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THE ADOBE BARREL VAULTED STRUCTURES IN ANCIENT EGYPT: A STUDY OF TWO CASE STUDIES FOR CONSERVATION PURPOSES

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ABSTRACT

This research aims at throwing the light on one of the few survived examples of ancient Egyptian vaulted structures; those are the storerooms of the temples of the Ramesseum and Sety I built in the 13th century BC. In the first case, only some of the adobe vaults and walls are still standing; whereas in the second case all the vaults collapesed and only the walls exist. Due to lack of maintanence and also scientific research on this topic, the survival remains may be lost forever. The research started with tracking the chronological developmenet, the architecture and the constuction of the adobe barral vault in ancient Egypt. The two case studies of the research were visually inspected and the existing damage symptoms and causes were reported and investigated. A structural analysis were carried out to understand the structural behavior and the casues of damage. Finally, a number of interventions were proposed that may help the exsiting ruins to survive.

KEYWORDS: adobe, vault, storerooms, Ramesseum temple, Sety I temple, damage, conservation.

1. INTRODUCTION

Egypt is a unique country with its architectural heritage. For preserving this national wealth, it seems that the scientific research orientated to the archaeological conservation of architectural heritage should be one of the priorities in Egypt. Particularly, the built heritage dates back to ancient Egypt hasn't received enough attention from specialists in architectural conservation. On the contrary, the movable antiquities have received great attention and a considerable research has been carried out on them.

The ancient Egyptian adobe vaulted structures, in specific, have not received enough attention by Egyptologists till the beginning of the 20th century. Before that, the survival remains of those vaults were disregarded in many archaeological Ancient Egyptian sites. Consequently, the vast majority of these structures were lost forever.

This paper aims at contributing to the few studies available about these structures. It presents the studies carried out on an example of adobe structures were usually built beside temples; those are the adobe vaulted storerooms. These structures were used to store different types of goods for the services provided in the temples. The storerooms of the two temples of Sety I at Abydos and the Ramesseum at west Thebes were the aim of the study. These two case studies have similarities in the function, the architectural form, the construction materials and methods, and shared a common in some damage factors, and being remains of the examples that they are close to extinction among the homeo- mud-brick buildings in the ancient Egyptian civilization.

Given that these vaulted-storerooms were constructed above - ground, which made them lack a support on the one hand, on the other hand, they have been destroyed intentionally or unintentionally (the same for houses), on the contrary; the vaults were built beneath the surface of the ground in tombs (over: staircases, corridors, large gates and long narrow chambers), which have survived and better documented, because the soil has protected them from destruction.

In this research, the architecture, the construction, the chronological development and the characteristics of the used bricks in the adobe vaulted structures in Egypt were briefly investigated. Afterwards, the studies of two adobe vaulted structures covered the description, the structural analysis, the current state of damage and conservation proposals.

2. ADOBE VAULT IN ANCIENT EGYPT

2.1. *Chronological development*

The adobe vault is one of the most protracted types ever invented across the ancient Egyptian civilization since First Dynasty period till the Coptic era. Ancient Egyptians developed betimes these vaults after they had known the construction using mud-brick. The ancient Egyptian architects used the adobe vaults above the ground (in houses and magazines) and under the ground (in tombs).

The earliest known adobe vault in Egypt was found in subsidiary graves of the tomb 3500 (Qa'a) in 1st Dynasty necropolis at Saqqara (Emery, 1958& 1961), Figure 1. More known examples were found in tombs at Beit Khallaf (in tombs K1 and K2), Raqaqnah (in tomb R1) (Garstang, 1903) and Saqqara (Quibell, 1923). In addition, there are many examples in funerary architecture of the Old Kingdom, where adobe vaults and arches had become common, and thick adobe vaults and arches were used either above the ground or under the ground in large Mastsbas in Saqqara, Dandera and Dara (Quibell, 1923; Spencer, 1979).

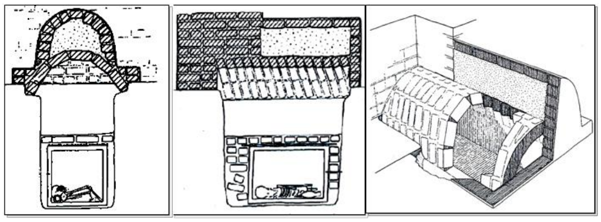


Figure 1. The earliest known vaults in Egypt in tomb Qa'a at Saqqara composed by one course of adobe masonry (after Emery, 1958).

In the Middle Kingdom, a lot of adobe vaults were used in many cemeteries independently to cover burial chambers and some of later examples of these burial vaults were built of burnt brick (Spencer, 1979). In domestic buildings there was a limited use of brick vaults (Petrie, 1912).

In the second intermediate period and pre-New Kingdom period, funerary adobevaulting continued to be used such as the vaulted roof of the causeway of Mastabet el-Fara'un (Jequier, 1928) and the vaulted chapel at the south pyramid of Mazghuna (Petrie, Wainwright & Mackay, 1912). Also, a few examples of non-funerary vaulting were found. Most of these examples collapsed and were lost.

In the New Kingdom period, ancient Egyptian architects tended to hewn–rock tombs, and continued in using brick vaults in funerary architecture particularly in Deir el-Medina and Dira abu'Naga, in addition to administrative buildings and palaces.

In the Late New Kingdom period onward, brick vaults were used commonly for all purposes (Garstang, 1901; Spencer, 1979), where they were used commonly in domestic architecture in the Late period, and more widespread in Ptolemaic period and Coptic era, such as the houses at Karanis, Dime, Medinet Habu and Edfu (Garstang, 1901; Spencer, 1979).

2.2. On architecture and construction

The simplest form of vaults is the barrel vault. It is composed by a series of arches placed side by side. Typically, it is formed by the protrusion of a single curve, typically circular, along a certain distance lending a semi-cylindrical appearance to the total design. It was used widely by early orient civilization such as Ancient Egypt and Mesopotamia. This construction method likely arose out of necessity to use masonry in roofing instead of the rare wood. Most of Ancient Egyptian masonry vaults were practically of this sort of vaulting.

The adobe masonry barrel vaults in Ancient Egypt were constructed of courses of horizontal or upright mud-bricks laid tilted, at a slight angle to the vertical, against the supporting wall,

Figure 2 (Van Beck, 1987; Spencer, 1979). The inclination of the bricks from the vertical led most of the weight of each brick to transfer to the lower course which already had been laid rather than acting downwards, thus, the weight of each new brick was borne by those already laid. The brick was held in its position and stuck to the brick of the lower course by mud mortar.

Figure 2. Mud-bricks laid tilted in an ancient Egyptian barrel vault (in the storerooms of the Ramesseum temple).

The barrel vault was erected mostly without temporary support or centering, for the reason previously mentioned, particularly in the case of vaults of internal room or cellar which were supported on the walls of the room or the cellar. In case of larger vaults, such as the 8.60 m vault of the royal stables at Madinet Habu, or in the case of a vault with a lower curve, they may have been constructed above a supporting arch framework of vertical (headers) bricks, or a temporary rough wall easily removed after construction (Choisy, 1904). For large vaulted tunnels and gateways, centering with earth materials was used. Examples are such as the arched gateway in the enclosure wall at El-Kab which has been still blocked with earth support. It is likely also that this method of centering was widespread particularly in funerary and domestic architecture, such as houses at Illahun according to the Petrie's belief, and the great arched tunnel in Mastaba M at Dara (Clarke, 1921). Also, the vaults of non-inclined arches were constructed with layers of straight bricks, consequently, were erected with supporting.

The number of courses used to form the adobe vault was from one to four, as shown in Figure 1 (one course); Figure 6 (two courses) and Figure 3 (four courses). The spaces between the adjacent vaults were filled, sometimes, with rubble; as well filling was added above the vaults to create a flat surface, Figure 3.

Figure 3. The adobe vault of the storeroom of the Ramesseum temple composed by four courses, the filling between the adjacent vaults can also be noticed.

The barrel vault in ancient Egypt was supported on adobe walls, stone walls and on burnt bricks in Roman period (Petrie, 1896; Mond & Myers, 1934). The adobe vaults and wall were plastered with thick layers of mud and whitewashed to increase their resistance and durability. Sometimes the adobe vaults were supported on architraves supported on columns such as the vaults of the palace throne hall of Ramesses III at Madinet Habu (Kemp, 2000).

In the early Old Kingdom period, appeared a slightly inclined vaults constructed with thin grooved bricks. In the Old kingdom period onwards, a smaller cap rounded ribs vaults appeared at Giza, in simulation of plant roof. Less common are vaults of low curved which constructed of non-inclined arches of straight bricks, and depended on a temporary rough earth, as mentioned above.

Small barrel vaults were constructed of a single ring, and the gaps developed between the wedge-shaped bricks on the outer top of the vault were filled with parts of bricks and stones.

The vaults of the magazines attached to the temple of Sety I at Abydos, the vaults of the magazines of the Ramesseum at West Thebes (the two case studies of this paper) and the vaults of the boat pit of the pyramid of Senwosret III, are examples of long barrel vaults in ancient Egypt architecture.

The longest span of adobe vaults in Ancient Egypt was 7.70 m in the mortuary temple of Amenhotep. While the longest span known is the span of the vault of the royal stables at Madinet Habu, reached 8.60 m, according to Hölscher, in addition to the vaults of the throne hall of Ramesses III at Madinet Habu, which settle on architraves, which in turn rest on columns. Also, the notable vaults of the pyramids of the late 12th and 13th dynasties, which spanned 12 m, however, they were not free-standing but they rested on relieving slabs.

