Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2020 Volume 26 Issue 1: 53–65
https://doi.org/10.3846/jcem.2020.11520

USING 3D LASER SCANNING TO ANALYZE HERITAGE STRUCTURES: THE CASE STUDY OF EGYPTIAN PALACE

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Received 29 August 2019; accepted 4 October 2019

Abstract. Preservation of heritage buildings should be carried out to get a better understanding of the behavior of their structures and keep them in a good condition. As such, corrective diagnosis of heritage buildings health conditions would help to identify potential risks and take remedy actions. This paper presents a framework for heritage Building Information Modeling (HBIM) application in Egyptian Heritage buildings. The framework is capable of utilizing processed point clouds using 3D laser scanning to create different purpose BIM models at the different levels of development to simulate the structural performances under different types of actions. The paper illustrates an extensive structural analysis for Tosson palace in Cairo – Egypt to assess its health state to assure its sustainability for future use.

Keywords: heritage buildings, building information modeling, 3D laser scanning, structural analysis, health conditions.

1. Literature review

1.1. Digital documentation of heritage using LiDAR

The 3D laser scanning advances have been presented in the field of surveying and can obtain 3D data about physical objects of different shapes and sizes in a cost and time effective way. Laser scanners enable a large number of points to be recorded in a few minutes. As a result of their common sense and flexibility, these sorts of instruments can be broadly utilized in architectural, archeological, and environmental surveying fields (Valanis & Tsakiri, 2004). Nex and Rinaudo (2010) worked on an algorithm that automatically combines information gathered from digital imaging and LiDAR to segment and detect heritage building features, such as building break lines. The automation algorithm, using high density point clouds, is time saving and it decreases human intervention in the process of documenting heritage buildings. Hesse (2010) developed a data processing method for the extraction of Local Relief Models from airborne LiDAR high density point clouds, which results in color-coded maps of local Relief Models. The proposed method was applied on LiDAR data (acquired by airborne 3D laser scanners) of Baden-Württemberg and proved valuable and accurate in mapping large archeological sites scanned with airborne 3D laser scanners. Haala, Peter, Cefalu, and Kremer (2008) utilized a kinematic terrestrial laser scanning approach to capture the dense point cloud for a historical town. The "Street Mapper" approach, on the other hand, depends on four vehicle-mounted 2D laser scanners and a high performance GNSS/inertial navigation system. Accurately providing the required dereferenced information, this method enables the automatic combination of the four 2D dense point clouds. The proposed approach achieved a feasible 3D laser scanning approach for large heritage sites with an accepted level of accuracy for many urban mapping applications of historical towns.

Coren, Visintini, Prearo, and Sterzai (2005) integrated LiDAR data with hyper-spectral data to evaluate irregular behavior of major ground indices, which in turn improves the discovery of new archeological sites. LiDAR provided the accurate surface geometrical data while the hyperspectral survey provided the specific humidity, vegetation, and thermal conditions of the target area. The integration of both technologies generated an accurate Digital Terrain Model (DTM). Sánchez-Aparicio, Del Pozo, Ramos, Arce, and Fernandes (2018) diagnosed the historical structures through multilayered point cloud analysis using the technology of laser scanning to observe the built pathologies. Radiometric and geometric data provide a 3D methodology to extract and quantify the different deformations and

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biological Conquest on the masonry. The Fortress of Almeida, in Portugal was examined for restoration activity. The complex diagnostic results of the radiometer were validated and compared with realistic photographs. Presence of salts and moisture were deduced from the deformation layers within the analysis results that revealed the direct relation between the visual diagnosis and that of the point cloud. Głowienka and Michałowska (2017) worked on a project named "Cultural Heritage through time" as a basis for web-based published material to provide 4D data that include time interventions of architectural and structural alterations. The UNESCO-listed historical site of Krakow was examined to forecast and analyze the facility modifications over time. Using LiDAR, UAV, TLS, and archived data, accurate 3D models were obtained which enhanced restoration even that of the underground unseen parts of the facility. Accurate data was provided for the excavation work that included deepness, slope, and thickness of buried masonry.

Further research efforts utilized 3D laser scanning (LiDAR) to document heritage sites. Cheng, Wang, Chen, and Li (2016) developed a method to automatically detect ancient walls features and extract its geometry from LiDAR point clouds. They applied their method to Nanjing city wall, along with the eight city walls of Min and Qing dynasties in China. Their work was used in understanding the current state of the historical walls, and added to their digital document, which represents the means of the wall's construction, rehabilitation, exhibition, and promotion. The integration of LiDAR and unmanned airborne vehicles (UAV) proved efficient in mapping large heritage sites in china. However, due to the vibrations, the collected data suffers from some distortions. Li, Yan, Jing, and Zhao (2015) designed, developed, and tested two platforms which are most suitable for mounting LiDAR to collect high density point clouds for heritage mapping projects in terms of stability, capacity, reliability, and vibrations. The limitations of traditional geometric data acquisition are listed in Table 1.

1.2. 3D parametric HBIM models

This section displays the previous efforts directed towards the process of generating 3D parametric HBIM models from point clouds, using terrestrial 3D laser scanners, along with some efforts in documentation, analysis, and dissemination of several historical sites using HBIM models generated from high density point clouds. Barazzetti et al. (2015) described the procedures of developing the HBIM model starting from point cloud data. The developed models were then reformatted to be displayed in mobile apps using augmented and virtual reality visualization technologies. Their purpose was to deliver HBIM models through widely available platforms for both expert and non-expert operators, which is valuable in the tourism and heritage dissemination sectors. Dore et al. (2015) deployed the Dublin historical BIM frame work to perform structural and conservation analysis for the Four Dublin courts. The analysis was intended to assess the damage subjected to the structure during the war. They developed a model using historical data, and another model using 3D laser scanning. The two models were simulated to assess the structural damage that still affects the structure till now, as well as to serve conservation and documentation purposes.

