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The Simulated Timber Structure of the Volumnis' Hypogen in Perugia, Italy

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ABSTRACT: The Etruscan Hypogeum of the Volumnis of the Hellenistic period is excavated in soft sandstone with an anthropomorphic plan and has a two-slope ceiling simulating the intrados of a wooden hut roof and square corbelled "wooden" coverings with the entire true scale carpentry. 3D-laser scanner technology combined with industrial deviation calculation procedure opened a new approach in experimentation of 3D-modelling with large input data developing a methodology for the recognition of sensible global deformations on local elements of an ancient deteriorated structure. The analysis of deformation morphology shows surprising results: carpentry members simulate flexion in stress condition of true wooden beams in similar conditions of support, span, loads. Detailed geometrical analysis of the model rouses suspicion of the presence of optical corrections for an enhanced perspective in late Etruscan funeral architecture and allows dimensioning in inaccessible points for Gaussian statistical evaluation obtaining important information about the use of ancient dimension units.

1 INTRODUCTION

1.1 The Hypogeum of the Volumnis and its roofing structures

The impressive Hypogeum of the Volumnis, prominent family from Perugia, was built in the Hellenistic period (probably III - II century B.C.) of the Etruscan civilization. The tomb was discovered (1840) in original conditions with incineration urns, still preserved and now exposed in situ which allowed scholars to propose a genealogical tree.

The monument is excavated in the soft sandstone with an anthropomorphic plan, articulated in a large *atrium* with a final *tablinum*, two *alae* and six lateral *cellae*; the *atrium* has a two-slope ceiling made in a way to resemble the intrados of a wooden hut roof: therefore the entire simulated carpentry - ridge beam, rafters, joists, boards etc. - are carefully carved in the rock, in a true scale; the same for the *alae* and *tablinum* which have square corbelled "wooden" coverings. The arrangement is made to give to the dead's afterlife the same comfortable setting of the house of the living people. There are other examples of this kind of apparatus in Italy (e.g. some Cerveteri Tombs) and in Sardinia (Puttu Codinu and others) but only a few are made in such a realistic way.

1.2 Reasons for a new digital survey with 3D-laser scanner technology

The documentation of the architectural layout of the tomb started immediately after the discovery in 1840, first by the Italian archaeologist Giovanni Battista Vermiglioli with very summary conventional drawings and later in the 1930s, done by the German historian of Greek and Roman architecture Armin von Gerkan, by a differentiated and dimensioned plan set. This last survey was worked out accurately but, operating in very tight and narrow subterranean conditions, it went beyond the capacity of the traditional survey instruments. The observations, interpretations and impressions stated out in the von Gerkan's final report, conscious about the limits of the survey instruments of his time, together with the well-known examples of Sardinian tomb architecture simulating wooden structures suggested to start a new survey with 3D-laser scanner technology expecting confirmations and new results; these were copious and surprising.

2 3D-LASER SCANNER SURVEY AND MODELLING

2.1 Data acquisition with 3D-laser scanner

The acquisition of the point cloud at a 1x1cm grid was done by two operators in the subterranean environment with 97% relative humidity in a time window of 14 hours without interfering with the affluence of tourist visits. The survey with a Leica Geosystems HDS 3000 laser scanner was integrated by the use of a total station Leica TCR 1101 which offered the possibility to use the topographic survey of 19 targets for the otherwise critical registration procedure. About 10.7 million points have been acquired in 23 scans from 13 positions.

Figure 1 : View from the *atrium* towards the *tablinum*. Photograph and point cloud from survey.

2.2 Point cloud preparation

After the registration of the single scans the extreme density of several parts of the point cloud, due to multiple overlaps, was reduced applying an overall redundancy filter with minimum radius of 0.5 cm using the Leica Cyclone™ 5.1 software arriving at a point cloud of 7.7 million points. The entire point cloud was reduced to its pure architecture weeping out modern installations, such as illumination and alarm, and furniture, such as the urns.

2.3 Advanced Modelling

2.3.1 The organic meshed model

The 3D-modelling procedure was carried out on a standard PC platform using INUS Technology Inc. RapidForm™ 2004 software.

