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Historical and architectural study for the numerical modeling of heritage buildings: the Tower of Comares of the Alhambra (Granada, Spain)

Estudio histórico y arquitectónico para la modelización numérica de edificios patrimoniales: la Torre de Comares de la Alhambra (Granada, España)

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ABSTRACT

Numerical analysis techniques are becoming an essential tool over the last few decades in the field of maintenance and preservation of architectural heritage. This study presents the development of a numerical model of the Tower of Comares, in the fortress of the Alhambra (Granada, Spain). A thorough research on the historical documentation was carried out, as a crucial step to understand the structural characteristics of a heritage building and to define the mechanical properties of its construction materials. With this information, a highly-detailed three-dimensional model of the tower was developed, on which a modal and a static analysis were performed. The development of this kind of models is the basis to simulate the structural behavior of heritage buildings under different load conditions and to assess their vulnerability.

Keywords: historic buildings; heritage conservation; numerical modeling; FEM simulation; Alhambra.

RESUMEN

Las técnicas de análisis numérico se han convertido en las últimas décadas en una herramienta esencial en el campo del mantenimiento y conservación del patrimonio arquitectónico. Este estudio presenta el desarrollo de un modelo numérico de la Torre de Comares, en la fortaleza de la Alhambra (Granada, España). Una exhaustiva investigación de la documentación histórica se ha llevado a cabo como paso fundamental para comprender las características estructurales de un edificio patrimonial y definir las propiedades mecánicas de los materiales que lo componen. Con esta información, se ha creado un modelo tridimensional con un alto detalle de la torre, sobre el que se ha realizado un análisis modal y un análisis estático. El desarrollo de este tipo de modelos es la base para simular el comportamiento estructural de edificios históricos sujetos a diferentes condiciones de carga y evaluar así su vulnerabilidad.

Palabras clave: *edificios históricos; conservación del patrimonio; modelización numérica; simulación MEF; Alhambra.*

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1. INTRODUCTION

Maintenance and preservation of the architectural heritage, with a high artistic and cultural value, is one of the main concerns of today's society (1). In this regard, the use of numerical modeling techniques has become increasingly important over the lasts years (2, 3), as they make it possible to reproduce and predict the structural behavior of existing buildings and hence prevent damage.

However, the structural analysis of historic buildings is often a difficult task due to the complexity of their geometry, the wide range of construction techniques used, the high variability of the mechanical properties of the traditional building materials and, frequently, the lack of knowledge about the existing damage (4, 5). To overcome these difficulties and create a model of the building that accurately represents its structural behavior, it is essential to carry out an exhaustive investigation including all the historical documentation regarding the considered building.

The development of these highly-detailed models requiring a thorough previous investigation and a careful and precise modeling process, with the consequent time cost, is particularly suitable for heritage buildings of special architectural or historical relevance and buildings with a high structural complexity. The Tower of Comares, at the Alhambra of Granada (Spain) meets both requirements.

The Tower of Comares (Figure 1) is one of the best-known buildings within the monumental complex of the Alhambra, which is currently one of the few preserved palatine cities of the Islamic period, constituting the best example of Nasrid art in its architecture and decorative aspects (6), being included in the UNESCO World Heritage List since 1984 (7). The Tower of Comares was built between the 13th and 14th centuries, and has undergone numerous modifications and alterations throughout its history, resulting in a building of high structural complexity that combines several materials and construction techniques.

Despite its great relevance, there are only a few studies concerning the structural evaluation of the Tower of Comares, most of them carried out during the last decade of the 20th century. Astiz (8) developed a 3D model with very simplified geometry and one single homogeneous and isotropic material and carried out both a static and a seismic analysis; similar procedure was followed by Santos et al. (9) but considering five materials (two different soils and three types of rammed earth). Most recently, Brazille Naulet et al. (10) analyzed the external layout of the tower identifying the existing damage, but without performing a structural analysis.

Figure 1. External view of the Tower of Comares.