Other examples of barrel vaults in ancient Egypt architecture, such as the ceiling of the burial chamber of the fourth dynasty stone mastaba in Dahshur, which discovered in 1992, whose span was 2.62 m. Also, a lot of true vaults constructed of wedge-shaped bricks were used in burial chapels and were found at Madinet Habu (divine consorts), at Giza (Campbells tomb), at Saqqara (Neferibre Sa-Neith, Wahibre-men, Hor) and at Abusir (Wedjahorresnet).

The barrel vault in ancient Egypt has continued in the contemporary period as a living tradition particularly in Nubia.

2.3. *The characteristics of the barrel vault bricks*

Ancient Egyptian architect used in the construction of the adobe barrel vaults bricks with specific shapes. To reduce the weight of the vault, the bricks were thinner than the ordinary bricks. Also, straw was added for weight reducing and to give some tensile strength to the brick and thus minimizing cracking. Bricks were given the wedged-shape to be more appropriate to the vault construction. Specific bricks were made with one curved side, Figure 4.

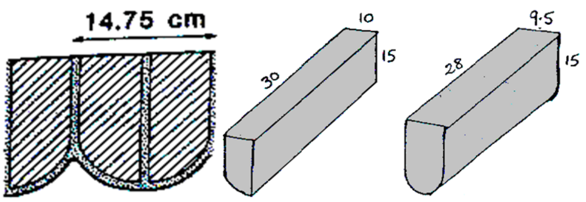


Figure 4. Bricks with curved sides made specifically for vaults construction. Discovered in a chapel of 4th dynasty in old Kingdom in Giza (after Fisher, 1924 and Spencer, 1979).

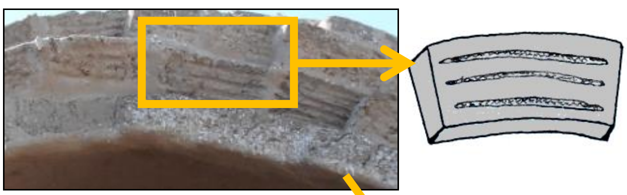


Figure 5. Bricks made with grooves to ensure the brick-mortar bond. The storerooms of the Ramesseum temple.

To ensure the brick-mortar bond, the brick was made with grooves arranged in parallel lines, Figure 5. The grooves were made by the workmen fingers during manufacturing process. The use of such bricks started as early as the Old kingdom period. These bricks were thin and were used in curved vaults. Also in the Old Kingdom period, sometimes special bricks were shaped with tooth-like snags.

As can be noticed in Figure 6, one of the special technique used was to manufacture the brick so as to have the lower side shorter than the upper side, this wedged-shape was more appropriate for vaulting. The resulted triangle-shaped spaces between these bricks were filled with mortar wider at the top than at the bottom.

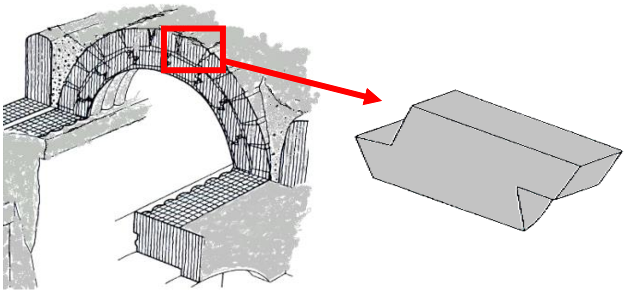


Figure 6. Adobe vault in ancient Egypt composed by two courses. The bricks were specially designed with interlocking edges, used over the chapel in the tomb of Sabef (6th Dynasty) at Giza (after Fisher, 1924).

Another example in which the ancient Egyptian mason succeeded in providing the vault with interlocking effect was found in the chapel in the tomb of Sabef (tomb 3033) (6th Dynasty) at the minor cemetery at Giza. As shown in Figure 6 , a special brick was manufactured to have alternate projections and recesses in its ends which allowed it to interlock with the adjacent brick.

3. THE CASE STUDIES

Two case studies of adobe vaulted storerooms dates back to about more or less 3300 years within the 13th century BC were investigated. Those are the storerooms of the temple of Sety I at Abydos and the storerooms of the Ramesseum temple at West Thebes.

In Ancient Egyptian architecture, usually each temple had its reliance such as storerooms (magazines) and granaries. These structures were used for storing goods, provisions, grains and offerings. They were constructed within the areas adjacent to the enclosure walls of the temple. These storerooms were designed to have a rectangular shape in plan. They were like long narrow tunnels on sideways of a courtyard, and were roofed with adobe vaults.

These buildings were constructed commonly using adobe masonry and their inside surfaces were plastered and whitewashed. Their lintels, doorjambs, columns, paving and architraves were made of stone masonry.

3.1. Construction and constitution

3.1.1 Construction

3.1.1.1 The common methods with other adobe structures

Construction of walls and floors of vaults would have begun after planning of the magazines, determination the number of bricks, and mortars needed, and plasters for the magazines (Arnold 1991:7-10; Clarke and Engelbach 1930: 47–68; Emery 2011:2), the foundations and wall footings laid in trenches upon a bed of sand, then the first course of bricks may have been laid out on the ground as the guideline for further construction (Choisy 1904:15; Kemp 2000:88; Spencer 1979a: 120; Emery 2011:2), where bricks were laid as headers on their long edges for compensating for diverse depth in the trench, and without doorways being marked with using mud mortar only in the horizontal joints between courses and not along the vertical joints between bricks in a course ((Kemp 2000: 92; Spencer1975: 1403; Emery 2011:3), according to different bonding styles, which was mostly an alternation of headers course and stretchers, aiming to flee the cracking of vertical joints if they were set above each other, so the same pattern was repeated only every fifth course, also bricks were laid sometimes diagonally (herringbone bonding) for reducing and adjusting the thickness (such as in the Ramesseum), the internal spaces were left open or filled with mortar, regarding to that the vertical joints were thin and negligible the easer method is regularity of setting of bricks with approximated 2:1 ratio of length to width. Bricks were laid on their long edge to add thickness and heights to a course (such as in the Ramesseum), the patterns of bonding in the two case studies explained below.

The walls and vaults of the magazines were plastered with mud plaster (range from 3 to 10 cm thick) was generally applied in a single layer, for achieving protection from weathering, improvement of appearance, improvement of mechanical strength and increase insulation (specially for granaries), high percentage of straw given for composition of plaster, where applied in steadily plastic state without too much water, then the plaster was coated with layers of white or cream whitewash.

The dimensions of the two case studies floors square mud bricks mud bricks tiles of; 44× 44×16 cm., it is assumed that the ground had been leveled, trampled, wetted and puddle of mud on the same ground, then were plastered with mud plaster

The intervening spaces (ridges) between vaults filled with brickwork or rubble, for creating a flat surface above these neighboring vaults, for roofing or for flooring of upper storey (while in Coptic era, the builder, instead, built smaller relieving vaults into these ridges, such as at St. Simons monastery at Aswan (Kemp, 2000: 93).

3.1.1.2 The special construction techniques used for the barrel vault and plain walls of the two case studies

The pitched bricks were laid with alternating angles of inclination with alternating angles of inclinatio. The Ancient Egyptian builder used the thicker and stronger (sometimes haunching) supporting walls, the parallelism (arcades), to create counter resistance, absorbing and balance, to springing and lateral thrusts (forces) (outward against the walls underneath the barrel vault), which have been created (exerted) from parts of the barrel vault - such as in all arch-based constructions- where the line of pressure does not conform to the shape of the arch, where the compressive stresses in vaults are transferred from the upper part of the vault to its sides, to the retaining wall and from there to the foundations and the ground, and therefore the crown tends to fall (where the bricks can slide) while the sides buckle out as a result of being pressed out above a secure springing (the outermost walls) or at the springing itself (walls which are located between paralleled vaults), as a result of the load which creates a lateral thrust, so, a balance of the static scheme is required along the sides of the vault which has been achieved and absorbed by the massive weight of the walling, which diverts the lines of thrust downwards, and have supplied the required resistance , accordingly these forces and thrusts, which already become quite small and well distributed will thus have negated each other.

The methods for laying the mud-bricks in the walls underneath the barrel vaults evidence a face bonding of various types in the two case studies, the first case study exhibits many types, the focus of this current analysis is on five types: the first type exhibits courses of stretchers and headers almost in alternative layers, specially one course consists completely of stretchers, and the other course consists completely of headers (Figure 7a) was used in the walls and floors of magazines, the second type which rarely used exhibits stretchers and headers in the same course (Figure 7b) (these two types were used also in the storerooms of the second case study), the third type used in the first twelve courses of the walls of the northwest group of the magazines of the Ramesseum, where exhibits edger headers in one course and stretchers in the next course alternatively (Figure 7c), the fourth type used in some door jambs of some passages of the storerooms (Figure 7d), the fifth type used as exceptions of irregularities at the corners of the walls of the storerooms (Figure 7e).

