



# ANCIENT RESTORATIONS: COMPUTER-BASED STRUCTURAL APPROACH FOR THE IDENTIFICATION AND REINTERPRETATION OF THE MEDRACEN'S CONSTRUCTIVE SEQUENCE

## RESTAURACIONES ANTIGUAS: ENFOQUE ESTRUCTURAL NUMÉRICO PARA LA IDENTIFICACIÓN Y REINTERPRETACIÓN DE LA SECUENCIA CONSTRUCTIVA DEL MEDRACEN

Lamia Amokrane<sup>a,\*</sup> , Tsouria Kassab<sup>a</sup> , Juan Monjo-Carrió<sup>b</sup> 

<sup>a</sup> Ecole Polytechnique d'Architecture et d'Urbanisme (EPAU), Laboratoire Ville, Architecture et Patrimoine (LVAP). BP 177, Route de Beaulieu, El-Harrach, 16200, Algiers, Algeria. [l.amokrane@epau-alger.edu.dz](mailto:l.amokrane@epau-alger.edu.dz); [t.kassab@epau-alger.edu.dz](mailto:t.kassab@epau-alger.edu.dz)

<sup>b</sup> Escuela Técnica Superior de Arquitectura de Madrid (ETSAM-UPM). Av. Juan de Herrera, 4, 28040, Madrid, Spain. [juan.monjo@upm.es](mailto:juan.monjo@upm.es)

### Highlights:

- Structural analysis, mainly through 3D modelling, is effective to retrace building chronology and historical stratigraphy by identifying repair additions and their role in an overall structure.
- Ancient restorations were not only intended as repair actions but also as an architectural upgrading and communication tool marking accordingly new eras in a building lifecycle.
- Medracen's restoration is a relevant example of architectural repair actions aimed at enhancing a building's image and function in the North African context during the 4<sup>th</sup>-3<sup>rd</sup> century BC.

### Abstract:

This paper addresses the importance of a structural approach for identifying and interpreting building chronology, as well as for the establishment of historical stratigraphy. Through structural analyses, carried out on the oldest extant royal mausoleum in North Africa, the Medracen (4<sup>th</sup>-3<sup>rd</sup> century BC), located in eastern Algeria, it has been possible to identify building sequences and structural characteristics; a reinterpretation of its constructive sequence within a specific historical context was also suggested. A static linear Finite Element Method (FEM) analysis was performed on a simplified 3D model conceived with solid elements to assess the structural behaviour of the structure under the effect of its self-weight and to identify, consequently, its construction sequence. The equilibrium approach was effective in identifying the structure's geometry. Results show that Medracen's ancient restoration was a strengthening intervention strategy and had a symbolic aim related to the function of the funerary building. Restoration works, consisting of repairing specific parts of the building and adding an external cladding, as a whole architectural entity, contributed to reducing the effect of tensile stress, therefore, stabilizing the inner core. Besides, this same action was a means for the Numidian elite to transform an ancient monumental burial (*sepulchrum*) into a monument (*monumentum*) with cultural significance likely to convey socio-political messages relating to power and sovereignty. Therefore, we can speak of an "evolutionary restoration" that reflects the ambitions of the Numidian elite to become part of the Mediterranean orbit.

**Keywords:** archaeological heritage; ancient restoration; structural analysis; building chronology; Medracen; Royal mausoleum of Numidia

### Resumen:

Este artículo aborda la importancia del análisis estructural para la identificación e interpretación de la cronología de la construcción y el establecimiento de una estratigrafía histórica. A través de un análisis estructural, realizado sobre el mausoleo real más antiguo que se conserva en Argelia en el norte de África, el Medracen (siglos IV-III a.C.) localizado en su parte oriental, se han podido identificar algunas secuencias constructivas y características estructurales con el objetivo de sugerir una reinterpretación de su cronología constructiva enmarcada en un contexto histórico específico. Se realizó un análisis estático lineal por elementos finitos sobre un modelo 3D simplificado, concebido con elementos sólidos, para evaluar el comportamiento estructural del monumento bajo el efecto de su peso propio e identificar, en consecuencia, su secuencia constructiva. Por otro lado, el enfoque del equilibrio del conjunto fue eficaz para identificar la geometría de la estructura. Los resultados muestran que la antigua restauración de Medracen tuvo como meta una intervención de refuerzo y un objetivo simbólico relacionado con la función del edificio funerario. La restauración, consistente en la reparación de partes específicas del edificio y la adición de un paramento exterior, como entidad arquitectónica de pleno derecho, contribuyó a reducir el efecto de las tensiones de tracción, estabilizando así el núcleo interno. Además, esta

\* Corresponding author: Lamia Amokrane, [l.amokrane@epau-alger.edu.dz](mailto:l.amokrane@epau-alger.edu.dz)



misma acción fue un medio para que la élite Númida transformase un antiguo sepulcro (*sepulchrum*) en un monumento (*monumentum*) con significado cultural capaz de transmitir mensajes sociopolíticos relacionados con el poder y la soberanía. Por lo tanto, se puede hablar de una "restauración evolutiva" que refleja las ambiciones de la élite nómida de integrarse en la órbita mediterránea.

**Palabras clave:** patrimonio arqueológico; restauración antigua; análisis estructural; cronología de la construcción; Medracen; Mausoleo Real de Numidia

## 1. Introduction

The concept of architectural restoration in its actual definition appeared in the 19<sup>th</sup> century with Eugène Viollet-le-Duc (1875) who argues that "to restore a building is not to maintain it, repair it or remake it, it is to re-establish it in a complete state which may never have existed at a given time". This definition of the stylistic restoration has been criticized and reviewed by John Ruskin. According to Ruskin, the so-called stylistic restoration alters the architectural structure's authenticity and the history it conveys. Thus, "conservation" is privileged rather than "restoration" in order to preserve the authenticity and integrity of a building, limit the deterioration process and ensure its longevity. Beyond these antagonistic visions of restoration-conservation, more recent notions such as reconstruction and reconstitution, are used to enlarge the actions field on architectural heritage structures. Consequently, restorers/conservers can easily adapt to the different architectural or archaeological sites' realities so that they can plan the most appropriate intervention.

In 1977, Cesare Brandi gave us a complete definition of restoration, which has the value of a moment of teaching and learning, while operating for the repair of a work of art in its material and immaterial integrity; "*restoration constitutes the methodological moment of recognition of the work of art, in its physical consistency and its double aesthetic and historical polarity, with a view to its transmission to future generations (...). Restoration must aim at re-establishing the potential unity of the work of art, provided that this is possible without committing an artistic or historical forgery, and without erasing any trace of the passage of this work of art through time*" (Brandi, 2001). Shall our interest be nowadays focused on the architectural heritage transmission to future generations, which is a worthy objective, it is noteworthy that in the past, restoration works had a totally different ideology. During antiquity, even if it is generally assumed that restoration, as a repair practice, was mostly limited to furniture or works of art, such as mosaics, ancient architecture, especially sacred and monumental buildings, also benefited from restoration works. At the time, restoration was carried out with the aim of extending monumental architecture's longevity for its definite usage and symbolic values. As a result, these restoration projects were justified and designed within an ideological vision and a philosophical approach generally related to the concepts of power and communication. Examples include the restoration of the Temple of Hercules Musarum, led by Lucius Marcius Philippus, the restoration of the Temple of Agrippa, rebuilt and transformed into the Pantheon by Hadrian after a destructive fire, and the numerous restorations of the Forum Romanum, which were aimed both at the maintenance of this urban area and the transmission of various messages relating to power (Jacobs, 2017). The latter successive restorations bear witness to the fact that the Romans were not only great builders but also restorers in a broader sense.

