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Modelling and Stability Assessment of the Rock Cliffs and Xrobb l-Ġħaġin Neolithic Structure in Malta

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Abstract: The stability of rock cliffs is a longstanding issue and is of practical significance. This case study demonstrates the application and use of advanced 3D modeling techniques, concentrating on the geological formations of the Xrobb l-Ġħaġin peninsula on the south-east coast of Malta, where the Xrobb l-Ġħaġin Neolithic site is located. In order to utilize a static and dynamic analysis of the investigated scenario, a 3D finite element model (FEM) of the geological formation in which the monument is set had to be created. To this end, 3D scanning, unmanned aerial vehicles (UAVs), and oblique photogrammetry were first used with state-of-the-art commercial packages for mesh reconstruction. As a result, a geometric and finite element model (FEM) was created, suitable for both static and dynamic analysis. In the second stage, a parametric investigation of the material properties of the structural system of the geological substrate was sought. The structural response of the system was evaluated for different loading scenarios assuming nonlinear finite element analysis. Collapse case scenarios were investigated for standard and weakened materials, predicting which components would collapse first and under which case of weakened materials the collapse occurs. Among other aspects, the main novelty of this paper lies in the integrated approach and multidisciplinary paradigm that supplement the available historical knowledge for this specific cultural heritage Neolithic site towards its conservation.

Keywords: structural analysis; numerical simulation; heritage conservation; FEM; megalithic monuments

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1. Introduction

The structural performance of monumental buildings plays a vital role in maintaining and protecting architectural heritage, allowing appropriate preservation strategies to be designed [1]. The damage caused by earthquakes, natural erosion, and deterioration of these buildings leads to loss of the architectural heritage, resulting in a risk for loss of revenue from cultural tourism, which has severe consequences for the local community [2–4], as well as the intrinsic value of the significant heritage sites themselves. On the other hand, the safety and functionality of historic buildings and infrastructure strongly affect people's quality of life. This is quite evident in South Europe, where a significant part of the territory is characterized by a high density of historic and monumental buildings, exposed to a high level of seismic hazard and loss of structural integrity due to deterioration of the geological substructure.

As a result, various researchers have developed new multidisciplinary approaches for the diagnosis and assessment of cultural heritage buildings, utilizing 3D finite element analysis of masonry structures to predict the type and scale of damage under different static scenarios [5–8]. They emphasized the importance of the geometrical survey which, combined with a diagnostic tool, could provide better insights into the underlying mechanisms governing the static and dynamic behavior of the entire building [9–11]. The Stability of rock cliffs is another example where geometry, material properties, possible cracks, and deterioration must be taken into account to predict safety at a given site [12–14].

Following previous research outcomes, this research aims to demonstrate and validate a 3D model of the megalithic temple site that lies on the Xrobb l-Għaġin peninsula in south-east Malta, with reference to modern FEM prerequisites. The Neolithic site, in its unique setting at the edge of an undercut cliff, is of significance as a cultural heritage monument, and valuable insights can be obtained through FEM modeling. Once the mesh and elastic characteristics of the system are defined, it is possible to simulate the actual structural conditions, applying various load and boundary conditions to the model [15,16]. An additional benefit of this paper is the enrichment of the available knowledge related to the Neolithic monument itself, which informs future conservation strategies and preventive action.

Numerical modeling research has been conducted to evaluate the structural response of the geological formation on which the megalithic monument lies. In particular, finite element analysis was selected and applied in this case since the research community widely accepts it as an effective method for the structural assessment of historic infrastructure in restoration plans [17,18]. Both static and dynamic numerical analysis are widely utilized for the modeling of the structural response of masonry structures. Nonetheless, in this approach, several challenges must be tackled in advance, depending on different parameters. Some well-known examples include the structural complexity and geometry of the geological structure, the material properties of the different elements of the structural system, the nonlinear behavior of the materials, and the existence of critical areas such as major cracks resulting due to weathering, deterioration, or other actions. Furthermore, there are uncertainties in the definition of material properties and the determination of the geometry of structural elements due to limited access, especially in the case of hazardous environments [19–21]. Therefore, modeling behavior or predicting the structural response of historical structures can be challenging due to uncertainties related to geometry and boundary conditions, material properties, and load history of existing structures. Ideally, experimental and numerical results are integrated as these may provide unbiased insights into the structural behavior of monuments and their supporting structures.

Finally, it has been possible to generate a 3D model, exploiting the modeling technologies of the Ansys software, Student version 2023. In this way, it was also possible to combine all data gathered including the structural and typological features recorded during the visual survey and site campaigns [20–24]. The integration of these aspects has allowed for the reproduction of the megalithic monument and its surroundings in a virtual environment, obtaining an adequate, versatile, and functional result for all subsequent operations. Through precise conversion steps, the three-dimensional object processed with reality-based modeling methodology was converted into a simplified analytical model using Ansys Student software to exploit it for structural analysis.