Table 1. Weaknesses of traditional geometrical data acquisition techniques

Acquisition method	Weakness
Survey points	• Get the coordinates of a few selected no. of control points • Impractical to generate dense point cloud • Prone to human error • Difficult to document the data acquisition process
Direct measurements	• Impractical to measure every possible dimension • Prone to human error • Difficult to document the data acquisition process • Difficult to document the data acquisition process
High quality digital imagery	• Missing information about depth, i.e. 2D information • Highly dependent on the quality of the camera, and operator • Highly affected by light and weather conditions • Less accurate information in the distorted parts of the photo • Difficult to document the data acquisition process
Photogrammetry	• Highly dependent on the quality of photos (refer to the previous entities) • Inherits the weakness of high quality digital imagery • Cannot generate accurate high dense point cloud • Needs immense post processing efforts to get the coordinates of selected points (sparse point cloud)
2D Projections	• Difficult to understand/interpret by non-practitioners • Difficult to visualize to non-practitioners • More challenging to visualize to practitioners compared with 3D models • Prone to coordination errors • Impractical to draw every possible section and/or elevation

Aside from buildings and terrestrial sites, some naval artifacts are considered of great heritage value, and it is of great difficulty to display and effectively disseminate a multitude of naval vehicles out of their context (water masses) in museums. Accordingly, Wetherelt, Cooper, and Zazzaro (2014) processed the LiDAR high density point cloud and generated photorealistic and accurate 3D digital models for the dhows. Their work is displayed in 2D, 3D, and virtual visualization in the National Museum of Qatar. Oreni, Brumana, Della Torre, Banfi, and Previtali (2014) created an HBIM model using terrestrial 3D laser scans and 3D images of the Basilica di Collemaggio in L'Aqualia as part of the restoration process of the site after the earthquake of 2009. The resulted model was used for structural analysis purposes to assess the feasibility of restoration methods. Brumana, Georgopoulos, Oreni, Raimondi, and Bregianni (2013) carried out a 3D laser scanning and a photogrammetric survey for the Church of S. Maria di Scaria (Vall' Intelvi). They processed the raw data from the survey and generated an HBIM model for the church which displays the construction methods and the various rehabilitations and expansions from the Romans era till the baroque period. Also, they developed an object library that can be used for modelling such buildings across Europe. The resulting model was easy to interpret and was used for dissemination purposes in the multimedia section of a local museum. Amans, Beiping, Ziggah, and Daniel (2013) proposed a framework for documenting heritage sites in West Africa. The framework pivots on the generation of 3D HBIM model from LiDAR high density point clouds. Their approach overcomes the limitations of the traditional methods in terms of accuracy and time consumption. The resulting digital documentation provides a guide to the preservation of heritage sites along with 2D, 3D and virtual visualization, and dissemination of heritage sites.

Dore and Murphy (2012) outlined the use of HBIM in modelling historic structures in the Dublin institute of technology. This approach depends on acquiring special data using 3d laser scanning and photogrammetry to develop an HBIM model using modelling objects from libraries of historical buildings elements. Moreover, the developed model is integrated with GIS data through the CityGML framework, thus creating accurate 3D GIS models. Such approach bridges the gap between 3D GIS and HBIM in documenting heritage sites. Murphy, McGovern, and Pavia (2009) outlined in detailed workflow of HBIM system which starts with point cloud and digital imagery, and results in a textured 3D parametric model. They extended the ability of the geometric descriptive language (GDL) to generate 3D parametric objects that they used to develop a library for historical 3D parametric objects of historical buildings' elements. Rubinowicz and Czynska (2015) examined the possibilities of applying LiDAR data, coupled with digital 3D-city models, in evaluating city landscape parameters for heritage rich contemporary urban areas. Such parameters will enable the evaluation of strategic city views, mapping landscape absorption limits, and delineation of heritage rich zones that needs protection from modern urbanization. Their efforts were crowned by developing the computational analysis method Visual Protection Surface (VPS) which enables the automatic collection and evaluation of city landscape parameters, and was successfully implemented in the city of Dresden. Fernández-Lozano, Gutiérrez-Alonso, and Fernández-Morán (2015) used 3D laser scanning in archeological works for discovering man-made structures and building ruins. They developed a detailed map of Roman ancient mining works in the areas of Las Medulas and Omanas along with Duerna and Eria river valleys. Their work provided insights into the Romans' exploitation hydraulic engineering techniques and geometry; which in turn highlighted the scope and impact of the Roman mining works that turned out to be more important than previously estimated.

1.3. Structural analysis of heritage buildings

The following section displays the previous efforts directed towards the structural analysis of heritage buildings specially the masonry structures. Many of the efforts were directed towards the accurate modelling of the structural material, others were directed towards the alignment between the accepted level of approximation and the purpose of the analysis while others presented Finite Element Analysis (FEA) on different heritage assets. The conclusion that can be drawn from the following literature review is the consensus on the importance of following the most accurate structural analysis methods to assess and strengthen heritage structures. Lourenço (2002) addressed the possibilities of analysis of historic structures and proposed a set of guidelines. They investigated what type of analysis should be used. It seems that all methods are of interest, depending on the actual constraints of the engineering problem. And they concluded that all the available techniques are of use and importance. Giordano, Mele, and De Luca (2002) investigated the applicability of different numerical techniques for the analysis of masonry structures by comparing the computed results with the experimental test data obtained on a full-scale masonry specimen. Three approaches are taken into account, including:

1) The standard FEM modelling strategy, based on the concepts of homogenized material and smeared cracking constitutive law, is used in the version implemented in the commercial code ABAQUS by HKS.
2) The program Visual CASTEM 2000 is used for the application of the finite element method with discontinuous elements, which are intended to simulate the presence of vertical and horizontal mortar joints.
3) Finally, the UDEC software by the ITASCA Group is adopted for the Discrete Element modelling.

They also provided a "ready-to-use" input parameter values, which are usually hard to decide. However, parameters are suggested, based on both extensive sensitivity analyses, and experimental validation. They also proved that the proposed values give reasonable results in the modelling of masonry structure under monotonously increasing loads. Kappos, Penelis, and Drakopoulos (2002) evaluated the relative accuracy of different models. Mainly intended for use by practicing engineers, the study focused on the analysis of unreinforced masonry buildings, and on determining whether or not a simple equivalent frame model can be used for design and/or assessment purposes, and under what conditions. They performed several parametric analyses including finite element (FE) models of 2D and 3D structures.

Furthermore, their results shed some light on the feasibility of using simplified and cost-effective analytical models as a tool for practical design and/or assessment of typical masonry structures. Lourenço, Mendes, Ramos, and Oliveira (2011) approved the notion that the assessment of the seismic performance of structures is still a challenge because historic masonry structures exhibit peculiar properties, low tensile strength and lack of box behavior, which makes the task of the analyst even more difficult. Traditional design and assessment methods, similar to the ones currently used for reinforced concrete structures, are not applicable. Thus, the authors provided a review of the seismic analysis of masonry structures without box behavior. They discussed different methods of structural analysis, and performed a comparison between pushover methods and non-linear dynamic analysis with time integration. They displayed their results through three cases studies, San Torcato church, Qutb Minar, and "Gaioleiro" buildings. The results show that traditional, adaptive or modal pushover analyses are not totally in agreement with non-linear dynamic analysis or experimental observations.