In North Africa, a regional hub in the very heart of the Mediterranean, data on ancient restorations is fragmentary. Due to the lack of a systematic study, at least carried out on the most representative structures of the time, ideologies underlying restoration projects are not clearly identified. Besides, North African populations evolved in a multi-cultural environment where they were able to preserve their local culture while continually opening up to the common Mediterranean one. This characteristic feature of "North African culture" implies concepts of change, continuity, identity and community (Moussa, 2007), which accordingly justify architectural restoration: an edifice repair aimed at marking a key moment in the history, materializing a social and cultural ideal, displaying technological progress, and conveying messages relating to power. Therefore, identifying ancient restorations in the North African architectural and archaeological context, and understanding moreover their underlying philosophy, is likely to lead to better restoration-conservation planning and management since:

- Additions are identified as well as buildings constructive sequence and historical phases. Concept of Authenticity (ICOMOS, 1994; Stovel, 1995; Jones, 2009) is accordingly defined, taking into account plausible hypotheses verified through virtual reconstruction (Muñoz Morcillo, Schaaf, Schneider & Robertson-von Trotha, 2017), to set the theoretical background of future restoration-conservation projects;
- Ancient restoration techniques can be studied and their effectiveness assessed so as to understand how they ensured the stability and longevity of a building.

Therefore, when observation or archaeological investigations bring into the spotlight evidence to anachronism inherent to building materials or construction techniques, a historical and technical study is most welcome in order to understand how these techniques and materials were articulated to repair an ancient edifice. Admittedly, we refer within this paper to qualitative-quantitative study. "*The qualitative approach is based on direct observation of structural damage and material decay as well as historical and archaeological research, while the quantitative approach requires material and structural tests, monitoring and structural analysis*" (ICOMOS & Iscarsah, 2005). When combining these approaches, the identification of the constructive sequence is accordingly justified and the building's evolution is placed within a specific historical, cultural and social context. As recommended, "*any intervention to an historic structure must be considered within the context of the restoration and conservation of the whole building*" (ICOMOS & Iscarsah, 2005).



**Figure 1:** General view of the Medracen, 2018.

This statement implies the identification of ancient restorations<sup>1</sup> that, unlike modern restoration works which are guided by several national and international charters and guidelines, are in most cases difficult to recognize, in order to understand building chronology. The latter is of paramount importance prior to any repair action. In fact, identifying a constructive sequence, whether it is related to restoration works, implying the concept of addition, or not, is indispensable to determining the structural role of each part of a building (e.g. [Pelà, Bourgeois, Roca, Cervera & Chiumenti, 2016](#); [Coronelli, Caggioni & Zanella, 2015](#); [Crespi, Franchi, Giordano, Scamardo & Ronca, 2016](#)) and to understand building phases and techniques of an architectural heritage structure (e.g. [Benito Pradillo, 2017](#); [Pulido, Durá, Fenollosa & Boquera, 2016](#)). Therefore, once an ancient restoration is identified, its study should be carried out for drawing up a relevant conservation-restoration plan which encompasses new diagnosis and analysis methods. Yet, as for archaeological sites and structures, study and diagnosis need to be carefully led in order to prevent additional damage. Structures of architectural and archaeological heritage, mainly masonry ones, present several challenges for their study, diagnosis and conservation. By their very nature, their geometric description, morphology, constructive history, properties of the building materials, damage and alterations ([Roca, Cervera, Gariup & Pela, 2010](#)), these structures are subject

to continuous alteration that needs to be urgently limited or repaired to ensure building's longevity. Consequently, computer-based approaches for building analysis are much needed to assess archaeological edifices' structural behaviour, identify its building sequence and suggest an action plan accordingly. This paper discusses building chronology and stratigraphy as a means of identifying ancient restoration and its underlying ideologies. We will perform a computer-based structural analysis on Medracen (Fig. 1) —the oldest existing royal funerary mausoleum in North Africa, in order to suggest a reinterpretation of its constructive sequence. This new view is based on direct observation of the monument ([Amokrane, Kassab & Monjo-Carrio, 2020](#)) and aims to highlight the cultural and social ideology underlying the ancient restoration of the Medracen during a period of time where North African kingdoms were being progressively annexed to the Roman Empire. At this point, it should be remarked that the identification and reinterpretation of Medracen's constructive sequence can mainly rely on a computer-based structural analysis taking into account materials and building techniques. This approach will fill the available data gap for the interpretation of Algerian archaeological heritage and its conservation as recommended in the *International Principles of Virtual Archaeology* ([Seville Principles, 2017](#)).

<sup>1</sup> In this paper, « ancient restoration » refers to possible restoration or repair works carried out during antiquity in the Numidian context, especially just before and just after the Roman takeover.

## 2. Related works

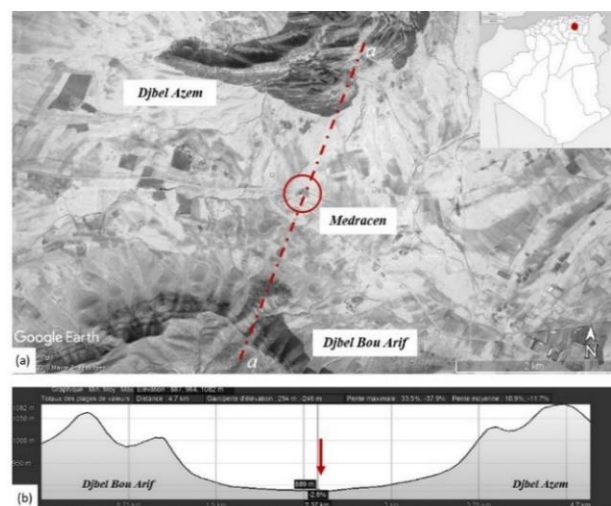
In order to better manage the use of new technologies in the study, analysis and diagnosis of ancient structures of the architectural and archaeological heritage, the London Charter has been published to give guidelines to follow and develop according to specific research aims before any computer-based visualisation project (London Charter, 2009). During the last decades, several methods have been developed to perform computational structural analysis, suggest hypothetical reconstruction, manage evidence-based restoration, or communicate and disseminate knowledge about cultural heritage. The developed approaches can therefore be divided into three main categories relating to the purpose of using a computational tool: 1) computer-based analysis-diagnosis methods (Finite Elements, Discrete Elements, etc.), 2) computer-based research visualisation, and 3) computer-based visualisation for communication and/or information (3D modelling, animations, rendering, virtual reality, etc.). In this paper, we focus on computer-based analysis-diagnosis methods. Most of the previous publications using computer-based tools for simulation and analysis are focused on ancient masonry structures of medieval architecture. Not only has their complex geometry arisen interest in this type of structure but also their urban location, touristic and usage values which engender continuous funding for their conservation-restoration. Several methods and tools aiming at studying these geometrically complex structures have been made available (see, e.g. Whiting, Shin, Wang, Ochsendorf & Durand, 2012; Barazzetti *et al.*, 2015, Pelà *et al.*, 2016; Benito Pradillo, 2017; Karanikoloudis, Lourenço, Alejo & Mendes, 2020) and are continuously developed to attain the most valid and reliable results. However, as for ancient buildings, mainly those with basic geometry (such as the Pyramids), computer-based analysis-diagnosis studies are less presented (see, e.g. Giannattasio, Grillo & Murru, 2016; Aguilar *et al.*, 2017; Masi, Stefanou & Vannucci, 2018; Giaccone, 2020). They are rather studied through virtual reconstruction for information-communication aims as they are considered as totally or partially lost buildings and artefacts (Younes *et al.*, 2017; Stampouloglou *et al.*, 2019; García-León, González-García & Collado-Espejo, 2021). Although the majority of ancient structures have basic structurally stable and self-supporting geometries, they are still unique study cases when considered for conservation-restoration. Put in the context of the time, these structures become an information source that allows nowadays practitioners of built heritage to learn more about ancient building techniques in order to respond to the requirements of actual restoration practices: similar techniques, same materials, minimum additions, etc. (ICOMOS, 1931; ICOMOS, 1964).