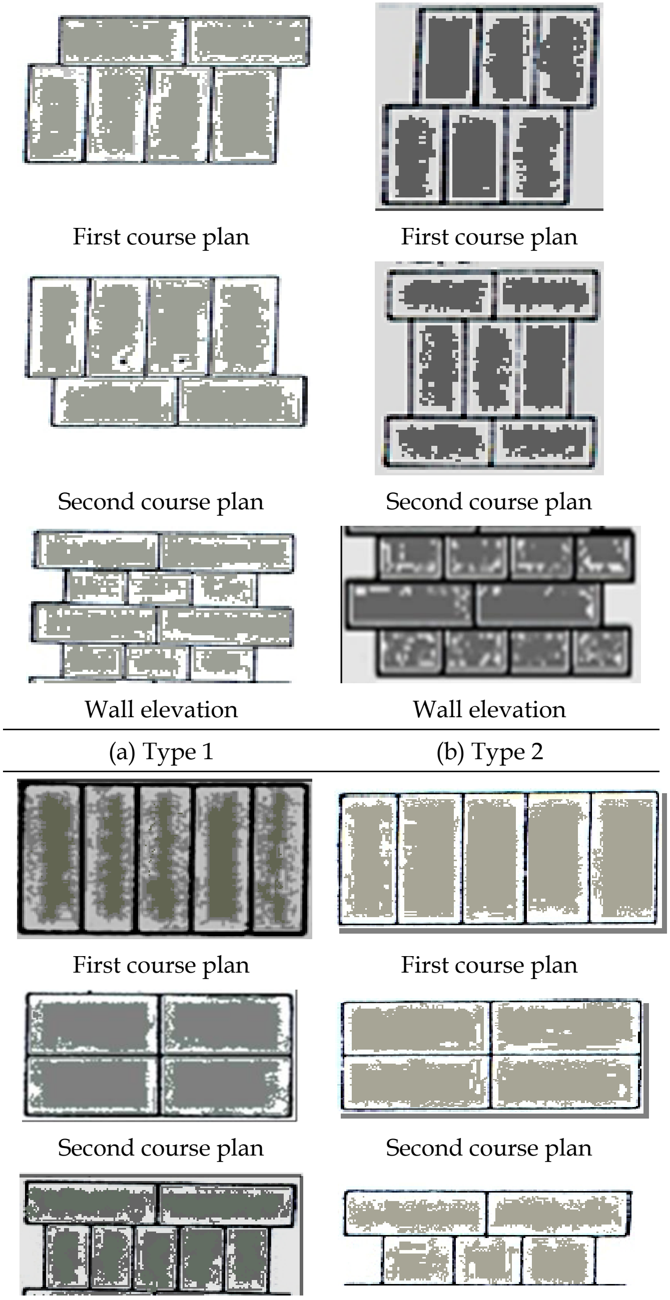


Figure 7.a, b, c, d Methods of mud-brick laying in the storerooms' walls (a) type 1, (b) type 2, (c) type 3 and (d) type 4.

The second case study exhibits the same first two types in the first case study (Figure 7a,b).

3.1.2 Constitution

The adobe, mortar and plaster used in the two case studies was composed- such as the vast majority of the earthen architecture in Egypt- by: silt, sand, straw, pottery shreds and small stones in different proportions depending on the function of each element, and the interpretation and analyzing the role of each element thereof, as follows:

1-coarse sand (aggregate) which provides strength to the brick. 2-fine sand, which provides filler, fills pores between the aggregate.3-silt and clay (from Nile alluvium or desert sediments/clays) which provides bind and plastic medium, which adhere other components. 4- chopped wheat straw or chaff (particularly in bricks of vaults and in plasters) to decrease shrinkage after drying, reduce cracking, to enhance compressive strength and sometimes to reduce the curing time, accelerate drying and catalyzes homogenous drying (Galan-Main, C. et. al. 2010: 1462), in addition to water and other additives such as ash, dust, sherds and fragments of stone working and dung, in same time we have to cite that the total absence of any of these components did not hinder manufacturing a satisfactory mud-brick.

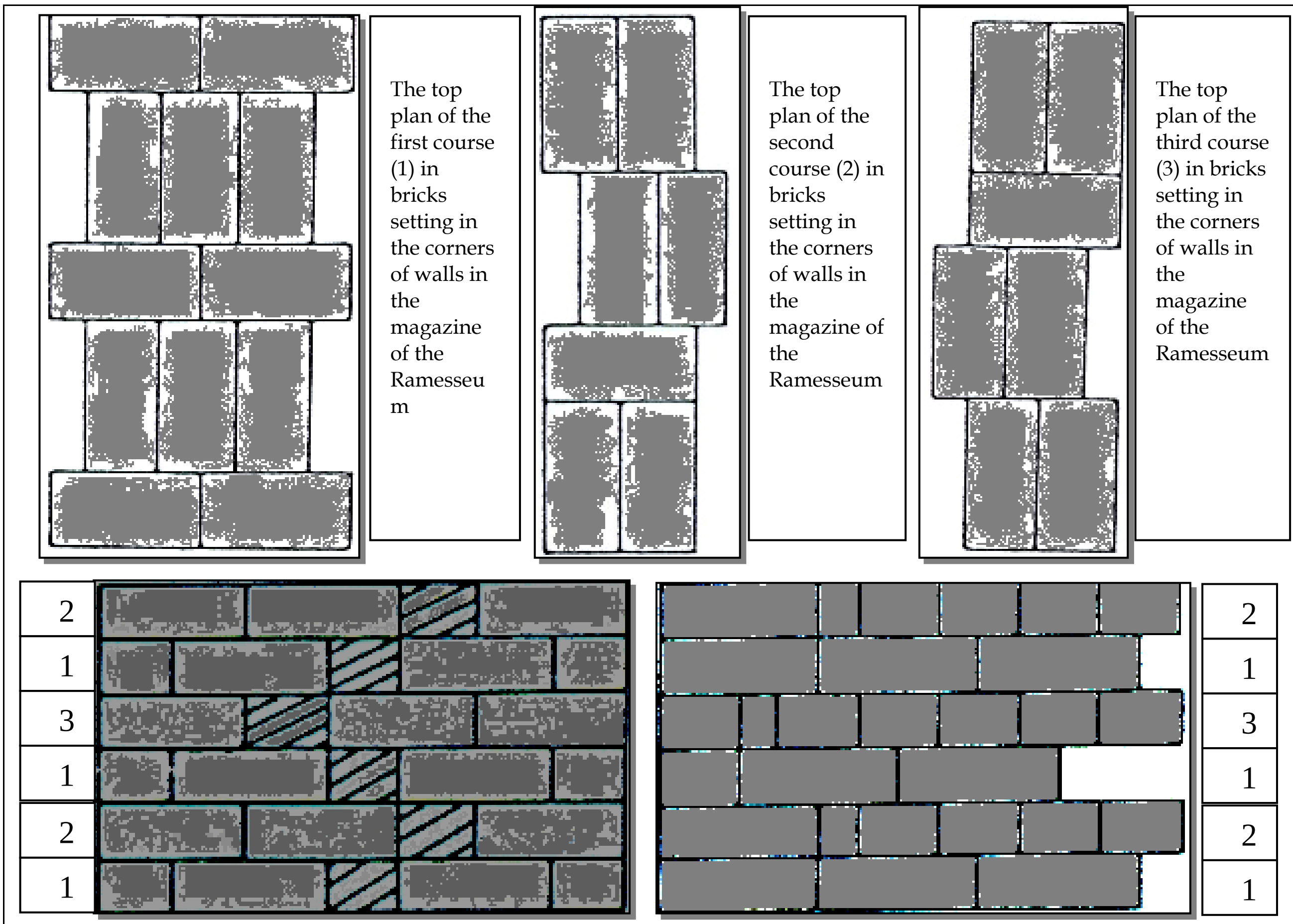
High percentage of clays resulted in bricks and plaster more resistant to erosion of wind and rain, and less strong, while high percentage of sand resulted in bricks and plaster stronger and less resistant to erosion of wind and rain.

High percentage of straw given for composition of bricks of vaults and plaster.

The two case studies were selected to highlight their bad state of preservation which is an alarm of possible losing of these invaluable architectural heritage forever. Unfortunately, they are possibly the last remained examples of such storerooms; therefore, losing them would be a great loss for humanity. This in turn calls for urgent interventions to be proposed which is one of the main objectives of this paper. These interventions should be evaluated against the concepts and rules of conservation of historical structures, and if accepted should be implemented, as soon as possible, to rescue these structures.

3.2 Architectural description

The first case study is the storerooms of the Ramesseum temple, which is historically the latter, the more preserved and the more solid, they are surrounding the temple from three sides occupying a noticeable area as highlighted in Figure 9. Large parts have been unfortunately lost for many reasons as will be discussed in the following sections. The storerooms, as can be noticed in the figure, can be divided into three groups. The focus of the current study is the group exactly behind the temple which is surrounded by red dashed rectangle, in view of its similarity with the second case study, in design and function, and in order that it is the oldest, the most interesting, compared to the other two groups. Photographical documentation of some of the remained parts is indicated in Figure 10.



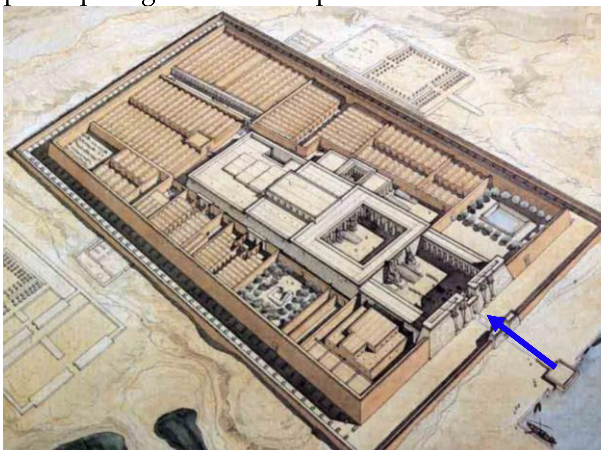
Latitudinal cross section in the corners of walls of the magazines of the Ramesseum, where courses setting patterns: 1, 2, 3 (note that the hatched areas point to the internal stretchers bricks.

The façade of the corners of walls of the magazines of the Ramesseum, where courses setting patterns: 1, 2, 3 (this type of setting of corners used commonly with another type of bonding of bricks).

