. The first methodology studies through two analysis cases the reconstruction of the citadel collapsed parts using the original building materials and construction technology (the authentic cases). Case-1 assumes the use of weak wooden roof that are usually found in all heritage buildings, while case-2 use more robust wooden beams for reconstructing roofs, which support on masonry arches (more stiff roofs).

The second methodology studies through case-3 the addition of reinforced concrete (RC) beams at the inner periphery of roofs (that overlooks the courtyard) and at the locations of masonry columns (across the roof and parallel to its wooden beams).

The third methodology studies through case-4 and case-5 the embedding of thin precast reinforced concrete slabs inside the wooden roof (to be placed above wooden beams of each roof and under the flooring). The last cases aim to provide floor roof with a diaphragm system.

This paper provides the major scheme for structural restoration and reconstruction works of *Al-Faqeer* citadel and reaches good conclusions and recommendations that would help to conserve and preserve similar architectural heritage structures in KSA.

1- Introduction

Kingdom of Saudi Arabia is rich in unique architectural heritage, of various types and styles, besides being distributed through its vast land. These buildings include mud architecture at the middle region of KSA, and the unique style of stone buildings at west and south regions. Among this great architectural wealth, are the Ottoman citadels that lie along the *Hajj* (pilgrimage) route which linked Egypt, Syria and KSA in the past. These citadels are considered of great importance; since they are found as almost complete buildings, or at least of complete outer façades, while other archeological and heritage buildings are mostly found in ruins. One of these Ottoman citadels in KSA is *Al-Faqeer* Citadel at *Al-ULA* Governorate. This citadel is among a number of heritage buildings in KSA that are neither documented nor studied sufficiently in the previous archaeological studies [(1)]. The researchers in this paper, together with a previous one, try to cover the various aspects of the preliminary studies about this citadel, in order to highlight the importance of this abandoned invaluable monumental building. Besides, the current structural condition of this building recommends conducting urgent rescue work and a complete conservation and restoration project, before we may lose this monument in the near future.

2- Historical background of Al-Faqeer citadel

The history of this citadel is not covered in most of historians' description; beside it does not contain a foundation plate or any carving which states the date of construction completion and the name of founder. Some historians mentioned this citadel in their description and called it "Citadel of Sheep Excavations". It is thought that this citadel was constructed during the 18th Century AD (12th Century AH). Also, the historian "*Ibn Abdel-Salam Al-Dir'i Al-Maghribi*" mention in his descriptions that he saw the erection of this citadel during his return from pilgrimage in 1196 AH/1781 AD [(2)].

3- Architectural description of the citadel

Full documentation for the citadel building was conducted in previous work of the researchers. It covers all remaining architectural elements of the citadel, including all visible collapsed parts and ruins, on its current condition. The documentation works include descriptive, architectural and photographic documentation. The study and analysis of these documentation works helped to predict the original design of the citadel building (original shape and planning) and its missing parts (collapsed and/or buried under thick layer of fill that covers the ground); on which the reconstruction scheme is based upon.

The building area is about 340 m^2 and consists of two floors. Total façade height is about 6.0 m above the current ground zero level. The plan of the citadel is almost squared (14.4 x 14.8 m) with one circular tower at each corner. The full and detailed documentation works of the citadel building are covered in a previous paper of the researchers [(3)].

Figures (1: a, b) show section plans of the two floor levels (at levels +1.50 and +4.0 m). Figures (2: a, b, c, d) show the four exterior façade walls, at their present state of deterioration. Most of interior elements of the building collapsed (collapsed partly or totally), except few masonry piers and walls, which remain partly. The building includes only one gate of small dimensions and few numbers of windows with very narrow area (about 15 x 10 cm). Simple cresting is still remaining at the top of some parts of exterior façade walls.

Plate (1) is a 3D-panoramic view of Al-Faqeer Citadel. It shows the remaining parts of the building which are the four façades, three towers of the four corner ones, and few of the interior walls. Most of the interior walls (almost all) and all wooden roofs had collapsed. Plates (2: a, b, c and d) show details of the high deterioration and destruction

conditions of the four façades of the citadel. Plate (2-b) shows the S-W façade with the South tower which is partly (about 2/3 of it) collapsed. The tower ruins are still at its site.

Plate (1): 3D Panoramic view of Al-Faqeer Citadel; shows the highly deterioration and destruction condition.

Plate (2-a): The N-W (main) façade.

Plate (2-b): The S-W façade (collapse of South tower).

Plate (2-c): The S-E façade destructions.

Plate (2-d): The N-E façade.

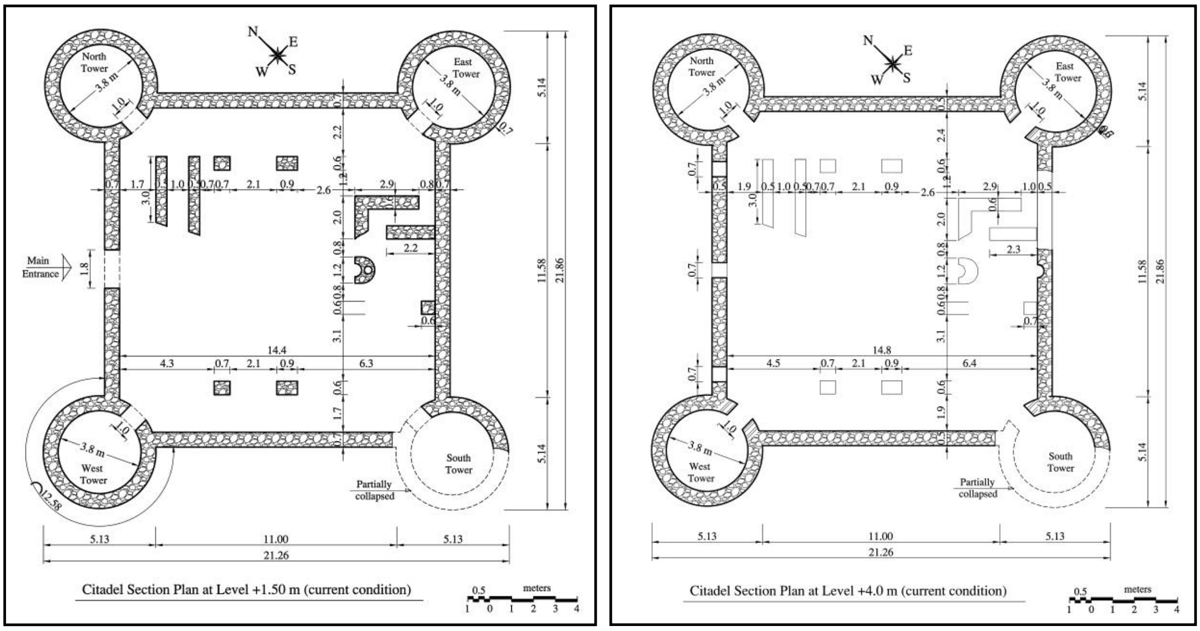
Plates (2: a, b, c and d): The high deterioration and destruction conditions of the four façades of the citadel.

4- Structural deficiencies and deterioration of the citadel building

Site inspection and analysis of the documentation work (both architectural and photographic) lead to determine the following structural deficiencies and deterioration phenomena in the citadel (see Figures No. 1 and 2):

- Most of the interior elements of the building (walls and roofs) collapsed. Only the mihrab (prayer niche) and a number of walls and piers are partly still standing.
- The South tower is partly collapsed, with its ruins lay down under its foot.
- The remaining three corner towers contain vertical structural wide cracks and some of these cracks widened to form separation in tower walls (width of about 0.5m).
- Upper-middle part of the S-E façade collapsed (see Figure No. 1-c).

- High deterioration is found in the plaster that covers façade interior and exterior sides. The plaster over the internal side of façade walls fill down completely, showing the stone and bricks under.
- Parts of the outer leaf of the multiple-leaf masonry walls demolished, whish expose the internal rubble infill.
- High erosion is found in the lime mortar at masonry joints.
- Cracks and breaks in the brick and stone masonry units.



(a) Section Plan at Level + 1.50 m. **(b)** Section Plan at Level + 4.0 m.

