EGE - Revista de Expresión Gráfica en la Edificación, Nº 17, 2022. ISSN: 2605-082X
https://doi.org/10.4995/ege.2022.19031
APEGA, UPV

GRAPHIC AND STRUCTURAL ANALYSIS FOR THE KNOWLEDGE OF ANCIENT ARCHITECTURAL HERITAGE: THE CASE OF THE TOWER IN THE IBERIAN SETTLEMENT OF ROCHINA

ANÁLISIS GRÁFICO Y ESTRUCTURAL PARA EL CONOCIMIENTO DEL PATRIMONIO ARQUITECTÓNICO ANTIGUO: EL CASO DE LA TORRE DEL POBLADO IBÉRICO DE ROCHINA

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Abstract

The survey of the real geometries of historical constructions and their graphic analysis becomes essential in the knowledge of past cultures, especially when there are no documentary references or architectural parallels to rely on. The study of the missing elevations of the tower in the Iberian settlement of Rochina can help to understand a way of building in the protohistoric period thanks to theoretical and justified three-dimensional tower recreations and their corresponding evaluations in terms of structural behaviour.

Keywords: Metric survey; Graphical representation; Structural behaviour; Tower; Iberian architecture.

Resumen

El levantamiento de las geometrías reales de las construcciones históricas y su análisis gráfico se hace imprescindible en el conocimiento de culturas pasadas, y más cuando no existen referencias documentales ni paralelismos arquitectónicos donde apoyarse. El estudio de los desaparecidos alzados de la torre del poblado ibérico de Rochina puede ayudar a entender un modo de construir en época protohistórica gracias a la elaboración de recreaciones tridimensionales teóricas de torres previamente justificadas y sus correspondientes evaluaciones en cuanto al comportamiento estructural.

Palabras clave: Levantamiento métrico; Representación gráfica; Comportamiento estructural; Torre; Arquitectura ibérica.

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Received: 16 December 2022, Accepted: 27 December 2022, Published: 31 December 2022

1. INTRODUCTION

There exist many historical constructions that deteriorate with the passage of time without having received the attention they deserve. This was the case of the Iberian settlement of “Rochina” in Sot de Ferrer, Castellón, where, despite being located a few kilometres from the municipality, only some of the oldest locals were hardly aware of its existence, its exact location or the extent of its architectural remains.

Fortunately, this circumstance changed completely thanks to the three archaeological campaigns throughout 2018, 2019 and 2021, revealing the true uniqueness of the protohistoric habitat. Its “central street” urban typology was uncovered reflecting a unique settlement among all those that belong to Iberian Culture[1] in Castellón.

However, in order to gain a more complete interpretation of the building complex and a better understanding of its foundational origin, the only study of the archaeological materials found remains insufficient.[2] It would be necessary to investigate about constructions. Particularly, about the architectural element par excellence: the tower (Fig. 1).

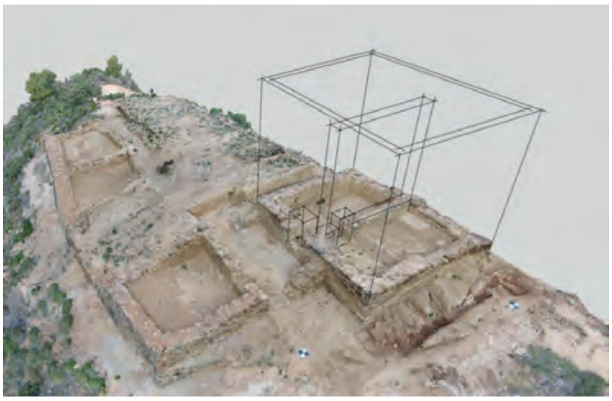

Fig. 1. Conceptualization of the figure of the tower on the Iberian settlement of Rochina (Source: Llop 2022).

Its location within the residential complex flanking the entrance not only implied defensive tasks but also it could have had propaganda functions in favour of the former landowners who ran the settlement.[3] The large rectangular floor plan formed by powerful stone plinths would allow a large elevation in the walls, although, unfortunately, this height magnitude is completely unknown to date. It is even difficult to interpret becouse there is neither documentary evidence nor other constructive evidence that could act as architectural parallels.

And it is at this moment that we are going to resort to computer tools from a scientific point of view to at least hypothesise on the original elevation of the tower and its limits. Something that will undoubtedly be attractive enough to professionals interested in ancient cultures.

For this purpose, it remains essential to have a set of graphic representations of the architectural remains of the site in order to be able to visualise towered element details. In addition, there are other digital aids that can be presented using modern calculation software to evaluate the theoretical structures and provide new interpretations of the Iberian tower and, therefore, of the Rochina settlement in general.

In short, the aim of this work is to open up new ways of knowledge about Iberian architecture, which is particularly unknown, and consequently to gain a better understanding of the monument in question.

2. OBJETIVES AND METHODOLOGY

The main objective of this work consists of a graphic and descriptive survey of the construction elements that form the settlement, paying special attention to the tower. Additionally, this study aims to analyse the theoretical elevations of the Rochina tower from a structural perspective, learning about its behaviour opposite to different loads and, consequently, about its construction practices.

In order to achieve the aforementioned objectives, an orderly methodology is proposed that includes

[1] “Iberian Culture” is the most common term used by disciplines such as History and Archaeology when referring to those protohistoric societies, without their own identity and political unity, formed by various indigenous people settled in the Mediterranean peninsular arc and within a chronological framework situated between the 6th and 1st centuries BC approximately.

