Investigating the Structural Validity of Virtual Reconstructions of Prehistoric Maltese Temples

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Abstract

The prehistoric temples found on the Maltese islands, dated from 3600 -2500 BC, are unique examples of truly megalithic complexes. Although the temples can still be viewed today, they are unroofed. One of the major questions that still has to be answered is: Were the temples roofed, and if so with what? The key evidence for the presence of roofs is the hypogeum temple at Hal Saflieni, found in 1902, which appears to be an imitation of the above ground temples and the discovery, at Mgarr, of a contemporary miniature model in limestone with a roof. Since then, Ceschi in 1939 and more recently Piovanelli in 1988 have proposed that the temples were roofed with Globerigerina limestone slabs. Although convincingly illustrated, neither of these "reconstructions" has been tested for real stability and strength. In this paper we describe a detailed investigation of the reconstructions of Ceschi and Piovanelli. We use computer graphics and structural engineering techniques, based on the actual measured strength of Globerigerina limestone, to show whether in fact these reconstructions are indeed valid.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Color, Shading, Shadowing, and Textures

1. Introduction

Figure 1: *Tarxien temple as it appears today.*

The prehistoric temples of Malta are some of the earliest examples of free standing, megalithic monuments in the world. Built throughout the period 3600-2500 BC, the temples are scattered over the Maltese islands. They all have common features, including a perimeter wall, often of megalithic construction, surrounding an inner structure of "apses" with an entrance portal and interconnection passages [Cla98]. They were built with a combination of Coralline limestone and Globigerina limestone which is much more easily dressable. Earlier temples were simple lobed ones, but later they comprised trefoil and more apses up to a six apse one. All the temples are currently unroofed and one of the important questions still asked by archaeologists is: Were they indeed roofed, and if so, by what?

In addition to the above ground temples, there were two hypogea constructed in parallel. These underground chambers were used for burial of the dead. The hypogeum at Hal Saflieni is carved directly out of the Globigerina limestone and mimics many of the features of the above ground temples. As discussed in section 3, this is often used as evidence for the form of the temple roofing [Cla98].

In this paper we analyse, by means of civil engineering

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techniques, two of the popular roof reconstructions theories, by Ceschi [Ces39] and Piovanelli [Pio88], to determine whether they are indeed feasible.
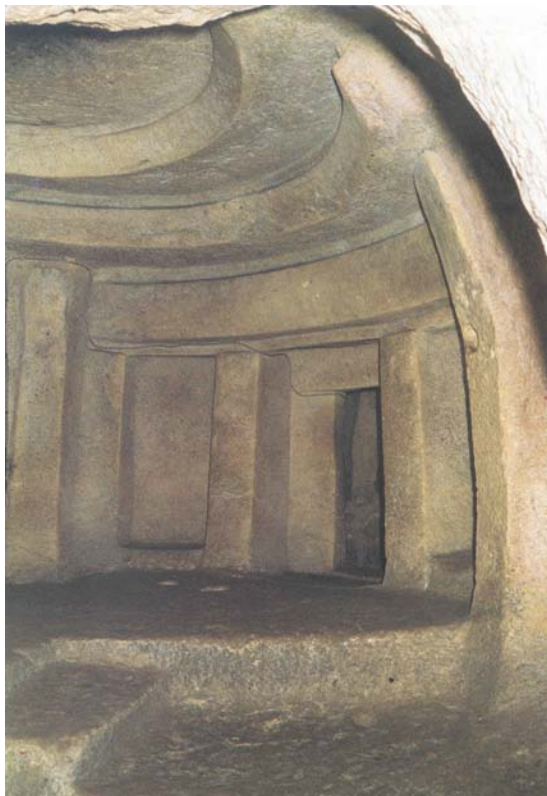

Figure 2: *Miniature temple found at Mggar.*

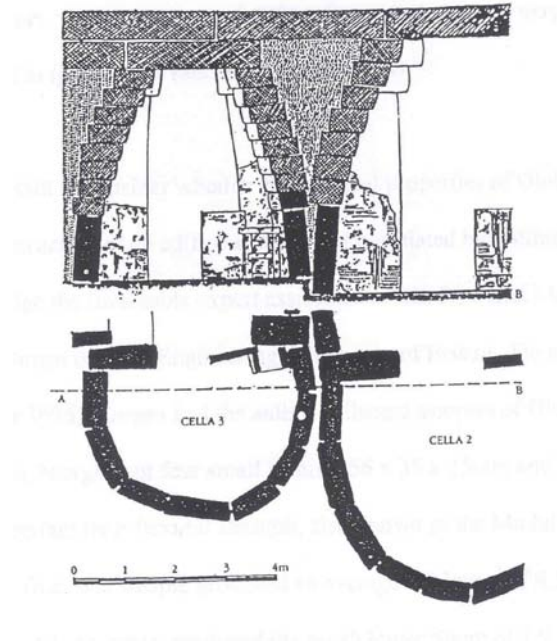**Figure 3:** *The hypogeum at Hal Saflieni [Bon91].*