2. Object of Study

The megalithic building site lies at Xrobb l-Għaġin, located in the South Eastern Region of Malta near Marsaxlokk. It is built upon the Upper Globigerina Limestone underlain by Middle Globigerina Limestone Marls [3]. The megalithic remains at the Xrobb l-Għaġin site are extremely dangerous to approach, as they lie at the very edge of a deeply undercut clifftop. This was already the case when the site was discovered and excavated a century ago. At that time, in 1915, a portion of the monument was already reported to have collapsed along with the rock on which it was built. The megalithic building has generally been presumed to have been lost to coastal erosion over the past century. However, in 2015, following fresh research on this monument, it was reported that the megalithic remains have not yet been claimed by erosion and cliff collapse [3]. The Neolithic building lies on a sloping spur terminating in a sheer cliff face exposing Upper Globigerina Limestone at an altitude of 20 m at the top and a minimum height of about 13 m at the edge of the cliff. The Xrobb l-Għaġin Neolithic monument is located within a well-frequented Nature Park and surrounding popular areas. In addition, due to the ongoing erosion, site access and onsite operations require extra precautionary measures. As such, a set-back zone has been established, limiting visitors and surveyors from reaching the cliff edge, rendering it difficult to get clear unobstructed views of the cliff and ongoing erosion. As a result of the undercut cliff, archaeological excavation of the site is inevitably conducted by archaeologists secured with harnesses to a steel grillage structure hanging from a crane, to comply with health and safety protocols (Figure 1).

(**a**)

(**b**) (**c**)

Figure 1. (**a**) Map of Malta as seen from Google Earth. The pinned location corresponds to the location of the Xrobb l-Għaġin Neolithic site; (**b**) Archaeological Excavation of the Xrobb l-Għaġin site during 2023; (**c**) 'Plan of Neolithic Remains at Xrobb l-Għaġin on the South-East Coast of Malta, surveyed in May 1915' (Ashby 1915, 209), reproduced from (3).

In the Xrobb l-Għaġin area, the geological formations consist of Upper Globigerina Limestone and underlying Middle Globigerina Limestone beds. In the area adjacent to the

Neolithic site (Figure 2), the Upper Globigerina Limestone is composed of three different geological beds with an upper yellow clayey limestone bed (about 3 m thick), a middle grey marl bed (about 2 m thick), and a lower yellow clayey limestone bed (about 4 m thick). The marl beds in the Upper Globigerina Limestone weather at a faster rate, resulting in a concave cliff face. Similarly, the underlying Middle Globigerina Limestone also weathers at a relatively faster rate, especially near sea level at the base of the cliff face. In the area adjacent to the Neolithic site (Figure 2), the main volume of the geological formation consists of a significant overhang, with a cave at sea level formed by gradual erosion over time and mainly attributed to natural agents including wind and sea at a fault.

Close observation of the geology of the cliff immediately under the Megalithic building at Xrobb l-Għaġin shows a similar condition evolving, with the formation of a large overhang and an underlying cave. The overhanging rock wedge eventually fails under its weight. The cliff falls progressively in this manner over time, and part of the Neolithic building had in fact already collapsed before its discovery in 1915. The erosion of the rock face due to the fatigue of small rock wedges is a slow process when compared to the undermining of the Middle Globigerina Limestone, which is a marl subjected to continuous wetting and drying, and the environmental agents include wave action.

The area investigated covers c. 191 m² and there is evidence of a surface crack in the rock outcrop, running parallel to the cliff edge (Figure 3). A crack in the ceiling, also running parallel to the cliff face is visible from within the cave and overhang immediately under the Neolithic temple and was recorded during previous site investigations by University of Malta researchers. Other transverse cracks are visible at the top of the cliff face.

Given the evidence above and considering the overhang at the temple site, consideration has been given to the recovery of the monument, including scientific archaeological excavation and its relocation to a safe distance from the shoreline to avoid its loss due to overhang failure (Figure 3).