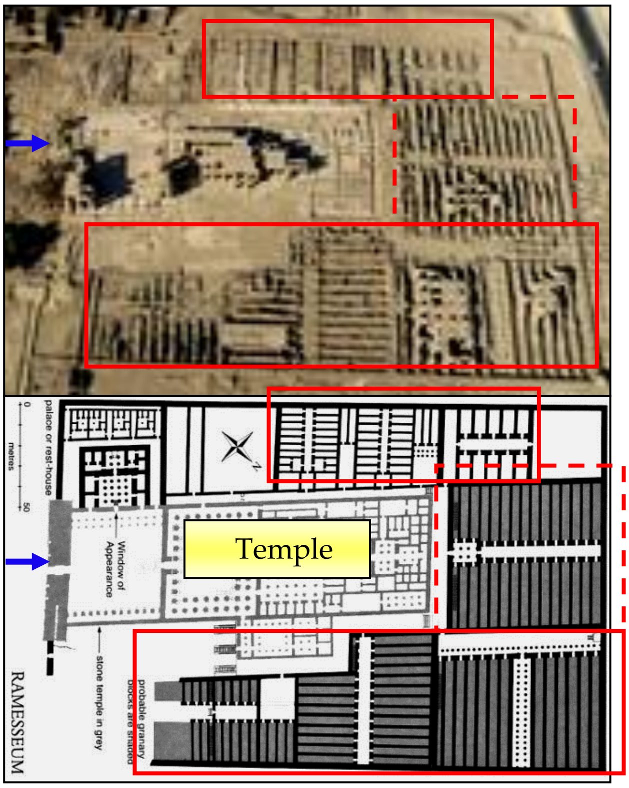
Figure 8.e The top plans of courses 1, 2, 3, the latitudinal cross section and the façade of the corners of setting patterns of bricks which used in the walls of the magazines of the Ramesseum, the type 5 (A10 according to Spencer, 1979 a)

These storerooms consist of two parts separated by a central vaulted corridor. Each part consists from a number of tunnels that have adobe masonry walls and vaults. Each tunnel is about 32 m long, 3.7 m width and 3.5m height. The walls are 1.5m thickness, which ascend vertically to a height about (2.50 m.), then the spring of the vault begins, where the arcs of the vaults constructed of bricks and were constructed using adobe bricks of size 40 cm × 20 cm × 12~14 cm. The vaults were constructed as a barrel vaults-as mentioned before-using adobe bricks of size 35 cm × 21 cm × 6~7 cm made with grooves (see again Figure 5), with filling spaces between bricks with fillers (such as fragments of stone and pottery). Any vault is composed by four courses of adobe masonry (see again Figure 3) resulting in a total thickness of about 80 cm, the vaults and walls were plastered with mud with a thick 3 and up to 10 cm. and whitewashed the vaults and walls were plastered with mud with a thick 3 and up to 10 cm. and whitewashed the vaults and walls were plastered with mud with a thick 3 and up to 10 cm. and whitewashed.

These storerooms were filled with grains from top via holes in the vault located each six meters, Figure 11. The holes were likely strengthened with stone frames and had covers. With time passing and due to different decaying factors, these holes became larger and representing nowadays weakness points participating in more collapses of vaults.



(a)



(b)

Figure 9. (a) 3D imagination of the Ramesseum temple and its storerooms (b) The storerooms of the Ramesseum temple are surrounded by red rectangles: aerial view showing the current state (top) and plan view (bottom). The blue arrow indicates the temple entrance. The dashed rectangle indicates the studied storerooms.

The second case study is the storerooms of Sety I temple shown in Figure 12. Nowadays, only the walls exist and all the vaults were lost as can be noticed from the aerial view. They are located to the left from the temple entrance occupying an area around 103 m × 60 m. The number of storerooms tunnels is twenty, ten tunnels at each side. Each tunnel is about 38 m long and 2.2 m high. All the tunnels are about 3.5 m except two tunnels (see Figure 12) that are wider and have about 6 m width.

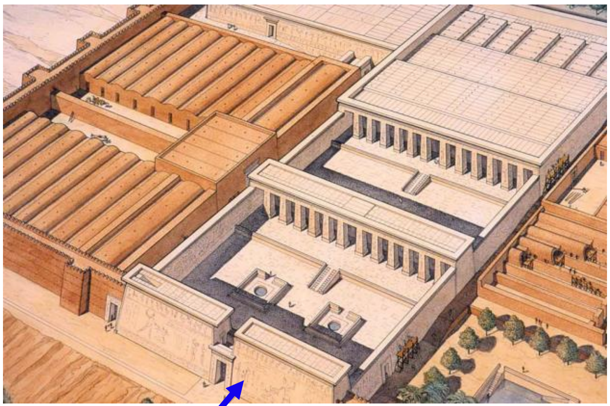
(a)

(b)

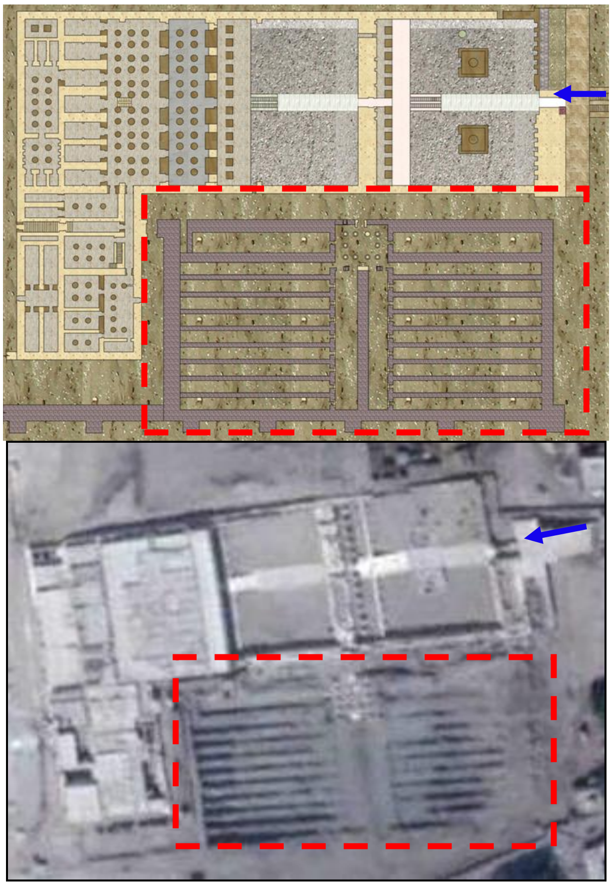
Figure 10. (a) The ruins of the Ramesseum temple and its storerooms vault and walls, (b) inside the storerooms.

Figure 11. Current state of holes used in filling the storerooms with grains.

The storerooms walls are 1.5 m thickness and were built using adobe bricks of size 40 cm × 20 cm × 14.5 cm. The vaults were formed by three courses of adobe masonry resulting in a total thickness of 70 cm, the used bricks had the dimensions of 60 cm × 22 cm × 7.5 cm.



(a)



(b)

Figure 12. (a) 3D imagination of Sety I temple and its storerooms, and (b) The storerooms of Sety I temple are surrounded by red rectangle: plan view (top) and aerial view showing the current state (bottom). The blue arrow indicates the temple entrance.

3.3 Damage symptoms and causes

Understanding the observed damage and its possible sources is crucial in the proposing of an accurate intervention measures, therefore, the following sections will cover to a large extent the symptoms of damage and their possible causes in the case studies before, during and after their discovery.

3.3.1 Before discovery

Both storerooms were covered for long periods of time by large amounts of filling including rubble, debris and sand. This overloading is considered the main cause of collapsing of the vaults and the supporting walls. Photos dates back to the last century showed clearly the filling above the storerooms before discovery, Figure 13.

(a)

(b)

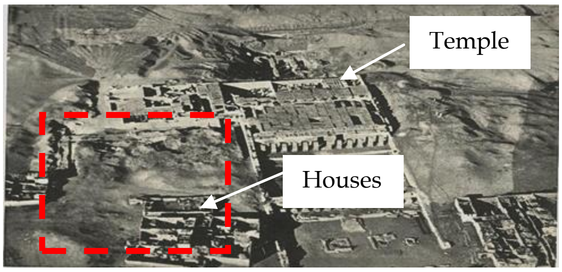


Figure 13. Photos date back to the last century before discovery of the storerooms: (a) The Ramesseum temple surrounded by filling from everywhere covering its storerooms, and (b) the storerooms of Sety I temple (in dashed red rectangle) covered by filling and houses.

The case of the storerooms of Sety I temple suffered from more damage causes than the storerooms of the Ramesseum temple. The villagers used to move over the covered storerooms with their animals, Figure 14. Furthermore, they destroyed a considerable part of the storerooms to build their houses in the same place, Figure 13. The early Copts escaped from persecution of the Roman emperors (before the recognition of the Christianity as the official religion of the Roman Empire) to these storerooms. They lived and worshiped in these storerooms and many other Ancient Egyptian temples. They looked to these structures as symbols of paganism; hence they destroyed and modified parts of these structures which participated in their damage (Ghazouli, 1964). A fire occurred and burnt these storerooms, a massive amount of animals burnt bones were found in the site as evidences of this accident (Ghazouli, 1964).

Figure 14. Photos date back to the last century before discovery of the storerooms of Sety I temple showing the villagers crossing over the covered storerooms with their animals.

3.3.2 During discovery

The adobe vaulted storerooms have not received enough attention by Egyptologists who excavated in the end of the 19th century and the beginning of the 20th century. They have disregarded the survival remains and evidences of those vaults among debris and ruins of a lot of Ancient Egyptian sites.

During excavations, it was a bad practice to give lower care to the discovered adobe structures and to care only about the stone masonry structures. Two striking examples can be mentioned here: the whole town which surrounded the temple of Hathur at Dendera was cleared away without record in quest of opening up the temple, and the same was repeated during the restoration of Horus temple at Edfu (Barsanti, 1907; Spencer, 1979a).

3.3.3 After discovery

In addition to the large loosed parts from the storerooms, currently they are suffering from many damage symptoms as shown in Figure 15:

- Wide visible cracks in walls, vaults and plaster,
- Partial collapses and losses of bricks and mortar in vaults and walls,
- Widening of the top holes used in the past to fill the storeroom with grains,
- Erosion of walls and plaster,
- Detachment and losing of considerable areas of plaster,
- Inappropriate interventions using incompatible materials like red bricks and cement mortar.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 15. Many symptoms of damage in the storerooms of Sety I and the Ramesseum temples (a) cracking, (b) partial collapses, (c) holes widening, (d) erosion, (e) plaster detachment and (f) restoration using incompatible materials.