[2] Llop (2015:70-72) presents the results obtained by Fletcher (1940) from the obtained pieces in the Fornés excavation between 1916 and 1919, and adds additional information according to other more contemporary research.

[3] Towers as a symbol of power have been a recurring theme throughout history. Thus, in protohistoric contexts in Hispania with regular episodes of social violence, the ruling elites sought both the defensive protection of their residences and the ostentation of the aristocratic status they represented.

a series of steps to achieve the final elaboration of the work, highlighting an important load of tasks related to the collection of dimensional aspects of the constructive structures and their graphic expression.

Thus, it is essential to use a series of means such as: the topographic station and laser scanner for a rigorous survey of the architectural complex, the CAD and REVIT tools in the design of tower prototypes and photogrammetry as an instrument for material surfaces texturing.

Apart from these procedures, the last stage of the research will consist of the application of the ANGLE programme to support the structural analysis on the previous representative models.

3. GENERAL DESCRIPTION OF THE TOWER IN THE IBERIAN SETTLEMENT OF ROCHINA

The tower of the Iberian settlement of Rochina is part of the site with the same name, and is located on a small hill on the banks of Palancia river, specifically in the municipality of Sot de Ferrer (Fig. 2).

The Iberian settlement, chronologically framed between the 3rd and 1st centuries BC I belongs to Edetan territory (Bonet 2010), and according to Oliver (2004: 153-154) is identified as a fortified farm dedicated to agricultural exploitation with secondary functions as territorial control. The built-up area is 480 m^2 and its urban layout consists of 17 departments organized according to the so-called “central street” model. In it, the enclosures are arranged in a row and on both sides of a longitudinal axis that acts as a street or spaces distributor, while the rear parts are limited by a wall that confines the perimeter of the fortified complex (Fig. 3).

Within the walled enclosure, the tower occupies an advanced position associated with the entrance area in the manner of a “turreted gateway”, undoubtedly to limit and control the access of personnel to the interior of the settlement. This architectural element, which is the largest

Fig. 2. Aerial perspective of the archaeological site of the Iberian settlement of Rochina and its closest natural environment, after the 2018 and 2019 campaigns (Source: Llop 2022).

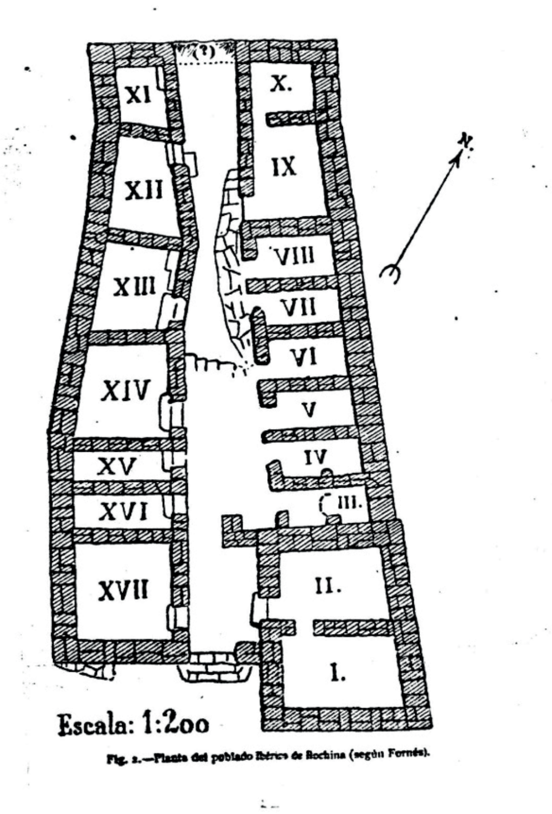

Fig. 3. Sketch of the Iberian settlement of Rochina by Emilio Fornés in 1913-1916 (Source: Fletcher, 1940:127).

Fig. 4. Ortho image (Source: Llop and Medina, 2018).

building unit, is made up of Departments I and II, which depend on each other, and the materiality of its thick walls and better execution suggests a singular treatment with respect to the rest of the existing remains.

Concerning the tower functionality, we can state that it has a multifunctional character.

The list of archaeological objects found, such as loom pieces, milling elements or ceramic containers, suggests storage purposes. On the other hand, the presence of a bench found in a corner of Department II also suggests a domestic use, although this is more difficult to justify. However, the numerous sling stones that were scattered around the tower reveal defensive purposes, a fact that is supported by its flanking position at the entrance of the settlement. Most of the authors treat the tower from a polyercetic point of view, as for example: Gracia (2000), Prados (2007), Quesada (2007)...

4. DIMENSIONAL ANALYSIS OF THE TOWER

During the progress of the excavation work of the Rochina site, various image capture operations were carried out while the architectural structures were gradually uncovered. These actions included aerial and terrestrial photogrammetry, laser scanners, and even point radiation by topographic stations in specific areas.

Photogrammetry has made possible to produce the volumetry and material textures in each of the different phases of the excavations. By means of drone technology, through RPAS flights,[4] a zenithal view is obtained which allows an aerial ortho image, with an accuracy of resolution per pixel of less than 0.8 mm (Fig. 4). Architectural details and material clues can be seen, which may lead to new hypotheses regarding the construction design.

Complementing photogrammetry (Fig. 5), laser scanning works have been carried out to obtain

[4] Remotely Piloted Aerial System.