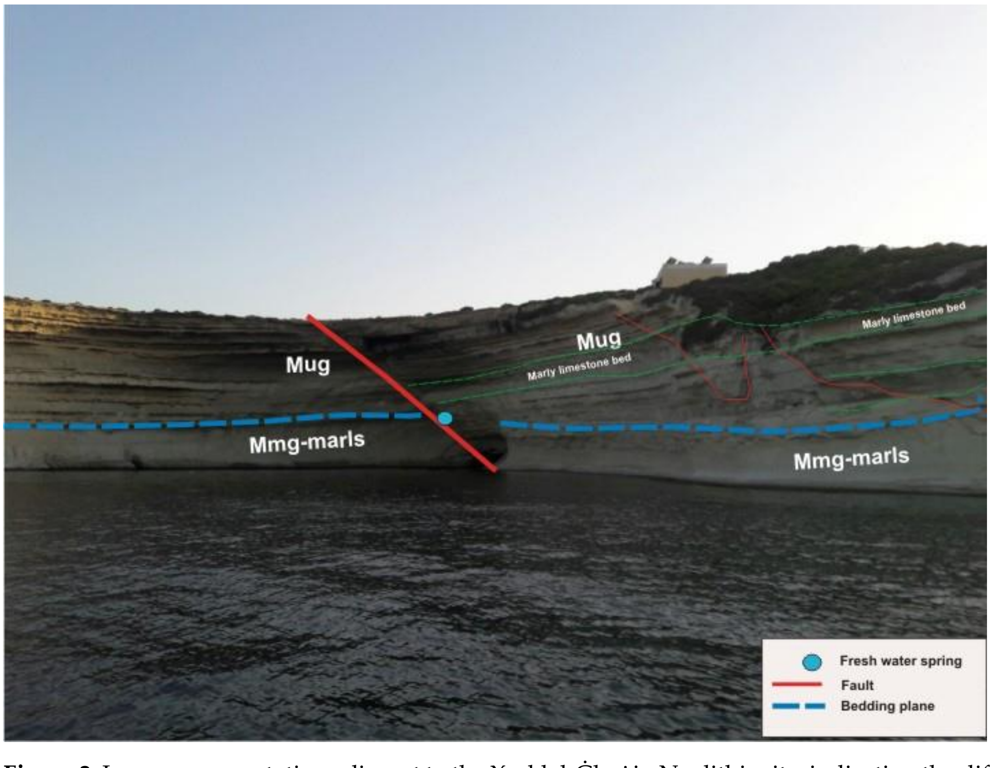


Figure 2. Image representation adjacent to the Xrobb l-Għaġin Neolithic site, indicating the different geological beds, a fault, and a spring. The Upper Globigerina Limestone acts as a local aquifer with the underlying impermeable Middle Globigerina Limestone marls and dipping beds, resulting in a spring in the cavern.; Mug: Upper Globigerina, Mmg: Middle Globigerina (Source: Geologist Saviour Scerri).

Figure 3. In this figure, taken from Google Earth, the blue line represents the major upper crack visible on site, extending to the area of the overhang with the overlying Neolithic building.

3. Materials and Methods

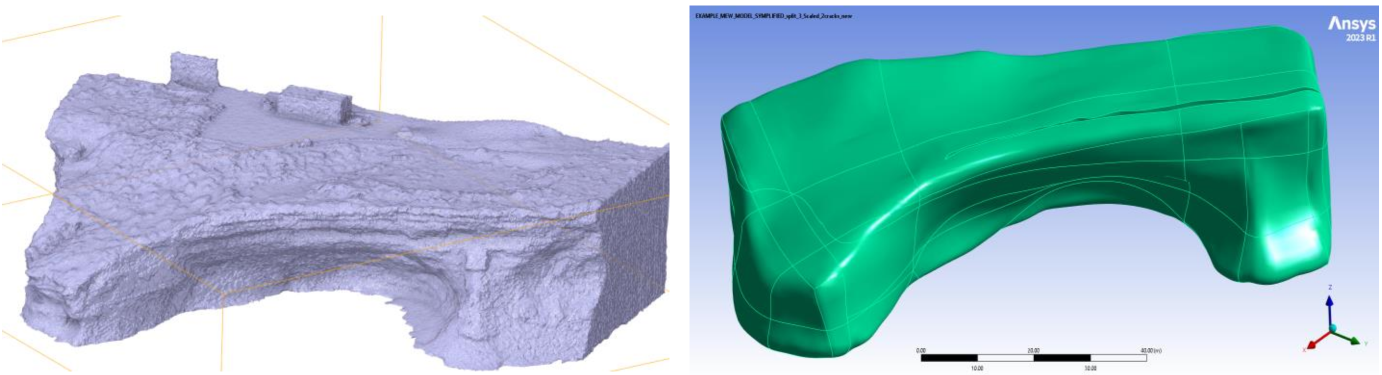
In order to obtain the 3D model of the Xrobb l-Għaġin temple, the oblique photogrammetric technique was employed. This technique can provide a geometrical representation with risk features of the environment in various formats without sacrificing critical structural information. Therefore, aerial-driven platforms were deployed since they can safely operate in inaccessible locations such as those associated with this current investigation. The digitizing pipeline encompasses high-resolution cameras and Structure-from-motion (SfM) image-based scene reconstruction. The UAV commissioned herein was a DJI Mavic Air 2s 2021 model with a 20.0 MP camera and 1-inch CMOS sensor, which flew within line of sight and under constant observation of a second spotter to ensure constant separation from infrastructure, traffic, personnel, and sightseers. In total, 2500 photos were captured, covering an area of 6500 square meters and with altitude varying from 12 to 20 m. Reality Capture software version 1.3.1 of 2023 year released from Epic Games was used to manage the post-processing of 2500 images. Once completed, it resulted in an accurate representation of the megalithic temple and cliff geometry and features (Figure 4).

Figure 4. The figure above presents a 3D reality-based rendered view of the site investigated. On the right-hand side of the image and just before the beginning of the promontory, one can see the cave that transcends parallel to the cliff. The main area of interest, with the Neolithic structure, lies on top of the cave and reaches the upper surface of the cliff.

Reality Capture software successfully provided the detailed output yielding back a model of 8M polygons along with a UV mapping, .mtl file, and a 16K resolution texture in a .png file format (Figure 5).

Figure 5. A 3D model render of the crack as it progresses through the Globigerina Limestone. The high-resolution model created allows for monitoring of the shape and dimensions of the crack.