Therefore, even if ancient buildings' geometry (general morphology and metric documentation) is rather easily accessible, structural schemes, including inner materials layouts, require specific methodologies, tools and more time to be identified. The heterogeneity of the materials, the innumerable discontinuities within a structure and its conservation state, in most cases, deplorable, mean that 3D surveys, using the most recent techniques such as laser scanners or photogrammetry (Alby, Vigouroux & Elter, 2019; Riveiro & Lindenbergh, 2020; Vital & Sylaiou, 2022) become very complex to carry out. Consequently, when the study, analysis and diagnosis of these structures are necessary, simplifying 3D models are most

welcome. At this point, defining the aim of the 3D reconstruction (Di Mascio, Chiuni, Fillwalk & Pauwels, 2016) is of paramount importance. When aiming at visualization or structural analysis for operational purposes, the most sound and reality alike model should be conceived. However, when aiming at research and historical interpretation, set in a remote timeframe, simplified models can be admitted as long as they preserve the building's main characteristics. High levels of materials heterogeneity and discontinuity constraint scholars to opt for simplified structural schemes to give some first interpretation. Simplified or basic models have the merit of becoming a source of information in their own right. Indeed, their design and the exploitation of the results obtained following their study and analysis make it possible to bring to light data that would not have been obtained without this modelling process and correct accordingly incongruities by going back and forth between the 3D model and the research sources (Demetrescu, 2018).

## 3. The case study: the Medracen or Royal Mausoleum of Numidia

Medracen is located in Batna, eastern Algeria (Fig. 2). According to radiocarbon dating the mausoleum was built between  $403 \pm 53$  BC and  $286 \pm 42$  BC (Camps, 1973). It has been described for the first time by El Bakri during the 11<sup>th</sup> century (El Bakri, 1913) and later by European explorers before the French occupation (Shaw, 1743; Peyssonnel, 1838). During the first years of French colonization (1830-1962), the mausoleum has been broadly studied by French archaeologists commissioned in Algeria (e.g., Becker, 1854; Foy, 1858; Brunon, 1873). More recently, several scholars continue studying this emblematic monument both as an architectural structure (Camps, 1973) and as an artefact of Numidia's history (Coarelli & Thébert, 1988; Rakob, 1983; Thébert, 2005; Quinn, 2013).



**Figure 2:** Medracen's location and site integration. Source: Google Earth.

As previous research suggested, Medracen was built for the royal family of Numidia that governed a large territory from Mulucha River in actual Morocco, to the western limits of Carthage. This kingdom was governed by Massinissa, Numidian King, *friend and ally* of the Romans, for more than fifty years where Numidia flourished as a Mediterranean potency. Medracen, a

monumental burial, has been accordingly associated with Numidia's history and its royal family that was deeply steeped in the Hellenistic culture, hence its Greco-Punic architectural cladding. However, even if the mausoleum has been widely studied, aspects relating to its building sequence, and the characteristics of the inner structure are still to be investigated for a better restoration-conservation and site management plan. It is noteworthy that Medracen was repaired in 1973 within the framework of an Italian-Algerian cooperation. The monument's stability was partially repaired by reconstructing part of the inner core, adding new molded conglomerate cement blocks, and proceeding to an anastomosis when it was possible (Donati, 1973). These restoration works remain the most accomplished to date, even if the added elements altered considerably the building's aesthetic balance and its authenticity. Between 2006 and 2008, urgent safeguard measures were undertaken in order to avoid the imminent collapse of the architectural cladding. The latter consisted of wooden props mainly added on the eastern side of the monument. Today, Medracen's safeguarding is one of the main concerns of Algeria in the field of architectural and archaeological heritage conservation. The monument is continuously being considered for international collaborative restoration-conservation projects for its historical, cultural and architectural values, and for being part of a large architectural series of royal funerary mausoleums in North Africa (UNESCO, 2002), built before the Roman takeover.

In order to meet the objectives of this paper, the Medracen seems to be a relevant example. Its study is to be considered at the intersection of the technical and historiographical research fields. Actually, the Medracen was built within a historical context marked by economic and cultural movements aimed at inserting Numidia into the Mediterranean orbit. On the economic front, Numidia was one of the main exporters of several agricultural products intended for Rome, ally and friend of the Numidians. While culturally, Numidian elite was voluntarily introducing the attributes of a *Numidian Hellenism* (Coarelli & Thébert, 1988) into the royal court. This kind of change dynamics naturally leads to renewed monumental architecture expression that goes along with the new needs of an elite aiming to assert sovereignty and power. As regards technical and structural aspects, Medracen presents an interesting particularity. Its overall structure consists of an inner nucleus to which an architectural cladding (E2) was added. The first entity (E1) is built of a stack of limestone slabs, while the external cladding consists of an assembly of sandstone blocks sealed with clamps. Previous research did present this aspect of Medracen's structure without attempting to understand the reasons behind this materials and building techniques choice, dividing the structure into two distinct entities. Besides, it has been previously shown that Medracen is the product of the fusion of a *choucha* (a cylindrical tower tomb delimited by a peripheral wall of variable dimensions) and a *bazina* (a tumulus tomb, generally covered with an architectural cladding (Camps, 1959), and enclosing the burial in its centre) which are two typically North African types of minor burials). Even if the stepped *bazina* is morphologically similar to Medracen, the latter cannot be a direct scale *monumentalization* (Laporte, 2009) of the *bazina* because its structure's characteristics cannot match those of a large sized monument like Medracen. Its structure (cylindrical base surmounted by a

stepped truncated cone structure) is much more analogous to a hybrid typology (*choucha* and *bazina*) than to a monumental *bazina* (Amokrane et al., 2020). Finally, these two aspects —related to the monument's general history and to its building techniques—, lead to redefining the notion of *monumentalization* (Laporte, 2009) to go beyond size and scale matters and, understand accordingly how monumentalization and restoration are articulated in the Medracen.

#### 4. Structural analysis: methods and materials

This section studies the hypothesis of a peripheral wall<sup>2</sup> supporting the inner structure of Medracen (equilibrium approach) and the structural role of the architectural cladding by means of a 3D simplified model (numerical approach). Due to the heterogeneous composition of the inner structure, following several collapses that occurred over time since its first construction and hence too complex to be fully and precisely modelled, it was essential to simplify the structure's modelling without neglecting its main characteristics in order to study the most reality alike model (ICOMOS & Iscarsah, 2005). The suggested structural scheme refers to Medracen's initial structure (4<sup>th</sup>-3<sup>rd</sup> century BC), considered with no alteration, i.e. idealised, in order to highlight its constructive sequence, and place it within the chronology of Numidian history and, suggest accordingly a historical interpretation of ancient restoration actions.

##### 4.1. Identification of the Medracen's geometry

Medracen is a cylindrical based structure topped with a succession of 23 steps, with an average height of 0.58 m each, while their diameter varies from bottom to top. The overall structure is 18 m high with a diameter of 58 m at its base. Since we have suggested an analogy between Medracen's structure and that of a *choucha*, combined with a stepped *bazina*, we assume that a peripheral wall supports the structure at its base as depicted in (Figure 3).

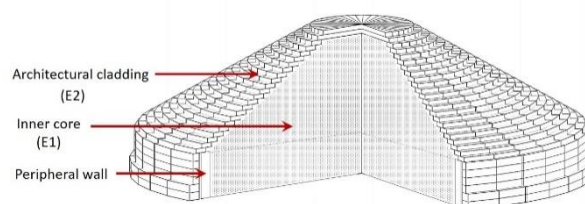


Figure 3: Identification of the main structural entities (E1 & E2) in Medracen.

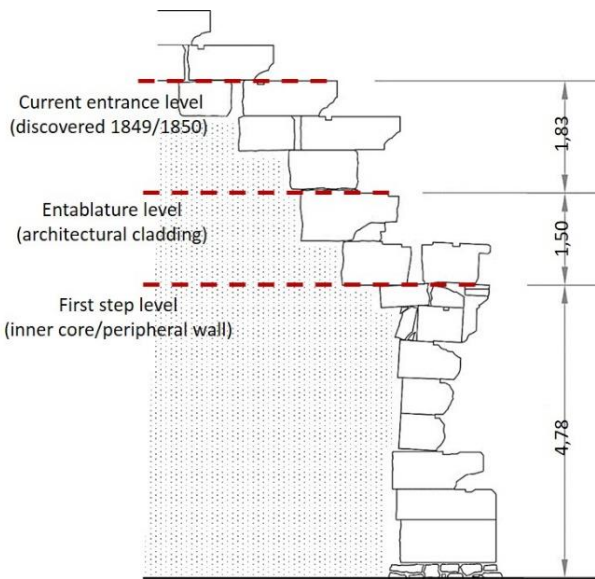
The latter, a large wall, functions as a monolithic tie supporting the nucleus which supports the weight of the overall structure and is able to ensure the stability (equilibrium and resistance) of the cylindrical base. Referring to a wall's fragment located to the east of the monument, measuring 1.2 m thick, we suggest that Medracen's peripheral wall is not only built according to the same technique (Fig. 4a) but also has a similar homogenised thickness.