Oyarzo Vera (2012) exhaustively investigated the dynamic characterization of unreinforced masonry (URM) buildings and the use of their distinctive modal properties in identifying damage. Their numerical and physical models were used to analyze the system applicability and identify damage in non-slender URM buildings. Model tests were conducted on two undamaged URM panels and an undamaged model of a one-story URM house. Impacts with a calibrated hammer were used to excite the specimens during the modal test, and also horizontal harmonic excitations in the case of the house model. Two system identification techniques, SSI and FDD, were considered for extracting the modal properties. The experimental results were then compared with numerical predictions obtained from finite element models originally generated based on geometrical and mechanical properties obtained by standardized tests. The numerical predictions were improved by applying sensitivity-based model updating techniques. The evolution of the modal properties of the URM panels and house model due to artificially induced damage were also investigated. Vibration-based and model updating-based damage identification techniques were employed to detect the damage distribution in the specimens. Finally, a seismic assessment was conducted on a typical New Zealand URM building by applying time-history analysis on finite element models. An original seismic hazard zonation and methodology for selecting appropriate ground-motion records in the North Island of New Zealand is described. A typical stand-alone two-story URM building was simulated using different finite element models. Material and geometrical properties estimated from traditional standardized test results, and properties estimated by a process of model updating based on the experimental data recorded in the vibration tests were considered for these models. The finite element models were analyzed using a time-history methodology for a building in Auckland and Wellington. The response of the building was compared to admissible limits established based on a stability criterion, taking into account three levels of intensity for the ground motion.

Betti, Galano, and Vignoli (2014) performed a comparison between different numerical structural analysis methods to predict the seismic behavior of unreinforced masonry heritage structures with flexible diaphragms. As a prototype for the analysis, the authors tested a two-story building on a shaking table undergoing increasing natural ground motion to analyze its seismic response starting from the prototype initial conditions until the mildly damaged reaching extensive damage states. The first method was the finite element analysis technique presenting the near exact approach while the second was a simplified macro-element method, presenting the simplified and less computationally demanding method. The results from the two methods along with the empirical prototype were compared resulting in the following observation. The finite element model was able to predict the damaged areas and the incipient collapse mechanism, as well as the collapse load. The macro-element model was able to predict the collapse load but due to some limitations of the approach, a satisfactory reconstruction of the actual collapse mechanism was not obtained. Nevertheless, the simplified model was able to deduce a fairly accurate estimate of the accelerations at the top floor measured in the tests. Elyamani and Roca Fabregat (2018a, 2018b) presents a literature review carried out to cover the current state-of-the-art of a number of investigation activities carried out integrally for the seismic safety assessment of historical structures, with minimal intervention due to the perseverance nature of the heritage buildings, that constraints the strengthening and structural interventions.

2. Case study

Tosson palace is a heritage building that was built in 1886 by Prince Omar Tosson in Shubra, Road El-Farag, north of Cairo, Egypt (see Figure 1). The palace is a 3,200-square meter building on three stories, with an arcade façade and an extended terrace on its upper floor. To diagnose Tosson

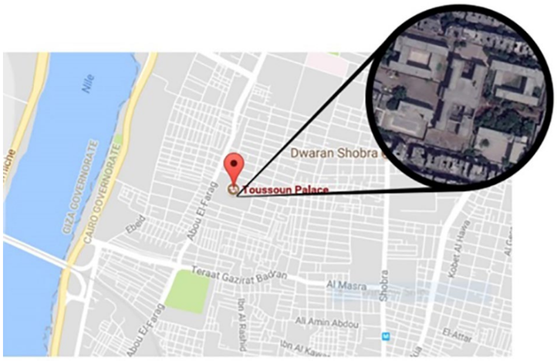


Figure 1. Ariel view of Tosson palace

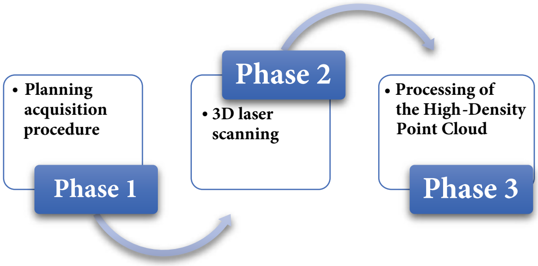


Figure 2. Proposed heritage digital documentation procedure

palace health condition, two main stages are performed; heritage digital documentation and structural model analysis. These stages are described in the following subsections.

2.1. Heritage digital documentation

Heritage digital documentation is composed of three tiers: 1) acquiring raw LiDAR data; 2) processing point cloud; and 3) generating the model. The output and benefits of every tier is inherited to the following because every tier is dependent on the product of the previous tier. The implementation process is divided into three phases as shown in Figure 2. Phase 1: planning acquisition procedure; Phase 2: 3D laser scanning of the site; Phase 3: processing of the High-Density Point Cloud (HDPC). Phase 1 is initiated by acquiring the layout of the site with all information collected via a total station survey and manual distance measurements. The team utilized a Z+F 3D laser scanner to acquire the HDPC. The planning depends on the number of scans required to capture the features of the palace from all directions internally and externally, while maintaining an adequate level of accuracy (HDPC density). A total of 160 scans were required to achieve the mission as depicted in Figure 3. The adopted resolution in Tosson palace was the super High resolution with 3.1 mm point spacing at 10 m distance. Phase 3 was performed utilizing a Dell OptiPlex 7020 Dell Alienware Area 51 workstation for the processing purposes. Phase 3 started with the registration of the individual HDPC generated from multiple scans.

The data was imported in Autodesk Recap for registration and noise removing. Auto-Registration feature in Autodesk Recap was used. The registered raw HDPC was produced, then, the noise data was removed from the scans as shown in Figure 4. It is worth noting that the average percentage of overlapping points within 1/4” (or 6 mm) of the corresponding feature in Tosson project obtained from Autodesk Recap during registration is 99.88%. The second step in processing phase is to create a 3D model of the palace. Two modelling techniques were used: 1) high detailed modelling for virtual reality purpose, and 2) medium detailed modelling to produce HBIM model for accurate structural analysis and Energy analysis. The HBIM modelling step started once the 3D point cloud was cleaned. Autodesk Revit 2018 was used for modelling as it provides quick, easily modifiable modelling that includes a high standard of structure documents. In addition, Leica CloudWorks, Revit plug-in, was used to help in modelling using as-built point cloud data captured by the laser scanner, directly within Revit for better BIM modelling of existing buildings. Leica CloudWorks used for importing point cloud as a database into the Autodesk Revit project is shown in Figure 4. Then, the point cloud is clipped to show the first and second floor separately. Afterwards, the modelling steps start with building the palace’s external and internal walls two floors (see Figure 5). Modelling structural elements was very important to enabling the calculation of loads on the walls and the floors for structural analysis.