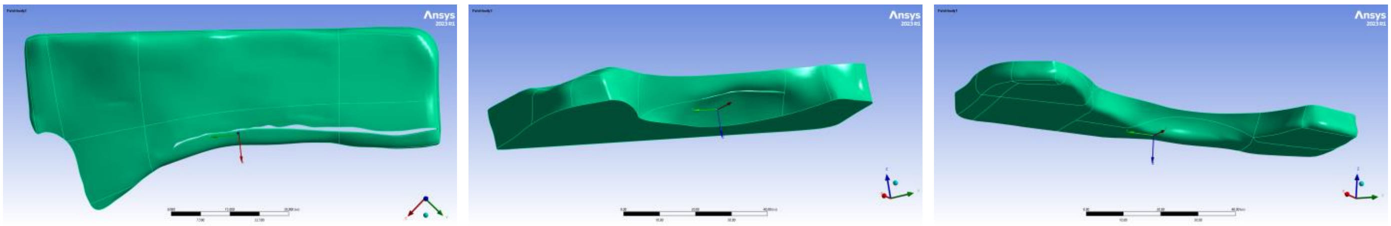
In the case of the Xrobb l-Għaġin Neolithic building, the solid geometry of the structure was created in Ansys Student software, based on the 3D point cloud of the monument. The final 3D model of the building and the surrounding terrain was exported as a .SAT file, which comprised the input for Ansys Student. Finally, finite element model conversion was performed after various optimization steps within the Ansys Student workbench. The approach adopted in this investigation was to obtain a 3D model from a photogrammetric survey for a FEM analysis. The 3d model which originated from the photogrammetry method is presented in Figure 6a. In order to create a 3d model suitable for FEM analysis, it must be transformed into a polygonal surface. For that purpose, the model was adjusted and simplified utilizing the Ansys SpaceClaim workbench, using a series of tools and commands, transforming the 3d model to its final shape, as seen in Figure 6b.



(**a**) (**b**)

Figure 6. (**a**) 3d model which originated from UaV photogrammetry method; (**b**) Final form after necessary processing, ready for FEM analysis in Ansys software environment.

Marly beds in Upper Globigerina Limestone weather at a relatively faster rate, creating a concave rock surface. Likewise, the underlying Middle Globigerina Limestone creates an overhang due to its faster rate of weathering, especially near sea level at the base of the cliff face. A fault and an associated cavern can also be seen in the cliff face. In the following figure (Figure 7), three different layers are represented to introduce the complex geological formations in the 3d model in a simplified manner. Therefore, the Upper Globigerina layer is represented through two distinct layers in the model (Layer A and B), with the top one including the overhang, as seen in Figure 7, and the underlying Middle Globigerina foundation layer (Layer C), in order to allow for parametric investigation. In the 3d model created, the two major cracks are noticeable in the first and second layers of the 3d model accordingly. The interface conditions between the three different layers, as presented above, are considered to be the tie constraint. This linear kinematic constraint permits no opening or sliding between the interfaces, considering them bonded layers.



(**a**) (**b**) (**c**)

Figure 7. The three different layers that comprise the final 3d model. (**a**) Layer A: upper globigerina layer with overhang and crack, (**b**) Layer B: upper globigerina layer with arch-type crack, (**c**) Layer C: middle globigerina foundation layer.

The model created on Ansys Student consists of 85,193 three-dimensional finite elements, covering a volume of 76,254 m^3. Figure 8 shows a closer view of the mesh density of the model. The finite elements are 4-node solid elements (Pyramid shape) with three displacement degrees of freedom at each node. Finally, mesh topology was utilized by invoking the Hex Dominate Method function, which is embedded in Ansys Student and iteratively converts the polygon mesh to a solid pyramidal mesh. Here, another constraint was added to limit each element to 2000 mm, due to the massive volume of the 3d model.

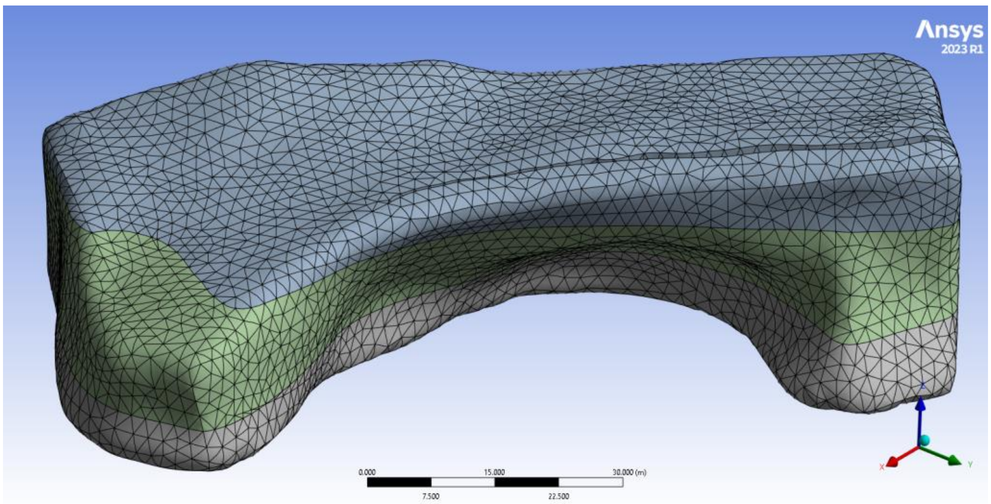


Figure 8. Mesh density of the model, of 85,193 three-dimensional finite elements. Diverse coloring refers to the three different layers that comprise the final 3d model.