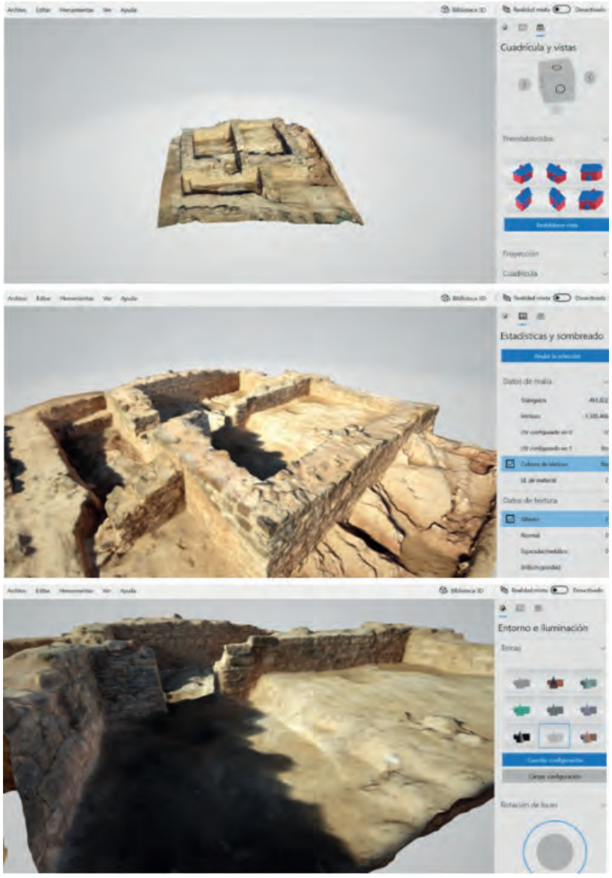

Fig. 5. Photogrammetric images in 3D from different perspectives (Source: Llop and Medina 2018).

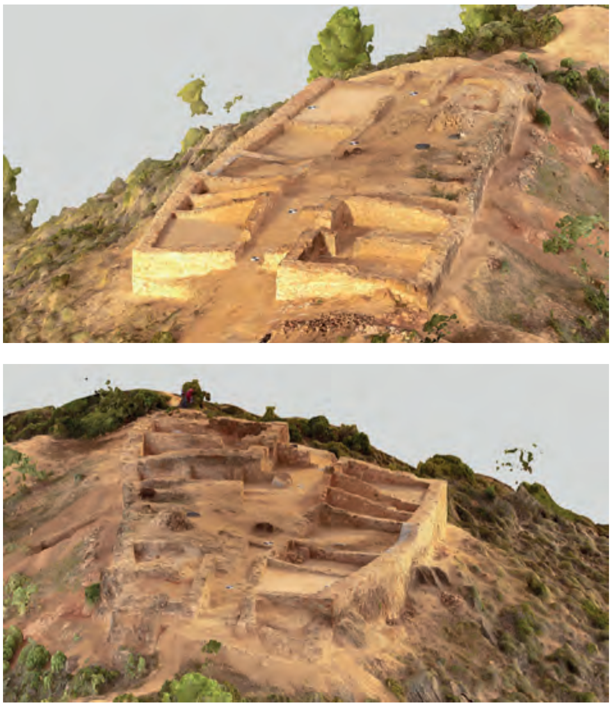

Fig. 6. Images from scanner laser and texturing work (Source: Llop 2022).

a point cloud of greater precision, with an error of less than 0.25 mm, where the fundamental objective is to achieve maximum precision in the geometry of the construction elements (Fig. 6). This method is very valid for the subsequent generation of technical documentation

Both techniques allow to generate a reliable digital model, from which we could elaborate virtual reconstructions based on other additional multidisciplinary information.

Thus, the volumetric and morphological analysis, with a precise graphic representation of the structures, reveals a series of technical observations that are absolutely necessary for our work. For example:

- According to the table of theoretical surface areas[5] by Llop (2015:60), and with the exception of the street as the open common space, the usable surface area of the tower without counting the possible upper floors is 46.71 square metres (m^2). This amount is by far the largest enclosure of the entire housing complex. The rest of the buildings are well below this figure, despite the existence of other large enclosure related to departments IX-X with 28.50 m^2. Therefore, an important use and activity value must be assumed in the tower.
- The built-up area of the tower, measured on the ground floor, amounts to 80.21 m^2. This means 20% in the approximate 300 m^2 of the sum of all the enclosed spaces, 15 units equivalent to 17 flats. This percentage represents the main investment in the construction of the settlement, in terms of the cost of the work and the material and human resources.
- The building belongs to the typology of compartmentalised towers, with 80.21 m^2 on the ground floor and 54.98 linear metres as an external perimeter. The tower is distributed

[5] The surfaces are defined as theoretical, as the archaeological excavation has not been completed for the entire extension of the settlement, so there are still structures to be discovered. We then proceeded to a projection of layouts based on the superimposition of the current partial topographic survey with the Fornés sketch. So far, a similarity can be observed between the two representations, so that the transfer of as yet unknown measurements from the Fornés drawing is reasonably justified.

in two interior chambers connected to each other and with similar usable areas: 24.01 square metres in Department I and 23.60 square metres in Department II.