<sup>2</sup> It is noteworthy to precise that the nucleus is 10-15 cm separated of the architectural cladding all along the cylindrical

base. This means the peripheral wall, supporting the nucleus, is also separated of the cladding.



(a)



(b)

**Figure 4:** Specific features of the structure: a) Wall fragment remains at the monument's eastern side; b) Height of the inner core (base, entablature and entrance in the upper structure) Section realized on the basis of Donati's surveys of 1973- source: Donati Jervis, P. & Donati, P. (1973). Archives of l'Office Nationale de Gestion et d'Exploitation des Biens Culturels (OGEBEC).

As for the height of this wall, necessary to calculate its volume and consequently, its ability to withstand the structure's loads, we estimate it at 5 m above the ground (Fig. 4b). Even though the current state of the monument's conservation does not allow precise identification of this wall's geometrical characteristics, surveys and photography realized after the dismantlement of the structure (for restoration) in 1973, give enough details to make potentially fruitful and testable hypotheses.

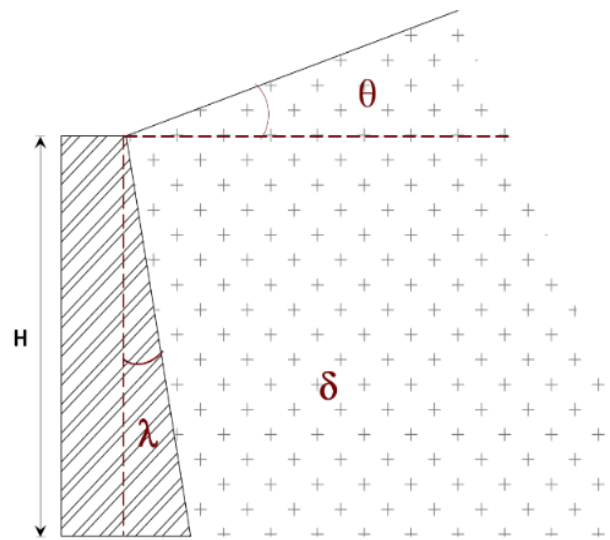
## 4.2. Geometrical analysis

After defining the geometrical characteristics of the structure, it was possible to compare Medracen's structural characteristics to retaining walls' behaviour towards soils. This analogy offers accordingly several valid methods to evaluate the thrust (P) on the peripheral wall of Medracen, considered with a constant thickness (e).

### 4.2.1. Characteristics and equilibrium of the peripheral wall

The equilibrium approach, based on Coulomb calculation method, allowed for the assessment of the peripheral wall's stability conditions and, consequently, its building characteristics. According to limit analysis considerations, masonry is assumed rigid and unilateral material infinitely strong under compression stresses (Ochsendorf, Hernando & Huerta, 2004). Thus, Coulomb method was applied since it considers the criteria presented in (Fig. 5):

- Stress distribution ( $\sigma$ ) that considers the effect of the thrust on the entire rear surface of the peripheral wall,
- Roughness of the wall creates friction that contributes to the reduction of the thrust. This friction creates an angle ( $\delta$ ) formed by the thrust (P) and the wall.
- Inclination of the filling behind the wall ( $\lambda$ ).
- Overloads (q) represent the weight of the upper structure with an inclination ( $\theta$ ) considered in the calculations.



**Figure 5:** Diagram of the angles to be considered according to the Coulomb method.

The calculation formula is given by the Coulomb method as follows:

$$P = \int_{A_0}^{A_f} \sigma_h(h) dA = \frac{1}{2} \sigma_h(h) h b(h) = \frac{1}{2} K_a \cdot \gamma \cdot h^2 b \quad (1)$$

where

p = thrust

$\gamma$  = unit weight (see, Table 1)

h = height of the peripheral wall

b = width of the peripheral wall studied section

And with a coefficient of active-earth pressure ( $K_a$ ):

$$K_a = \frac{\cos^2(\varphi - \lambda)}{[\cos \lambda]^2 \cdot \cos(\lambda + \delta) \left[ 1 + \frac{\sin(\varphi + \theta) \cdot \sin(\varphi + \delta)}{\cos(\lambda - \theta) \cdot \cos(\lambda + \delta)} \right]^2} \quad (2)$$

where

$\lambda$  = inclination of the filling at the rear surface of the peripheral wall. In this case  $\lambda = 0^\circ$

$\delta$  = friction angle.  $\delta = (2/3)\varphi$ . In this case  $\delta = 33^\circ$

$\varphi$  = angle of internal friction (see, Table 1)

$\theta$  = inclination of the upper structure

when considering overloads ( $q$ ), the formula becomes:

$$P = P_Y + P_q \quad (3)$$

where

$P_Y$  (thrust of the filling of the inner core behind the wall):

$$P_Y = \frac{1}{2} (K_a) \cdot \gamma \cdot h^2 b \quad (4)$$

$P_q$  (effect of the upper stepped structure considered as an overload):

$$P_q = (K_a) \cdot q \cdot hb \quad (5)$$

The normal force ( $P$ ) must fall inside the middle third of the section at the base of the wall to ensure its equilibrium (Ochsendorf et al., 2004). Stress values ( $\sigma$ ) resulting from the overload and the thrust of the filling behind the wall are obtained:

$$(K_a \cdot \gamma \cdot h) + (K_a \cdot q) \quad (6)$$

Given the symmetry of the monument, the geometric analysis is carried out on a representative section of the structure (Fig. 6a). A rectilinear section (Fig. 6b) of the peripheral wall is tested in different thicknesses: 1.2 m and 3.5 m, chosen according to constructive similarities observed in other North African burials (Camps, 1961).

#### 4.2.2. Stability of the peripheral wall

In addition to the equilibrium approach, and considering the same equilibrium hypothesis relating to the geometry of the peripheral wall, its stability is assessed according to sliding and reversal criteria (Fig. 7).

Sliding stability is verified when

$$\frac{\sum F_{H,retaining}}{\sum F_{H,reversing}} = \frac{R_H + H}{P_H} \geq 1 \quad (7)$$

where

$R_H$  = horizontal component of the ground reaction:

$$R_V = W + P_V \quad (8)$$

$$R_H = R_V \tan(\varphi) = (W + P_V) \tan(\varphi) \quad (9)$$

where

$H$  = effect of the cohesion estimated in the form of a force:

$$H = C \cdot b \text{ with } b = 1 \text{ m.}$$

Reversal stability is verified when

$$\frac{\sum M_{retaining/O}}{\sum M_{reversing/O}} = \frac{M_{/O}(W + P_V)}{M_{/O}(P_H)} \geq 1 \quad (10)$$

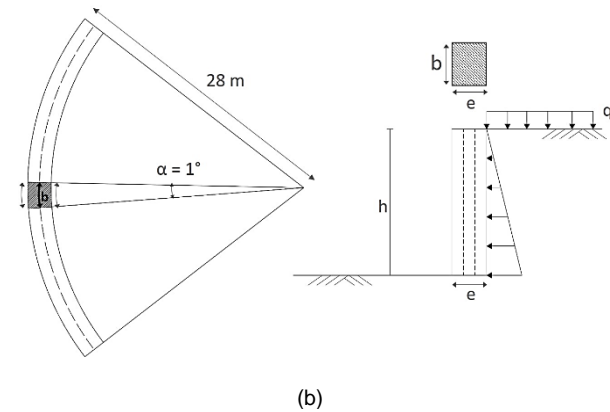
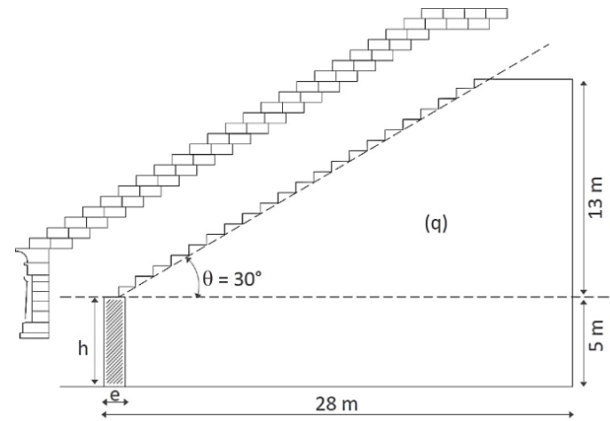


Figure 6: Geometric data used for the equilibrium approach: a) Studied section of the inner core; b) Studied section of the peripheral wall.