The mechanical properties of the different layers composing the cliff beds were complex to determine due to the hazardous environment of the cliff, rendering it impossible to extract actual samples of the Marly bed across its entire depth at present. Close observation of the geology of the adjacent accessible site shows a similar condition to that seen at the Megalithic temples at Xrobb l-Ġħaġin, creating an overhang that produces a hanging rock wedge that eventually fails under its weight. The Upper Globigerina Limestone Member is reported in the Geological Map of Malta as very weak, poorly, ~~too~~ to thickly bedded to massive, cream to yellow, wacke-stone limestone and subordinate, extremely weak, thickly bedded to massive, light grey marly mudstone. Also, the middle Globigerina limestone member consists of very weak, pale grey to dark green-grey marly biomicrites, and mudstones with marly mudstones. For this first model assessment and parametric investigation, the material properties were based on data in the literature [25]. As a result, two different Model case scenarios with different mechanical material properties were created (Tables 1 and 2). For the first case scenario, the material properties proposed have higher mechanical properties, as seen in Table 1. For the second case scenario, a weakened version of the material properties is proposed for the Upper Globigerina top layer A (Table 2), whilst retaining the same material properties for the underlying two layers. We believe that this second case scenario is the most prominent to accurately diagnose the behavior of the critical areas (the top overhang and the arch type crack below) of the geological structure on which the Megalithic temples at Xrobb l-Ġħaġin lie. In these case scenarios, we encapsulate the behavior of the cliff, noting the areas where stress and strain forces are concentrating and, in addition, the areas where the loading forces, attributing to the weight, are distributed. Finally, the behavior of the cliff and its cracks is evaluated for potential risk of detachment in the case of the application of an external force of up to 40% of the initial force that is already imposed due to its weight. In this case scenario, we consider vertical uniformly distributed forces for orthotropic materials, with mechanical properties, as presented in Tables 1 and 2. Each case is further elaborated hereafter in the following chapter.

Table 1. Material Properties: Case 1 scenario.

	Layer A: Upper Globigerina	Layer B: Upper Globigerina	Layer C: Middle Globigerina
Density	1750 kg/m^3	2150 kg/m^3	2300 kg/m^3
Young modulus	50 Mpa	3784.5 Mpa	19,350 Mpa
Poisson's ratio	0.4	0.3	0.2
Shear modulus	277 Mpa	144.7 Mpa	8062.5 Mpa
Compressive ultimate strength	10 Mpa	13.8 Mpa	16.71 Mpa
Tensile ultimate strength	5 Mpa	5 MPa	5 MPa

Table 2. Material properties: Case 2 scenario.

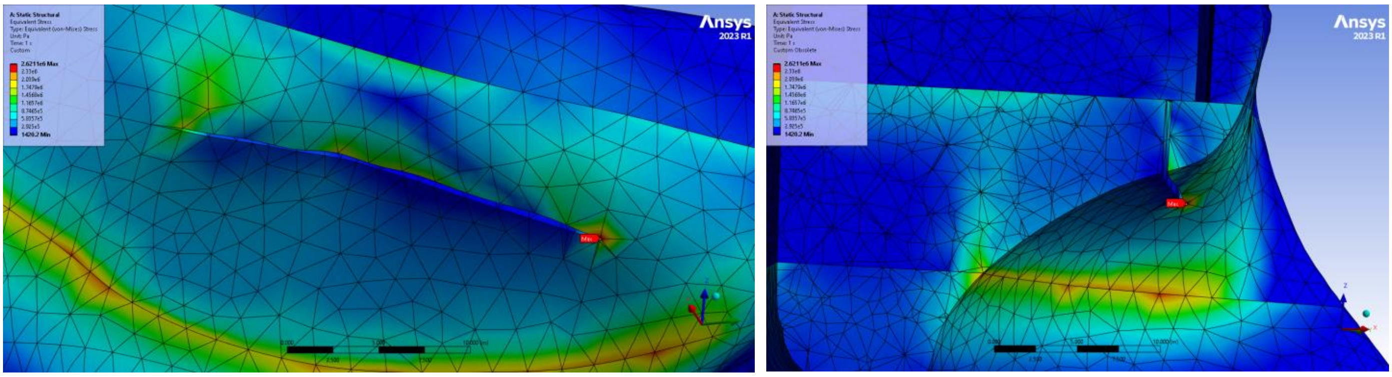
	Weakened Material Properties (Layer A) [1]
Density	1750 kg/m^3
Young modulus	15 Mpa
Poisson's ratio	0.3
Shear modulus	277 Mpa
Compressive ultimate strength	10 Mpa
Tensile ultimate strength	5 Mpa

[1] Upper Globigerina top layer.

4. Results

It is of great importance for the long-term preservation of the megalithic monument and its intrinsic value to assess not only the condition of the geological bed on which the building rests, but also the contribution of the cracks that have already formed, which are visible to the naked eye along the ridge and extending to the top of the cave. The first parametric analysis is conducted to investigate the structural behavior of critical areas of the geological bed using different load scenarios and under different numerical models that shape and predict the structural response, thus exposing the areas where stress is focused. At this point, the precise depth of the cracks is considered unknown due to challenges in direct measurement due to the precarious state of the site. Nonetheless, an informed guess could be made based on previous research endeavors in this area [3,16]. In this regard, a depth of 3 m is assumed for the primary crack, and approximately 2 m is considered for the second crack, reaching the upper wall of the cave beneath. These crack depth estimates serve as a practical and reasonable approach considering the actual site conditions.

Figure 9 represents the current state of the geological bed on which the temple is built, showing the areas where stress is concentrated, due to its gravity load (self-weight of the structure) of 9.81 m/s^2, by calculating the equivalent (Von Mises) stress. As we can see in Figure 9, stress is concentrated in the edges of the arch-type crack, with the maximum stress value being equal to 2.6 MPa. The stress value is lower than the yield strength of the materials, and this confirms our hypothesis about the critical areas at the edges of the bottom crack where stress is accumulated. As a result, no collapse is bound to happen in these areas, even though the crack formed is creating a perilous situation for the monument.