Figure 4: *Ceschi's reconstruction of the Tarxien apses [Ces39].*

2. Valid Virtual Archeology

Archaeological sites have been studied and recorded for hundreds of years, from medieval drawings of the sites, to the systematic illustration of the 18th century, to photographs of the early 20th century and finally computer graphics from the 1980s onwards [CD02, MR94, Nov98, RS89].

Computer graphics is now regularly providing powerful tools for modelling multi-dimensional aspects of data gathered by archaeologists [BFS00]. In recent years, techniques have been developed which can be used to reconstruct and visualize features of sites which may otherwise be difficult to appreciate. While these new perspectives may enhance our understanding of the environments in which our ancestors lived, if we are to avoid misleading impressions of a site, then the computer generated images should not only look "real", but must simulate accurately all the physical evidence for the site being modelled [DC01, Mar01].

High-fidelity reconstructions of archaeological cites has typically focussed on the use of laser scanners or photogrammetry for creating accurate models, for example [Add01, BM02, GG03], or the authentic illumination of the models, for example [DC01, CR03, SCM04].

3. Roofing the Temples

The major debate about the roofing of the temples is whether they were roofed by stone beams laid over the walls of the
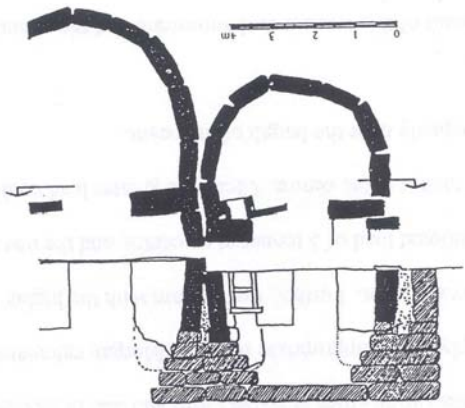
Figure 5: *PiovanelliŠs reconstruction of the Tarxien apses [Pio88].*

apses, the so-called Italian view, or by timber beams overlaid with bushes, the British view [TVC87]. Evidence used to counter the British view is the current lack of suitable wood on Malta and the lack of any supporting evidence in the form of trade goods with neighbours who could have provided the wood, for example Sicily. Of course in prehistoric Malta there could indeed have been a sufficient supply of suitable wood [Eva59]. In this paper we only consider the structural feasibility of the Italian view.

Ceschi in [Ces39] compared the Maltese temples with similar structures in Sardinia, Pantelleria and the Balearics. One of the key pieces of evidence he used to support the theory of stone slab roofs is the small limestone model of a temple excavated at Mggar, figure 2. As can be seen, this miniature temple is roofed with horizontal slab roofing at right angles to the long axis.

Furthermore, as figure 3 shows, the underground hypogeum at Hal Saflieni exhibits very similar architectural features to the above ground temples, and its roof is carved in the shape of overlapping stone slabs. Figure 4 shows the reconstruction of the roofing at Tarxien of two apses that Ceschi proposes.

Although Piovanelli [Pio88] had his doubts about the massive nature of Ceschi's reconstructions, he also supported the stone roofing theory. Using Hal Saflieni as his example, he suggested that concentric rings of stone were placed on the inward sloping walls of the apses. Such a construct progressively reduces the space to be covered and closely matches the form of the hypogeum. Piovanelli's proposed reconstruction is shown in figure 5.

4. Structural Analysis

The stability of the proposed reconstructions depends on the arrangement of the constituent blocks of stone. Each block needs to remain in position under the combined action of its own weight and of the forces which are being applied to it by adjoining blocks [Gor78].