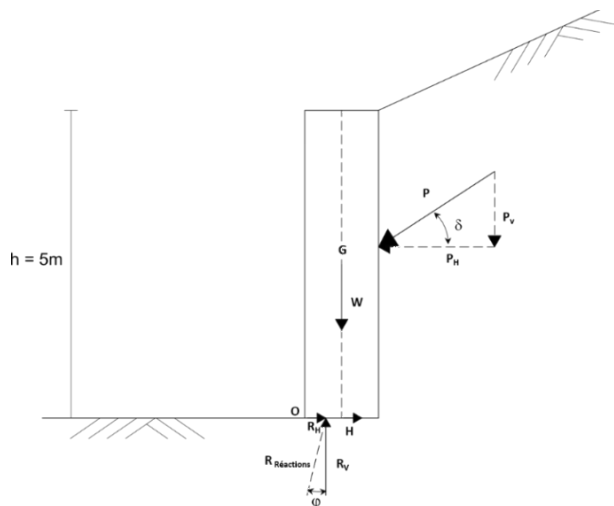


Figure 7: Representation of stresses ( $P$ ) and reactions ( $R$ ) in the peripheral wall.

#### 4.3. Numerical analysis

To perform our structural analysis, the model conceived takes into account three main aspects necessary for any structural computational calculation: the structural

scheme (the two main entities which are the nucleus (E1) and the architectural cladding (E2), and their geometry), the material characteristics (Table 1) and the actions to which the structure is subjected. Since we are considering the structure at its initial state to identify the role of (E2) in the overall structure, we only consider the structure's self-weight as the main action to which it is subjected.

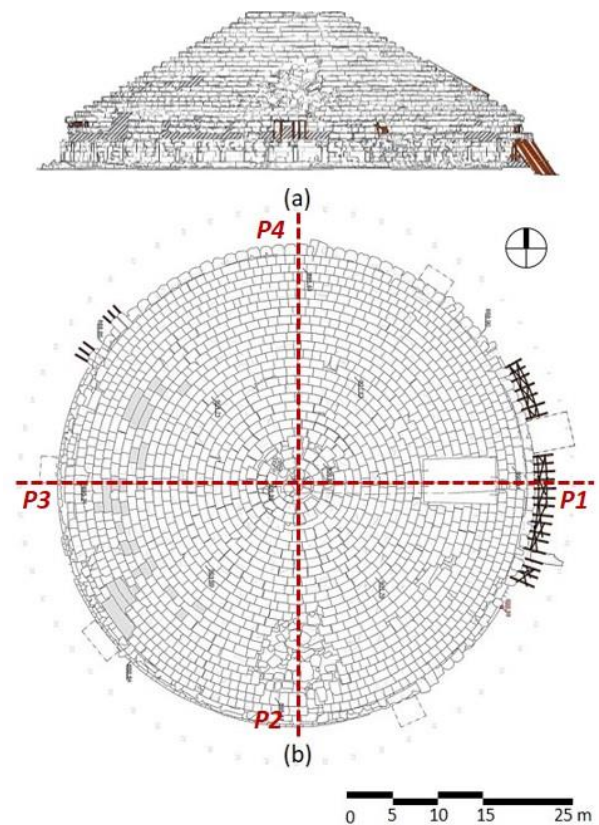
#### 4.3.1. 3D geometric conception

Surveys on the monument have been realized within the framework of the Programme Patrimoine Project (2015) for safeguarding and enhancing the Medracen mausoleum<sup>3</sup>. A photogrammetric survey was carried out by the first multidisciplinary work team in 2015. Two-dimensional (2D) documentation (plan and elevation views) were kindly entrusted to us as a trustable source of metric documentation (presented in vector format in Autodesk Autocad). The latter was used as a reference during the 3D modelling process (Fig. 8).

Prior to any modelling of an archaeological site or artefact, Mascio argues that it is of paramount importance to properly define the object to model, the aim of the 3D reconstruction and the most relevant methods and techniques to consider (Di Mascio *et al.*, 2016). By doing so, one can define the most appropriate sequence process to conceive a 3D model (Verdiani, 2017). Herein, we aim to reconstruct Medracen's structure at its initial state taking into account the differentiation of the two main entities (E1) and (E2), identified on the basis of direct reading of masonry stratigraphy (Fig. 3): (E1) represents the initial state of the nucleus, which is to be considered as the stratigraphic unit (SU.1), and (E2) represents the initial state of the architectural cladding identified as the stratigraphic unit (SU.2). This denomination, suggested by Demetrescu to refer to the different time-stratigraphic units (Stein, 1990; Demetrescu, 2015), will be useful later on for the interpretation of the results obtained.

Before going any further, it is noteworthy to precise that while modelling Medracen's inner structure, the challenge was to find out the most appropriate structural scheme and the most relevant method that meets our research objectives and which is totally in line with the available resources. Through centuries, Medracen's inner core has been subjected to several alterations that were hardly managed during the last decades' restoration campaigns. Besides, previous research on Medracen (1973 Camps' study is the most recent to date) lacks accuracy when describing the inner structure. The cognitive landscape of Medracen's architecture and construction techniques is therefore filled with incongruities. Naturally, and in order to propose a first computer-based structural study, we opted for a simplified digital model since alteration and damage that occurred over time cannot be precisely identified. Thus, a homogenous macro-model (Roca *et al.*, 2010; Lourenço, 2002) is conceived to understand where tensile stresses are located and how intensive compression stresses are by studying the nucleus and the architectural cladding separately, then together, we assess the role of the latter in the behaviour of the overall structure.

Although it has been admittedly shown that Computer-Aided-Design (CAD) software such as Autodesk AutoCAD offers limited tools to perform accurate computer-based visualisation projects (Lluís Fita, Besuievsky & Patow, 2017), yet, it remains useful when it comes to structural analysis as an engineering purpose. This situation coincides with the aims of this work focusing on providing an analysis of the stress state within Medracen's overall structure. The conceived 3D model was accordingly characterized by its monolithic and continuous shape. Through solid modelling of Autodesk AutoCAD, we were able to conceive a 3D scheme, thought as a methodological guideline, prior to the structural analysis. Thus, we defined a basic solid module to conceive the inner structure. The chosen module was duplicated according to a rotationally symmetrical pattern with a constant scale at the base and a variable scale at the upper structure, to represent each step level as shown in (Fig. 9). The same modelling approach was used to conceive the architectural cladding with a geometrically different basic solid module.