In order to arrive at a completely meshed model by triangulation the point cloud was divided in eleven parts, due to the logical morphology of the object, cutting through the small sections of the short corridors. This operation was essential to avoid overloading the computer memory during the mesh calculation operations, which, nevertheless, remained critical. During the single meshing operations a couple of uncovered fields, like back face areas of the urns, had to be integrated by homogenous point grids which were generated with Rhinoceros® software.

For the gathering process of the meshed units occurred an intelligent decimation of the flat areas to 60%. After gathering the units got sewed and then an overall decimation to 80% was applied in order to flatten the joints and to arrive at a handy model of about 2.9 million triangle surfaces that corresponds to a 48% reduction of the original.

2.3.2 The Summarizing 3D surface model of the main ceilings

This step of the research was aimed at the visualization, the control and the quantification of the distortions and deviations of the units composing the carpentry; first by a global approach to distinguish between deviation tendencies and decay situations of the more than 2000 years old surfaces in natural sandstone and then, if global morphological tendencies were identified, by local investigation on the single members of the units choosing representative sections.
A summarizing model, built on the main ceilings of the organic triangle meshed model, with straight surfaces was required in order to calculate the spatial differences of homological carpentry members, in the situation of overlay with the organic triangle meshed model.

During the modelling process, carried out with the software RapidForm^{TM} 2004, the operator had to create straight surfaces by intelligent choice of anchor points identifying every single carpentry member and its logical deformation property to load conditions in order to orientate the straight surface on its restraints using a pondered average and not on intermediate and eventually flexed parts (arithmetic average). In this way all flexing carpentry members would result curving below the ideal (straight) carpentry members and therefore give a homogenous global overview. An average position of three points per short edge was chosen (six points per surface) in order to avoid wrong orientation of the straight surfaces on single conditioned anchor points.

3 INVESTIGATIONS WITH THE MODELS

Different information can be obtained from the models by their single valuation and by elaboration, calculation and valuation in overlapping combination.

3.1 Measured plan set based on the organic triangle meshed model

A complete plan set of the Etruscan tomb of the Volumni was worked out sectioning and projecting the meshed model, overlapping with processed bidimensional sectionlines from CAD applications.

The plan set of the 1930's of von Gerkan was updated and - comparing the two sets - as a first result the supposed regular orientation of the satellite rooms, the *cellae*, has to be corrected to a less regular disposition.

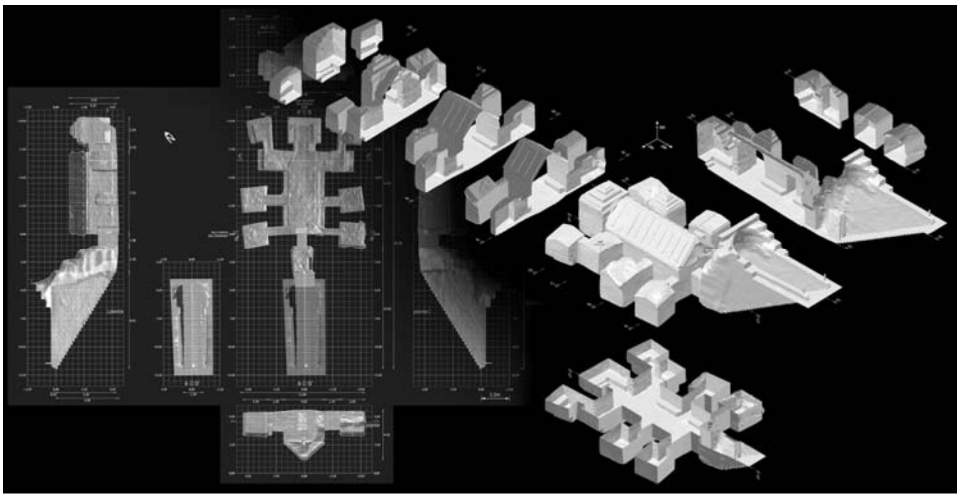

Figure 2 : The organic triangle meshed model. Plan set and exploded axonometric view.

3.2 Reconstrucion of the carpentries based on the summarizing surface model

The summarizing true scale model was an ideal platform to elaborate a series of theoretically possible versions of carpentry systems for the simulated wooden ceilings of the main rooms of the Volumnis' hypogeum which in literature are commonly named the *atrium*, the *tablinum*, the left *ala* and the right *ala*.