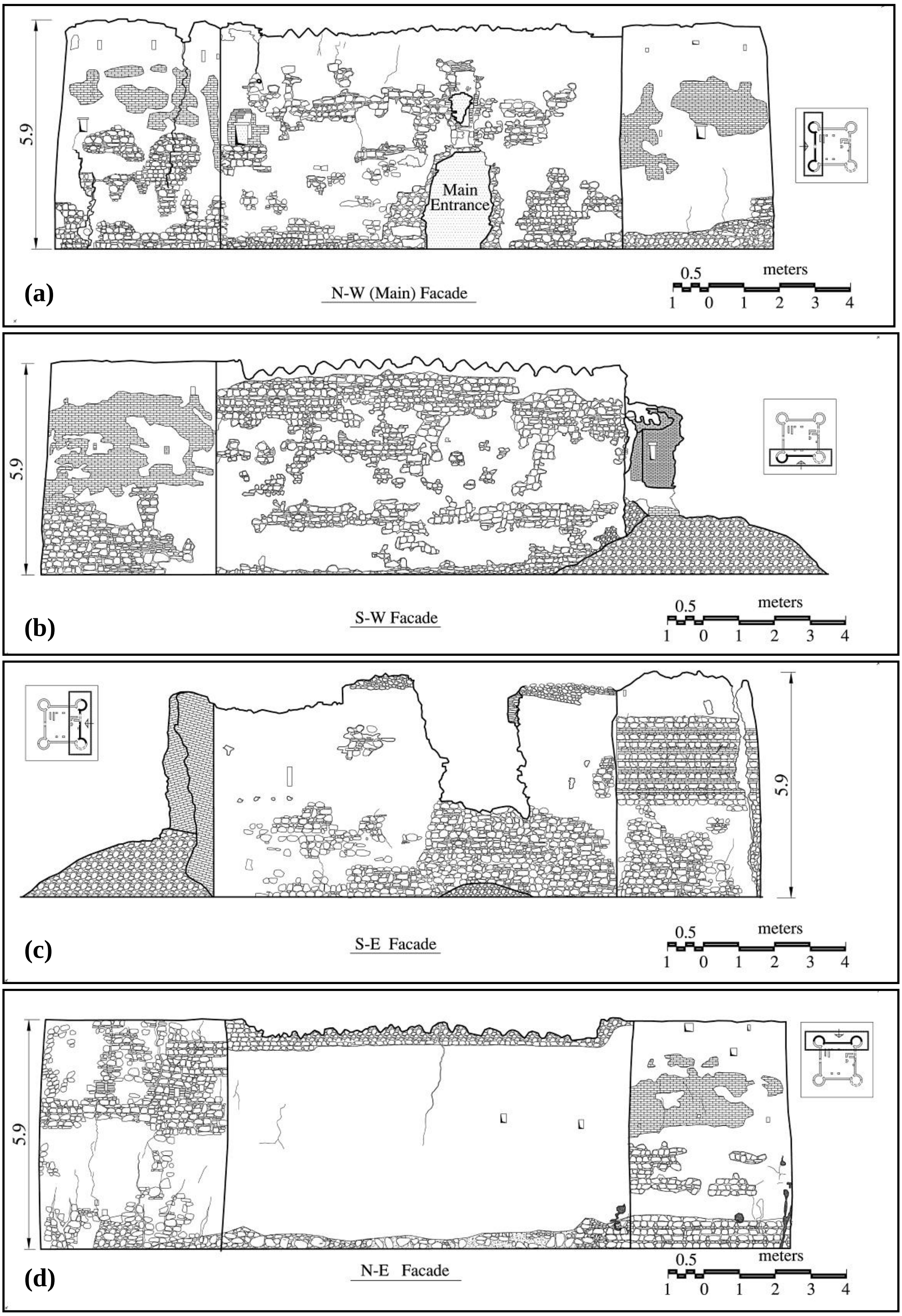
Figures (1: a, b): The main two plans of Al-Faqeer Citadel; with scale and dimension. They show the remaining architectural elements of the collapsed parts of the building.

5- Building Materials

The citadel is still abandoned and closed by the Saudi Commission for Tourism and Antiquities (SCTA) until the current time, who built a light metal fence around the building with a locked gate. The detailed exploration work for building materials, soil and foundation would be conducted in the future, with the start of restoration and conservation project for the citadel building. For these reasons, a preliminary investigation for main properties of different building materials in the citadel was achieved through this paper.

A number of samples were taken from various locations in the masonry (stones, bricks, mortars and plaster) to preliminary study the main properties of masonry materials. These properties were compared with other experiment results for similar masonry materials which were found in Dadan (Kheraiba) historical site, nearby the citadel and published in previous paper of the researcher [(4)].

The masonry work of the citadel building is constructed following the multiple-leaf system; which is composed of two leaves (built of coursed random rubble stones or brickmasonry) with rubble infill in-between. Walls were plastered with lime-base mortar that covered walls' inner and outer surfaces (see Plates No.1 and 2).The majority of outer leaves of the masonry walls are built of stone masonry, while the upper parts of walls inside the citadel building and the circular four towers with their entrance sides are built of red-brick masonry work.



Figures (2: a, b, c and d): Architectural documentation of the four façades of Al-Faqeer Citadel; with scale and dimension, which record the high deterioration and destruction condition of façades.

Field observation and testing results for stone samples showed that they are sandstones, with different colors (yellow, red and sky-blue). The colors of stones are due to the various mineral minor compositions. The results of the preliminary investigation for the main properties of masonry materials can be summarized as follows:

- Red-bricks are made of burnt local mud and shaped in small dimensions (average dimensions of bricks are: 22 x 12 x 5.5 cm).
- Testing results showed mortar samples, which are taken from rubble infill, masonry joints and walls' surface plaster; are made of lime, sand and fly-ash (with average composition ratio 1 : 1 : 0.25).
- Specific weight of mortar samples ranges between 1.2 to 1.45 t/m^3, while their porosity ranges between 10-19 %.
- Sand-stones have apparent specific weight (γ) ranges = 2.1 - 2.5 t/m^3 and porosity ranges = 7 – 11 %.
- Red-bricks have apparent specific weight (γ) ranges = 1.62 – 1.74 t/m^3 and porosity ranges = 6.7 – 9.7 %.
- The results of standard compression test on Sand-stone cubic samples (5x5x5 cm) showed modified compressive strength of these samples ranges =210 – 280 kg/cm^2 .
- The average value for the compressive strength of Sand-stones = 245 kg/cm^2.
- The compressive strength values for red-brick samples tested ranged between = 31–55 kg/cm^2, with average compressive strength = 43 kg/cm^2

6- Future Reconstruction Plan

To achieve a complete project for restoration and conservation of the citadel, the following plan should be implemented:

- Rescue operation includes scaffoldings for all separated, tilted and partially collapsed walls should be made to secure these remaining structural elements from failure by any earthquake or environmental action.
- Excavate the site of the citadel by removing with care all loose soil, around and inside the ground of the building till reach the original ground level.
- A number of open pits should be made near the foot of different walls to reach the foundation level and to check type and condition of the footings.
- The architectural documentation of all the building elements (including the new findings from excavations) should be updated and completed.
- A number of bore-holes should be carried out to conduct a complete soil report; which includes the soil description, ground water analysis and level, and the bearing capacity of soil at foundation level.
- Detailed analysis and testing works of all building materials (stones, bricks, mortars and plasters) should be conducted using more advanced techniques to determine their properties and deterioration phenomena.
- Analysis and assessment of all data, besides considering the architectural design of similar Ottoman citadels that lie along the Hajj (pilgrimage) route near and around the site; will help to reach the original scheme and plan of Al-Faqeer Citadel building.
- A complete structural analysis and design of the citadel reconstruction work should be conducted. They aim to increase the structural safety factors of the building against earthquake action, which affects the whole area and is

considered the predominant force for various destructions and deficiencies found in the citadel building.

- Conduct rehabilitation project for the building and its site around, beside its correlation with Dadan (Kheraiba) nearby archaeological site, to be a tourist site of heritage tourism.

7- Reconstruction Study and Assessment

The current structural condition of the citadel building requires urgent conservation and restoration works for the various deficiencies found in building elements, beside reconstruction for the collapsed and missing parts (e.g. roofs, piers, etc.). This paper studies and assesses among three approaches for structural conservation and reconstruction work. The first approach is the authentic case (to reconstruct all collapsed parts following the original material and technology of the citadel building). The second approach studies the use of stiffer wooden and reinforced concrete (RC) beams. The RC-beams will be embedded within roofs' beams and located at masonry piers and columns only. The third approach studies the embedding of thin precast reinforced concrete slabs between the wooden beams of each roof and their above flooring layers. These three approaches are studied in five analysis cases.

This study is considered preliminary since the full excavation and exploration works of the embedded elements of the citadel building, under the thick layers of mud and rubble stones from building ruins that fill the ground inside and outside the building; have not been completed yet. These analysis works are efficient to select the best methodology for structural conservation and reconstruction of this historical building.

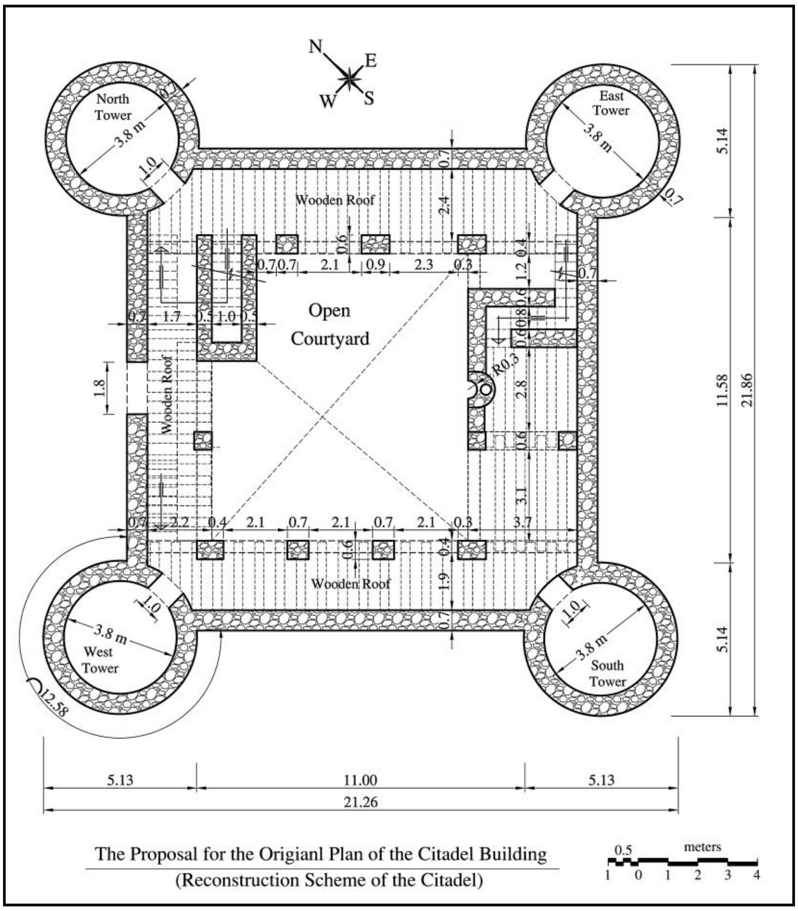
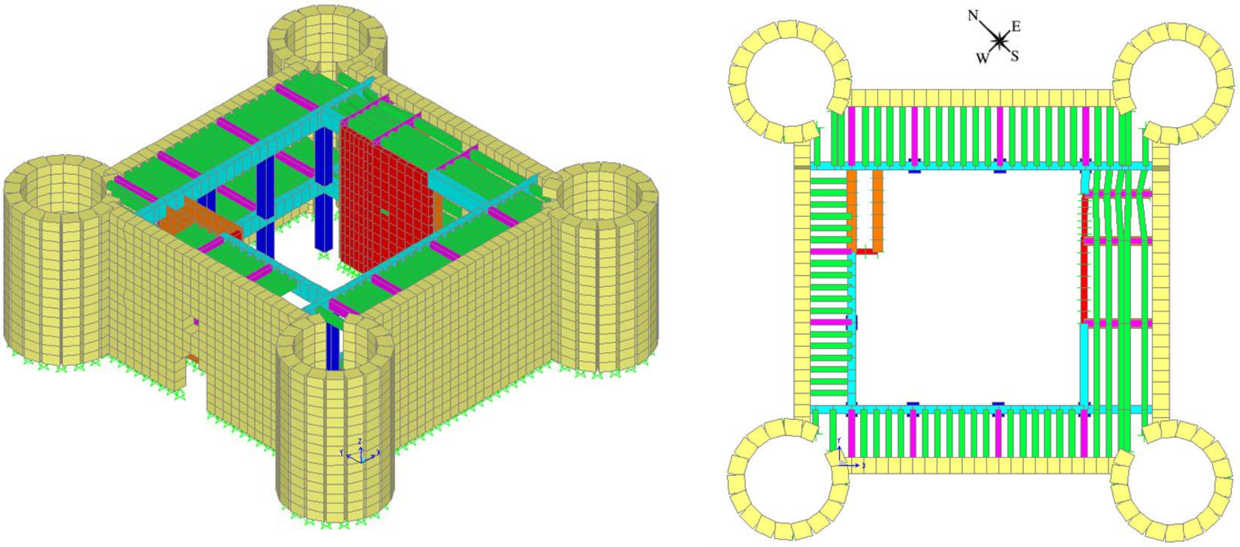