These storerooms, as well as many other Ancient Egyptian adobe structures, suffered and still are suffering from some of the villagers who lived and still living in the neighbourhood. In the past they mined, dug, and destroyed the remains and ruins to get the adobe bricks to reuse them in the construction of their houses. The people who are doing so are called *sabbakheen* and obtaining the adobe bricks is considered like a job for them. In the current times, some villagers are again using the adobe bricks and mortar as fertilizers owing to the high percentage of nitrogenous earth the adobe has. They destroy the structure and use the fractions and crumbs to cover their agricultural lands.

Some animals like foxes and dogs made holes in the adobe walls of the storerooms to live in; Figure 16 .These holes represent places of weakness due to decreasing the wall section at the base where the highest compressive stresses due to self-weight exist.

(a)

(b)

Figure 16. Holes made by animals (a) Sety I storerooms and (b) the Ramesseum storerooms.

Ants and micro organisms attacked the storerooms structure to feed on the abundant chopped straw or chaff contained in the mud bricks. This resulted in reducing significantly the tensile strength of the adobe and consequently cracking and possible partial collapses occur in the attacked places. If no collapse occurs, such attack leaves the mud brick full of holes giving a bad appearance, Figure 17. In the Ramesseum storerooms, the wild bees participated in the deterioration of the adobe and evidences were found for their existence, Figure 18.

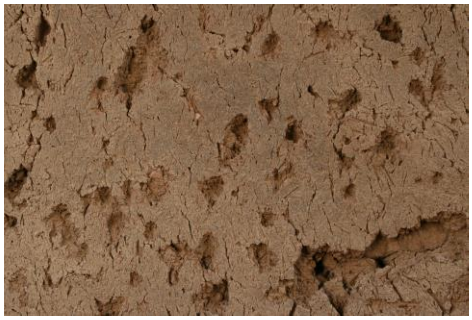


Figure 17. Holes made by wild bees after eating the straw in the plaster in the Ramesseum storerooms.

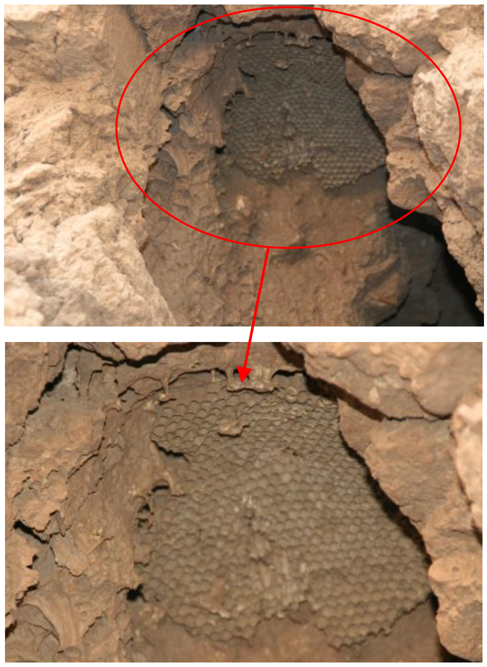


Figure 18. Wild bees nests found in the walls of the storerooms of the Ramesseum temple.

In the case of the Ramesseum storerooms, recently, the water table has risen due to the surrounding agriculture lands and houses, Figure 19. The ground water seeps into the bottom of the walls that absorbs the water by the capillary rise. This causes the swelling of the clay minerals contained in the adobe. Afterwards, the evaporation of water results in shrinkage and cracking, and after water drying the salts in the water crystallizes on the wall surface making it much more fragile, Figure 19. The wind blows removes that fragile parts resulting in more erosion of the wall in a continuous process.

(a)

(b)

Figure 19. (a) Agricultural lands and houses around the Ramesseum, and (b) salt crystallization on the wall surface.

A summary of some of the damage symptoms and causes in the two storerooms are given in Table 1.

Table 1. Summary of some of the damage symptoms and causes in the two case studies.

Damage symptoms and causes	Ramesseum storerooms	Sety I storerooms
Collapse of vaults	most	all
Collapse of walls	> 1/3 of walls	> 2/3 of walls
Reuse in the past	No	Yes
Exposure to disasters	No	Yes (fire)
Passing over by villagers before discovery	No	Yes
Damage by trampling and illicit activities in the present .	Yes (fewer)	Yes (more)
The absence of constructional support	the arcs (four layers) elaborately-made of setting of bricks Various method of bricks setting in walls Circular filling holes (weakness ponts)	the arcs (only three layers) weaker in setting of bricks Only one method of bricks setting in walls The same is
The absence of structural and constitutional support	The natural shortage of tensile strength and weakness of mechanical properties of mud-brick Straw disappearance (basic reinforcement) which, devoured by insects	The same is
Suffering live overloads in the past	Little more (the laden of the rubble, debris and sand)	much more (the laden of the rubble, debris, sand and villagers houses)
Encroachment upon by from villagers (Sabbakheen)	Yes	Yes
Suffering dead overloads in the past and present	the brickwork or rubble which filled the ridges between each two vaults	The same is
Ground water negative effect	Yes	No
Intervention trials to rescue	1906-1976-2004	No
Negligence and disregard in in the past and present	Yes	Yes

4. STRUCTURAL ANALYSIS

3D numerical model of the storerooms of the Ramesseum temple was created using the finite element (FE) software SAP2000. The objective was to understand the structural behavior under the different loading conditions that the storerooms had subjected to. These loading included the self-weight and the filling that covered the structure for long times before its discovery. Another objective was to investigate the effect of the increasing in the filling above the vaults to reveal its role in the failure of the vaults.

The walls and the vaults were modeled using shell elements. The lintels of the entrance doors were modeled using frame elements. A typical bay was studied first. This allowed a first understanding of the structural behavior easier than dealing with the 3D model directly. Afterwards, the complete bays of the storerooms were studied. Table 2 summarizes the used materials properties. These values were based on previous studies found in the literature for similar historic adobe (Varum et al., 2014; Silveira et al., 2013; Adomi et al., 2013 and Silveira et al., 2012).

Table 2. The used properties of materials

Material	Unit weight (kN/m3)	Modulus of elasticity (GPa)	Poisson ratio
Adobe masonry	18	0.4	0.3
Stone masonry	25	2	0.3

The FE model of the typical bay is shown in Figure 20. The model comprised 2294 shell elements. The maximum size of any shell was 0.5 m X 0.5 m. The total number of nodes was 2381 nodes that resulted in 13791 Degrees Of Freedom (DOF).

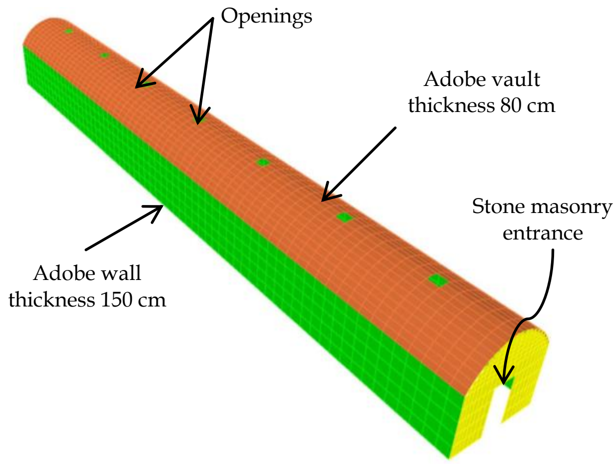


Figure 20. 3D model of the typical bay of the Ramesseum storerooms. Different colors indicating different thicknesses or different materials.

The linear elastic method of analysis was used. It is well understood by the authors that the nonlinear analysis is necessary when dealing with historic structures; however, this simplified analysis was preferred because the aim of the analysis was only to understand the behavior.

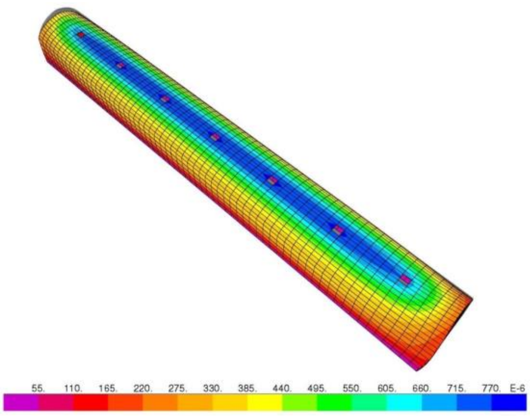


Figure 21. Resultant deformations (m) of the typical bay of the Ramesseum magazines.

The structure was analyzed under its self-weight first. The resultant deformations are shown in Figure 21. The maximum displacement occurred at the vault mid span. Near to the entrance and to the end wall, the displacement values were much smaller than the mid span.

The cracking of no-tension materials like the adobe masonry occurs at the places of the maximum principle stresses (tensile stresses). Figure 22 shows these places. As can be noticed, they are at the outer face of the vault springing and the inner face of the vault mid-span.

In Figures 22 and 23, the minimum principle stresses (compressive stresses) are shown. These places are attributed to the failure due to crashing. For the vault, these stresses occur at the inner face of the vault mid span and at the outer face of the vault springing. For the walls supporting the vault, these stresses are found at the inner face and the bottom of the outer face.

After finishing the analysis of a typical bay, the full magazines structure was analyzed. The resultant deformations are depicted in Figure 25 . As can be seen, the deformations of the intermediate spans are similar in magnitude to those obtained from the analysis of the typical bay. The value of these deformations was found to be approximately from 0.75 to 0.80 mm. For the first and the last bays, higher deformations were found with a value slightly higher than 1 mm. This explains why the end walls were built with a thickness of 3 m that is double the thickness of the intermediate walls.