3.2.1 The two-slope ceiling of the atrium

The slopes have an unusual emphasized inclination of 47° and are supported by lateral beams at the bottom (725 x 23 left / 27 right x 12 cm, 4 cm overhanging from the walls) and at the top by a ridge beam (725 x 33 x 7 cm) which itself is laid on double corbels.

The slopes have an extension of about 730 x 230 cm and can be divided in four categories of carpentry members (with average visible dimensions): 11 rafters (230 x 43 x 8 cm), 2 joists next to ridge and bottom beams (visible in 10 spots between the rafters, 25 x 25 x 4 cm), boards (visible in 10 spots between the rafters, 166 x 25 cm) and 20 small closures at the ridge and the bottom beams. The pediments have rafters that directly rest on the ridge beam and have a bottom beam (inner pediment: laid above the bottom beams of the slope; outer pediment: no level change) and are 25 cm high in section, with 4 cm overhang from the walls.

The experimentation of an ideal reconstruction of the two-slope roof carpentry based on the true scale summarizing model, together with observations of Armin von Gerkan, conduced to the following thesis: the main supporting structure is given by a non-joint disposition of bottom beams fixed with the larger face of the cross-section on the surrounding walls, and the triangular shaped ridge beam supported by double corbels. The corbels are anchored directly in the wall structure and the rafters of the pediments work as spacers to disable the horizontal movement of the ridge beam. The previously identified rafters and boards could both consist of equal boards (280 x 43 x 8 cm) staggered in two layers. The joists result as inserted boards between the first layer of rafters in order to keep them in position during the execution of the work. The small closures are shaped boards and work as spacers between ridge beam and joists.

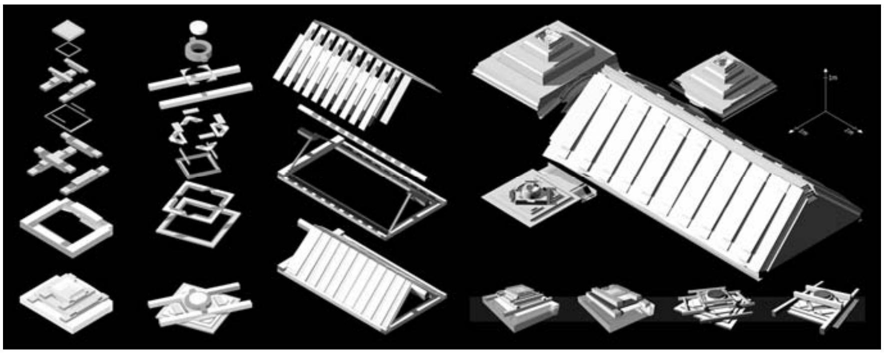

Figure 3 : Solutions for ideal carpentries' reconstructions. Summarizing model of the main ceilings.

3.2.2 The square corbelled coffered ceilings of the tablinum and the right ala

The ceilings built on rectangular plan are arranged with two overhanging orders of each two parallel couples of joint beams (4 cm level change per couple) and a top closure with a framed sculptured head. The transitions to the orders are closed with shaped frames.

During the investigation on the coffered ceilings it was clear that the data available today, based on a simulation in rock-cut sandstone of the inner surface of a wooden structure, was not sufficient to determine a final solution of the original carpentry set. Therefore it was reasonable to work out a number of solutions which differ not only by arrangement of elements, but as well by system and material. Some of the proposals for the original carpentry set could be discarded due to the direct dimension control handling with a true scale model, but are still considerable as functional carpentry systems. Finally, three different carpentry systems for the square corbelled coffered ceilings have been worked out:

- Visible squared partially joint beams, wooden frames and closure stone plate;

- Roughly squared eventually joint beams, panelling, wooden frames and closure stone plate;
- Visible squared beams and partial panelling, interposed stone plates and closure stone plate.

3.2.3 The diagonally corbelled coffered ceiling of the left ala

The ceiling built on an approximate square plan is arranged with two overhanging orders without level change between the parallel couples, a 45° rotated diagonal framework which remains in the same level of the second order and a joint centre torus with a framed sculptured head. All resulting triangles are sheet covered and framed.