- Access to the tower is from settlement interior, specifically from the street area closest to the entrance. The entrance, directly into Department II, is through a 1.30 metres wide opening raised some 50 centimetres above street level. Circulation between the rooms is solved thanks to an existing opening on the dividing wall, in this case a little more than one metre wide.
- The plan corresponds to a slightly irregular rectangular geometry due to an adaptation of its structures to the orography of the terrain. The north wall shows a deviation from its theoretical orthogonal layout. Therefore, the external measurements of its opposite sides are not equal: 10.08 metres on the north-east side compared to 9.50 metres on the south-west side; and 7.91 metres on the north-west side compared to 8.48 metres on the south-east side.
- The tower was erected according to the same criteria and in a coordinated manner in its four elevations, leaving the construction of the party wall to the end, as there was no evidence of any kind of interlocking with the tower's enclosing wall. The thickness of the plinth walls varies according to their location. On the one hand, the perimeter walls are between 0.90 and 1 metre thick, while the interior wall is around 60 centimetres thick.
- In relation to the previous point, some particularities have been observed, such as: a small misalignment of the soffit of the south-west wall, due to possible rectification in the layout during the execution of the masonry; and the creation of construction joints in some parts of the plinth.
- There are perceptible variations in the material composition of the walls, different stone formats among the walls. It could be a case of a constructive upheaval depending on the availability of the stones at the time.
- Other wall structures corresponding to the perimeter defensive system of the settlement are attached to the tower construction, such as the north-facing wall and part of the entrance to the east. There are even other elements as vertical supports in Department III. There are no union between the respective factories.

The geometric and metrological analysis of the Rochina tower (Fig. 7), with formal similarities with other nearby Iberian towers and the attempt to relate its figure to a regulating module in the complete construction of the settlement were interesting. (Llop, 2015) Both studies have evolved recently, as other researches has progressed in this way Specifically, two new developments have been discovered.

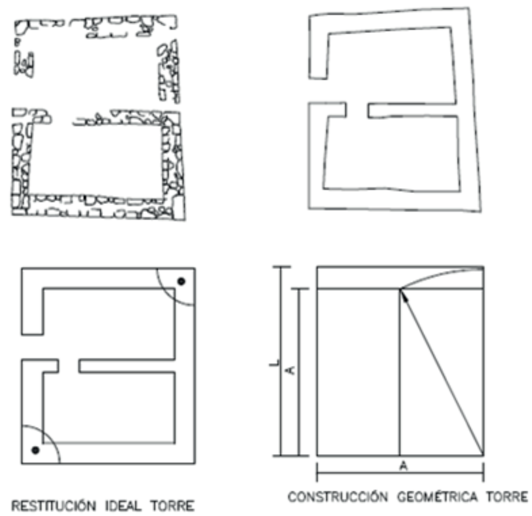

Fig. 7. Geometric analysis of the Iberian tower of Rochina (Source: Llop 2015).

On the one hand, the initial information from 2015 has been supplemented with respect to the previous geometric examination with a new design that fits the idealised outline of the tower. The geometric figure in question is called a hemidiagon, and its construction is based on a square and the extension of one of its sides. The dimensional increase is given by the prolongation of the diagonal of the half-square, giving a width-to-length ratio of 1:1.18, which is precisely repeated in the formation of other Iberian towers near the Rochina site (Llop 2017:44).

Likewise, the theoretical planning of ordered spaces based on the tower element in the Iberian settlement of Rochina is somewhat similar to the configuration of another settlement with the same urban pattern (Fig. 8). We are referring to Puntal dels Llops, in Olocau, where an apparently regular

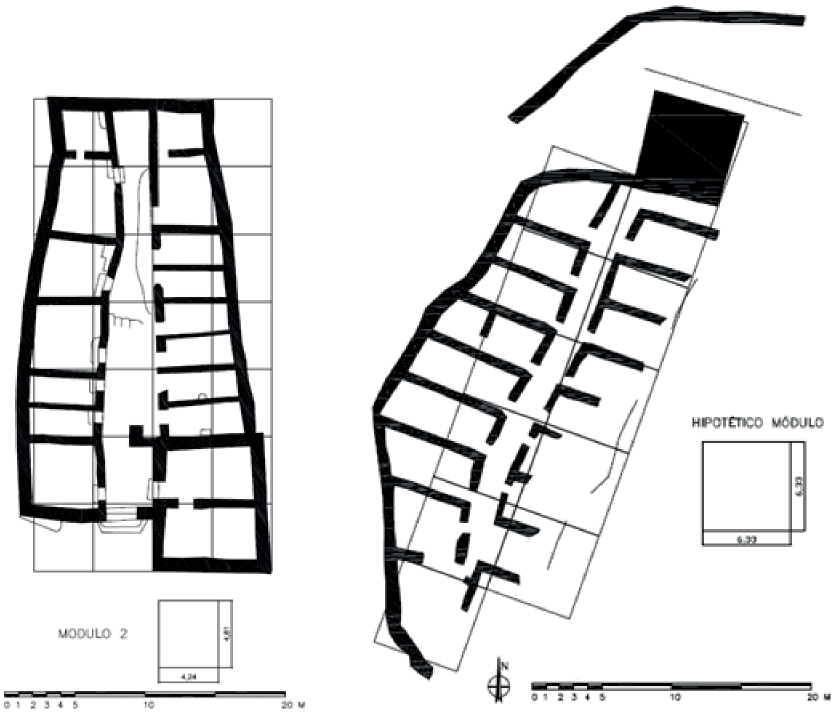

Fig. 8. Modular study on the lifting of the Iberian settlement of Rochina, Sot de Ferrer, and Puntal dels Llops, Olocau, paying special attention to the participation of the tower in its construction process (Source: Llop 2017).

grid formed by a juxtaposition of departments in a longitudinal direction would start from the figure of the tower (LLop 2017:47-50).

5. STRUCTURAL ANALYSIS OF THE TOWER

The chosen procedure for the structural study of the Rochina tower is the Non-Linear Finite Element Method due to nature of the ancient building structures: different responses to tensile and compressive stresses within the same constructive element, material heterogeneity and discontinuity in the elevations with joint presence.