Figure (3): Proposal plan for the reconstruction work of the citadel building (Section Plan at level +1.50).

8- Structural Analysis and Assessment

Structural study and assessment for a number of alternatives of the reconstruction approach for the citadel building depend mainly on the results of structural analysis work. Numerical modeling technique, using Finite Element Method (FEM); is adopted for the structural static and dynamic analysis works. One of the most famous world wide computer software (5) is used in the analysis works. 3D-numerical model is prepared to represent the full citadel building, following the assumed reconstruction scheme in Figure (3). Walls are modeled using shell elements while columns and roof beams are modeled using frame elements. This 3D numerical model is analyzed five times with modification for each run to represent one of the case studies.



(a): Isometric extruded view. **(b)**: Plan extruded view.

Figures (4: a, b): 3D numerical model for the citadel building (Isometric and Plan extruded

The following input-data are considered for various cases of structural analysis:

8.1- General Input-Data for Structural Analysis Work

The following material input-data (i.e. parameters and properties) are considered for all structural analysis works, following test results in previous item No. 5 and reference (6):

<u>For masonry work:</u>

- Specific weight (weight per unit volume) = 2.30 t/m^3.
- Masonry density (mass per unit volume) = 0.2345 t/m^3.
- The Young's Modulus of Elasticity (E) for masonry = 6.0×10^5 t/m^2.
- Shear Modulus (G) = 2.40×10^5 t/m^2.
- Poisson's Ratio (ν) = 0.25
- Proportional damping for all Eigen-modes of the structure = 5%.
- Positive sign denotes tensile force or stress value, while negative indicate compressive force or stress value.

<u>For wooden elements:</u>

Since no wooden elements are found in the building, the following conservative values are assumed according to previous work of the researcher (7):

- Young's Modulus of Elasticity (E) = 3×10^4 t/m^2
- Specific weight (γ) = 0.30 t/m^3.

These values will be for the new timber elements used for the reconstruction of the roofs.

8.2- Structural Unsafe and Failure Criteria

The failure criteria adopted in this paper for assess the structural analysis results are fulfilled by the exceedance of allowable working stresses at any section considered in the structure (i.e. wall, column, beam, etc.). From material properties data and following the least limiting stress values allowed for all masonry work in the building codes (to be more conservative), the following allowable working stresses values will be respected in the structural assessment of reconstruction alternatives:

- Axial compressive stresses = 100 t/m^2.
- Flexural compressive stresses = 120 t/m^2.
- Shear stresses = 15 t/m^2.
- Direct tensile stress = 0 t/m^2 (direct tensile stress is not allowed).
- Flexural tensile stresses = 5 t/m^2.

These values are the least calculated values from different reference approaches [(8)], [(9)], [(10)], [(11)] using test results in previous item No. 5. When checking the safety of the resulting working stresses due to seismic load cases, it is allowed to raise the previous allowable stresses by 20% [(12)].

8.3- Earthquake Records for Dynamic Time-History Analysis

Due to the absence of accelerogram records of the earthquakes in Kingdom of Saudi Arabia (until the present time); a number of earthquake acceleration records, which are available in the data library of the analysis software [(13)]; were examined to finally select three records that cover a wide spectrum of frequencies and (a/v) ratios, which represent low, medium and high frequencies and seismic effects. The selected records are: (Altadena-Eaton Canyon Park), (El-Centro, Array 6, Huston Rd.) and (Lexington Dam), see Figures (6: a, b, c). All these records are scaled to peak ground acceleration (PGA) of 0.12g; which corresponds to the maximum PGA expected in Al-ULA[(14)] (see Figure 5).

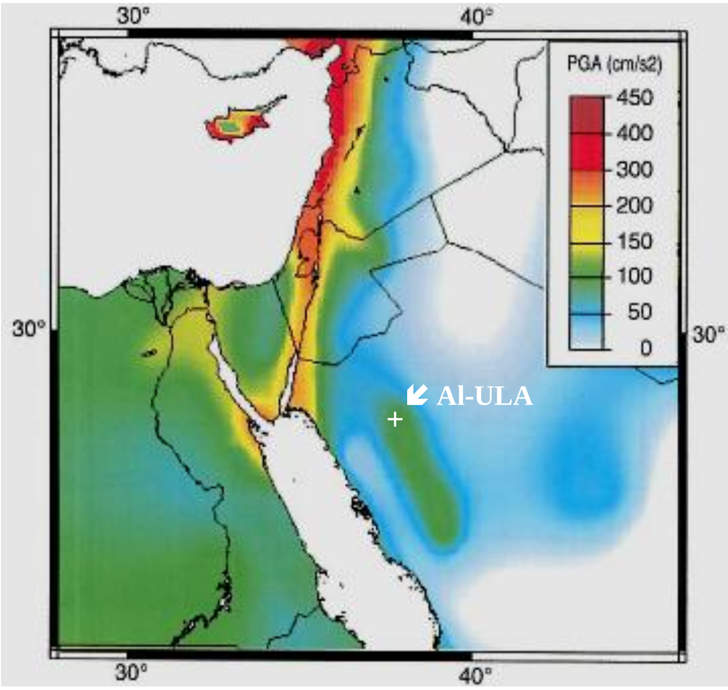
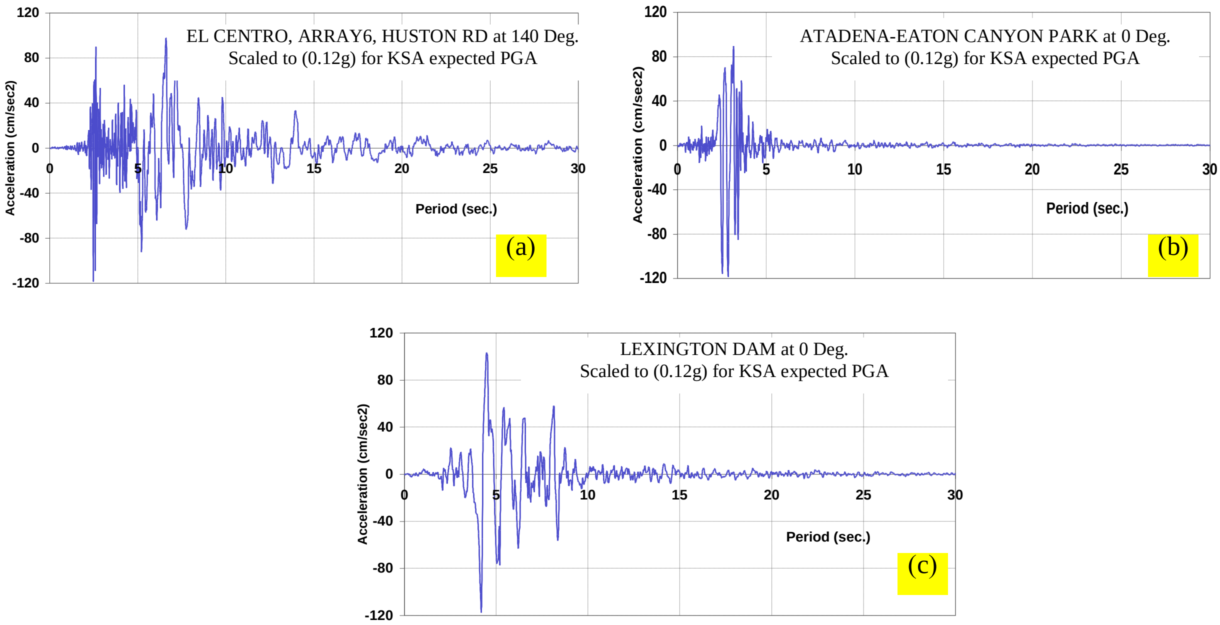


Figure (5): Map of seismic hazard, representing peak ground acceleration (PGA) expected at 10% probability of exceedance in 50 years [(14)].



Figures (6: a, b and c): The selected earthquake acceleration records scaled to peak ground acceleration (PGA) of 0.12g [15].