The diagonally corbelled coffered ceiling is to be considered a very similar system with the difference that the supporting structure can be done by partially visible squared beams with panelling or roughly squared beams with complete panelling. The last one lets open several variations of the supporting structure.

3.3 Deformations of the carpentries and observations of geometric anomalies based on the overlapping combination of the two models

On the archaeological site direct observation of the carpentries does not clearly allow the observer to decide if deformation of a stressed wooden structure under load condition is simulated or not. This was tried to be controlled with the help of the digital models.

3.3.1 Deformation control of the carpentry members by "deviation check" procedure

Overlapping the meshed and the summarizing surface model and calculating the spatial difference in every single point would give information about the global tendency in single members of the carpentry and would make it possible to quantify the deviations within a certain limit of precision, due to the laser scanner accuracy and decimations during the modelling process. The two models were imported in a RapidForm™ 2004 scene and overlapped.

The "deviation check" procedure, which usually is to be considered an application for industrial quality control between CAD model and final product, was experimented on architectural scale to visualize global deviation tendencies of the elements of the ceilings. The procedure was carried out first on the complete ceiling. The obtained visualization showed clearly the presence of flexion tendencies of the two slopes of the roof like under load condition.

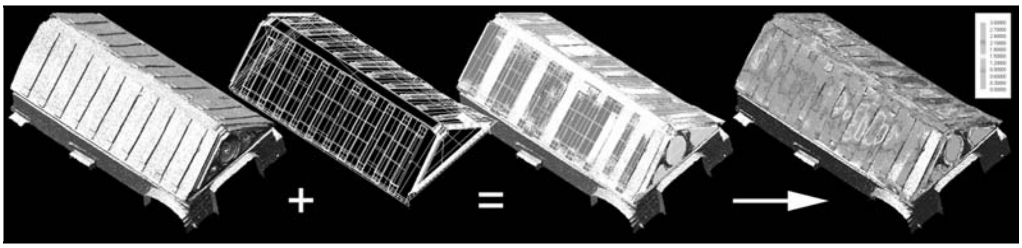

Figure 4 : Inspection procedure. Overlap of the two models and application of "deviation check".

In consequence the same procedure was carried out on every category of carpentry members choosing every time an optimal calibration for the colour scale visualization.

In the two-slope ceiling of the *atrium* the adopted categories of carpentry members were ridge beam, rafters, joists, boards and closures. Clear global tendencies of flexion could be observed in the main categories.

The rafters (approximately 230 x 41 x 8 cm visible dimensions) have an average flexion of 2.1 cm and a maximum of 3.2 cm with the peak in the centre line area. A selected section shows the section line close to a circular segment which corresponds to the simulation of stress condition under vertical distributed load with hinge restraints at top and bottom.

The boards (approximately 167 x 28 cm visible dimensions) have an average flexion of 1.7 cm and a maximum of 3.2 cm with the peak in the centre line area. The selected section gives the same result as the rafters.

The ridge beam (approximately 745 x 33 x 7 cm visible dimensions with 671 cm length between corbels) has a flexion with its peak of 3.1 cm. A centre line section shows a deformation curve of a wooden beam with hinge or maybe even joint restraints under vertical distributed load. But the curve is not symmetric with its peak at 105 cm from the centre point which could correspond to a further decentred punctual load. Investigations on the first plan set from the 1840s, drafted by Giovanni Battista Vermiglioli right after the discovery of the tomb, and the description by Vermiglioli of the conditions of the original set of the interior of the tomb at the moment of the discovery in 1840, revealed that the position of the maximum flexion of the ridge beam corresponds with good approximation to the position where the hanging oil lamp of the *atrium* was found at the moment of the discovery. Vermiglioli states out that this terra-cotta lamp, just like one other found in the passage between the *atrium* and the *tablinum*, was found crashed and destroyed on the ground but still with the suspension stick in its original position hanging from the ceiling. This position was identified as a small hole on the surface of the ridge beam closed with moisture during one of the many non-documented restorations. The original fragments of the lamps have been lost during the last century.