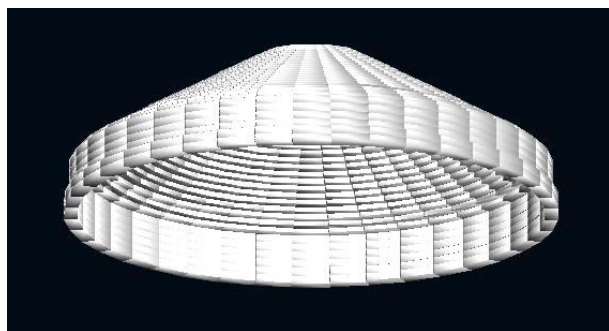


**Figure 8:** 2D documentation issued from photogrammetry surveys: a) southern elevation; b) plan view. Source: Programme Patrimoine Project (2015). Conception et suivi des travaux dans le cadre du « Programme Patrimoine » pour la sécurisation et la mise en valeur du tombeau Imedghassen à Batna : Rapport de fin de phase APS. Unpublished report

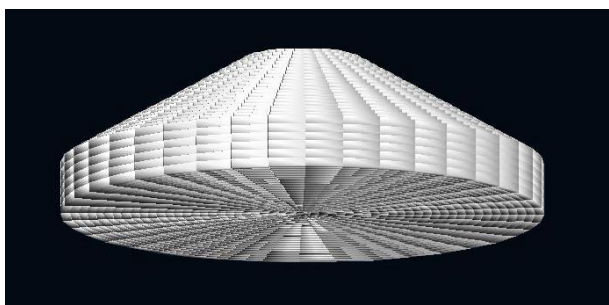
<sup>3</sup> This pilot project was carried out within the framework of a collaboration between the Algerian Ministry of Culture and the European Union set up for the Protection and Enhancement of

Cultural Heritage in Algeria. Photogrammetry surveys were carried out by AKHET S.R.L on behalf of Louis Berger Engineering Algeria.

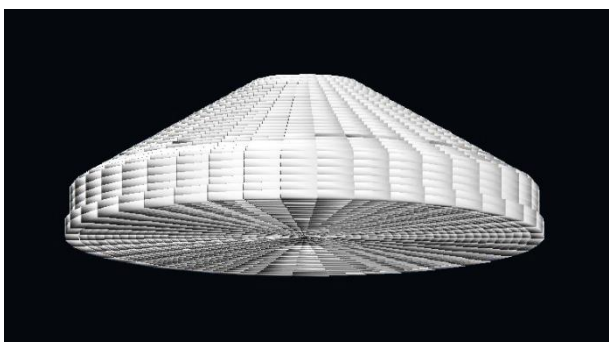




(a)

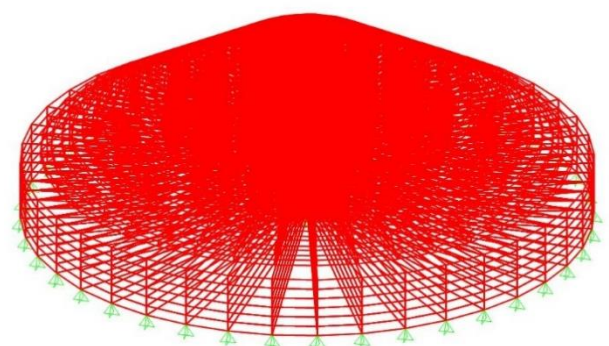


(b)



(c)

**Figure 9:** CAD based model geometrical model: a) inner core (E1); b) architectural cladding (E2); c) inner core and architectural cladding (E1+E2).



**Figure 10:** Radial division mesh.

**Table 1:** Medracen's building material parameters. Source: [Programme Patrimoine Project, \(2015\)](#). Conception et suivi des travaux dans le cadre du « Programme Patrimoine » pour la sécurisation et la mise en valeur du tombeau Imedghassen à Batna : Rapport de fin de phase APS. Unpublished report.

Materials per entity	$\varphi$ [°]	$\gamma$ [kN/m <sup>3</sup> ]	$E$ [kN/m <sup>2</sup> ]	Poisson coefficient
Inner core (limestone)	50	27.1	50 10 <sup>6</sup>	0.25
Architectural cladding (sandstone)	62	26.4	50 10 <sup>6</sup>	0.25

The structural analysis by the Finite Element Method (FEM) is used to study the structure as a whole under the effect of its self-weight to assess compression stresses and localize tensile stresses. The structure is assumed monolithic and continuous with homogeneous and isotropic material. Material parameters implemented in the equilibrium approach and the FEM analysis are shown in Table 1. The difference between the materials density is negligible.

A mesh model was created through a regular model using solid elements of SAP2000 to generate a radial division mesh (Fig. 10). Each entity (E1 and E2) was realized separately. (E1) was implemented first to assess the structural behaviour of the nucleus, then (E1+E2) in order to identify the role of (E2) in the overall structural behaviour.

Since Medracen is directly built on the rock, constraint joints are applied at the limits of all solid elements at the base. For practical reasons, and in view of its conservation state hence too complex to model, the gallery inside the monument was studied separately apart from this computational analysis presented in this paper using elementary beams calculation methods.

## 5. Results and discussion

To date, our knowledge of the Medracen is still insufficient, mainly knowledge about its structural features. This situation led to repair and safeguard measures that were limited in terms of long-term efficiency. This paper, where a structural analysis was performed as a novel contribution to the writing of Medracen's history, presents a preliminary evaluation of Medracen's structural behaviour, and suggests a constructive sequence followed by an in-context historical and cultural interpretation. For heritage practitioners, this contribution aims to give a preliminary hypothesis about ancient repair action in the Medracen mausoleum and what information can be learned for planning and managing future restoration-conservation projects.

### 5.1. Characteristics and equilibrium of the peripheral wall

At first, we assess the equilibrium of the peripheral wall relating to its geometry (thickness). Thus, without considering the wall's weight, its equilibrium is assessed by the effect of the thrust on its overall structure:

$$P = P_{\gamma} + P_{\text{q}} = 227.41 \text{ KN} \quad (11)$$

For a wall with a homogenized and constant thickness of 1.2 m and 3.5 m, the force falls outside the geometry of the wall as presented in Figs. 11 and 12, which implies tension and wall instability.

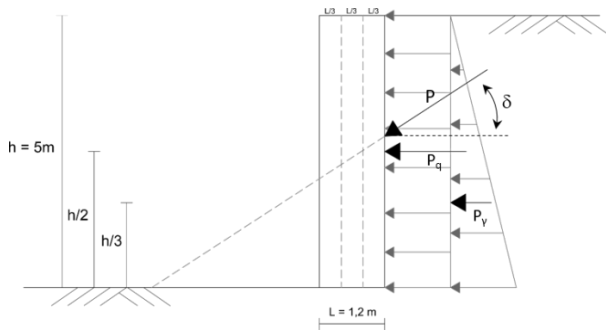


Figure 11: Thrust (P) exerted on the peripheral wall for a homogenized thickness of 1.2 m.

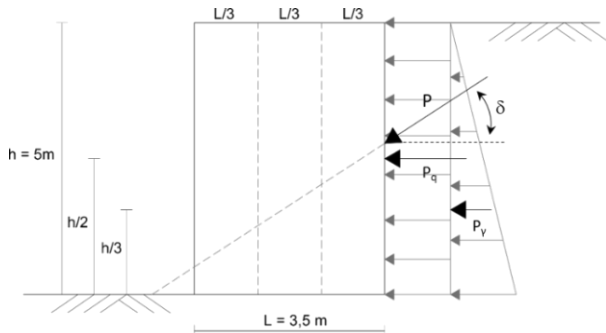


Figure 12: Thrust (P) exerted on the peripheral wall for a homogenized thickness of 3.5 m.

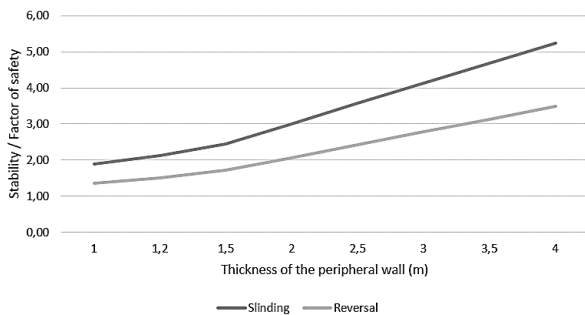


Figure 13: Evolution of the stability of the peripheral wall according to wall thicknesses.