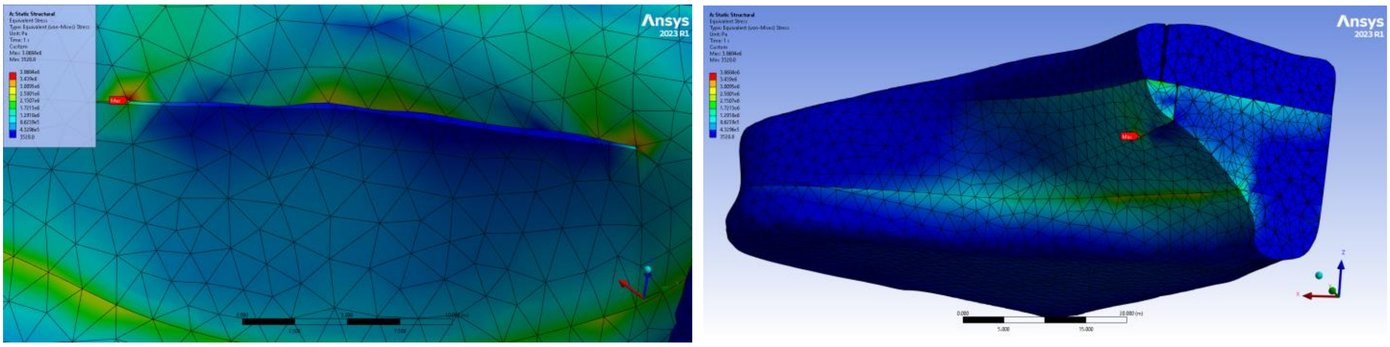


(**a**) (**b**)

Figure 9. (**a**) Equivalent Von Mises stress, with a maximum stress value equal to 2,621,100 Pa, (**b**) cross-section of the area investigated.

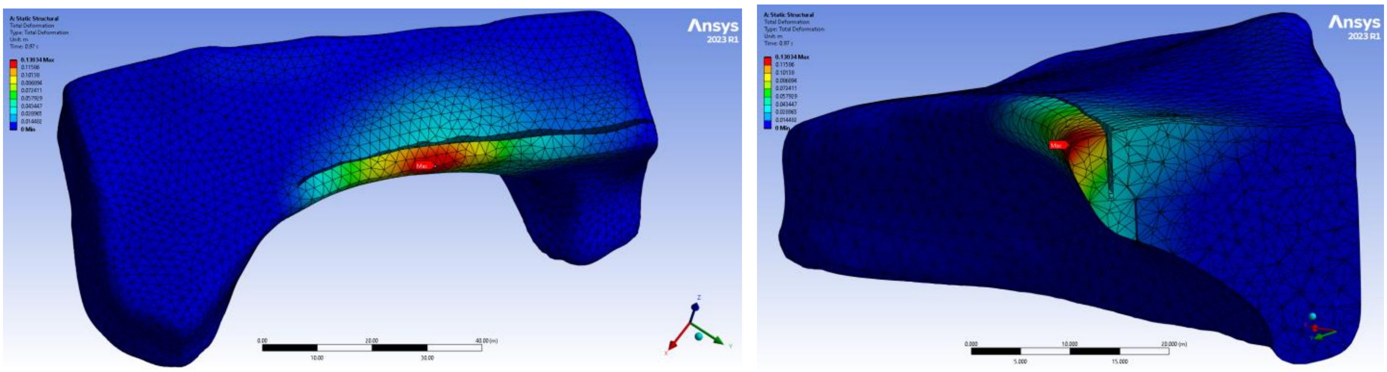
In the following case scenario, the behavior of the geological bed is analyzed, focusing on the critical areas when, in addition to self-weight, there is applied homogenous distributed vertical load at 40% of the original gravity load due to its weight. This is a composite case scenario, where the mechanical material properties of the Upper Globigerina limestone Layer A are considered with respect to two different case scenarios, as seen in Tables 1 and 2.

For this case, the material properties that are considered are presented in Table 1. The simulation analysis yielded interesting results regarding stress distribution on the geological bed in static conditions. As expected, the maximum stress values were found at the edge of the bottom arch-type crack, with the highest value equal to 3.8 MPa, as shown in Figure 10. Moreover, due to the external uniformly distributed load, a displacement in the area where the overhang is positioned is bound to happen, thus giving us a 13 cm total deformation at the center of the overhang, with an approximate crack length of 68.4 m. Figure 11 represents the areas and magnitude of the calculated displacement. The total deformation represents 0.2% of the total length of the crack. Finally, Figure 12 indicates the shear stress distribution, whereas expected the maximum shear stress appears at the center of the top bed crack.



(**a**) (**b**)

Figure 10. (**a**) Equivalent Von Mises stress, with a maximum stress value equal to 3,868,400 Pa, (**b**) cross-section of the area investigated.



(**a**) (**b**)

Figure 11. (**a**) Total deformation of the overhang area, due to external uniformly distributed load, equals to 13,034 cm. (**b**) cross-section of the 3d model in the area investigated.