This study presents the development process of a finite element method (FEM) numerical model of the Tower of Comares at the Alhambra of Granada (Spain). This process begins with a thorough historical and architectural investigation and leads to the creation of a detailed 3D model of the structure that is subjected to a static analysis in order to verify the accurateness of its behavior. The structural complexity of the building, together with its great historical and artistic significance, makes it necessary to elaborate a highly-detailed numerical model in order to successfully carry out its structural analysis and so be able to ensure its preservation in safety conditions. The model developed in the present study aims to be the basis for future works regarding dynamic analysis and reliability assessment of such a relevant heritage building.

2. THE TOWER OF COMARES: HISTORICAL CONTEXT

The origins of the Tower of Comares date back to the 13th century, when the enlargement of the walled perimeter of the Alhambra carried out by the emir Muhammad I (1237-1273), also known as Alhamar, and his successor Muhammad II (1273-1302) already included a small military tower, probably in Almohad style, at the location of the current Tower of Comares (11–13). Remains of this primitive tower can still be found in the basement of the present tower, as the great hardness of the material made it very difficult to demolish, so the following constructions were developed on the existing ones.

Afterwards, around 1314, Ismail I built a first palace in the same location, but it was demolished by Yusuf I between 1333 and 1354 to build, using rammed earth (RE) construction technique, which is considered the main structure of the current Tower of Comares (14). The works were finished by Muhammad V, who also added the court, the portico and the Hall of the Boat (*Sala de la Barca*). The architectural design of the tower is characteristic of the Nasrid architecture, where it is frequent to observe a contrast between the sumptuousness of the inside, typical of a palace, and the sobriety of the outside, typical of a defensive tower placed in the walled perimeter of a fortress (15).

During the following years, there were only minor alterations in the tower. The most relevant event affecting the tower during the 16th century occurred in 1590, when an explosion in a nearby gunpowder factory affected the Tower of Comares causing severe damage to windows, floor slabs, partition walls and external walls (16). The repairs, made with brick masonry, were not enough to solve the structural damages (17, 18).

The structural pathologies present in the tower got exacerbated over the next decades due to the lack of maintenance and the execution of several inadequate alterations (10). Thus, during the first third of the 17th century, a number of reforms were made in the basements, causing the collapse of the north wall of the central vault of the primitive tower (16), which was still preserved, and the opening of a hole in the north wall of the new dome, dating back to Yusuf I (19). Also in the first half of the 17th century, wooden braces were placed in the south wall to ensure its stability and to resist the lateral forces resulting from the heavy dome that closed the tower. This wooden braces were later replaced by new ones made of iron (8).

In the year 1644, the master builder of the Alhambra, Bartolomé Fernández Lechuga, expressed his concern about the structural state of the Tower of Comares. In order to avoid its collapse, the windows at the lower floor were filled in, and the demolition of the battlements and the upper vault was proposed to reduce weight. Taking into account that the current battlements are made of brick masonry, instead of rammed earth, it seems reasonable to think that they were actually removed (10).

Over the next years, several alterations and repairs were done in the tower due to its precarious structural conditions. Between 1671 and 1674, the underpinning of the south wall and main entrance of the tower was required (20), but this measure was not enough to avoid its partial collapse. In view of this situation, in 1688 the preservation works were resumed under the direction of Juan de Rueda, beginning with the substitution of the original vault, made of bricks, by a wooden truss covered with tiles (16). This new pyramid hip roof, which remained erect until 1931, was lighter than the previous one and stood above the profile of the tower. The works also included the underpinning of the tower and the reinforcement with Alfacar travertine of the spaces between the lower windows (10). These interventions significantly improved the structural integrity of the tower.

Later on, in the 18th century, a report of the royal master builder in 1734 noted the existence of a large crack on the tower walls, from the ground floor level to the top of the building, as a consequence of a previous earthquake. During the following years, more underpinnings were made in the tower, being worth to mention the one on the northeast corner in 1791 (16, 21) and another one in 1814 at the part of the tower in contact with the perimeter wall.

In 1822, another seism caused damages in the main room of the tower, the so-called Chamber of the Ambassadors (*Salón de los Embajadores*), been necessary to tighten the armature of the roof from its basement (22). These works started in 1837.