All of this entails a complex structural behaviour, which can be studied using ANGLE. The programme, developed by UPV, is a pioneer in the structural treatment for historic buildings.

This programme is based on two different stages: the first stage is dedicated to materials and construction systems characterisation and representative volumetry; and the second one is reserved for the mentioned ANGLE with the assignment of calculation walls and loads, until the structural behaviour in the selected models is finally discovered.

5.1 PRELIMINARY ACTIONS AND STUDIES PRIOR TO STRUCTURAL ANALYSIS).

- Characterisation and construction parameters

First, we must provide a list of construction elements and their characteristics. So a graphic table is created describing the material configuration of the tower (Fig. 9).

The explanatory table appears as a starting point to find out the mechanical properties. The values to be considered are among others: bulk density, weight, compressive strength, tensile strength and modulus of elasticity, where all of them are taken conservatively, i.e. on the safe side.

The information in question can be obtained in two ways: from specific ad hoc tests on own samples carried out in laboratories and from the appropriation of technical data through the research paper or other scientific document that deal with these issues. For example: Llopis (2014), Gómez (2016), ...

- Modelling

The modelling has been developed using the CAD design tool with a view to reproduce as faithfully as possible the volumetric composition of the

THEORETICAL CONSTRUCTION SYSTEM	ELEMENT	DESCRIPTION
	Foundations	It does not exist. The structures rest directly on the ground, rocky and gravelly-earthy soil.
	Lower structure	Plinth made of ordinary double-leaf masonry and internal infill, with stone laid with mud mortar and partially screeded.
	Upper structure	Wall made of adobe bricks, alternately interlocked with the help of mud mortar grout. Laying is preferably by shearing, and by shearing and stringing.
	Floor slabs	Log beams arranged equidistantly and perpendicular to the entrance to support a mesh of branches or logs, another interwoven mulch and a top layer of compacted earth.
	Soils	Floor slabs shall be finished with layers of sand and lime or stone paving.
	Coatings	Application of mud mortar in layers according to the type of canvas. They have no impact on the structural analysis.

Fig. 9. Explanatory table of the construction characteristics of the Rochina tower s (Source: Llop 2022).

tower that no longer exists. Its three-dimensional design must meet justified criteria, but at the same time be relatively simplified in its geometrical forms. The reason behind this is to facilitate, *a posteriori*, the best possible interpretation of the structural material responses of the individual building elements.

Accordingly, the following considerations are set out during the design operation:

- The three-dimensional model is erected from the same horizontal plane.
- The elevation of the vertical elements, walls, respects the real contour of the ground plan.
- The lower volume of the elevations, representing the stone plinth, rises to a height of 2 metres and ends with a level finishing.
- The upper volumes of the elevations, represented by the other external enclosures, maintain the same thickness and reach the maximum height of the tower.
- The horizontal forms reproduce the floor and slab elements. The estimated thickness of the floor slab is 35 cm.
- The clear height between floors is estimated at 2.40 metres.
- The layout and design of passageways is in accordance with the evidence.
- The tower's finishing elements remain to be determined.

Within the planned modelling, the aim is to create different prototypes according proposed heights, two and five levels (Fig. 10). For the justification of their choice, we recall the words of Vitruvius, where the towers had to be higher than the walls, at least two storeys high, and other historical sources, such as Livio, where towers of up to five storeys are mentioned. Both mentionsare found in protohistoric contexts, such as the Iberian settlement of Rochina (Llop 2022:65).

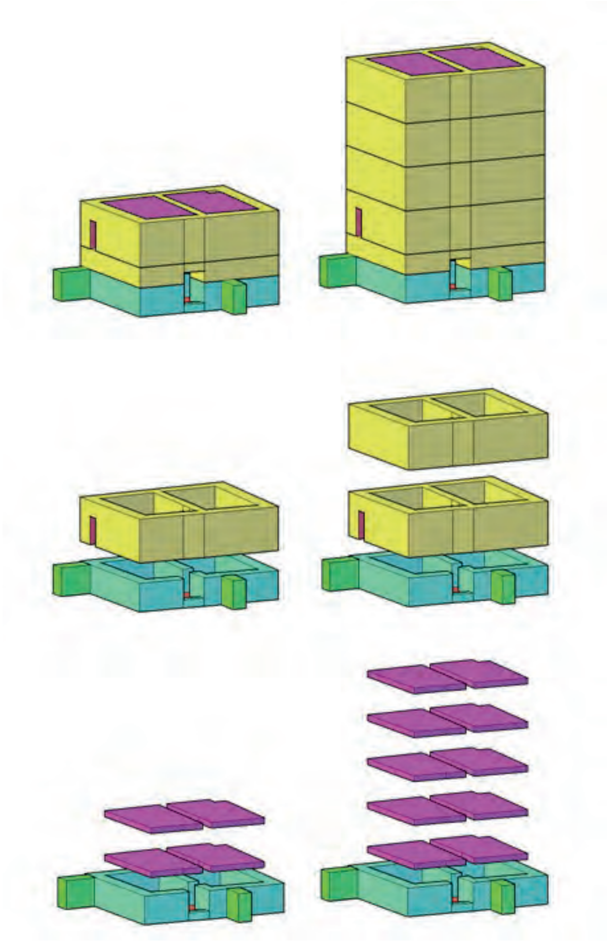

Fig. 10. Modeling of two and four heights using CAD for subsequent structural analysis (Source: Llop 2022:11).