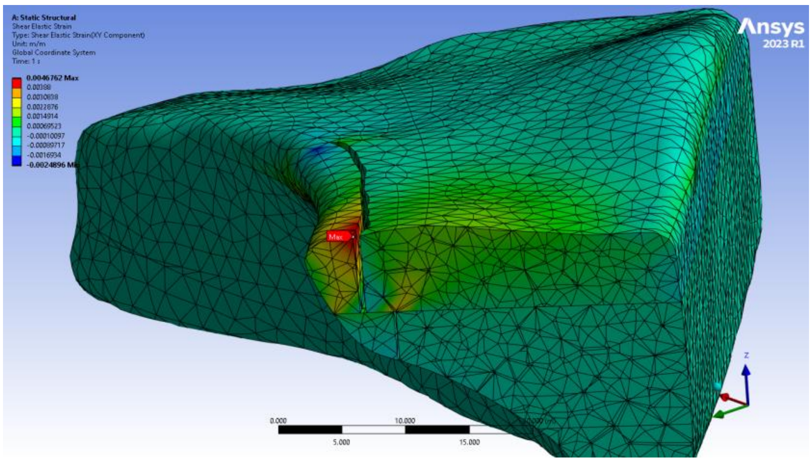
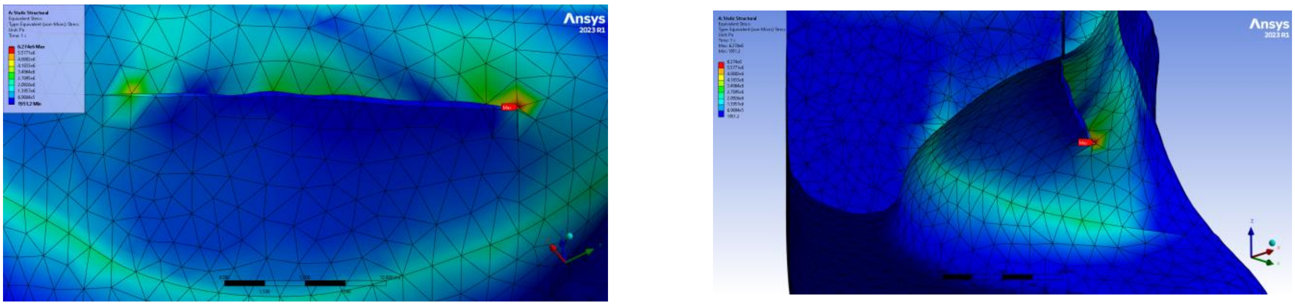


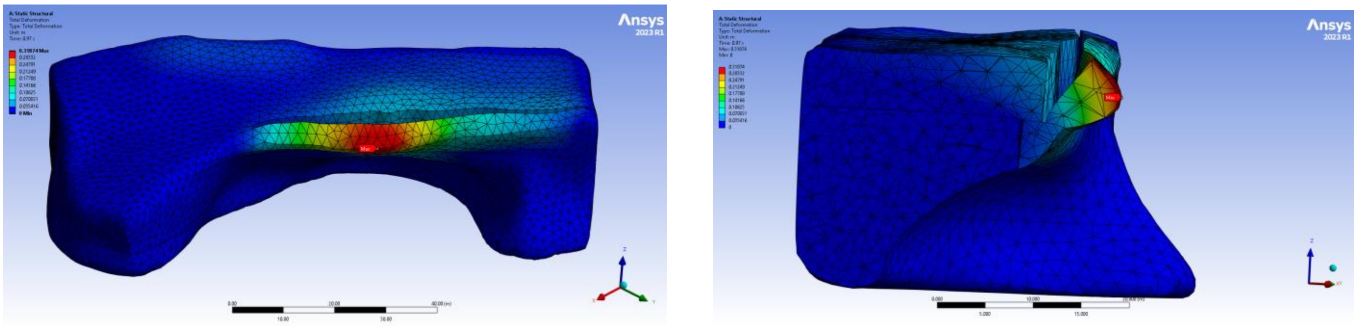
Figure 12. Shear stress distribution.

In the second case scenario, a weakened version of the material properties for the Upper Globigerina limestone Layer A is adopted, as seen in Table 2. As mentioned before, we strongly believe that this case scenario may represent a more realistic behavior of the cliff eventually compromising its structural integrity. Figure 13 represents results regarding stress distribution, showing a structural failure at the area with the maximum value, at 6.2 MPa, a value larger than the Tensile ultimate strength, set at 5 MPa, even though it is smaller than the compressive ultimate strength of the material, which is set at 10 MPa. The critical area is again the edge of the bottom arch-type crack, as seen before. The total deformation is obtained at the center of the top major crack, creating an overhang, with a value equal to 32 cm, as seen in Figure 14. In this case, the total deformation represents 0.5% of the total length of the crack. Finally, Figure 15 indicates the shear stress distribution, and as expected, the maximum shear stress appears at the center of the top bed crack. From these results, it can be concluded that this loading case scenario may prove to be a serious threat to the structural integrity of the geological formation on which the megalithic monument lies. Also, we have to mention that the movement of a single stone can cause a ripple progressive reaction, which will cause soil detachments to follow triggering the surrounding region to be further destabilized [16,26].



(**a**) (**b**)

Figure 13. (**a**) Equivalent Von Mises stress, with a maximum stress value equal to 6,274,000 Pa, (**b**) cross-section of the area investigated.



(**a**) (**b**)

Figure 14. (**a**) Total deformation of the overhang area, due to external uniformly distributed load, equals to 31,874 cm. (**b**) cross-section of the 3d model in the area investigated.