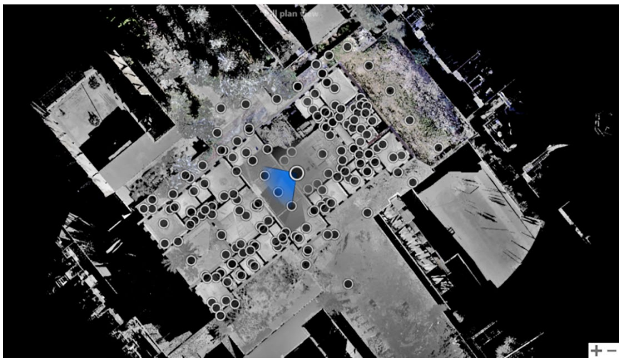


Figure 3. Layout of the 160 required scans

Figure 4. Point cloud of Tosson palace

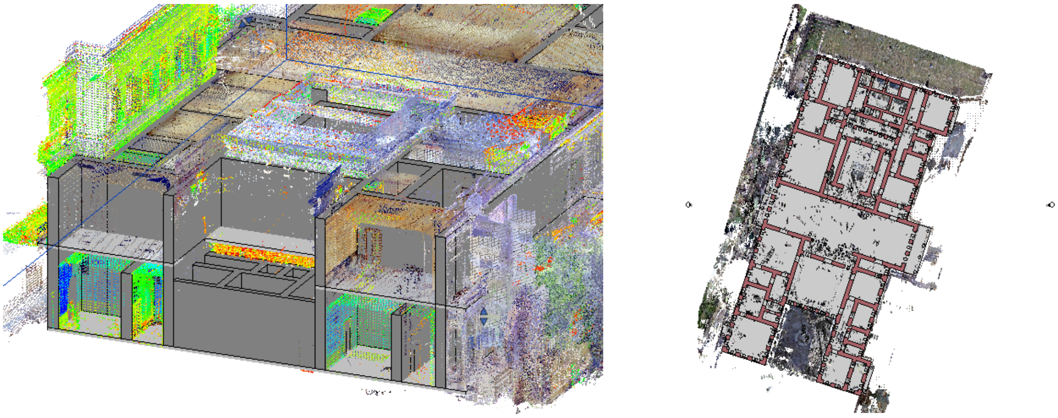


Figure 5. Modelling of structural elements in Tosson palace

2.2. Load assessment and materials properties

The walls were analysed under full dead and live loads from different levels. The dead loads consist of the weight of all permanent construction and were computed based on the roofing layers used. The live loads were input in accordance with the Egyptian code (ECP, 2012). Hence, live loads were considered equal to 0.2 t/m^2. With resepct to seismic loads, the response spectrum and time-history methods were used to evaluate the additional stresses due to earthquake loading. The mechanical properties for both clay bricks and limestone block that are considered in the analysis are listed in Table 2.

2.3. Horizontal elastic response spectrum

As for the response spectrum analysis, it was conducted according to the provisions of the Egyptian code (ECP, 2012). Accordingly, Tosson palace is located in the second zone, so the models will be analysed considering a peak ground acceleration level equal to 0.12 g and using type (1) response spectrum in the Egyptian code. According to the previous researches, soil type (B) is considered in the analysis. A time-history analysis was performed to assess the seismic vulnerability of Tosson palace, despite being time-consuming, 100 hrs per run in this model. The time-history analysis is an accurate and reliable analysis to predict all possible failure mechanisms due to seismic actions as a result of its capability to evidence both in-plane and out-of-plane, local and global failure mechanisms of the structures. A dynamic analysis was carried out using an artificial accelerogram compatible with the elastic response spectrum of the Egyptian codes. It is worth noting that the artificial accelerogram is developed for assessing the dynamic response of structures due to seismic actions. The corresponding acceleration history applied at the basis of the palace, having a total duration of 10.06 sec., is illustrated in Figure 6. The seismic behaviour of the palace, the seismic, horizontal actions along the longitudinal (X) direction only is considered. The transversal (Z) direction was not analysed according to the long time consumed in the longitudinal (X) direction. In addition, the longitudinal (X) direction is considered a more critical direction.

2.4. Structural assessment

In order to establish the numerical model, information is gained from the geometrical survey as well as material properties in order to construct a finite element model.

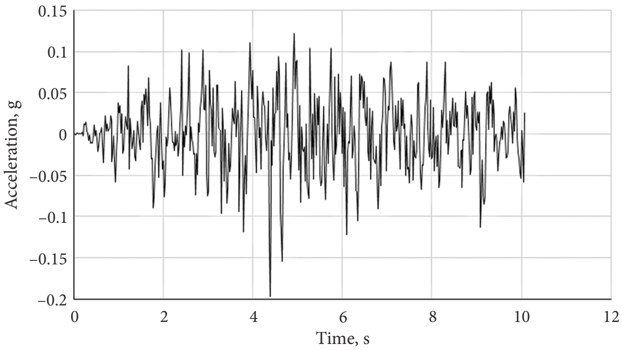


Figure 6. Acceleration history artificially generated (accelerogram)

Table 2. Mechanical properties for both clay bricks and limestone block

Item	Unit weight, kN/m^3	Compressive strength, MPa	Tensile strength, MPa	Modulus of elasticity (E), MPa	Poisson ratio (υ)
Walls	23	8.67	0.86	1460	0.2
Columns	24	9.47	0.94	1500	0.2
Vaults	16	9.32	0.93	1900	0.2
Woods	7	–	–	10000	0.3

The finite element model is used to simulate the behaviour of the structure and estimate the stresses in different elements under various loading conditions. The structural model is used to examine various loading scenarios and predict the crack patterns based on estimating the maximum tensile stresses in the structural elements. The model shall also be used to examine the dynamic characteristics of the structure, natural frequencies and corresponding mode shapes. Analysis of the model output is used to draw conclusions and recommendations to judge the safety of the structure. A 3D model is used to analyse Tosson palace walls under various loads. The 3D model is used to simulate the response of the structural elements under static loads and used for checking settlement and internal stresses in walls. ANSYS software is used to conduct the finite element model. Solid elements with variable thickness are used to represent the walls and floors. Solid elements are removed from opening locations such as doors and windows.

Modelling of the monument considers geometrical and loading conditions aspects. As for the geometrical aspect, these models are built using the given AutoCAD drawings coming from the 3D laser scanning techniques then extracted to the used software analysis program. Besides, horizontal restraints are assigned to the location of the floors as per site observations. The results of the analysis of the Palace focus on estimating the stresses in various structural elements. The assessment is performed considering vertical and lateral loading. Evaluation of tensile stresses in the walls is performed using the finite element method. The stresses are computed from the various load combinations will be compared with the acceptable levels of stress for such construction.

Quadratic solid elements with variable thickness are used to represent the walls. Hence, each node has six degrees of freedom, three translational and three rotational. Shell element size was restricted to 0.5 m, and the ratio between element sides is kept in the range 1:1 as possible. Modeling of the monument considers geometrical, loading, and construction materials conditions aspects. As for the geometrical aspect, these models are built using the HBIM model created from 3D laser scanning techniques, then, extracted to the used software analysis program. Besides, horizontal restraints are assigned to the location of the floors as per site observations. All members of the palace, walls and floors, are simulated using 3D 8-noded brick elements. The element is defined by eight nodes, each having three degrees of freedom, translations in the nodal x, y, and z directions. In ANSYS, the solid element is called SOLID65. The element is capable of plastic deformation and cracking in three orthogonal directions, hence, it is used to model all elements. The palace elements are all assigned elastic behaviour where the resulted values of stresses are lower than the allowable. For this reason, nonlinear materials are not used in the analysis to avoid the unnecessarily long analysis time. Figure 7 illustrates the geometry of the whole model. It is worth noting that the mesh consists of 468,076 elements and 1,408,551 nodes. The model uses standard fixities. As such, the displacements at the lower surface of the walls are prevented in the horizontals and vertical directions (U_x= 0, U_z= 0, and U_y= 0).