5.2 ANALYSIS OF THE ANGLE STRUCTURAL PROGRAMME UNDER DIFFERENT SCENARIOS

Once the constructive materiality and the volumetric design of the tower have been established, the next step is to work on the models according to the ANGLE through two phases. Phase 1 will consider the responses to the gravitational action of self-weight, and phase 2 to the seismic action, responding in turn to the damage model and the pushover method, respectively.

The tower proposals to be studied are based on two modelling prototype, two-storey and five-storey model.

The former is created from 69,834 tetrahedral elements and 14,949 nodes, while the latter has 66,934 tetrahedral elements and 15,209 analysis nodes (Fig. 11).

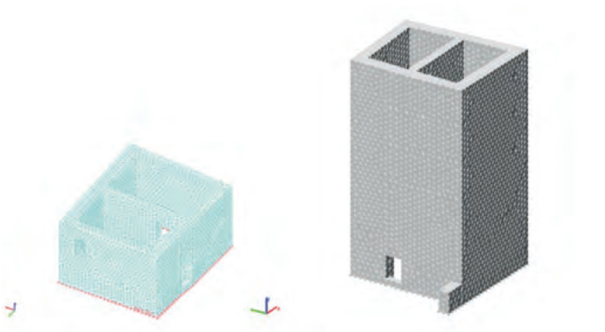

Fig. 11. Image of the two models to analyze with the corresponding mesh (Source: Alonso-Llop 2022).

The structural study is then carried out with the following hypotheses:

Hypothesis 1. Single-layer masonry socle with adobe upper structure, up to 2 storeys high.

It is a towered figure based on constructive evidence: a lower base made of stone and an upper structure made of earthen masonry. It is simple in its height, seeking only to protrude one level above the height of the wall to achieve an acceptable defensive function.

As for Phase 1, its low height compared to the thickness of the load-bearing walls means that all stress values under self-loading are much lower than the estimated strengths of the masonry and adobe masonry as a whole. Therefore, the turreted element does not suffer any deformation (Fig. 12).

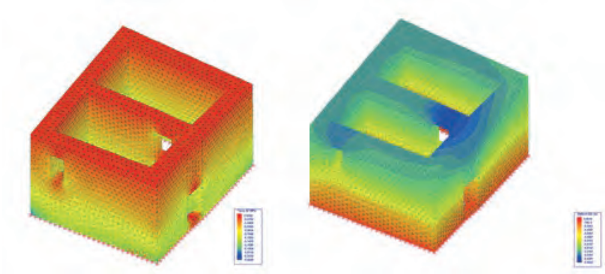

Fig. 12. Strain and stress state image in model 1 (Source: Alonso-Llop 2022).

There is no sense in applying seismic action in this case, phase 2. It is understood that there is no incidence due to the configuration and solidity of the tower itself. In addition, the stability against horizontal stresses is increased thanks to the position of the interior dividing wall.

Hypothesis 2. Single-layer masonry socle with adobe upper structure, up to 5 storeys high.

Variant 2 follows the material construction pattern of the previous example number 1, but increasing its height considerably to almost 14 metres, until it formed a prismatic volume of remarkable development. Its five storeys offer greater defensive capabilities with a good firing range to repel possible attacks. At the same time, it ensures high visibility in the surrounding area, improving the image of prestigious architecture and improving visual communication with other strategic enclaves, also populated, in the surrounding area.

In Phase 1, the maximum stress values occurring in the base plinth are far from collapse. Similarly, the maximum compressive stresses in the adobe factory are lower than the strengths of the adobe bricks. Consequently, it can be said that the stress values observed are not an aspect that could limit the height of the towers, taking into account that, due to their low slenderness, they do not present problems of stability against buckling (Fig. 13).

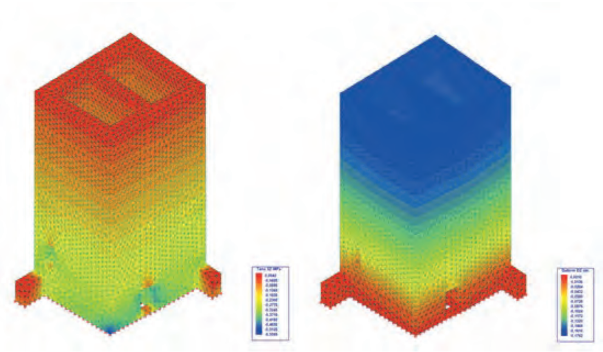

Fig. 13. Strain and stress state image in model 2 (Source: Alonso-Llop 2022).

In Phase 2, in order to carry out the seismic analysis, the modal forms of vibration of the structure are first calculated, with the frequencies and period of vibration in the first 6 modes (Figg. 14-15).

The result is the capacity curve which shows the response of the structure to a horizontal seismic action until collapse. The capacity graph shows this effect by plotting the relationship between the applied action and the deformation produced.

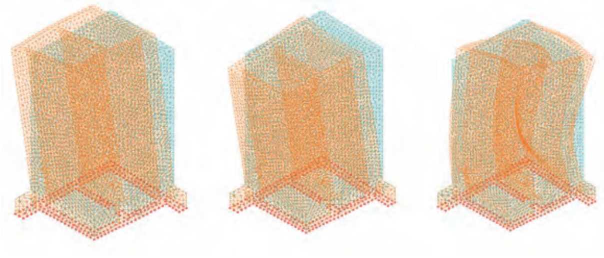

Fig. 14. Damage frequency (Source: Alonso-Llop 2022).

Vibration mode	Frequency (Hz)	Period (sec).
1	3,345	0,299
2	3,567	0,281
3	5,417	0,184
4	6,670	0,149
5	10,271	0,097
6	10,446	0,095

Fig. 15. Frequencies and periods of vibration of the first 6 modes (Source: Alonso-Llop 2022).