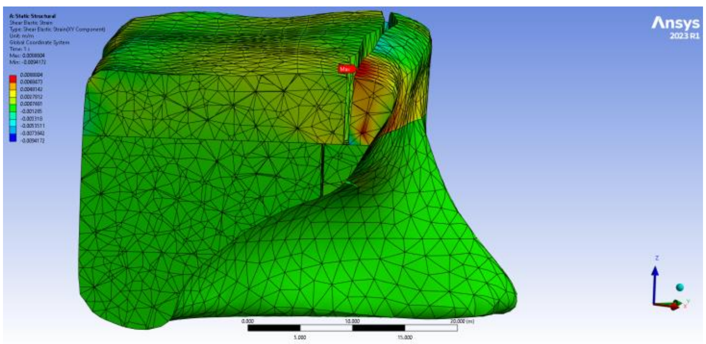


Figure 15. Shear stress distribution.

5. Discussion

Finite element analyses have been extensively used to model multi-drum free-standing columns, typical representatives of ancient Greek antiquity [1,20,22,27,28]. However, limited studies have been conducted on Megalithic Neolithic monuments [16,22,29,30], and even less on complex scenarios of Megalithic monuments on complex geological cliff formations, as presented in the current study. To date, complexity in the scan-to-BIM reversed engineering workflow still undermines HBIM (Historic Building Information Modelling) and FEM integration in various applications [6,7,9,10]. However, structural analysis is a critical part of asset management and can provide useful insights to improve the maintenance and restoration of these indispensable assets in an integrated and multidisciplinary fashion [31–33].

In the present study, UAV photogrammetry is used for geometrical reconstruction of the remains of a megalithic temple and its geological bed. The megalithic temple site lies at Xrobb l-Għaġin, located in Malta. The geometric model is used for subsequent implementation in structural assessment tasks. Aerial and stationary photogrammetry significantly contribute to the accurate geometric representation of historical structures with millimetric precision [34–36]. It is essential to note some limitations of using the photogrammetric method. Despite the high level of detail recorded, greater precision may be needed to detect movement or subtle displacements of the geological bed and its overhangs. The exact geometry obtained from this method is then used for the investigation of the ultimate behavior of the assembly.

Due to the complex and weak material properties that compose the geological beds in the investigated area, further studies are required to assess the impact of catastrophic actions including severe storms on the Neolithic structures According to the present investigation, the Neolithic structure and the cliff are expected to be compromised, and a collapse is bound to occur in the case of a severe earthquake, due to the location of the Neolithic structure remains on top of the overhanging cliff. It should be noted that most results are based on linear elastic analysis, given the many uncertainties due to material properties and the internal structure of the rock cliffs. The analysis can be refined depending on the available data.

Several complex three-dimensional, non-linear models have been developed for the sake of this analysis. In order to define the limit load and the collapse mechanism of the overhang and the crack beneath it, continuum damage models have been used in the present as well as in previous studies. Moreover, the influence of parameters such as the thickness of the structure and the tensile strength of the material in the force–displacement diagrams are shown. Finally, valuable results are obtained when the existing cracks in the geological structure are incorporated into the simulation. Additionally, the variation of the elasticity modulus of the geological beds may significantly influence the values of crack opening in the structure.

6. Conclusions

In the present study, two different case scenarios related to the mechanical behavior of the critical areas of the cliff site are presented. A finite element model is created, originating from UAV photogrammetry measurements, for the mechanical simulation and the estimation of the limit loads. The first part of this study is dedicated to the investigation of the influence of the overhang and crack in Layer A and the arch-type crack in the cave beneath Layer B, under the effect of its weight, as seen in Figure 9. The second part focuses on the behavior of the geological formation, emphasizing the critical areas when, in addition to self-weight, there is applied homogenous distributed vertical load at 40% of the original weight. This is a composite case scenario, where the mechanical material properties of the Upper Globigerina limestone are considered with respect to two different material data assumptions, as seen in Tables 1 and 2.

The solid geometry of the structure was created in Ansys Student software, in the environment of SpaceClaim, based on the 3D point cloud of the monument originating from photogrammetry using, Reality Capture version 1.3.1 of 2023. However, the model generated in this environment needed adequate editing in order to obtain an accurate model of the cliff and to be imported into the FEM software. To reach this purpose, a procedure based on the use of SpaceClaim in Ansys Student software was developed. Thanks to the use of specific tools for three-dimensional modeling as well as tools for the simplification of the triangular mesh in quad mesh, it was possible to generate a 3D model very close to reality, even though simplification was necessary.

Further research could thoroughly compare the FEM results disclosed here against those from a fully automated mesh segmentation algorithm. Moreover, the importance of linear and non-linear analysis of geological structures should be emphasized, while taking into account dynamic analysis that would allow for confirmation of the results. Finally, further research needs to be done concerning the investigation of the behavior of shallow arches beneath the overhang, creating a cave. As the compressive collapse of the overhang is the primary failure mode, a more accurate failure model needs to be adopted, instead of the cap model with the hardening law used in this study. For instance, a model with a softening law could be considered. As a result, an investigation of the limited behavior of the abutments should be conducted.

It should be emphasized that no recorded scientific data of movements, foundation settlement, or other previous actions on the geological formation were available. The assumptions presented in this first analysis of the site are academic and help us demonstrate the ability of the model to predict the influence of various events on the stability of the geological site and its critical components.

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