2.5. Structural analysis results

The results of the analysis of the palace focused on estimating the stresses in various structural elements. The assessment is performed considering vertical and lateral loading. Evaluation of tensile stresses in the walls is performed using the finite element method. The geometry of the wall, as well as the mechanical properties, are taken as previously discussed in this report and are used to produce the numerical models representing the various structural elements of Tosson palace. The models are subjected to loads and deformations as seen relevant, and the stresses are computed for various load combination scenarios. The stresses computed from the various load combinations are compared with the acceptable levels of stress for such construction. Table 3 lists the results of the numerical models for different load cases.

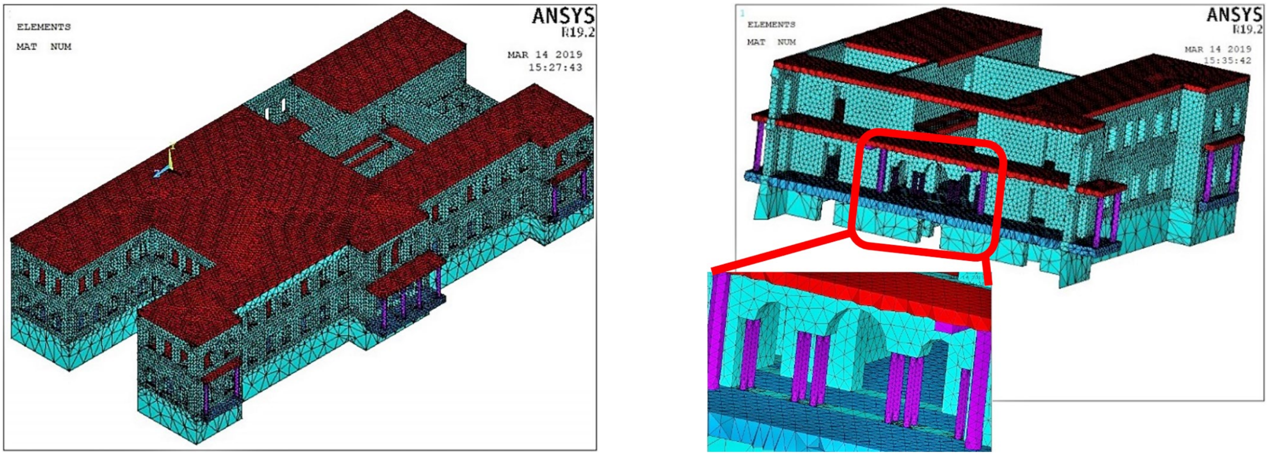


Figure 7. The complete geometry of the FE model for Tosson palace

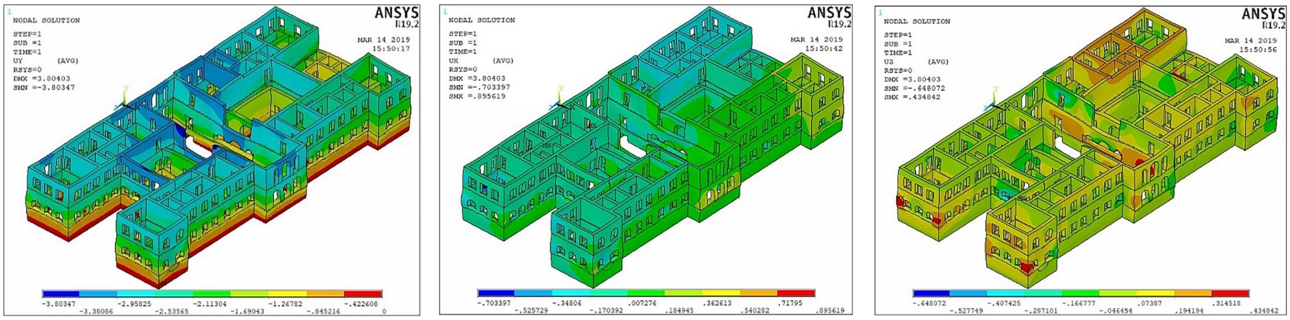
Table 3. The stresses due to different cases in walls and circular columns

	Walls				Circular Columns			
	Horizontal		Vertical		Horizontal		Vertical	
	Compression (MPa)	Tension (MPa)	Compression (MPa)	Tension (MPa)	Compression (MPa)	Tension (MPa)	Compression (MPa)	Tension (MPa)
Vertical loads (D + L)	–0.69	0.7	–1.46	0.53	–1.24	0.27	–0.44	0.50
Response Spectrum	–0.90	0.90	–0.96	0.96	–0.53	0.53	–0.74	0.74

Figure 8 shows a plot for the deformed shape under vertical loads, whereas, Figures 9 and 10 show the deformed shape under seismic loading in X-direction and Z-direction, respectively. Figure 11 illustrates the equivalent stress (Von-Mises) and the stresses in the three principal directions (X, Y, and Z) under vertical loading. Figure 12 illustrates the equivalent stress (Von-Mises) and the stresses in the three principal directions (X, Y, and Z) under seismic loading in X-direction, whereas Figure 13 depicts the same under seismic loading in Z-direction. Five mode shapes resulting from free vibration analysis are illustrated in Figure 14. Table 4 lists the natural frequencies for the first 5 vibration modes in the three principal directions (the transversal, longitudinal and vertical direction). It is worth noting that the time-history of the horizontal displacements at the top of the building in X-direction under seismic loads effect in X-direction. The resulted maximum horizontal displacement in X-direction is about 30 mm.