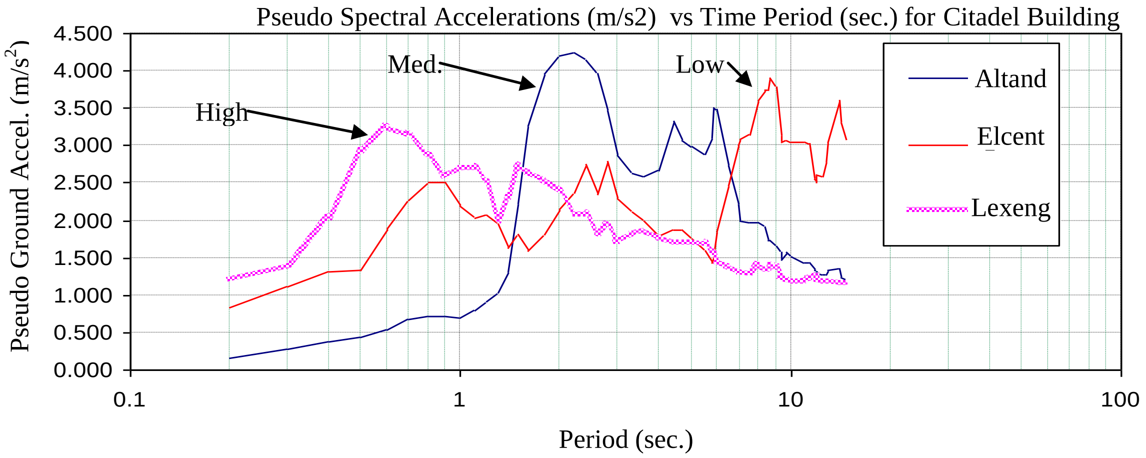


Figure (7): The ground acceleration response spectra (Pseudo Spectral Accelerations vs Time Period), for citadel building under the three selected earthquake records (damping = 5%), which provide low, medium and high frequencies. (Graph in Log. Scale)

Eigen-value analysis determines the undamped free-vibration mode shapes and frequencies of structure. These natural modes provide an excellent insight into the behavior of the structure [16], besides using them as the basis for other dynamic analyses types (e.g. Response-Spectrum and Time-History). The following numerical models will be analyzed for 15 modes. Results of modal participating periods for all analysis cases are shown in Table (1) and Figure (15). For each case, the first modal shapes will be demonstrated.

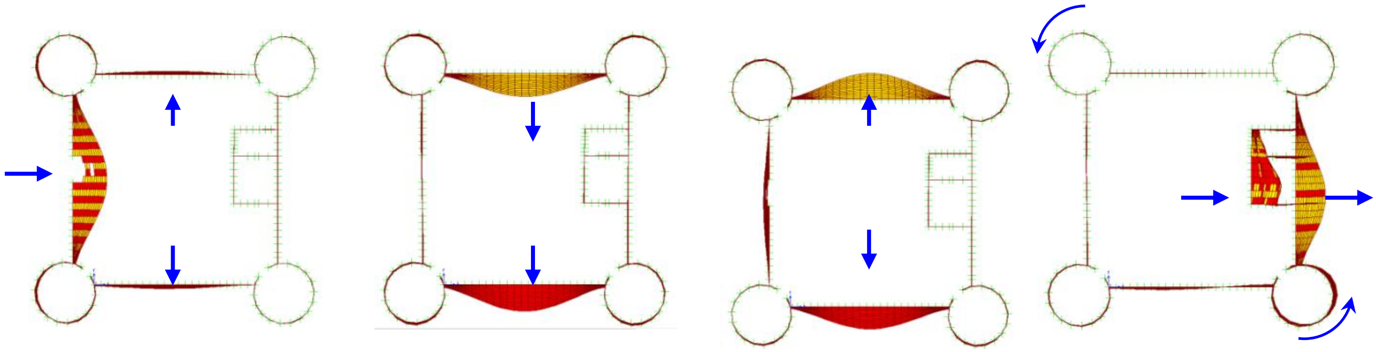
Time-History analysis is a step-by-step analysis of the dynamical response of a structure to a specified loading that may vary with time. The analysis may be linear or nonlinear. If acceleration loads are used, the displacements, velocities, and accelerations are all calculated relative to the ground motion [17].

The various stress results due to static (permanent and dead) loads are mostly compression and safe; as maximum value does not exceed 24 t/m^2. Thus, the results of dynamic analyses (Eigen-value and Time-History) will be crucial for judge among reconstruction methodologies. Results of the five structural analysis cases are discussed in the followings sections:

8.4- Case-1: The Weak Authentic Condition

Case-1 studies the reconstruction of the citadel following the original building design and materials. 3D-model for the citadel building is prepared, with properties of building materials and section of various parts and elements; following the authentic building materials and construction technology of the citadel in the past. Roofs of two floors are considered to be built of weak timber beams, which type is usually Tamarisk (*Athel*) tree trunks.

This case studies and assesses the structural condition of the original complete building of the citadel, with its worst structural condition (being very weak against seismic forces) through neglecting roof bracing action. This can be real due to the structural weakness of the original timber beams of roofs. Besides, the insufficient connection between wooden beams of the roofs and their supporting walls. To represent this worst condition, the 3D model will consider only the main masonry walls, which are the four façades and corner towers, beside the attached walls to the S-W façade wall. The wooden roofs and other structural elements that are connected to façade walls through roof will be removed from the model. These internal elements will be free standing walls or columns, and their existence will affect the results of the dynamic analysis of the 3D model.



a) 1st Eigen-mode; T = 0. 142 sec.   **b**) 2nd Eigen-mode; T = 0. 132 sec.   **c**) 3rd Eigen-mode; T = 0. 131 sec.   **d**) 4th Eigen-mode; T = 0. 097 sec.

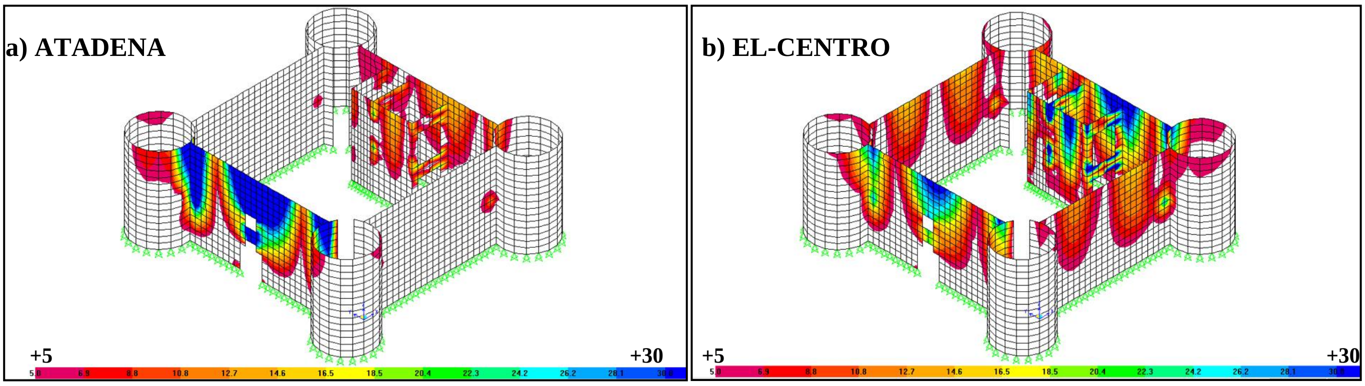
Figures (8: a, b, c and d): Deformed shape plans of the first four Eigen-modes of the building (case-1).

The first four modal shapes, which resulted from Eigen-value analysis, are shown in Figures (8: a to d). They are mainly bending modes. Their corresponding natural period values are shown in Table (1). In the first mode N-W façade responded with minor affect for N-E and S-W façades. The N-E and S-W façades responded in the same direction in the second mode, and in opposite direction for the third mode. S-E façade responded with its attaching walls in the same direction, while rest of the building responded in torsion.

Since most of the cracks occurred on the citadel is nearly vertical, the most critical results for Time-history analysis are the horizontal tensile stresses (S11). Also, by reviewing the various types of stresses result from the structural analysis (static and dynamic), we find that S11 is also the most crucial of all other stresses result.

Figures (9: a, b and c) show color-code diagram for the distribution of horizontal tensile stresses (S11) in the citadel walls in Case-1, under the three selected earthquake records. El-Centro record shows the highest values, while Atadena is mild and Lexington is the least. All highest stress locations match the failures and cracks locations that are found in the citadel at present. The blue color shows S11 values equal or greater than 30 t/m^2, where cracks are expected. White color shows S11 values equal or less than 5 t/m^2, where stresses are structurally safe. This analysis shows how weak and structurally unsafe

condition of the authentic building against seismic loads. Thus, to raise safety factors of building, the reconstruction should include some structural means to resist expected seismic action and enhance the performance of the building against its loads; since Al-Ula is a seismic prone area.



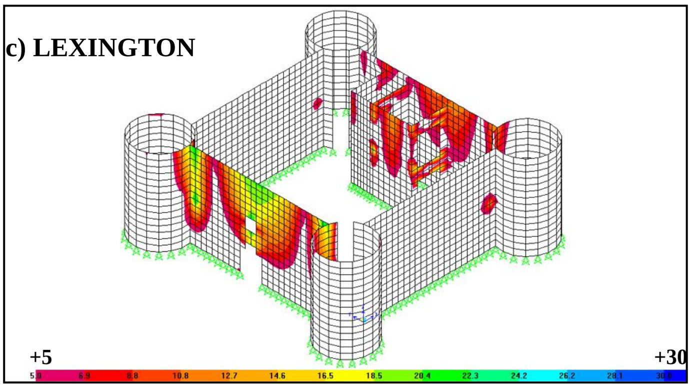
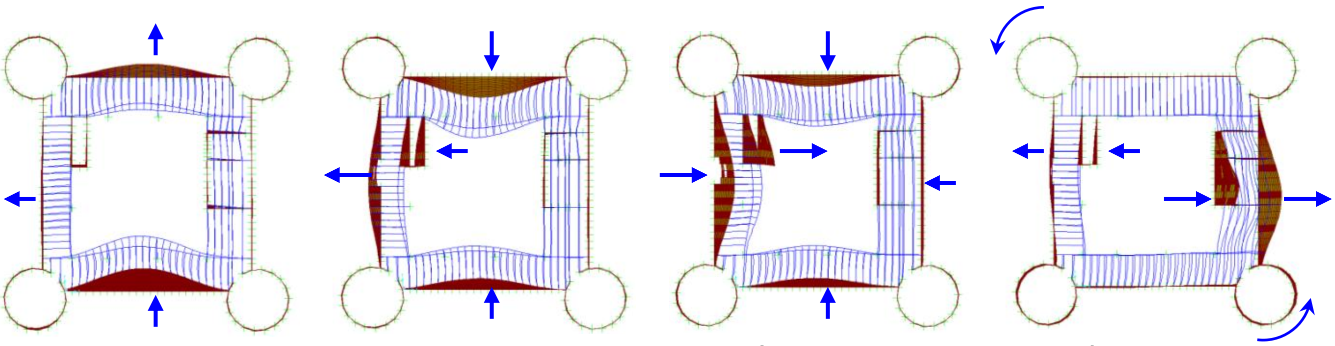


Figure (9: a, b, c): Maximum tensile stresses (t/m^2) in horizontal direction (S11) under the three selected earthquake records for Case-1. Highest values coincide with failure and cracks location found in the current condition of the citadel.