It is believed that the filling existed over the magazines vaults for centuries resulted in their collapse. Therefore, the structure was analyzed under the combination of the self-weight and the filling. The filling was applied as a uniform pressure above the vaults. The unit weight of the filling was assumed 1.8 t/m3. In Figure 26, the resultant deformations due to this load combination are plotted. Comparing the two figures 6&7 (plotted with the same scale), the increasing in the deformations due to the filling load can be easily recognized. Due to the filling loading, mostly all the bays deformations reached values higher than 1 mm.

The exact depth of the filling existed above the vaults before its discovering is not exactly known. Therefore, it was tried to apply a filling with 1m, 2m and 3m depth. To show the effect of the increasing filling, the deformations along the transversal section "S-S" (Figure 26) was depicted in Figure 27. In this figure, the horizontal axis starts with x-coordinate equals to zero (the most left of the section "S-S") and ends with the x-coordinate equals to 51.8m (the most right of section "S-S"). For the first and the last bays mid-spans, x=1.8 and x=49.95, respectively, the deformation due to 3m filling is near to five times to its counterpart due to self-weight only. This clearly shows the effect of the increasing in the filling depth on the deformations, thus the strains and the stresses which resulted at end in the collapse of the vaults.

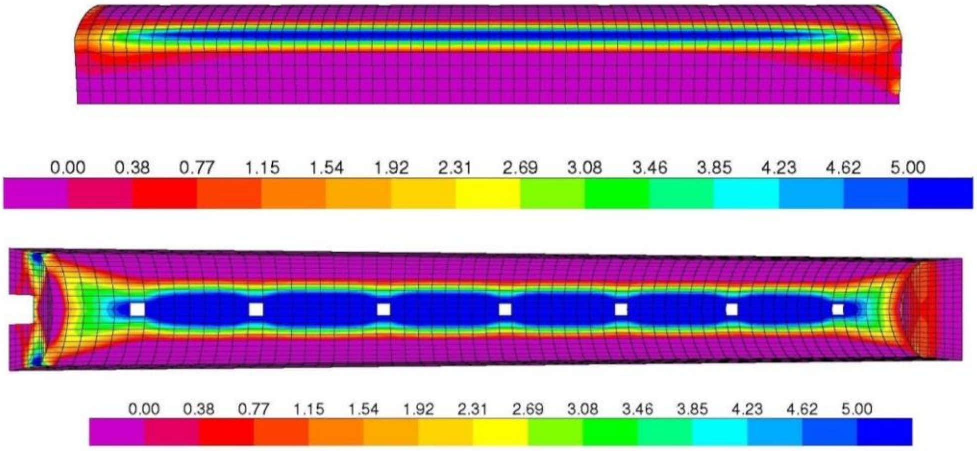


Figure 22. Locations of the maximum principle stresses (tensile stresses) (t/m2): at the outer face of the vault springing (top) and the bottom face of the vault mid span (bottom).

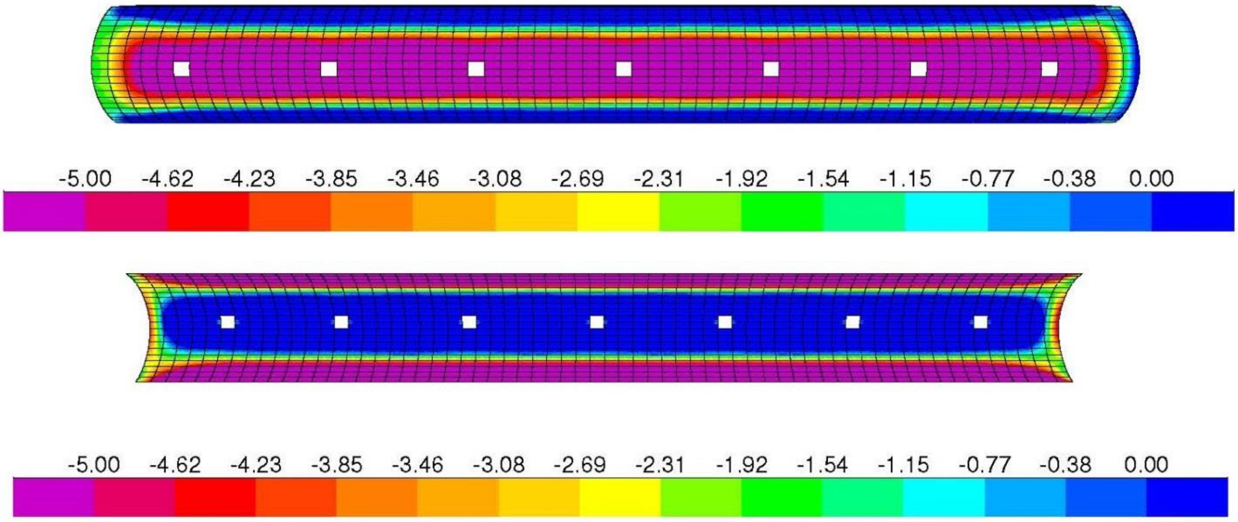


Figure 23. Locations of the minimum principle stresses (compressive stresses) (t/m2) in the vault of the typical bay of the Ramesseum magazines: at the outer face of the vault mid-span (top) and the inner face of the vault springing (bottom).

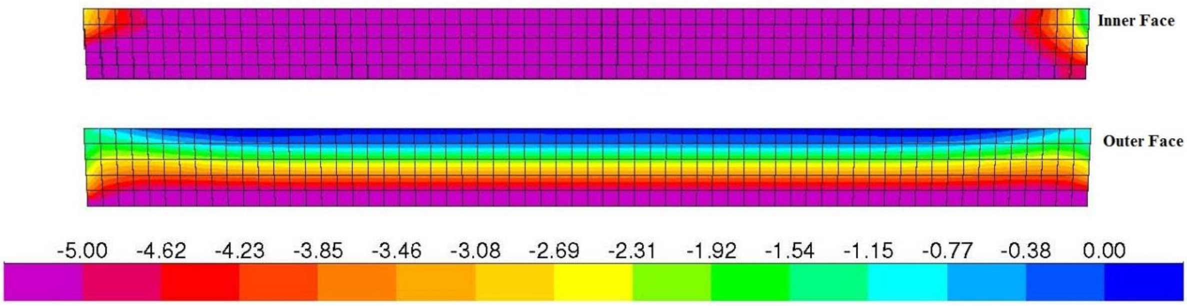


Figure 24. Locations of the minimum principle stresses (compressive stresses) (t/m2) in the walls of the typical bay of the Ramesseum magazines: at the inner face of the wall (top) and in the outer face of the wall (bottom).

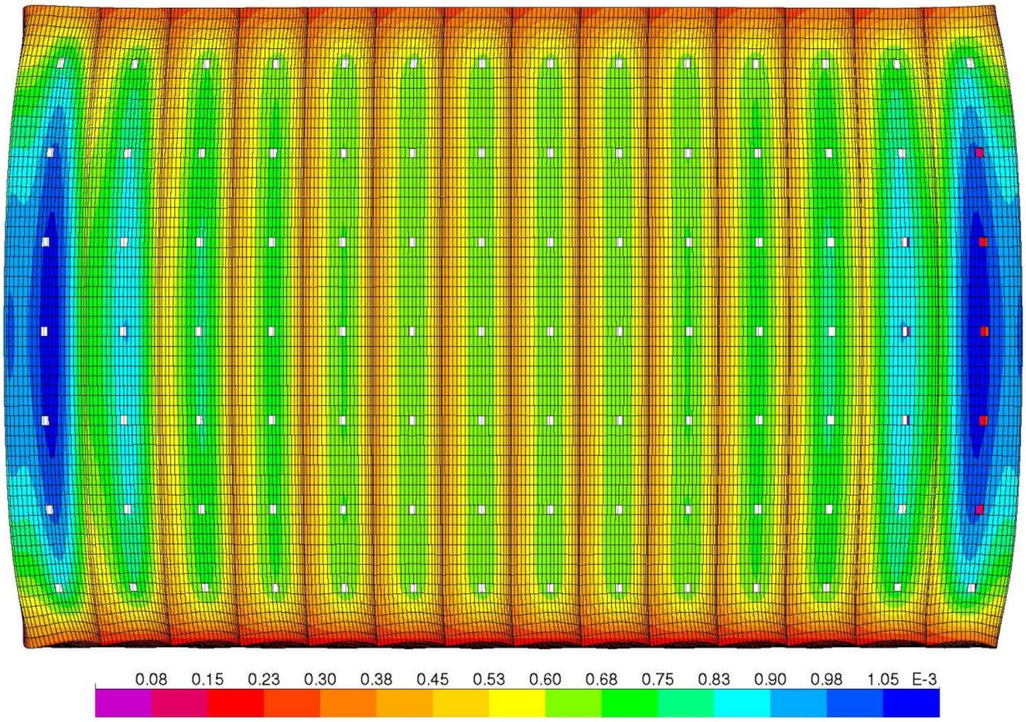


Figure 25. Resultant deformations (m) of the magazines of Ramesseum temple, case of self-weight only.