Table 4. Natural periods and frequencies for the three principal direction

MODE	Frequency	Period	Mode type
1	3.7989	0.26323	Translation in transversal
2	4.48123	0.22315	Translation in longitudinal
3	4.51313	0.22158	Translation in longitudinal
4	5.30252	0.18859	Torsional
5	5.67505	0.17621	Torsional



a) Vertical deformation b) Horizontal deformation (X-direction) c) Horizontal deformation (Z-direction)

Figure 8. Deformation shapes under static loads effect

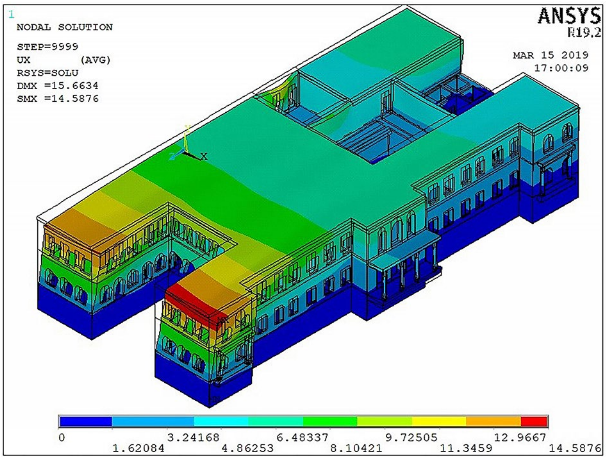


Figure 9. Horizontal deformation (X-direction) shape under seismic loads effect in X-direction

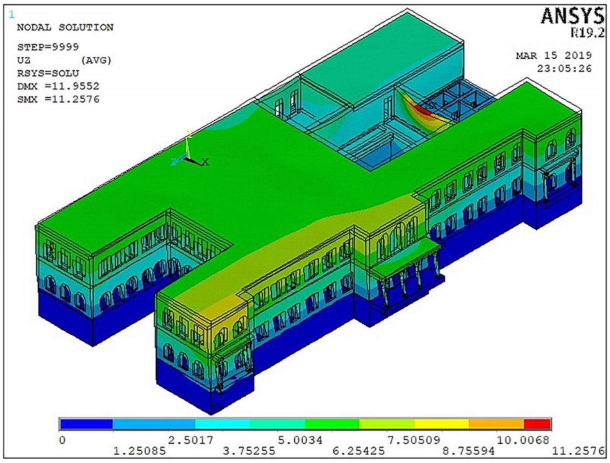
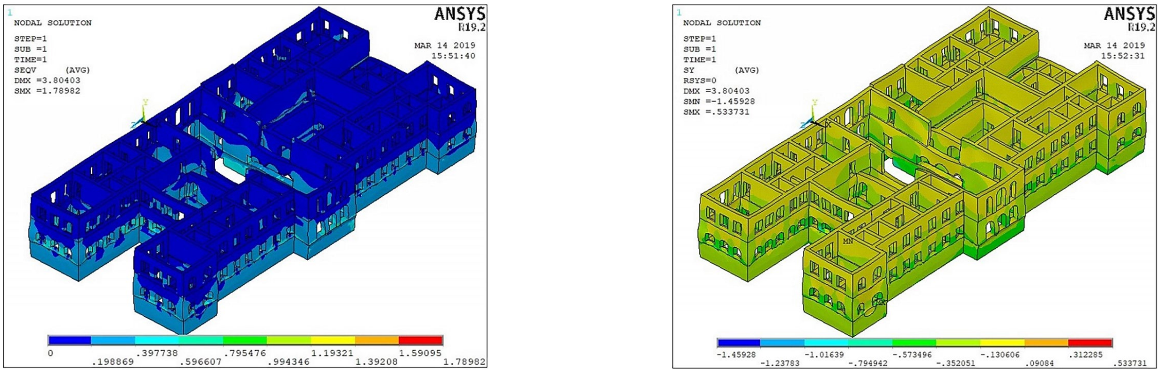
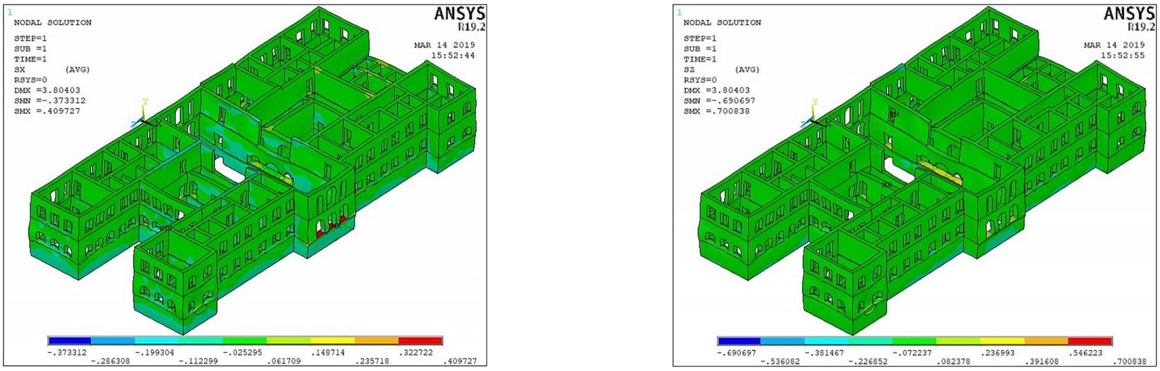


Figure 10. Horizontal deformation (Z-direction) shape under seismic loads effect in Z-direction



a) Equivalent stresses (Von-Mises)

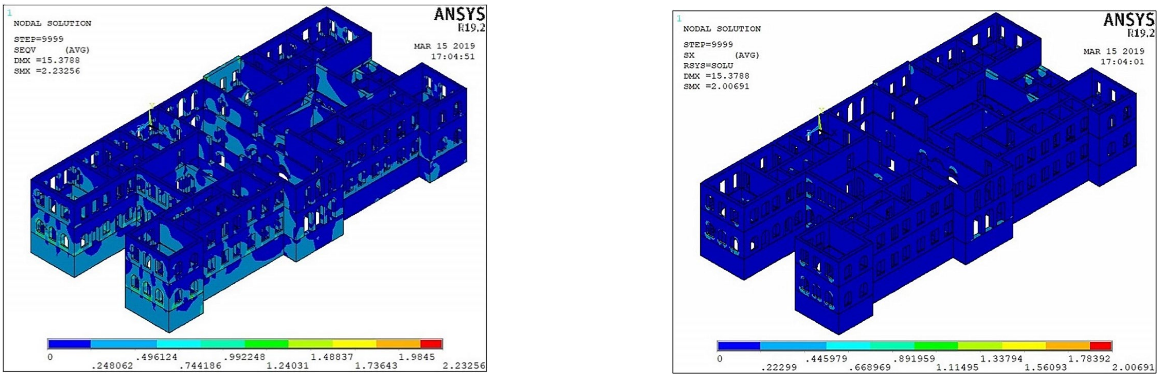
b) Vertical stresses (Sy)



c) Horizontal stresses (Sx)