8.5- Case-2: The Robust Authentic Condition

In the previous analysis case-1, the structural weak condition of roofs (due to weak wooden beams, their small cross-sections and inefficient connection with their supporting walls) makes them of neglected bracing effect for building masonry walls.

Case-2 takes roofs into consideration (roofs are included in the 3D model) and enhance lateral bracing action to their supporting walls by adding masonry arches over the stone columns and piers on the interior façade that overlooks the courtyard to carry the roof. Besides, interior masonry cross-arches are added, which are parallel to the wooden beams in the roof and rest on the stone columns. The other roof beams are built of original tree trunks.



a) 1st Eigen-mode; T = 0. 141 sec.

b) 2nd Eigen-mode; T = 0. 133 sec.

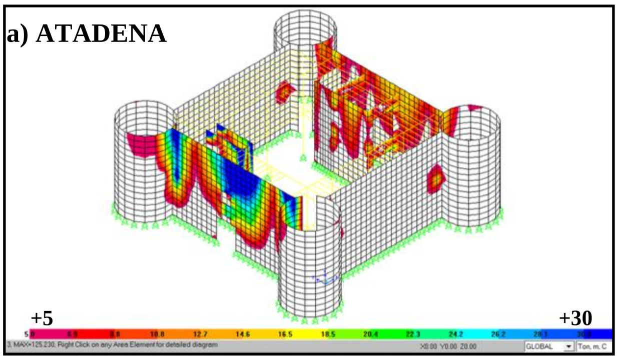
c) 3rd Eigen-mode; T = 0. 130 sec.

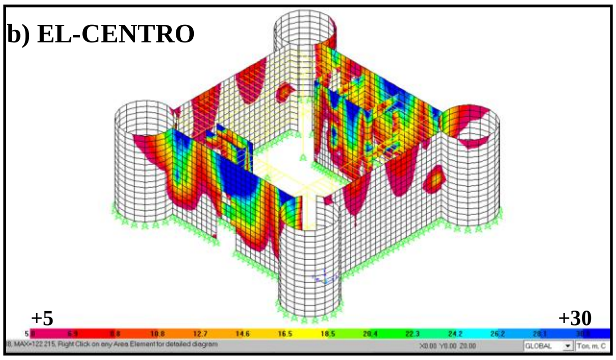
d) 4th Eigen-mode; T = 0. 086 sec.

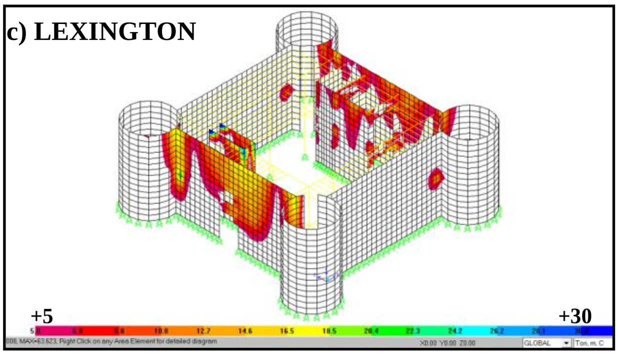
Figures (10: a, b, c, d): Deformed shape plans of the first four Eigen-modes of the building (case-2).

The first four modal shapes of case-2, as before in case-1, are shown in Figures (10: a to d). They are also mainly bending modes. In the first mode, mass is concentrated in both N-E and S-W façades, which responded in the same direction. In the second and third modes, N-E, N-W and S-W façades beside the staircase walls responded perpendicularly to their directions. Less response of S-E façade is found in the third mode, while being major with its attaching walls in the fourth mode.

Results of maximum tensile stresses of Time-history analysis of case-2 are nearly similar to case-1, comparing results in Figures (8) and (11). It shows that this reconstruction methodology is also inefficient to enhance the overall structural stability of the building against seismic loads, although the improvement in behavior and results than case-1.







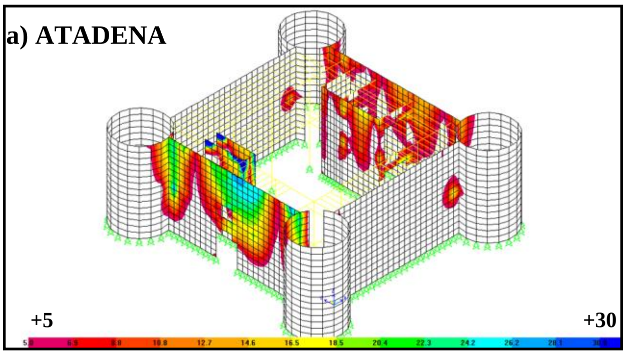
Figures (11: a, b, c): Maximum tensile stresses (t/m^2) in horizontal direction (S11) under the three selected earthquake records for Case-2. They are similar to that of case-1.

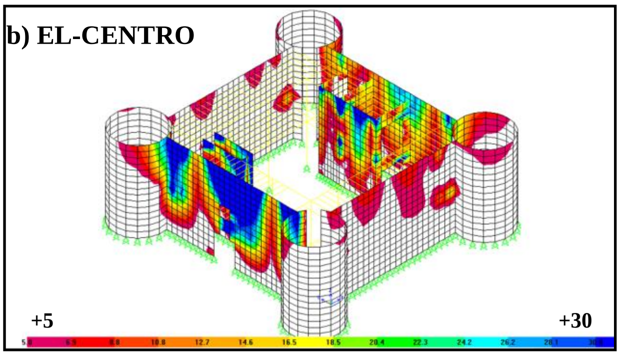
8.6- Case-3: The insertion of RC-beams

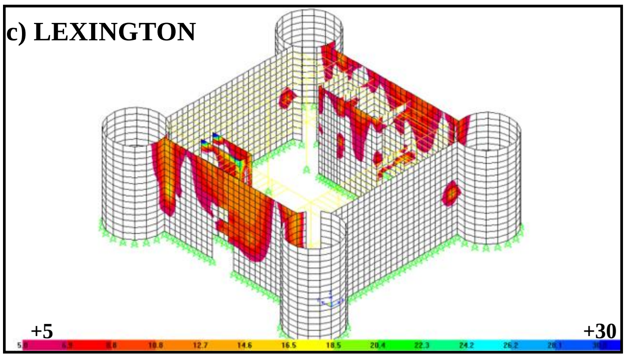
In this analysis case, the masonry arches that support the roof, beside the cross masonry arches inside the roof (in case-2), are replaced by reinforced concrete (RC) beams of cross-section similar to adjacent wooden beams. This proposal aims to embed robust and limited structural elements within the roof, to create frame-action between RC-beams and masonry columns, which would act as a bracing system against seismic loads.

The model analysis of case-3 shows good enhancement in the mass participating ratio than previous two analysis cases and the resulting stresses (S11) values are also less than that of these two cases, see Figures (12: a, b and c). Model shapes of analysis case-3 are identical to that of analysis case-2.

This case directs to use such system, incase that the architectural study shows that no-arches were used inside the building. Besides, the limited use of RC-beams in this case makes it of least intervention and very close to authentic case. Although, this methodology still weak against seismic loads, since the stresses, shown in Figures (12: a, b and c); are generally still high as in the previous two analysis cases.



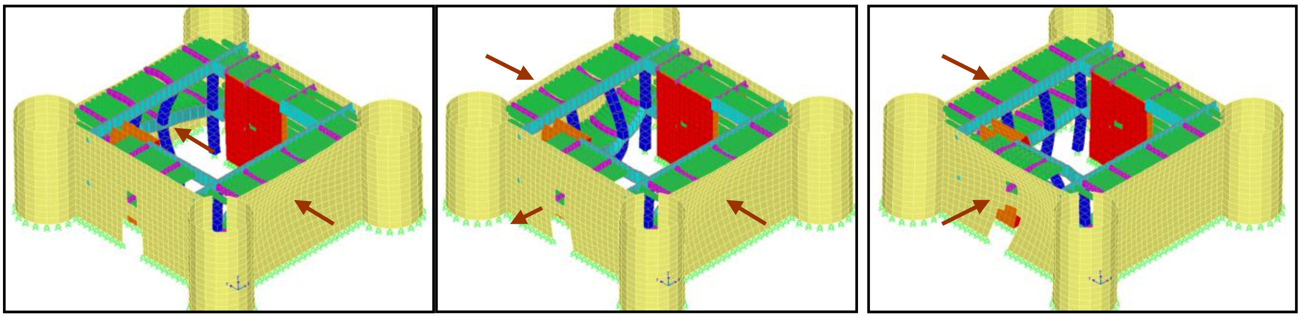




Figures (12: a, b, c): Maximum tensile stresses (t/m^2) in horizontal direction (S11) under the three selected earthquake records for Case-3. They are generally less than their counterpart of the previous cases (except El-Centro loads).

8.7- Case-4: Embed RC-Diaphragm in the Upper Roof Only

This analysis case studies embedding thin precast reinforced concrete (RC) slabs, of 5 cm thickness, inside the second floor roof only (last roof).These slabs are placed as strips embedded inside the roof (placed above the wooden beams and under flooring layers). These slabs should be inserted inside their supporting masonry walls for a considerable distance that will ensure its efficient connection with walls. To strength this connection, slabs will be also connected to walls using stainless steel angles from its upper side, which will be bolted with slabs and walls. These RC slabs create a continuous diaphragm, which will enhance greatly the seismic behavior and its factor of safety.