The deviation visualization of the joists and closures didn't lead to a clear identification of deformation tendencies.

The same operation was carried out also on the square corbelled ceilings of the *tablinum* and the two *alae*. The symmetrical flexion around the short centre line of emphasized rectangular elements was observed in about 50% of the experiments. Because of the smaller dimensions, decay and non-documented restorations, the accuracy error of the computer model remains relatively high and therefore the results cannot be considered scientifically significant.

3.3.2 Geometric anomalies and their quantification

The possibility to overlap the two models offers the occasion to carry out different measurings by average centre plane calculation of the rafter disposition and the ridge beam. This gives the possibility to obtain measures of hypothetic points which would be important to measure in a real wooden carpentry but that are impossible to measure on the archaeological site, having at disposition just the inferior surface of a rock-carved simulation.

In the 1930s Armin von Gerkan mentioned in the survey report that he had noticed the couples of rafters not being set in perfectly vertical planes. He interpreted this fact to be induced by an execution error of the Etruscan workers or a partial collapse of the sandstone surface already during the works at the inner pediment, which actually contains torsion deformation. During the works, departing from this pediment, according to von Gerkan, the error would have been tried to be reduced gradually to zero, resulting the last couple of rafters in a vertical plane. The measuring on the overlapped digital models using average centre planes of the couples of rafters showed that the inclination, departing from the inner pediment (omitting the first couple of rafters no. 11 with 1.3°), starts at 3.2° (no. 10) increasing gradually to 4.7° (no. 7) and ends at the opposite pediment reducing to 3.4° (no. 1).

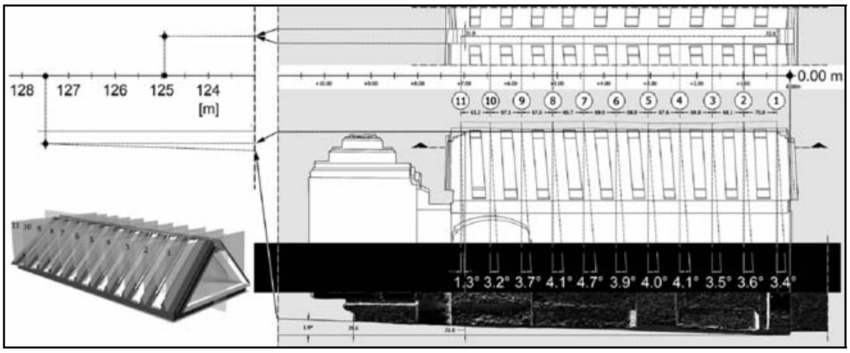

Figure 5 : Two-slope ceiling. Inclinations of rafters, focal points and determination of average planes.

A detailed investigation on the ridge beam revealed that on 745 cm length (671 cm free length between corbels) the cross section changes gradually of about 1.8 cm, from 33.6 cm at the outer pediment to 31.8 cm at the opposite one. Disaccording to the logical expectations, the minor cross section of the ridge beam rests on its corbel at a 1.4 cm lower level than the other major extremity instead of raising up in order to give a horizontal support to the rafters. Symmetrically the earthen floor raises approximately 30 cm on its overall length from the entrance to the *tablinum*.

Extending the centre line of the lowering surface of the ridge beam and the corresponding floor plane it is possible to determine the theoretical focal point at approximately 127 m far in the mountain, measured from the entrance.

The extended centre lines of the side faces of the ridge beam converge in a theoretical focal point at approximately 125 m far in the mountain.

3.4 Statistical analysis of repeated elements in the two-slope roof of the atrium

Finally a statistical analysis, based on the Gaussian distribution, on the measuring unit used in the two-slope roof of the *atrium* was carried out having available series of repeated equal elements.

As already stated the couples of rafters are arranged in non parallel planes that rotate around a perpendicular direction to the axis of the ridge beam. These non-linear rotations determine significant differences of distance between the rafters at the bottom, but keeping quite constant values at the top. A possible explanation is that the execution of the ceiling was carried out from the ridge beam towards the bottom beams.

During the execution of a real wooden carpentry the rafters get arranged along the ridge beam at a fixed distance. Therefore the statistical analysis was done with three logical measures: the interaxis of the rafters measured in the summarizing model above the centre line of the ridge beam, the net distance between the rafters and the width of the rafters themselves.