The shape, size and type of the building material will affect the way in which the materials and structure will deflect. If the force applied to a constituent block is too great for the strength of the material then it will break. In addition, the forces present in the structure must be in equilibrium. That is, every force must be balanced and reacted by another equal and opposite force at every point throughout the structure, If this is not the case then the structure will fall.
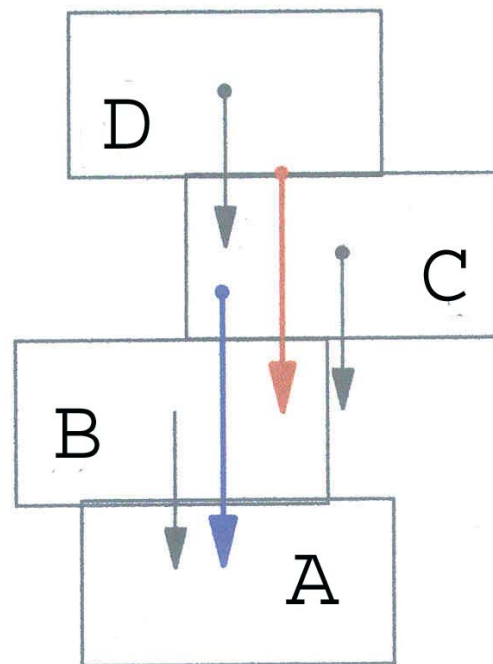

Figure 6: *Determining the thrust lines.*

4.1. Stability

The stability of a structure can be evaluated by translating Newton's laws of equilibrium to the components of the structure. For example, if block B is positioned on top of block A then block B will balance on top of block A provided the centre of gravity of block B acts down between the areas of contact between the two blocks. If block B is moved outside this bound of block A then B will unbalance and fall over. If it is desired that B's centre of gravity is outside the bounds of block A then either another block must be placed

on top of B to counter balance it, or a block can be placed under B.

In the former case, a thrust line approach may be used to determine the stability of the structure. A thrust line is a position from which a given mass acts down. This is equal to the centre of gravity of a single block. For a stack of blocks, the centroid and each block's mass comprise the thrust line acting on the blocks below. If this thrust line moves outside the bounds of the structure then it will fall. For example, as shown in figure 6, the stability of the structure can be tested by considering the highest block first. If block D's thrust line is outside the bounds of block C then the structure is unstable. If it is within the bounds of C then the stability of C and D on B can be tested. A new thrust line for C is computed which is the combination of the thrust lines for C and D. If this combined thrust line is within the bounds of block B then the combination of C and D on B is stable. If not, then the combination of C and D on B is unstable.

The centroid of a three dimensional composite mass of two blocks with centroids C1= (x1, y1, z1) and C2 = (x2, y2, z2) and masses M1 and M2 can be calculated

$$x' = x1M1 + x2M2/M1 + M2$$
$$y' = y1M1 + y2M2/M1 + M2$$
$$z' = z1M1 + z2M2/M1 + M2$$

In the case where a block is supported by two (or more) other blocks placed underneath it, then the weight of the supported block will, of course, act down through both supporting blocks. The weight acting on each support block is proportional to its distance from the thrust line of the supported block and is calculated, as shown in figure 7 as:

$$Weight\ acting\ on\ B = WAb/a + b$$
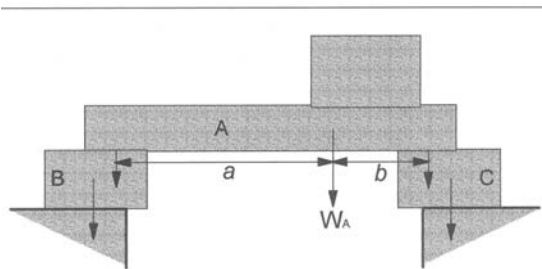$$Weight\ acting\ on\ C = WAa/a + b$$

Figure 7: *Calculating the weight acting down on a block.*

4.2. Spanning

Having established the stability of a spanning block, it is equally important to ensure that the block is indeed strong enough not to crack under its own weight or the weight of any blocks above it. The spanning ability of a beam depends on the tensile strength of the material.

$$Self weight\ per\ metre\ length = \\ width(w) * height(h) * density(d)$$

also,

$$Section\ Modulus\ Z = (w * h^2)/6$$
$$Moment\ M = Z * tensile strength(s)$$

The spanning distance (l) can now be calculated as:

$$l^2 = (8 * s * Z)/Self weight$$

As described in section 4.3, the tensile strength of Globigerina limestone was found to be $4.6N/mm^2$ and density $1725kg/m^3$. So, for example, for a regular block of Globigerina of height and width 0.5m.

$$Self weight\ per\ metre = 0.5 * 0.5 * 1725 = 4.31kN/m$$

$$Z = (500 * 5002)/6 = 20833333mm^3$$

So $l = 13.34m$. This means that the maximum distance a block of Globigerina limestone with dimensions $0.5 * 0.5m$ can span is $13.34m$. Any further than this and the block will break under its own weight.