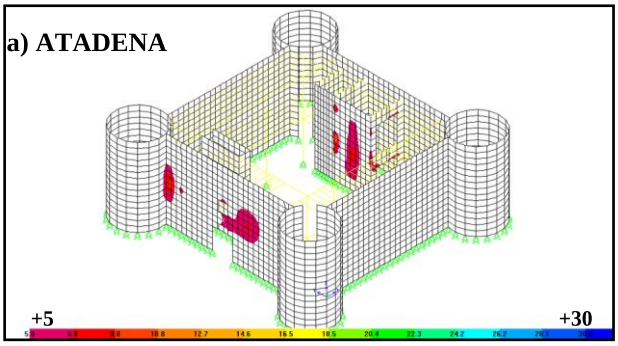
a) 1st Eigen-mode; T = 0. 0739 sec. **b**) 2nd Eigen-mode; T = 0. 0708 sec. **c**) 3rd Eigen-mode; T = 0. 0691 sec.

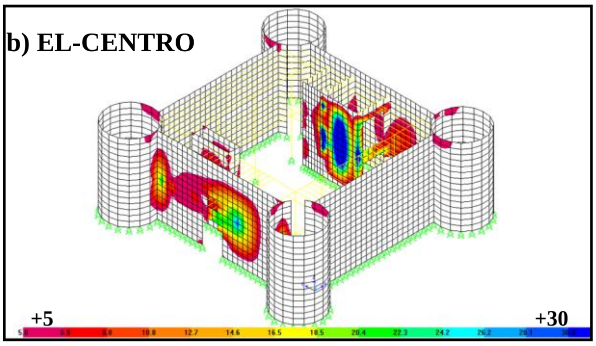
Figures (13: a, b and c): Deformed shape isometric views for the first three Eigen-modes of the building (case-4). Only the first roof respond, while the upper roof (where diaphragm) is stiff.

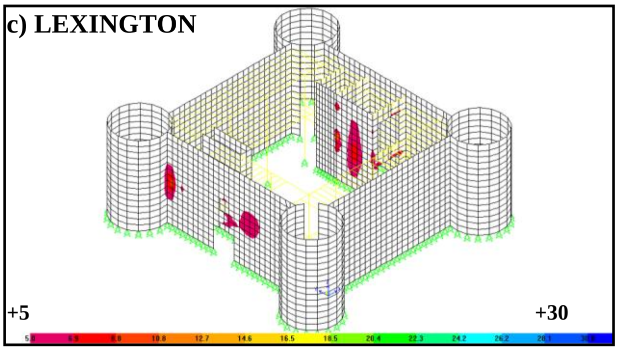
The first three modal shapes of case-4, which resulted from Eigen-value analysis, are shown in Figures (13: a to c). Only the first floor roof moves and responds, while the upper floor roof (with diaphragm) is relatively stable and at rest. Values of mass participating ratios, represented by the modal periods, have reduced respectably than all previous cases.

This shows the great enhancement in seismic resistance and its safety factor of the current structural system. Also the values of horizontal stress resulting from Time-history analysis are respectable less than the corresponding values of all previous analysis cases.

This analysis case proves the essential role which stiffness of floor roofs plays for the overall stability of load-bearing masonry structures and enhances their behavior under seismic loads. Thus, the more the stiffness of roofs are the higher the safety factor obtained against seismic loads.





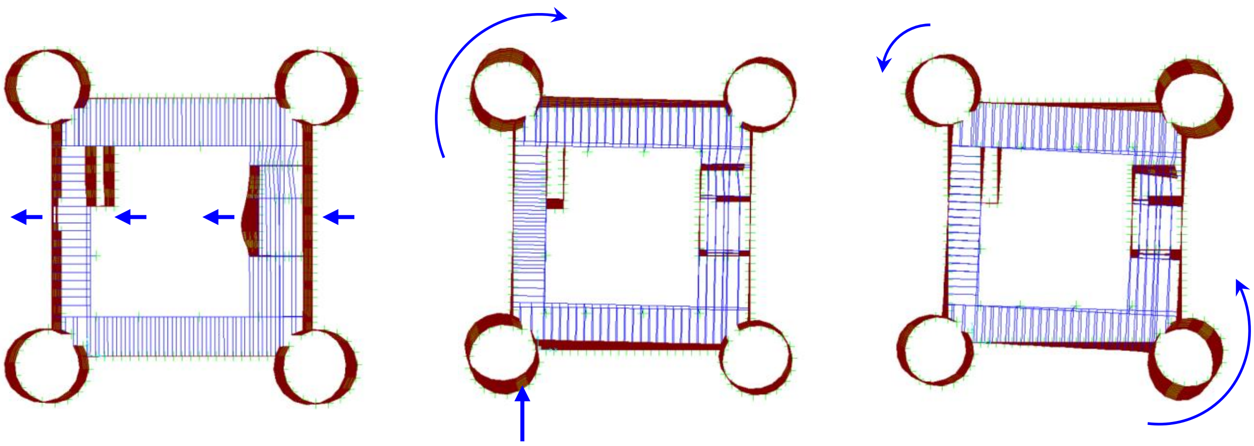


Figures (14: a, b and c): Maximum tensile stresses (t/m^2) in horizontal direction (S11) under the three selected earthquake records for Case-4. They are respectably less than their counterpart of all three previous cases.

8.8- Case-5: Embed RC-Diaphragm in Each Roof

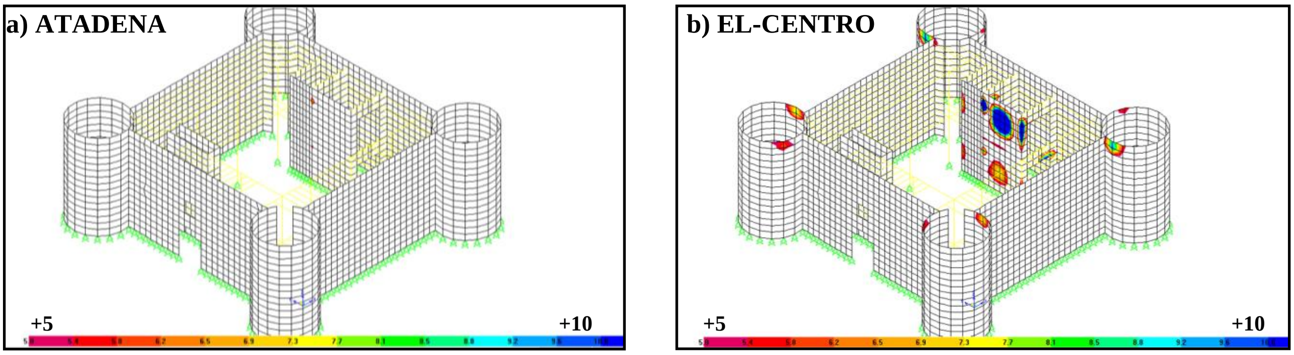
This analysis case studies embedding thin precast reinforced concrete (RC) slabs of the previous case-4 inside all floor roofs of the citadel (in both ground and first floor roofs). Case-5 applies the same idea of case-4, but with all roofs instead of the last (upper) roof only. This methodology enhances structural behavior of the citadel in case-4, since Eigen-modal shapes in case-4 showed concentration of mass at ground floor roof level.

Figures (15: a to c) show the first three Eigen-modal shapes for case-5. These modal shapes demonstrate the great enhancement in the structural behavior of the building under seismic loads, which is considered the best of all the previous four analysis cases. The first mode is bending in analysis E-W direction, while the other two modes (2nd and 3rd) are torsion. The modal participation mass ratio represented in the modal period is reduced to 39.6% from the original building in case-1 (see Table 1), and is the least of all previous four analysis cases. This shows how the last reconstruction methodology for the citadel (case-5) is considered the best. Also the maximum tensile stresses (S11), result from Time-History analysis, have reduced greatly; as their values are generally less than 5.0 t/m^2 (see Figures 16: a and b) and these values are structurally safe (see item No. 8.2).



a) 1st Eigen-mode; T = 0. 0561 sec. **b**) 2nd Eigen-mode; T = 0. 0556 sec. **c**) 3rd Eigen-mode; T = 0. 0500 sec.

Figures (15: a, b, c and d): Deformed shape plans of the first three Eigen-modes of the building (case-5).



Figures (16: a, b): Maximum tensile stresses (t/m^2) in horizontal direction (S11) under the three selected earthquake records for Case-5. They are generally less than 5 t/m^2 and structurally safe.

8.9- Discussion of Structural Analysis Results of the five cases

The study of the five structural analysis cases of the citadel building, and reviewing the different results discussed in the previous sections, beside Figure (17) and Table (1); will lead the followings:

1. The citadel building, like all other heritage masonry buildings; are usually structurally safe against static permanent loads (dead and live loads), except the cases in which building is reused in wrong functions, which are not compatible with its original functions or present condition.
2. Seismic is the most critical loading condition for the citadel building, which caused most of its present collapse and destruction. This proved by field observation and the comparison between current deficiencies (cracks, separations and failures) in building structural elements and the stresses resulting from seismic loads in the structural analysis works.
3. Assessment among various proposed methodologies for reconstruction and restoration of the citadel building would depend on results of dynamic analysis works (Eigen-value analysis and Time-History analysis) of 3D numerical models.
4. There is a great need to add some structural elements to play the role of lateral bracing system against seismic loads, since the authentic building design does not contain any robust elements to resist these loads.

5. Wooden roof, either the original weak *Athel* tree trunks (similar to roofs in traditional heritage buildings in KSA) or by using new stronger wooden beams with masonry arches on the periphery; does not provide the citadel building with efficient bracing action against seismic loads. Thus, masonry walls in the citadel behave as almost free-standing cantilevers, although the better behavior of the second case. This was shown from the similarity of stress results in Figure (9) of case-1 and Figure (11) of case-2. Model of case-1 does not contain wooden beams (since its action is neglected), while model of case-2 (and all the subsequent models) contains beam elements represent the two roofs.
6. The use of reinforced concrete beams inside the two roofs (they are parallel to wooden beams and located at masonry columns) forms flexible framing action and enhances the behavior of citadel building under seismic loads, although they do not provide sufficient safety factor against seismic.