The interaxis result 679 mm and a standard deviation of ±14 mm calculated with 19 inputs. The net distance between rafters is 253 mm ± 18 mm with 20 inputs and the width of the rafters is 428 mm ± 14 mm with 20 inputs.

The units and multiples chosen to check were the Roman Foot (296 mm) proposed by Matteini-Chiari, the Etruscan Foot (324 mm) proposed by Hallier and a nameless unit observed in several tombs of the area of Chiusi (200 – 210 mm), in consideration of Chiusi’s wide influence on Etruscan Perugia.

There was no result of good compatibility in order to prefer one of the units for interaxis, rafter distance and rafter width. The only good compatibility was observed for the rafter width 428 ± 14 mm with two units from Chiusi 400 – 420 mm.

4 CONCLUSIONS

The 3D laser scanner survey and the elaboration of a triangular meshed model made it possible to update the 2D plan set from the 1930s and to evidence the differences of regularity between the main rooms *atrium – tablinum – alae* and the satellite *cellae*.

The ideal reconstruction of the Etruscan wooden carpentries was worked out on information based on the rock-cut simulation of the inner skin of a wooden covering. Different solutions of systems have been worked out. The preference was given to systems based on simplicity and easy execution. These are not definitive results but should be considered a starting point of investigations by laser scanner surveys on other Etruscan tomb architecture, e.g. at Chiusi, to be compared with.

The application of the “deviation check” procedure with RapidForm™ 2004 on a summarizing model built on a triangular meshed model with provenience from a laser scanner survey is a methodology to visualize global deformation tendencies for ancient architecture with overall phenomenon of decay. Only in consequence of tendency observation it was possible to choose representative section planes.

The verified flexions of the elements are not evidenced enough in order to exclude a systematic error due to the execution techniques of the Etruscan workers, e.g. the curving of a stretched cord (2 – 3 cm on the length of 230 cm), but they are as well compatible with the historical experience in funeral contexts of even older communities that populated Central Italy and surroundings, e.g. some Cerveteri Tombs and the *Domus de Janas* in Sardinia.

Certainly, it can be discussed if an oil lamp with probably about six flames, in the Etruscan houses usually used a bronze model for daily use probably over many decades, is able to induce deformation on a ridge beam, but obviously, an uncommon fact is the peak of the asymmetrical flexion of the ridge beam corresponding to the position of the oil lamp.

The tapered ridge beam respects the natural form of a beam of these dimensions of shaped from a tree trunk.

The existence of two focal points between the directions between floor and ridge beam, and between the tapering sides of the ridge beam, on the same side and close to each other opens a reflection about a possible situation of optical correction in sense of an enhanced effect of perspective. An important fact to sustain this thesis - or not - would be the converging behaviour of the bottom beams, too. But this fact is missing. In our survey the two beams result parallel, but, as visible on a photograph from the early 1900s where the right beam is missing due to decay, today the right beam must be entirely a modern reconstruction while unfortunately there are no information available about the original conditions of the left beam; the same about the several not documented restorations since the discovery in 1840.

Maybe accidentally the rotated rafters - due to an execution error or not, but certainly not linearly diminished in rotation towards the entrance - contribute to a slim effect for more optical depth of the *atrium*, observed from the position of the entrance.

It may be helpful to note that the problem of dating the Volumnis' hypogeum is still not completely resolved. Recently the period of III - II century B.C. was proposed. For sure it is considered to be built under strong influence of Hellenistic Greece, as confirmed by the sculptural work of the pediments.

The numerous investigations on the Parthenon in Athens (V c. B.C.) have revealed the use of optical corrections handled by light inclinations of the outer columns with different focal points vertically above the monument. These corrections have been measured in 1996 by the Greek archaeologist Manolis Korres.

Since optical corrections in Etruscan architecture hadn't been observed, yet, this thesis should be further discussed by archaeologists. At least, we can state that in the case of the Volumnis' hypogeum it could be possible, from a chronological point of view.

Finally, the elaborated statistical values can be used as material for comparison of similar carpentry elements in investigation projects on other Etruscan tombs.

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