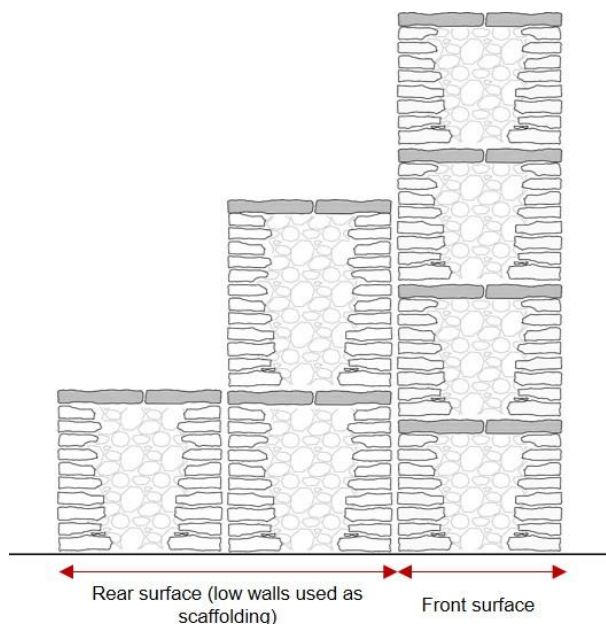


Figure 14: Hypothetical 2D reconstruction of the peripheral multi-leaf wall.

The equilibrium approach shows that the multi-leaf masonry wall must measure, theoretically, more than 3.5 m thick to ensure relative stability of the structure. For a lower thickness, the wall becomes unstable (appearance of cracks in the masonry) by increasing the stresses at its base due to thrust (Figs. 11 and 12). We think that for lower thicknesses the filling, consisting of a mixture of earth and stones, affects the stability of the homogeneous limestone wall (Ortega, Vasconcelos, Rodrigues, Correia & Lourenço, 2017). Over time, cracks, combined with water infiltration and mass loss, cause a partial or total collapse of the wall due to its expansion (Villemus, 2004). This depends essentially on the characteristics of the wall: constructive mode and characteristics of the filling behind the wall.

When considering the wall's weight, sliding stability is confirmed since the ratio of the sum of the horizontal forces retaining the wall and the sum of the horizontal forces dragging the wall is greater than the safety factor considered:

$$\frac{R_H + C.b}{P_H} = 2.12 \geq 1 \quad (12)$$

Reversal stability is also confirmed since the ratio of moments retaining the wall and moments reversing the wall is greater than the considered safety factor:

$$\frac{M_{jO}(W+P_V)}{M_{jO}(P_H)} = 1.50 \geq 1 \quad (13)$$

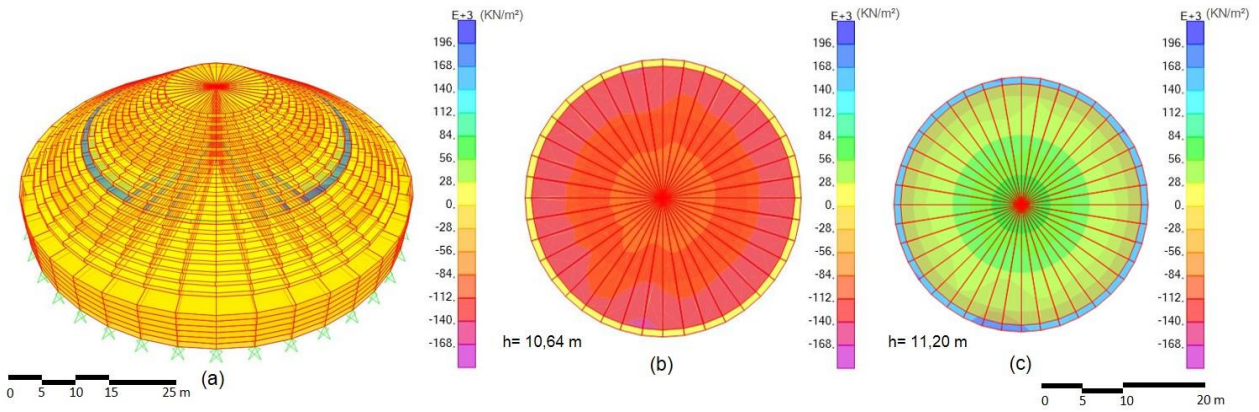
Therefore, the peripheral wall supporting the filling of the nucleus is able to withstand sliding and reversal even with a relatively low thickness (1.2 m, the most critical case according to the equilibrium approach, Fig. 13). Its self-weight is sufficient to retain the filling and guarantee the stability of the structure. However, according to the geometrical approach, the wall cannot ensure its retaining function. Thus, we believe that initially the peripheral wall delimiting the cylindrical base of Medracen was most likely inclined or stepped to ensure the structure's balance and stability. Considering the constructional features of Medracen, particularly the stepped shape of the upper structure, the peripheral wall was probably stepped on its rear surface as illustrated in (Fig. 14). The construction technique by "successive degrees" (Crozat, 2002) allowed ancient builders to raise high walls (5 m in the case of Medracen) gradually by accretion of a wall at its base to raise the previous one.

## 5.2. Structural role of the architectural cladding

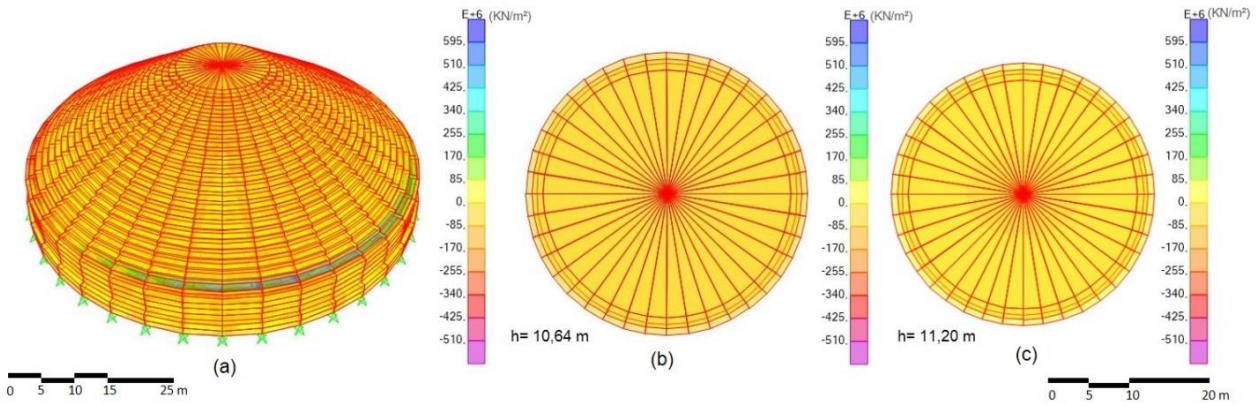
Before adding the architectural cladding, the inner core is mainly subjected to compressive stress (Fig. 15a). Yet, the main tensile stress concentration appears approximately in the middle part of the upper structure at a height of 11.20 m (Fig. 15a,c), with values varying between 94 (E+3) KN/m<sup>2</sup> and 175 (E+3) KN/m<sup>2</sup> measured at the centre and four chosen points as indicated in (Fig. 8).

These tensile stresses are mainly due to the circular geometry of the structure. Centrifugal thrusts, resulting from the expansion of the peripheral wall, produce tensile stresses. Their concentration indicates the areas of breaking lines formation mainly at junctions that are unable to withstand tensile stress. Thus, these areas are potentially subjected to partial collapse, which is difficult to predict and quantify through the history of a masonry

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**Figure 15:** FEM analysis. Stress distribution under the effect of the nucleus self-weight before adding the architectural cladding: a) general stress distribution in the overall structure with the corresponding values; b) stress distribution at a 10.64 m high section; c) stress distribution at an 11.20 m high section.



**Figure 16:** FEM analysis. Stress distribution under the effect of the overall structure's self-weight after adding the architectural cladding: a) general stress distribution in the overall structure with the corresponding values; b) stress distribution at a 10.64 m high section; c) stress distribution at an 11.20 m high section.