Table No. (1): Modal Participating Mass Ratios

Model No.	Case-1	Case-2	Case-3	Case-4	Case-5
	Period Sec.	**Period Sec.**	**Period Sec.**	**Period Sec.**	**Period Sec.**
1	0.1416	0.1407	0.1296	0.0739	0.0561
2	0.1323	0.1328	0.1194	0.0708	0.0556
3	0.1305	0.1304	0.1173	0.0691	0.0500
4	0.0973	0.0988	0.0932	0.0549	0.0453
5	0.0775	0.0862	0.0804	0.0537	0.0412
6	0.0677	0.0669	0.0623	0.0507	0.0361
7	0.0667	0.0658	0.0614	0.0491	0.0328
8	0.0582	0.0634	0.0585	0.0474	0.0319
9	0.0573	0.0593	0.0546	0.0454	0.0317
10	0.0543	0.0591	0.0542	0.0439	0.0315
11	0.0540	0.0570	0.0519	0.0429	0.0308
12	0.0516	0.0560	0.0513	0.0420	0.0303
13	0.0507	0.0538	0.0505	0.0405	0.0284
14	0.0502	0.0528	0.0493	0.0388	0.0283
15	0.0502	0.0524	0.0489	0.0383	0.0282

7. Embedding thin precast reinforced concrete (RC) slabs inside the wooden roof is considered one of the innovative structural restoration techniques adopted in some heritage buildings in Europe [(18)]. This technique is selected among other proposals, since it suits the condition of heritage buildings in KSA, easy to achieve and economic.
8. Thin precast RC-slabs provide the citadel building with lateral bracing system (create horizontal diaphragm at each roof level), which causes all masonry walls in the citadel to behave together to resist seismic forces. Each masonry wall will resist part of the overall seismic forces according to its stiffness and location in building plan.
9. Applying the diaphragm for the last upper floor only causes mass to concentrate in the lower floor (without diaphragm), beside the response of the building, analyzed in the Eigen-value analysis; is not uniform.

10. The optimum proposal for restoration the citadel building, from the structural analysis point of view; is reconstructing the building following the authentic building materials and construction technique, and embedding a diaphragm of thin precast RC-slabs inside each floor of the two roofs of the citadel. This will reduce greatly stress results from seismic forces (values are less than 0.5 kg/cm^2) and increase the structural safety factor of the building against seismic loads.

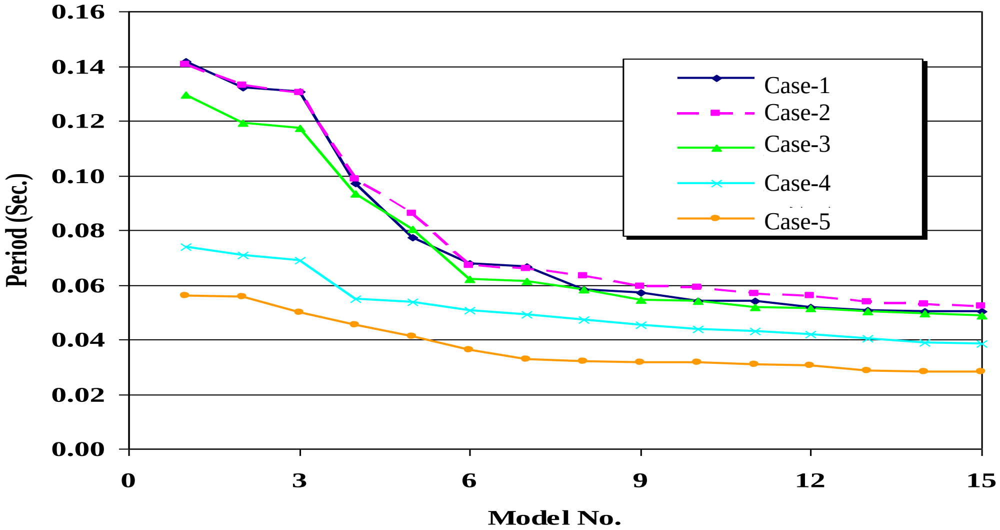


Figure (17): Distribution of Modal participating periods for 15 modes of Eigen-value analysis of the five case studies.

9- Proposal Restoration Technique to Create Roof Diaphragm

A number of alternatives are proposed in previous work [19] for achieving diaphragm action in wooden roofs of heritage buildings, experienced in Italy and other European countries. The first proposal is the use of RC-slabs and the second is the use of thin steel plates (see Figure 18: a, b). Opposition on these solutions is due to their heavy weight which adds to wooden beams and their supporting masonry walls. Two other solutions for diaphragm are proposed by using either wooden panels connected together with nailed steel straps or stud connected wooden planks (see Figure 18: c, d). They are encouraged for their light weight and consistency with original wooden roof.

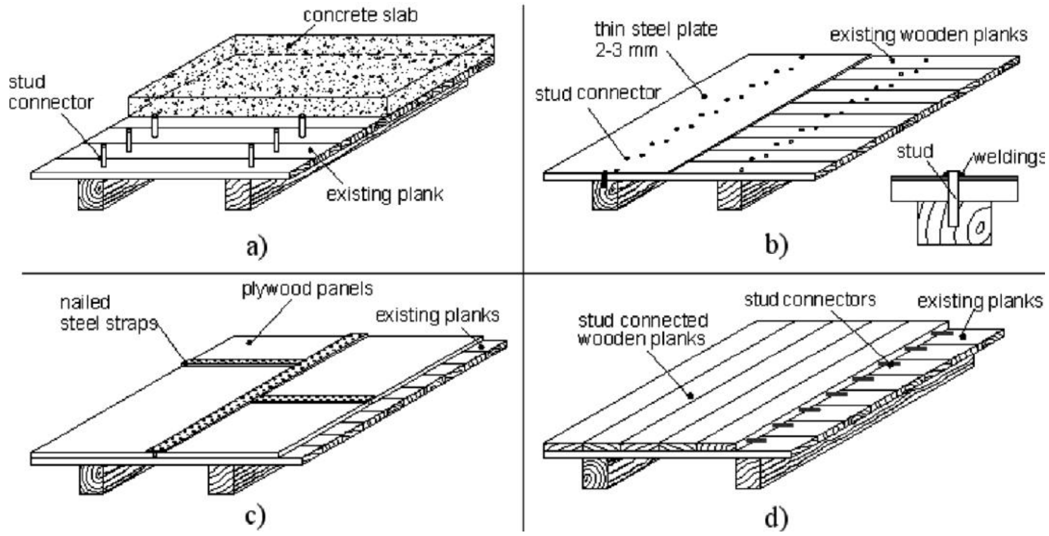


Figure (18): Schematic illustration of strengthening wooden roofs by means of overlaying: (a) thin ordinary concrete slab; (b) thin steel plate; (c) nailed plywood panels; and (d) stud connected wooden planks [19].

The structural efficiency of the last two diaphragm systems (built of wood) is questionable and uncertain, due to the weak stiffness of these systems, their tendency to bend in-plane and the weakness of their connection within their elements and with the roof.

We recommend using either precast thin RC-slabs or any new similar stiff panels made of new stiff fibers (Fiber Reinforced Polymers: FRPs). The first proposal is available, economic, and can be controlled to light its weight and tight its connection within each other and with masonry walls. Besides, its high stiffness is assured. The use of steel plates is the stiffest solution, but it is not recommended due to heavy weight of steel and its corrosion problems, beside it is uneconomic.

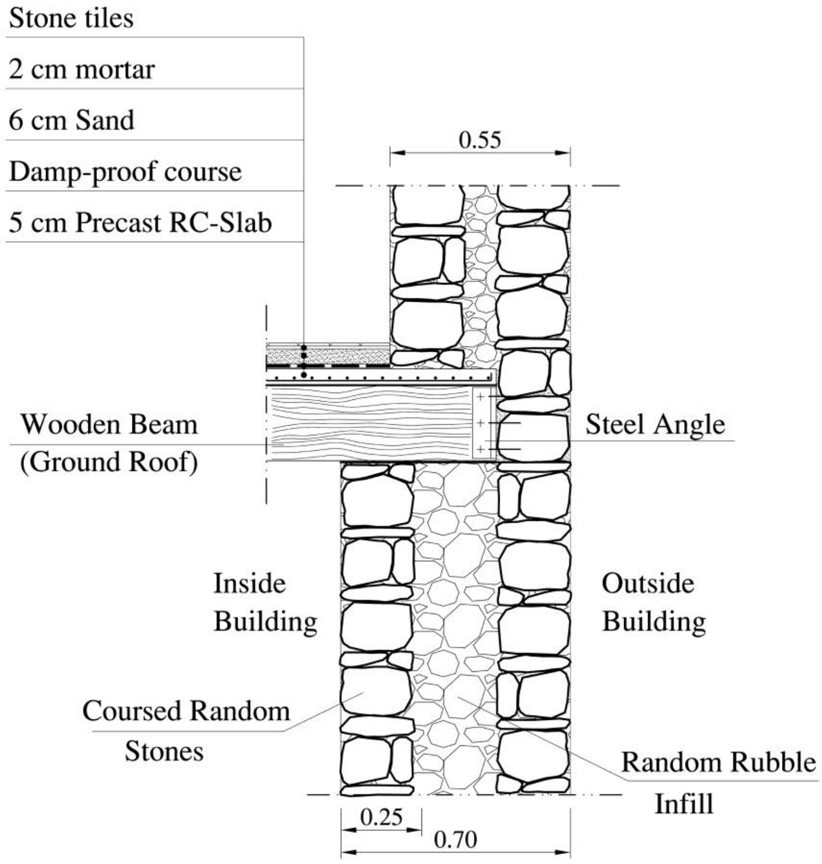


Figure (19): Detail of reconstruction of masonry walls and wooden roof, including the embedding of Precast RC slabs.