This maximum distance is, of course, shortened if the block is carrying any other blocks. This reduced length can be calculated by determining the additional weight acting on the block through the thrust line.

4.3. analysing Globigerina limestone

Samples were collected of Globigerina during a visit to Malta. From these three small beams of $256 \times 35 \times 35mm$ were cut from one sample, and fourth similar size beam from a second sample. These beams were subjected to a tensile test by the Civil Engineering Department of the University of Bristol to determine their flexural strength, or Modulus of Rupture. An increasing load was applied to cubes of Globigerina through steel plates until the cubes failed. The results obtained are [Por98]:

Table 1: *Results of Globigerina analysis*

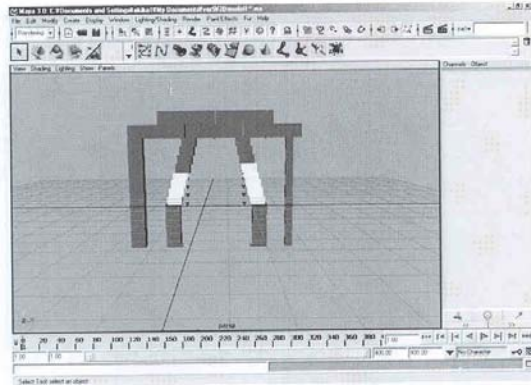| Cube Number	Cube mm	Area mm^2	Density kg/m^3	Load kN/mm^2	Strength N/mm^2
1A	35	1.225	1.725	15.3	12.5
1B/1	35	1.225	1.725	17.4	14.2
1B/2	35	1.225	1.725	15.6	12.7
2A	35	1.225	1.725	20.9	17.1

Figure 8: *Structural analysis of CeschiŠs proposed reconstruction.*

5. Results

The structural analysis techniques were implemented as a plug-in to the modelling package Maya from Alias. This enabled the reconstructions to be simply modelled using Maya and then tested for stability and spanning ability. Any part of a reconstruction which is not structurally sound is highlighted by colouring the unstable blocks white.

Figure 8 shows the model of the reconstruction proposed by Ceschi after it has been analysed by our system. As can be seen, the structure is unstable and thus the reconstruction infeasible.

The calculated thrusts lines for Piovanelli's reconstruction are shown in figure 9. All the thrusts lines are within the bounds of the structure and thus this part of the reconstruction is structurally sound. Figure 10, shows the analysis of the reconstruction of the entire apse. Here one of the blocks now becomes unstable.

6. Conclusion

The roofing of the prehistoric Maltese temples remains one of the key unanswered questions about these unique sites. Computer graphics together with structural engineering techniques and a detailed analysis of the building materials can be used to validate at least the structural feasibility of any reconstruction. As our results have shown, the reconstruction proposed by Ceschi in 1939 is not stable, while for

that of Pavionelli, although the front section is stable, when the entire apse is considered the structure would also fail.

We will never know how the temples were roofed. A system, such as we have developed, can be used as one of many tools by the archaeologists to enable them to explore at least structurally feasible possibilities of reconstructions.

To provide a more general system for analysing archaeological site reconstructions, a complete database of the tensile and compressive strengths of possible building materials needs to be collected. We intend to continue collecting this information in conjunction with archaeologists and civil engineers.
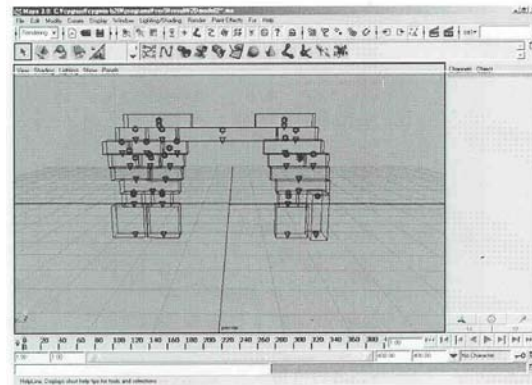