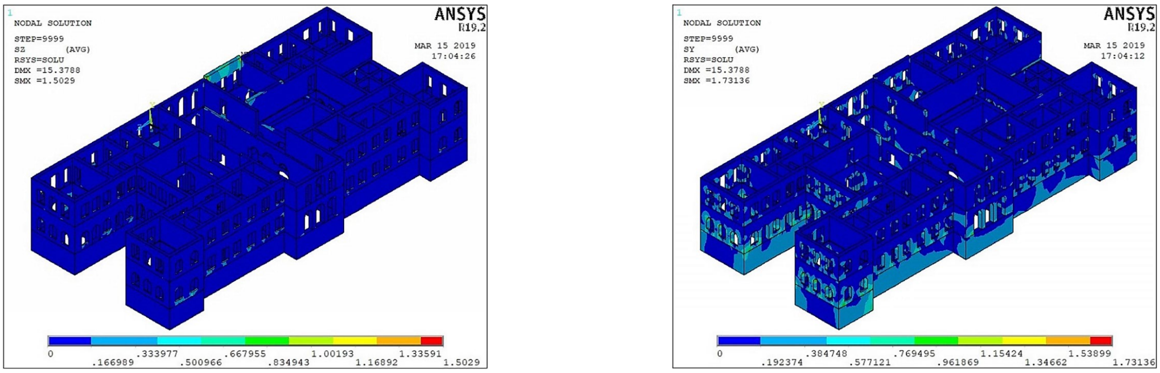
d) Horizontal stresses (Sz)

Figure 11. Stresses under static loads effect



a) Equivalent stresses (Von-Mises)

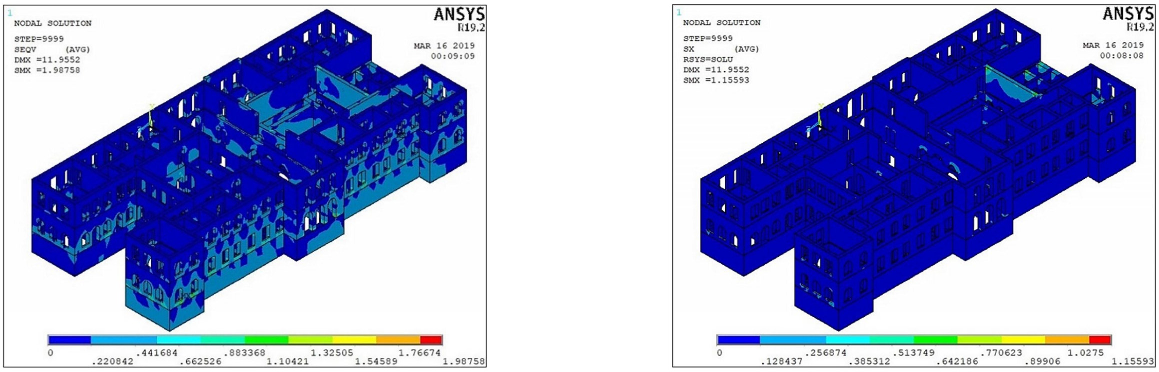
b) Horizontal stresses (Sx)



c) Horizontal stresses (Sz)

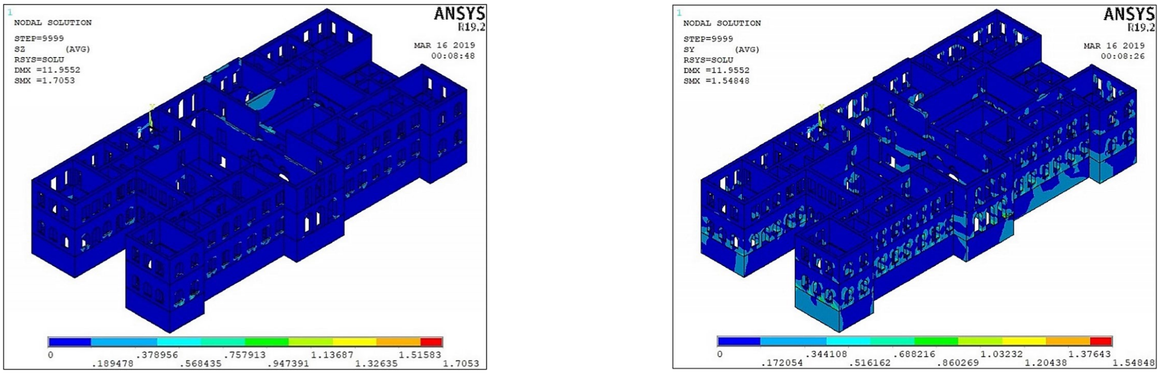
d) Vertical stresses (Sy)

Figure 12. Stresses under seismic load effect in X-direction



a) Equivalent stresses (Von-Mises)

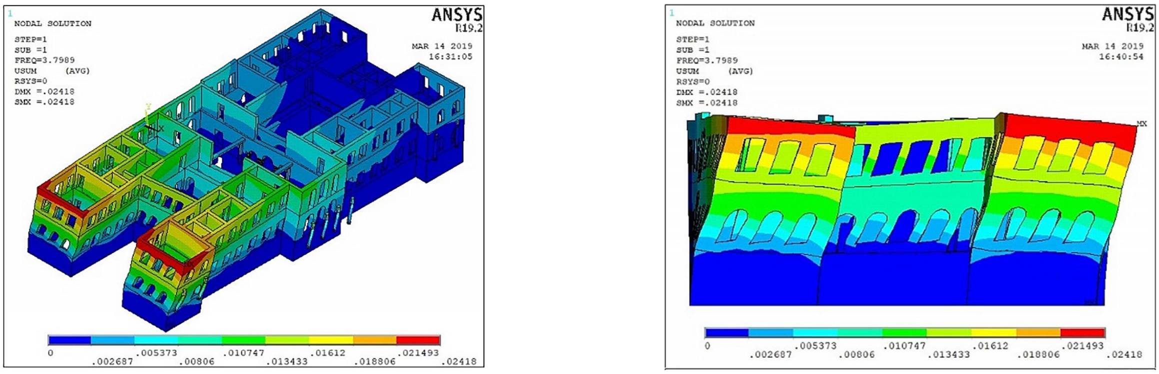
b) Horizontal stresses (Sx)



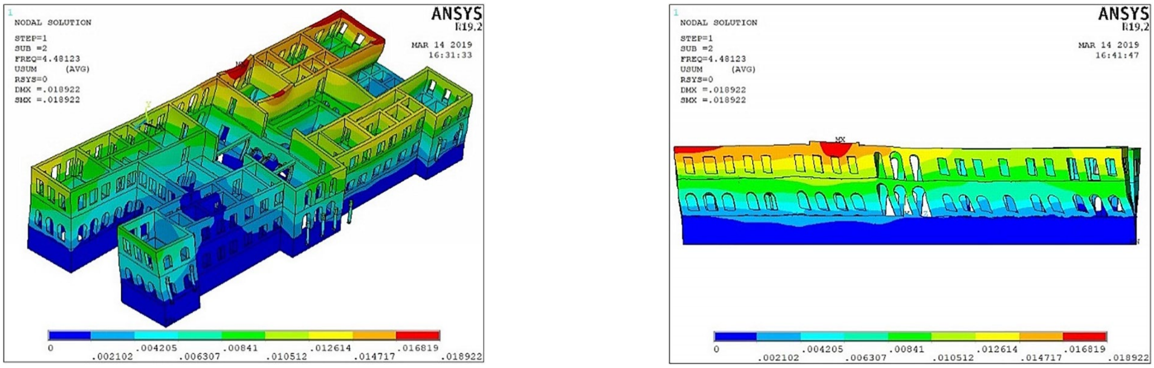
c) Horizontal stresses (Sz)

d) Vertical stresses (Sy)