Figure (19) shows a typical detail for reconstructing masonry walls and wooden roofs, besides the embedding of (5 cm) precast RC slabs above wooden beams of the roof and below flooring layers. The RC-slabs will rest on thin plywood panels to hide it from in-between the roof wooden beams. Connection between wooden beams and their supporting masonry walls can be increased by using steel angles (shown in Figure 19) which are bolted to both wooden beams and walls. Besides, the wooden beams should be inserted inside masonry walls for sufficient bearing length.

Figure (20) shows plan and section elevation of the precast RC-slabs. The proposed dimensions of each slab are 1.0x1.0x0.05 m, and its weight is about 100 kg. To reduce the dead loads of roof, light aggregates can be used in the preparation of concrete mix and thickness of sand layer in flooring can be reduced to minimum (6 cm instead of 10 cm). Slabs will be connected together with three steel bolts from two sides see Figure (20).

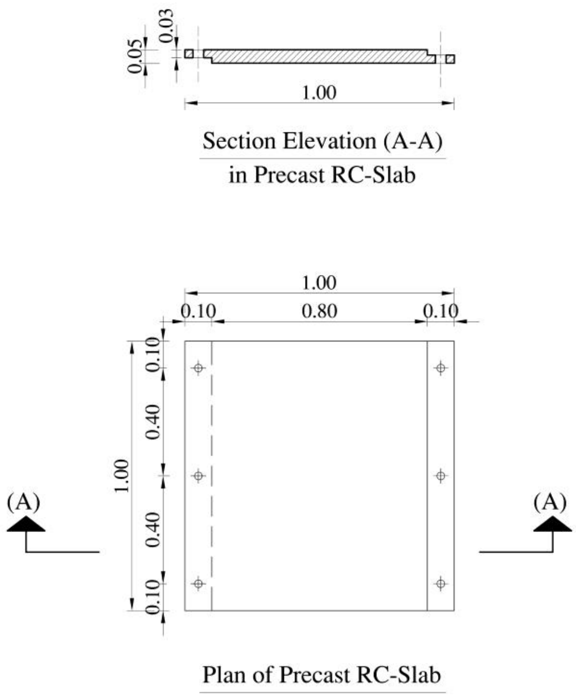


Figure (20): Typical detail of Precast RC slabs (Plan and Section Elevation).

10- Conclusions and Recommendations

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

1. The structural response and behavior of historical masonry buildings subjected to earthquake loads depends on many factors, such as the overall plan layout, distribution of walls through it, interconnection and texture of the masonry walls, location and size of openings, typology of roofs, and floor-to-wall and roof-to-wall mutual connections. As a result, failure mechanisms are not straightforward, and they are usually particular for each building [(20)].
2. Structural analysis of monumental and heritage buildings using numerical modeling technique of Finite Element Method (F.E.M.) plays an essential role in the assessment and design of the structural conservation and restoration of these buildings [(21)].
3. Structural conservation of heritage buildings must provide adequate safety factor against all possible direct and indirect actions and forces which affect the building[(22)].
4. Safety factors of modern building codes are not convenient or applicable to heritage and monumental buildings. Experience and engineering practice are the best guide till specialized codes in monumental buildings are available.
5. The original construction technology and building materials of the monumental and heritage buildings in KSA cause these buildings to be structurally unsafe against moderate seismic actions and/or soil and foundation problems. This can be proved by the few number of complete structures found standing till the present time, excluding human destruction (e.g. wars, fire, etc.).
6. Reconstruction and restoration of heritage buildings in seismic prone cities, following the original (authentic) building design, by using the original materials and construction technology, is an unsafe methodology, since most of cracks, failures and collapses found in such buildings are caused mainly by seismic loads. This means that they are liable to collapse again in the near future by seismic action.

7. Restoration and conservation of heritage buildings should get benefit from the latest technology in structural analysis, construction materials and technologies, but in conservative and well-examined techniques to enhance the structural behavior and safety factors available, beside prolong conservation works to the maximum possible period of time [(23)].
8. High stiffness of roofs in monumental masonry buildings enhances the structural behavior and factor of safety of these buildings against seismic loads. They form diaphragm action that will connect masonry walls together and makes them all contribute in resisting seismic loads.
9. One of the modern techniques to increase roof stiffness is to make wooden roofs in each floor level create diaphragm action by embedding precast reinforced concrete slabs above wooden beams and under flooring layers of each roof. These slabs are not required to resist vertical loads, since their thickness is small and their reinforcement is minimum.
10. Precast reinforced concrete slabs provide good conservative solution to enhance the seismic behavior and factor of safety for masonry heritage buildings. These slabs have small thickness (5 cm) which can be embedded within the layers of flooring, thus become invisible. They have light weight, which can be reduced more by using light weight aggregates in their concrete mix. Thus, their additional loads to on wooden beams and masonry walls would be safe. They can also be easily handled and constructed in the site with no damp or destruction problems.
11. The choice among the previous five alternatives of reconstruction depends on many parameters, such as economic aspects, historical and architectural studies of the citadel, the adopted methodology of conservation and restoration of the building, the recommendation of soil and foundation report, etc.
12. The full reconstruction plan and work will be provided in future paper, after the excavation of the citadel site is conducted and embedded building elements are revealed. Also the opening of the site for study will enable to finish more experimental and testing works for all building materials.
13. Foundation and soil investigation will lead to solutions for stabilizing soil and restoring footings.
14. Reconstruction of all missing or partially collapsed masonry walls and wooden roofs would be conducted following the authentic materials and technology. Some additional and innovative techniques may be embedded in them to increase their resistance to various expected loading condition [(24)].
15. Cracks and separation, especially in towers, would be provided with robust wooden beams, embedded through masonry courses, and extended to sufficient length on both sides of the crack, and distributed along the crack. These wooden beams will resist the tensile forces in these locations and stop cracking in the future.

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الدراسة الإنشائية لعدد من البدائل لمنهجية إعادة بناء قلعة الفقير العثمانية لتحسين سلوكها الإنشائي تجاه الزلازل – محافظة العلا – المملكة العربية السعودية

د. عبد الناصر بن عبد الرحمن الزهراني
أستاذ مشارك، قسم إدارة موارد التراث والإرشاد السياحي، كلية السياحة والآثار
جامعة الملك سعود، الرياض، المملكة العربية السعودية
naserz@ksu.edu.sa

د. ياسر يحيى أمين عبد العاطى
أستاذ مساعد، قسم إدارة موارد التراث والإرشاد السياحي، كلية السياحة والآثار
جامعة الملك سعود، الرياض، المملكة العربية السعودية
yamin@ksu.edu.sa

(قدم للنشر في / / 1432 هـ ؛ وقبل للنشر في / / هـ)

الكلمات المفتاحية: قلعة الفقير – إعادة البناء - التحليل الإنشائي – مستوى أفقي قوي – الزلازل.

ملخص البحث:

يدرس هذا البحث عدداً من البدائل الممكنة لمنهجية إعادة بناء قلعة الفقير العثمانية فى محافظة العلا بالمملكة العربية السعودية، حيث تعتمد الأفضلية ، للمنهجية المختارة، على مدى توفيرها لمعامل أمان إنشائي أكبر لمبنى القلعة تجاه قوى الزلازل، التى تعدّ المسبب الرئيس للمشكلات والانهيارات الإنشائية الحالية فى المبنى.

وقلعة الفقير هي واحدة من القلاع العثمانية المنتشرة على طريق الحج الشامي المصري ، شمال غرب المملكة العربية السعودية، حيث يمثل هذا المبنى مع باقي القلاع العثمانية جزءً مهماً من تاريخ المملكة وتراثها المعماري والحضاري العريق. كما أن قلعة الفقير تقع فى محافظة العلا ، التى تعدّ واحدة من أهم محافظات المملكة فى مجال السياحة التراثية. ويمثل هذا البحث دراسة مبدئية لمبنى القلعة الحالي حتى تتم أعمال التنقيب وإزالة طبقات الردم التى تغطى معظم الموقع.

وتعتمد عملية الدراسة والتقييم على نتائج أعمال التحليل الإنشائي لعدد من النماذج الرقمية للحاسب الآلي ، التى تمثل المبنى، وباستخدام طريقة العناصر المحددة (Finite Element Method)، من خلال أحد برامج الحاسب المشهورة فى هذا المجال.

ويتم دراسة ثلاث منهجيات من خلال التحليل الإنشائي لخمسة نماذج حالة ، حيث تعتمد المنهجية الأولى على دراسة إعادة البناء لمبنى القلعة باستخدام مواد وتقنيات البناء الأصلية للمبنى. في الحالة الأولى تستخدم مواد وطرق البناء التقليدية، بينما تستخدم الأخشاب القوية (مثل الخشب العزيزي) فى بناء الأسقف فى الحالة الثانية.

وتعتمد المنهجية الثانية على وضع كمرات من الخرسانة المسلحة (ذات قطاعات صغيرة) عند مواضع الأعمدة الحجرية، وفى الحدود الداخلية للسقف (المحيطة بالفناء الداخلي للمبنى)، من خلال الحالة الثالثة.

أما المنهجية الثالثة فتدرس وضع مستوى أفقي قوي (Diaphragm) داخل الأسقف الخشبية، يتكون من بلاطات من الخرسانة المسلحة سابقة الصب بأبعاد محدودة (1.0×1.0 م) وبسمك 5سم، توضع فوق الكمرات الخشبية وأسفل طبقات الأرضيات، حيث تدرس الحالة الرابعة وضع هذا المستوى فى سقف الدور الأخير فقط، بينما الحالة الخامسة تدرس وضعه فى جميع أسقف المبنى.

نتائج هذه الدراسة تفيد فى تحديد الأسلوب الأمثل فى إعادة بناء مبنى قلعة الفقير بهدف تقويته تجاه الزلازل، وتطرح عدد من البدائل والأفكار الممكن تنفيذها فى أعمال الحفاظ والترميم للمباني التراثية بالمملكة.