When the data between the seismic demand, response spectrum, and the capacity of the structure is cross-checked, the level of damage or collapse suffered by the structure for an earthquake represented in the spectrum is determined.

In the present case, the numerical simulation predicts that this tower would collapse under the action of an considered value earthquake considered (Fig. 16).

Hypothesis 3. Single-layer masonry socle and masonry upper structure, up to 5 storeys high.

In this option, the tower element maintains the volume of scenario 2, but varies in its material composition. The new approach consists of a change in the percentage contribution of the masonry. Specifically, the continuity of the stone plinth is sought throughout the entire elevation, in the same way as in other territories in the Iberian period. The reason for this is to find out how it would behave with the new construction model.

With respect to Phase 1, and repeating the calculations as in the previous case of the upper adobe structure, the gravity loads give similar results, with the stresses being somewhat higher because the masonry is heavier than the adobe (Fig. 17).

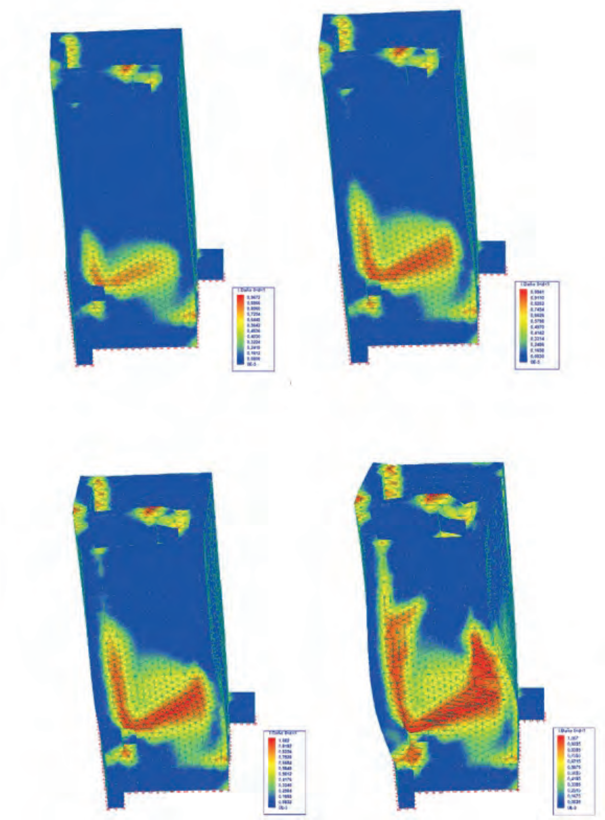

Fig. 16. Sequence image of structural failure by earthquake in model 2 (Source: Alonso-Llop 2022).

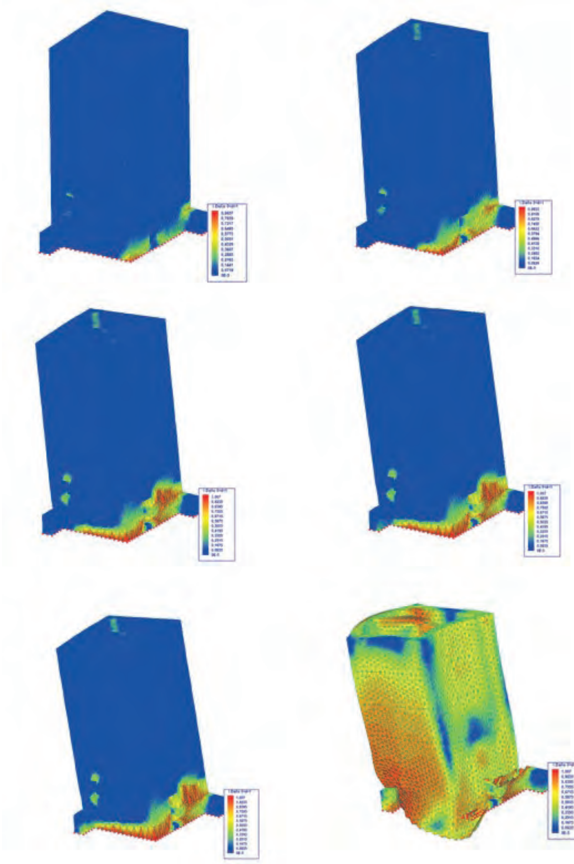

Fig. 18. Sequence image of structural failure by earthquake in model 3 (Source: Alonso-Llop 2022).

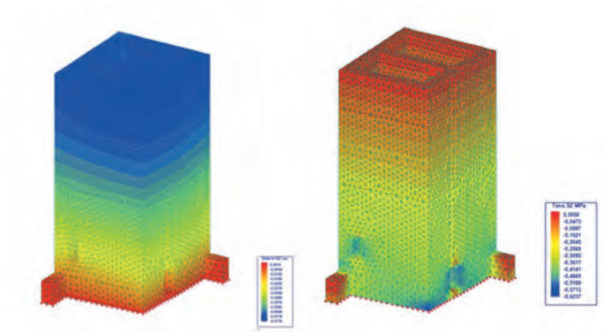

Fig. 17. Strain and stress state image in model 3 (Source: Alonso-Llop 2022).

Phase 2, applying the same as scenario 2, shows a different capacity curve showing that masonry walls have a higher capacity, in the order of twice as high as adobe walls. In the graphical sequence of structural failure, it can be seen that as the earthquake increases, there are certain areas where stresses are concentrated, increasing significantly and reaching the fracture of the masonry. We refer to the base of the tower, the shaft of the tower remains uncracked until the collapse occurs (Fig. 18).