Figure 13. Stresses under seismic load effect in Z-direction

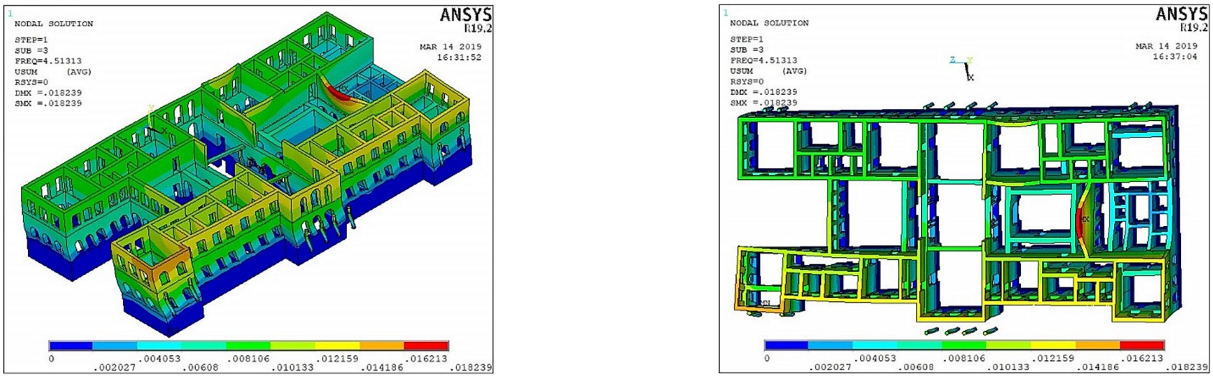


a) Mode shape 1

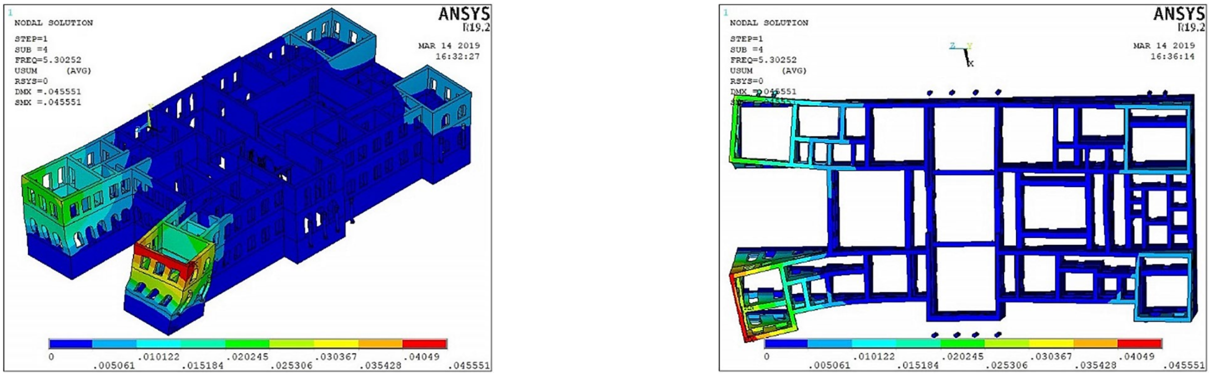


b) Mode shape 2

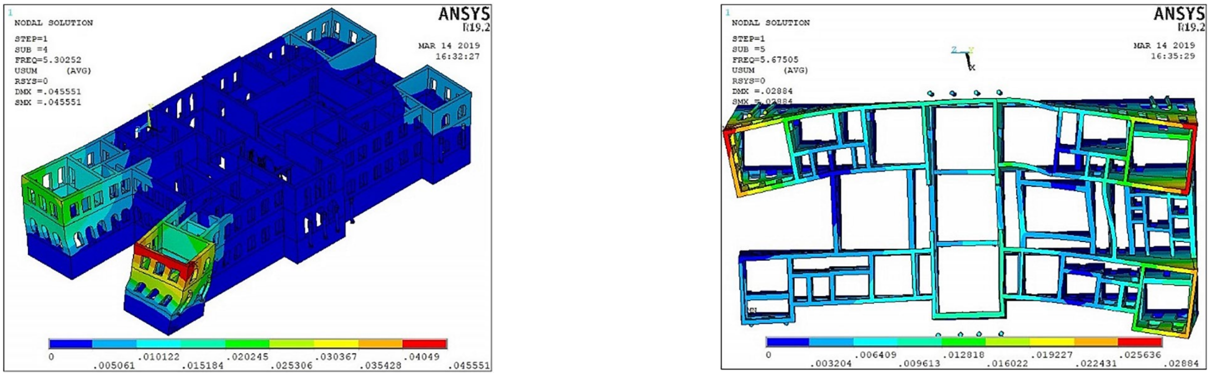
Figure 14. *To be continued*



c) Mode shape 3



d) Mode shape 4



e) Mode shape 5

Figure 14. Five mode shapes resulting from free vibration analysis

Conclusions

This paper presented a framework for heritage Building Information Modeling (HBIM) application in Egyptian heritage buildings. It reviewed the digital documentation of heritage using LiDAR, 3D parametric HBIM models, and structural analysis of heritage buildings. The proposed framework has been implemented in Tosson palace, a 19th century heritage building located in Cairo, Egypt. The procedure for heritage digital documentation is composed of three tiers: 1) Aquire Raw LiDAR data, 2) Process point cloud, and 3) Generate the model. CloudWorks, an Autodesk Revit plug-in, was used to help in tracing the as-built point cloud data captured by the laser scanner. The generated HBIM model was used to perform structural analysis using the finite element model. The analysis showed that, in general, the range of stresses in the walls and columns are relatively low, even less than the acceptable values for such construction. This confirms the initial assessment that from a structural point of view, the monument is in good condition. However, there are some locations where there is visible deterioration of materials and mortar, probably due to environmental conditions that affected the structure throughout its lifetime. The current situation of cracks is generally stable but it is necessary to take concrete steps to replace the damaged materials and repair the cracks. Many deterioration signs in the palace's walls and finishes are related to moisture. The current measured moisture content in the lower part of the walls is rather low; consequently, the deterioration is probably due to an earlier time when the moisture content was high, due to the rise of groundwater, water leakage from the water supply, or collection networks.

Acknowledgements

This research was financially supported by Egypt-UK Newton-Musharafa Fund: Institutional Links; STDF (the Science and Technology Development Fund), Egypt, Grant No. 26150.

Funding

This research was funded by Egypt-UK Newton-Musharafa Fund: Institutional Links; STDF (the Science and Technology Development Fund), Egypt, Grant No. 26150.

Disclosure statement

The author declares that he does not they have any competing financial, professional, or personal interests from other parties.

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