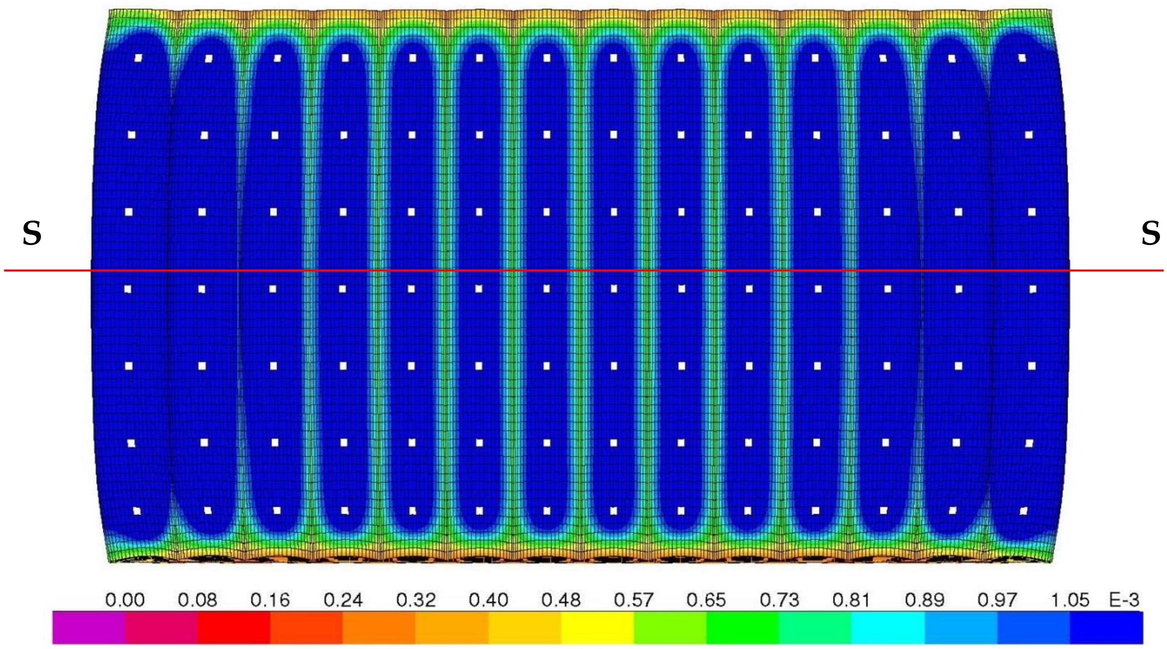


Figure 26. Resultant deformations (m) of the magazines of Ramesseum temple, case of self-weight+1 m of filling. The red line indicates the place of the transversal section in the vaults "S-S".

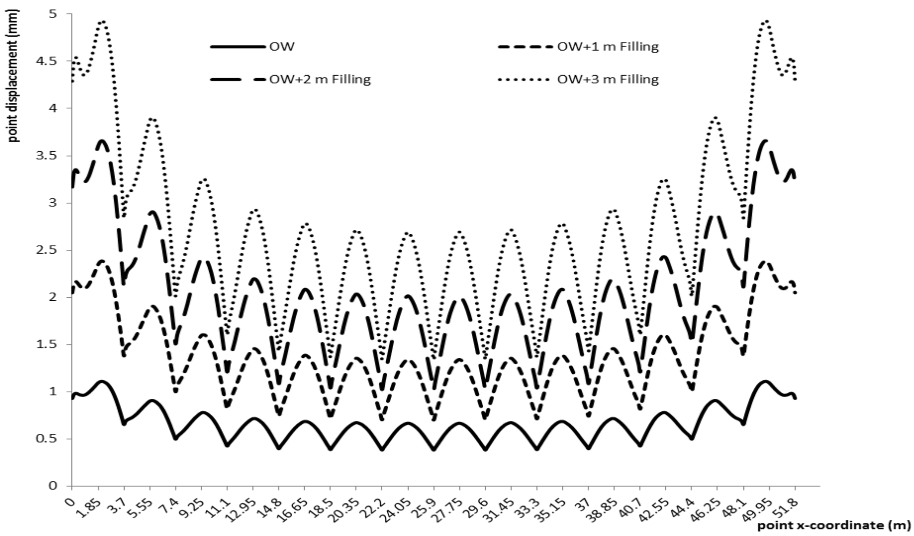


Figure 27. The effect of increasing filling depth on the Resultant deformations (m) of a selected transversal section "S-S" in the magazines of Ramesseum temple. OW=self-weight.

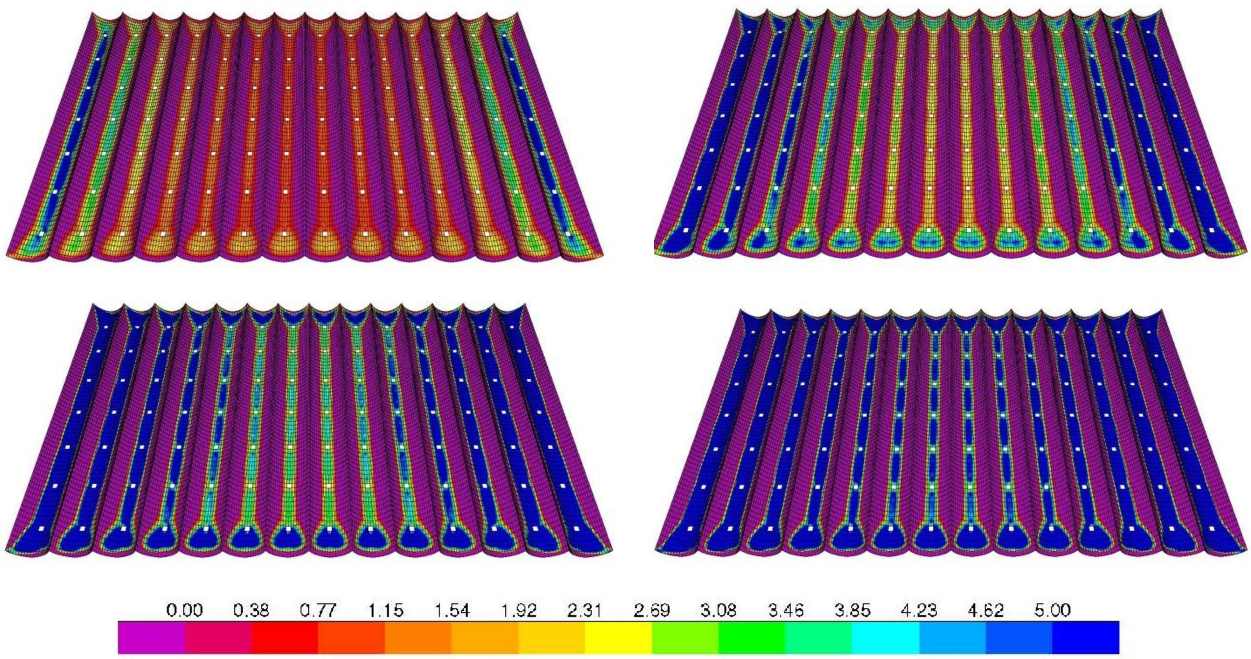


Figure 28. The effect of increasing filling depth on the maximum principle stresses in the vaults' inner face in the magazines of Ramesseum temple. The cases from top left to bottom right are: self-weight (OW), OW+1m of filling, OW+2m of filling and OW+3m of filling, respectively.

To reveal more the damaging effect of the filling existed above the vaults, the maximum principle stresses (tensile stresses) in the inner face of the vaults is plotted in Figure 28. It can be easily shown the increasing of the tensile stresses with the increasing of the filling depth which resulted in the collapse of the vaults.

5. INTERVENTION PROPOSALS

For the preservation of the two case studies, the archaeological site including the temples and the storerooms, with taking into account the fact that keeping the authenticity requires considerably more efforts to conserve the survival remains, then to reconstruct new ones, so, it should be protected by reconstruction of the original enclosure walls of the two sites (for instance, the original mud-brick temenos wall of the second case study (of 5.00 m. thick, supported with buttresses of (4.70 × 2.15 m.), constructed of mud-bricks (40× 20×14.5 cm.) (the same brick and brickwork of the enclosure wall's) which begins from the small end of the first pylon of the temple and progress straight then turn the corner at right angle to the southeast, so it is fit enough for protection), with conformation the distinction between the archaeological and reconstructed parts. As well, a sufficient safeguard for the site with the necessary equipment should be assigned. This will control to a large extent the lateral effects of wind influences, robbery, visitors, Intruders, the anthropogenic actions and the entrance of animals like foxes and dogs to the site, especially with the fragility of the remains of the two sites.

A protective temporary shelter should be installed above the remains of the two sites, with appropriate materials, form and construction technology, to protect the sites from weathering and rare severe rain falls.

Patching and replacing the missing bricks partially or wholly with same form and material and with the same mortar, with differentiation with stamps, in case of partial missing or disintegration of a brick it should be patched after matching and obtained in situ nearby.

The existing parts of the storerooms of the Ramesseum were provided in earlier times with steel supporting structures, Figure 29. This strengthening intervention is believed to be one of the reasons behind the survival of these parts up to date. Therefore, it is proposed to apply the same intervention for the remaining parts of the Ramesseum storerooms. This intervention, however, has some disadvantages that should be avoided. First, it decreases the authenticity of the storerooms. Second, steel corrodes. Third, the compatibility in the mechanical properties between the steel and the adobe is low. The steel has much higher tensile and compressive strengths than the adobe. Finally, the steel is supporting the adobe structure and is not working with it monolithically. When the structure is subjected to the external forces, the steel structure does not absorb all the developed tensile strains and the adobe structure is subjected to some of them. Therefore, some cracks are present at the locations where the intervention exists as can be noticed in Figure 30 .

For the disadvantages of the existing strengthening mentioned above, another modern intervention could be done using polymer grids. Polymer grids are made from polypropylene resins that are chemically and biologically inert and resistant to degenerative process of adobe. Polymer grids resist the developed internal forces in the adobe structure via mechanical action developed using: mechanical connections and/or mud plaster (Torrealva, 2008). In this intervention a polymer grid is to be attached to the external and/or the internal faces of the vaults and the walls and connected with them using nylon threads, Figure 31. Afterwards, the grids are covered with mud plaster having the same mechanical, chemical, physical, thermal and other properties like the historical plaster. This created mud-grid material which is capable of resisting applied forces as a composite. Torrealva et al. (2008) showed the efficiency of such a technique in the strengthening of Nubian vaults. The polymer grids could be also placed between the wall courses as have been already implemented in the restoration works of the historical adobe structure of Shunet el-Zebib in Abydos, Figure 32.