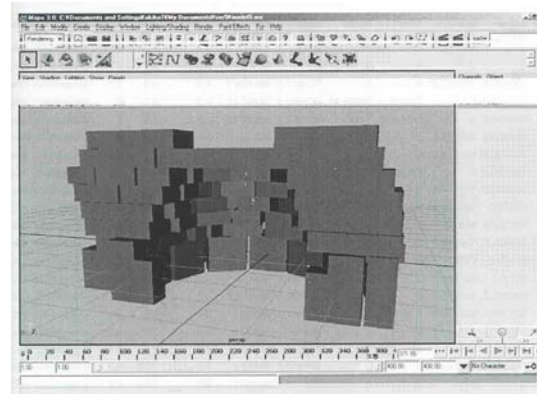**Figure 9:** *Thrusts lines for the PiovanelliŠs reconstruction.*

Figure 10: *Analysis of the complete apse reconstruction showing the instability of the structure.*

7. Acknowledgements

References

[Add01] ADDISON A. C.: Virtual heritage: technology in the service of culture. In *VAST '01: Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage* (New York, NY, USA, 2001), ACM Press, pp. 343–354.

[BFS00] BARCELO J., FORTE M., SANDERS D.: *Virtual Reality in Archaeology*. ArchaeoPress, 2000.

[BM02] BOEHLER W., MARBS A.: 3d scanning and photogrammetry for heritage recording: A comparison. In *12th Int. Conf. on Geoinformatics - Geospatial Information Research: Bridging the Pacific and Atlantic University of Gävle* (2002).

[Bon91] BONANNO A.: *An archaeological paradise*. MJ Publications, 1991.

[CD02] CHALMERS A., DEVLIN K.: *Recreating the Past*. ACM SIGGRAPH, July 2002.

[Ces39] CESCHI C.: *Architettura dei Templi Megalitici di Malta*. Fratelli Palombi, 1939.

[Cla98] CLARK D.: *Insular monument building: A cause of social stress? The case of prehistoric Malta*. PhD thesis, University of Bristol, 1998.

[CR03] CHALMERS A., ROUSSOS I.: High fidelity lighting of knossos. In *VAST '03: Proceedings of the 2003 conference on Virtual reality, archeology, and cultural heritage* (New York, NY, USA, 2003), ACM Press, pp. 47–56.

[DC01] DEVLIN K., CHALMERS A.: Realistic visualisation of the pompeii frescoes. In *AFRIGRAPH 2001* (November 2001), Chalmers A., Lalioti V., (Eds.), ACM SIGGRAPH, pp. 43–47.

[Eva59] EVANS J.: *Malta*. Praeger, 1959.

[GG03] G. GODIN F. BLAIS L. C. J. B. J. D. J. T. M. R. S. E.-H.: Laser range imaging in archaeology: issues and results. In *cvprw vol. 01, p. 11* (2003).

[Gor78] GORDON J.: *Structures or why things don't fall down*. Penguin, 1978.

[Mar01] MARTINEZ P.: Digital realities and archaeology: a difficult relationship or a fruitful marriage? In *VAST '01: Proceedings of the 2001 conference on Virtual reality, archeology, and cultural heritage* (New York, NY, USA, 2001), ACM Press, pp. 9–16.

[MR94] MILLER P., RICHARDS J.: The good, the bad, and the downright misleading: Archaeological adoption of computer visualization, computer applications in archaeology. *British Archaeological Reports (Int. Series, 600)* (1994), 19–22.

[Nov98] NOVITSKI B.: Reconstructing lost architecture. *Computer Graphics World* (1998), 24–30.

[Pio88] PIOVANELLI G.: *Missione a Malta*. 1988.

[Por98] PORTER S.: *Civil engineering constraints for prehistoric site reconstructions*. Final year project Thesis, University of Bristol, 1998.

[RS89] REILLY P., SHENNAN S.: *Applying solid modelling and animated three-dimensional graphics in archaeological problems*. Tech. rep., IBM Uk Scientific Centre, 1989.

[SCM04] SUNDSTEDT V., CHALMERS A., MARTINEZ P.: High fidelity reconstruction of the ancient egyptian temple of kalabsha. In *AFRIGRAPH 2004* (November 2004), ACM SIGGRAPH.

[TVC87] TAMPONE G., VANNUCCI S., CASSAR J.: Nuovo ipostesi sull'architettura del tempio megalitco di ggantija a gozo. *Bollittino Inegheir* (1987), 3–20.