Hypothesis 4. Multi-layered masonry socle and upper structure up to 5 storeys high.

The example under study maintains the stone form up to its completion, and differs from model number 3 in its construction. In it, the masonry wall made of stones that only interlocked with each other has been replaced by a double-leaf stone masonry structure with an interior earth filling.

In view of the gravity loads of the current prototype, which would be very similar to case 3 or even lower, it was decided to omit Phase 1. It is clear that the results would be more advantageous, and therefore free of stability risk.

On the other hand, in Phase 2, the seismic load is applied again and with the same criteria, until the structure collapses. New data is recorded and reflected in the corresponding capacity curve, and in the images of the evolution of the tower during the action of the earthquake, it can be seen that the breakage of the masonry walls with earth inside, the collapse process develops along the entire shaft, unlike the previous model (Fig. 19).

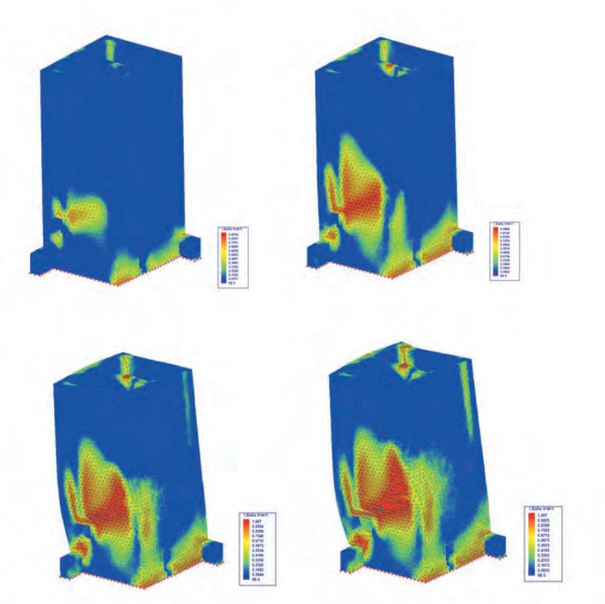

Fig. 19. Sequence image of structural failure due to earthquake in model 4 (Source: Alonso-Llop 2022).

5. DISCUSSION

Structural analyses in different variants of the Iberian tower of Rochina have shown that:

- In Phase 1, with regard to the behaviour of the tower in the face of the gravitational action of the structure's own weight, none of the chosen models suffer from stability risks, regardless of their material composition and height. Even in the most unfavourable example due to its greater load, scenario 3, the weakest parts of the structure, corners and spans, barely suffer, with more than enough margin to continue rising to unusual heights before reaching a problematic situation.
- In Phase 2, in the face of seismic action, the collapse loads are different in the three models analysed, those of 5 heights. When comparing the capacity curves, specifically those values on the ordinate axis, reprensenting the force that causes the rupture, it is concluded that the model that resists the most is the one with the total masonry structure without interior earth filling, hypothesis 3. In contrast, there is the model with stone plinth and adobe upper walls. In between them, the masonry with internal stone infill has a lower resistance than model 3 (Fig. 20).

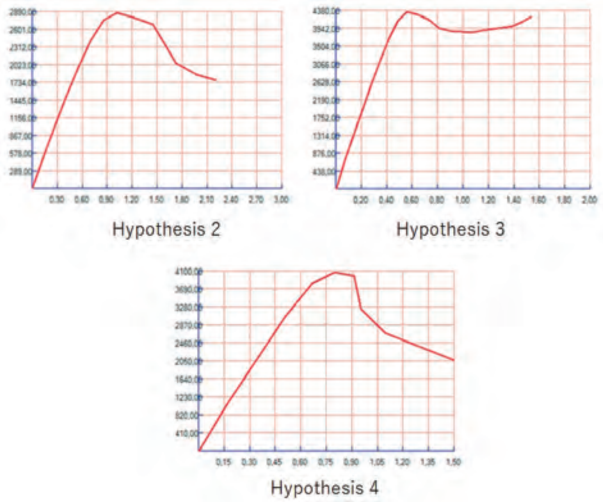

Fig. 20. Comparison of the models for scenarios 2, 3 and 4 (Source: Alonso-Llop 2022).

6. CONCLUSIONS

The conclusions of the research can be summarised as follows:

- The study of the graphic representations of architectural elements can decipher new aspects in the configuration of spaces, with the implementation of geometric forms of towers and modular approaches in residential complexes based on the tower element.
- The photogrammetries can advance a way of building, in the case of Rochina: construction survey as the raw materials are obtained from the immediate surroundings, with the existence of construction joints and order in the execution of the wall elevations.
- Graphical representations are used to decipher the structural behaviour of buildings,
- Gravity loads do not affect structural stability in any of the models studied.
- Seismic actions do affect slimmer models, with those made of stone masonry without interior infill resisting much better, as opposed to models with adobe on top.
- And finally, there is no structural coherence in erecting towers with thick walls on seismic-free sites, suggesting an assimilation of construction habits from other geographical areas.

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How to cite this article: Alonso Durá, A., Llop Gil, J. 2022. “Graphic and structural analysis for the knowledge of ancient architectural heritage: the case of the tower in the iberian settlement of Rochina”, *EGE Revista de Expresión Gráfica en la Edificación*, No. 17, Valencia: Universitat Politécnica de València. pp. 43-55. https://doi.org/10.4995/ege.2022.19031.