For the case of the Sety I storeroom, the main interventions are: cleaning, strengthening, compensation, rebuilding and reconstruction.

So it could be proposed the re-clearance of the site with cleaning of the site with ultimate care sensitivity for collecting archaeological sporadic bricks, removing accumulation, and assembling these ancient bricks, then cleaning and removing the loose.

Stabilization and repair the structural function, stability, esthetic form, prevention further falling, through repairing wall foundations, which have been burrowed by foxes and other animals and have exposed the surrounded parts for more erosion and collapse, filled and packed with new mud-bricks, providing support for the structure, repair or compensation with the same types of materials and with the same techniques of construction.

For reconstruction justification of the two case studies, (see: warrants for ancient Egyptian buildings and sites's remains and ruins reconstruction, in: El-Derby, A. A.O.D., 2012), consequently: reconstitution of damaged parts of original mud-brick walls and vaults, through reconstituting damaged parts of original mud-brick by using mud-bricks had fallen from the original buildings, with using BX1200 Geogrids among courses to reinforce the walls and vaults.

Partial reconstructions of the missing parts using new mud-bricks, with similar new mud-bricks in material and form, with the same original technique of setting and construction and with the same original stylistic architecture, differentiated with stamps and Geogrid textile to separate the new materials work from the archaeological ones, or any features, saving the authenticity and avoiding misleading, with using BX1200 Geogrids (which provides long-term performance and resists weathering) among courses and sparing from straw in new mud-bricks combination, avoiding its decomposition, consume and loss by insect in the future, where should be compensated with raw, unprocessed sheep fiber wool(10 mm long) which selected other natural reinforcement materials; jute, coir, sisal, bamboo, wood, palm leaf, coconut leaf truck, coir dust, cotton and grass etc., produce acceptable mechanical characteristics, and it is more suitable than modern stabilizer such as Portland cement and lime (C. Galan-Main et.al,2010:1462).

Figure 29. Two forms of the steel supporting structures used as strengthening interventions in the Ramesseum storerooms.

Figure 30. Large cracks at places of strengthening intervention.

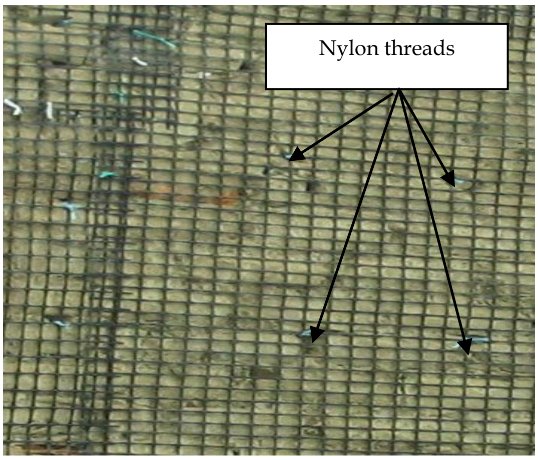


Figure 31. The application of polymer grids to an adobe wall (Source: Torrealva, 2008)

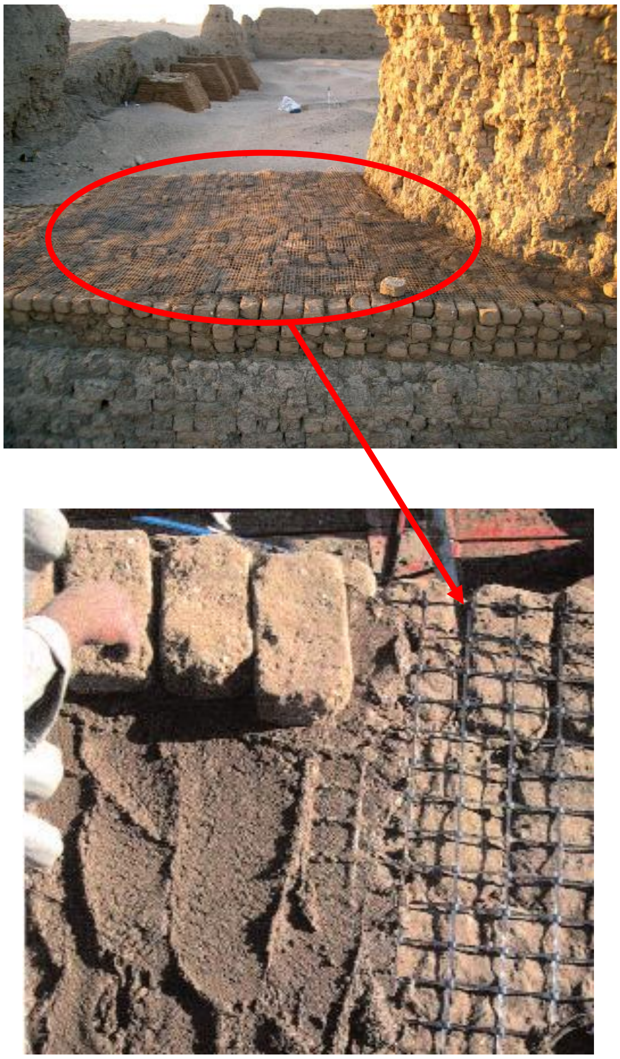


Figure 32. The application of polymer grids between adobe wall courses in Shunt el-Zebib in Abydos.

Reconstruction of the missing areas of plaster of walls and vaults with appropriate plaster; this method had been common in preserving ancient mud-brick buildings since ancient Egyptian periods: plastering the missing areas of the same original plasters walls and vaults, sparing from straw in combination of new plaster, with using BX1200 Geogrids, seeing to that this method hide the original interior and exterior faces of walls and vaults, we have to leave appropriate (well-preserved) areas without plastering, seeking for partial authenticity and presentation.

For the case of the Sety I storeroom, it one bay of the collapsed walls and vaults should be reconstructed. The objective is to give the site visitor an impression about the historic structures existed before. Alternatively, the full storerooms vaults could be reconstructed, Figure 33. In the reconstruction process, the historical setting of mud-bricks in walls and vaults must be followed. The new walls and vaults could be strengthened with polymer grids for durability issues.

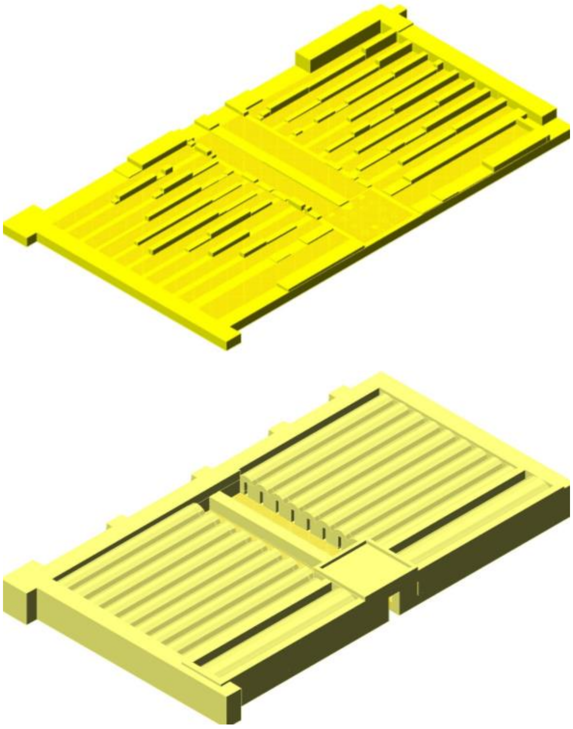


Figure 33. The documentation of the current state of collapse of the Sety I storerooms (top) and a 3D view of the proposed reconstruction (bottom) (after, El-Derby, 2005, figs. 224, 281).

For conserving the remaining parts of the two case studies, the following are proposed:

- Reconstruction of the areas of walls where large visible cracks exist;
- Splits inside walls are either injected with mud mortar, by using special pressure pups or manually and regularly maintained;
- Injection of narrow cracks with mud mortar
- compatible with the historical adobe to avoid any future separation;
- Re-plastering the missing areas of the plaster of walls and vaults using new one having, as mentioned before, the same mechanical, chemical, physical, thermal and other properties like the historical plaster;
- Capping of the existing adobe walls by placing at the wall top a new one or two courses of adobe masonry and plaster layer containing Water repellent and abrasion resistant materials, and compatible with the used historical ones to protect ones underneath from continuous erosion;
- Stopping the biological deterioration caused by ants and wild bees using appropriate environmentally friendly chemicals,
- For the Ramesseum storerooms, in specific, the waste water coming from surrounding agricultural lands and houses should be drained away from the historical site.

6. CONCLUSIONS

The paper presented the studies carried out on two adobe vaulted storerooms of the Ramesseum and Sety I temples from Ancient Egypt. Both date back to the 19th Dynasty of Pharaonic period. All the adobe vaults of the Sety I storerooms collapsed because of the filling existed above them for centuries before the discovery and also because of anthropogenic actions. The remaining adobe walls are suffering from many damage symptoms and causes and are in a very bad need for interventions. In the case of the Ramesseum storerooms, only small parts of some of the vaults exist. A 3D numerical model was analysed and it showed that the filling contributed significantly in the damage and collapse of the storerooms. The strengthening intervention carried out in the last century may have contributed in preserving the vaults of this case study. Therefore, a similar intervention was proposed in this research with the usage of polymer girds instead of steel to avoid the problems created by the latter. The proposed interventions are believed to be able to stop the noticed causes of damage which may give the chance to this invaluable human heritage to survive for the next generations.

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