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 Globigerina 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 Globigerina 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

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 hypogeas 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
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.](image)

![Figure 3: The hypogeum at Hal Safieni [Bon91].](image)

![Figure 4: Ceschi’s reconstruction of the Tarxien apses [Ces39].](image)

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: Piovanelli’s reconstruction of the Tarxien apses [Pio88].

Figure 6: Determining the thrust lines.

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.

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 block 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 \( C_1 = (x_1, y_1, z_1) \) and \( C_2 = (x_2, y_2, z_2) \) and masses \( M_1 \) and \( M_2 \) can be calculated

\[
x' = x_1 M_1 + x_2 M_2 / M_1 + M_2
\]
\[
y' = y_1 M_1 + y_2 M_2 / M_1 + M_2
\]
\[
z' = z_1 M_1 + z_2 M_2 / M_1 + M_2
\]

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:

\[
\text{Weight acting on } B = W A b / a + b
\]
\[
\text{Weight acting on } C = W A a / a + b
\]

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.

\[
\text{Self weight per metre length} = \text{width}(w) \times \text{height}(h) \times \text{density}(d)
\]

also,

\[
\text{Section Modulus } Z = (w \times h^2) / 6
\]
\[
\text{Moment } M = Z \times \text{tensile strength}(s)
\]

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

\[
l^2 = (8 \times s \times Z) / \text{Self weight}
\]

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

\[
\text{Self weight per metre} = 0.5 \times 0.5 \times 1725 = 4.31 \text{kN/m}
\]

\[
Z = (500 \times 5002) / 6 = 20833333 \text{mm}^3
\]

So \( l = 13.34m \). This means that the maximum distance a block of Globigerina limestone with dimensions 0.5 \( \times 0.5 m \) can span is 13.34\( m \). 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 \( \times 35 \times 35 \text{mm} \) 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]:

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Table 1: Results of Globigerina analysis

<table>
<thead>
<tr>
<th>Cube Number</th>
<th>Cube Area mm²</th>
<th>Density kg/m³</th>
<th>Load kN/mm²</th>
<th>Strength N/mm²</th>
</tr>
</thead>
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<tr>
<td>1A</td>
<td>35</td>
<td>1.225</td>
<td>15.3</td>
<td>12.5</td>
</tr>
<tr>
<td>1B/1</td>
<td>35</td>
<td>1.225</td>
<td>17.4</td>
<td>14.2</td>
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<tr>
<td>1B/2</td>
<td>35</td>
<td>1.225</td>
<td>15.6</td>
<td>12.7</td>
</tr>
<tr>
<td>2A</td>
<td>35</td>
<td>1.225</td>
<td>20.9</td>
<td>17.1</td>
</tr>
</tbody>
</table>

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 that of Piovanelli, 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.

7. Acknowledgements

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References