**Table 2:** FEM analysis results and stress values at five specific points.

Section at (m)	Stress values (KN/m <sup>2</sup> ) - Nucleus (E1)					Stress values (KN/m <sup>2</sup> ) - Nucleus & cladding (E1+E2)				
	Centre	P1	P2	P3	P4	Centre	P1	P2	P3	P4
0	-48,76	-49,68	-50,73	-49,69	-50,76	-4,40	-727,08	-100,40	-725,63	-110,55
3	-26,89	-27,14	-27,36	-27,14	-27,36	-88,08	-113,40	-127,57	-113,41	-127,29
5	-8,54	-8,56	-8,56	-8,56	-8,56	-425,55	-429,70	-433,29	-429,69	-432,56
10.64	-71 926,61	3 965,48	3 879,60	3 534,40	3 782,52	-230 006,66	-32 233,45	-316 653,60	-436 573,16	-445 363,18
11.20	93 534,45	161 394,20	174 188,12	160 573,74	158 625,68	19 478,03	20 660,89	21 112,67	20 468,38	20 308,66
17.6	-278,81	61,41	28,80	91,94	-154,72	18 485,84	6 685,42	12 170,37	6770,38	12 115,58



**Figure 17:** Current conservation state of the Medracen since August 2018.

structure, and that could lead to a general collapse. After adding the architectural cladding, we notice a redistribution of loads and stresses as presented in (Fig. 16). The overall structure (E1+E2) is now subjected to compressive stresses with greater values. Here, the architectural cladding is to be considered as an overload added to the inner core (E1). By comparing the results as shown in (Fig. 15b, c, and Fig. 16b,c), we observe that tensile stresses are reduced and, at some points, shifted into compression stresses reducing consequently structural disorders leading to collapse (Table 2). Assuming that masonry is infinitely strong under compression stresses, we can argue that the architectural cladding reinforces the monolithic behaviour of the overall structure, by reducing tensile stress.

Today, in Medracen, we observe collapses at the entrance to the monument (located in the third step of the upper structure) and the middle part of the southern side of the upper structure (Fig. 17). According to the FEM analysis, areas where these collapses are observed, coincide with the region where the maximum tensile stresses are estimated. Previous collapses, recorded during the 19<sup>th</sup> century surveys (Brunon, 1873) and the Italian-Algerian restoration campaign (Donati, 1973), were also observed in the same areas. Consequently, the results of the FEM analysis are completely reliable since reality validates the conceived model. Finally, the numerical analysis indicates that adding the architectural cladding represents a first repair approach of Medracen. This intervention was essential to repair structural disorders observed in the inner core. Definitely, the architectural cladding is an additional load, but it contributes to the stabilization of the inner structure for its building techniques. The finely cut ashlar arranged in steps according to a precise scheme and sealed together with lead-coated wooden clamps (Donati, 1973) guarantee monolithism to the architectural cladding that encloses the inner core. Furthermore, these results allow us to consider that the undergone damage is mainly related to the geometric characteristics of the inner core. The circular form produces centrifugal thrusts, which affect the inner core, but also the junction between the latter and the architectural cladding where tensile stress is observed (Fig. 16). Today, ashlar constituting the junction lie on the ground due to the effect of the mechanical action of the structure and the stolen lead clamps. Water infiltration also has a significant impact on the alterations of the inner core. By reducing the mass of the latter, the filling tends to find a new state of stable equilibrium in order to accommodate

the undergone alterations (Heyman, 1995). Besides, hygrometric tests (Hamiane & Assafsaf, 2016) show that the amplitude of temperature variations between day and night, during winter and summer, contributes to the deterioration of the architectural cladding, leading to the overall structure to a progressive and certain collapse.

## 6. Conclusions and future works

The present research described the use of a structural approach (geometrical and numerical) for the identification of building chronology and historical stratigraphy in the Royal Mausoleum of Numidia (Medracen). The monument that was most likely built during the 4<sup>th</sup> – 3<sup>rd</sup> centuries BC, bears witness through its materials and building techniques to ancient repair works led during the same period, or on a time frame that could be extended to the 2<sup>nd</sup> century BC. The Medracen, which is part of an architectural ensemble of Numidian and North African emblematic funerary monuments, represents a relevant example of a monument that, following a repair action, which could be part of a holistic restoration approach, was able to combine both local (Numidian and North African) and foreign (Mediterranean) features. A structural analysis, mainly through 3D modelling, was effective to understand the structural behaviour of the monument brought back to its initial condition immediately after its construction. This approach was helpful in identifying the natural damage process relating to the building and materials characteristics. After assessing the monument's structural behaviour and arguing that a repair action was carried out for technical reasons, we were able to suggest a reinterpretation of these repair works with symbolic aims. The latter were, among others factors, relating to Medracen's function evolution over the time that coincides with the evolution of the Numidian elite and society. If the initial structure (SU.1) (product of the fusion of a bazina and a choucha) was essentially aimed to be used as a burial, probably for a local chieftain, its ancient restoration, implied adding a Greco-Punic architectural cladding (SU.2), aimed at evolution from a simple tomb (SU.1) to a funerary monument (SU.2). According to Ulpian, "a tomb is the sum of two different concepts, the *sepulchrum*", where human remains are buried (or cremated), and the *monumentum*", which consists of any structure built at ground level for the purpose of perpetuating the memory of the deceased". Therefore, a tomb is *sepulchrum* only once the deceased (or his remains) has been buried and the funeral rites performed; the tomb thus becomes sacred and, according to the Roman laws on funerary monuments, falls within the domain of *res religiosae* (religious artefacts). As for the *monumentum*, its function is only to protect the initial burial, but it can acquire the status of *res religiosae* if the burial contains human remains. This definition of a tomb and a funerary monument suggests that a tomb is considered as a funerary monument when an addition, independent of the initial construction of the burial, is added afterwards. As a result, a tomb, such as elementary bazinas, chouchet, tumuli, cairns, etc. is not necessarily designed to last over time and perpetuate the memory of the deceased, otherwise, it would have been built using materials and techniques aligned with the aim of ensuring longevity. However, the monument, not only by its scale but also by its complex building or repair techniques, is intended (whether from its first conception or subsequently to a specific historical key period), to last over time and perpetuate the memory of the deceased for

cultural or socio-political consideration. The Medracen in North Africa is a pertinent example to illustrate this ancient approach to enhancing building status, longevity and architecture. The initial structure, built using elementary construction techniques, was probably not aimed at long-term longevity even if it could have a commemorative conception, herein expressed through the structure's scale. However, for its cultural, religious or symbolic values, the Medracen benefited from a restoration project, which philosophy was aimed at ensuring cult continuity and asserting a new form of rule, inspired by the Hellenistic model as a common form of rule during the 3<sup>rd</sup> century BC. This restoration, considered in a technological context that most likely evolved since the Medracen's nucleus was built, was an opportunity for ancient builders to ensure better stability for the mausoleum (by adding an architectural cladding assembled with more complex techniques than those observed in the nucleus) and promote its status from that of a basic tomb to that of a monument that becomes one of the most emblematic symbols of the Numidian history. The use of the term "evolutionary restoration" is accordingly applicable in the present context since restoration was used as a means of architectural evolution to mark a key moment in Numidian history.

Finally, it is noteworthy to precise that this paper intends to open and articulate a debate on how Medracen was built, reused and repaired within a specific cultural and historical context. As far as we know, this work constitutes

the first contribution to studying the Medracen through a computer-based approach. Despite the variety of heterogeneous and fragmentary information, we were able to suggest a first constructive sequence. As a future line of research, it could be interesting to simulate the behaviour of the architectural cladding as an independent entity. Since it has been added as a repair "shell", its action should be analyzed in detail (joints displacements, clamps action, etc.) prior to any intervention. Results could be hence useful to understand how ancient restoration was conceived in order to plan future restoration actions. Another remarkable line of research would be the study of Medracen's conservation-restoration possible scenarios on the basis of procedural modelling (Whiting, Ochsendorf & Durand, 2009; Lluís Fita et al., 2017). Once the structural behaviour of the architectural cladding is assessed, multiple restoration techniques could be studied before choosing the most relevant and appropriate action.

### Acknowledgements

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