Between 1853 and 1857, some other maintenance works were carried out, concerning the restoration of the vault of the Chamber of the Ambassadors by placing new wooden ribs and an iron compression ring with clamps at the top part of the structure. The works also included the reparation of the lateral arches of the main chamber and some improvements in the staircase at the southwest corner of the tower (14, 16).

In 1917, the Conservation Plan of the Alhambra (23) was established, including in its eighth section the maintenance works to be carried out in the Tower of Comares as a matter of urgency. In 1923, the architect Leopoldo Torres Balbás was designated as chief conservator of the Alhambra and, two years later, he presented a first restoration project concerning the recovery of the passage between the Hall of the Boat and the Chamber of the Ambassadors (24). Within this project, probably also the north wall of the passage was rebuilt.

Between the years 1930 and 1931, relevant restoration works were carried out by Torres Balbás, including the filling of the cracks in the north wall of the Chamber of the Ambassadors and the staircase. The pyramid hip wooden roof built in the 17th century was dismantled and replaced by a reinforced concrete slab placed on steel joist resting on a steel I-beam (16). These interventions during the first half of the 20th century can be considered as the last significant structural alterations carried out in the Tower of Comares.

3. MATERIALS AND METHODS

3.1. Materials characterization

The evolution of the tower throughout history and the many additions and interventions have led to a great heterogeneity in the materials and construction techniques present in the building. This section aims to identify the existing materials and their position within the structure and to determine their mechanical properties.

The foundations of the building, whose construction began during the early Nasrid period, are made of RE with a very hard clayey matrix with river stones, resulting in a mixture with a very high strength. The walls of the main body of the tower of the 14th century are also made of RE, using a mixture of fine gravel, sand, ferruginous clay and a significant percentage of lime (around 20 %), with a particle size of the coarser materials smaller than the one used in the foundations (16, 25, 26).

According to the studies developed by González Limón et al. (25), the RE present in the Tower of Comares has an average bulk density equal to 2250 kg/m^3 and an average pore size of 0.0174 µm. The same authors carried out uniaxial compression test, according to standard UNE 83.304:84, on ten RE samples extracted from the tower, obtaining a compressive strength (f_c) equal to 2.45 MPa for the material of the walls and 7.85 MPa for the foundations (9, 25). Both values, especially the one obtained at the foundations, are much higher than the ones typically obtained for RE (27). The reason could be the great compaction reached after centuries of load bearing.

RE has very low tensile strength (f_t), in this case it was measured equal to 0.29 MPa for the walls and 0.74 MPa for the foundations. Via uniaxial compression tests, also the elastic modulus (E), 0.92 GPa for the walls and 6.18 GPa for the foundations, and the Poisson's ratio (ν), 0.3 for the walls and 0.2 for the foundations, were obtained by (25).

Another material with a significant presence in the structure of the tower is brick masonry. The bricks are made of fired clay and joined together with mud and lime mortar (25). This masonry was used in combination with rammed earth in the walls of the vaults at the lower basements (24), in pilasters at the corners of the tower, between the arches of the tower of the 14th century and lining the north, east and west walls under the pavement level of the Chamber of the Ambassadors.

Table 1. Mechanical properties of the materials present in the Tower of Comares.
Density (ρ), compressive strength (f_c), tensile strength (f_t), elastic modulus (E) and Poisson's ratio (ν).

Material	Ref.	ρ [kg/m3]	f_c [MPa]	f_t [MPa]	E [GPa]	ν [-]
RE (walls)	(9, 25)	2250	2.45	0.30	0.92	0.30
RE (foundations)	(9, 25)	2250	7.85	0.75	6.18	0.20
Brick masonry	(25)	1440	3.88	0.19	2.94	0.25
Travertine	(5, 28)	2140	29.40	1.00	23.67	0.35
Cedar wood	(31)	560	55.00	140.00	9.20	0.15
Pine wood	(31)	520	43.00	114.00	7.50	0.15
Carbon steel	(32)	780	-	400.00	196.00	0.30
Wrought iron	(8)	6920	-	390.00	190.00	0.25
Concrete	(30)	2200	16.00	1.30	27.00	0.20

According to the aforementioned study (25), the brick masonry has a density of 1440 kg/m^3. The compressive strength is equal to 14.71 MPa for the bricks and between 1 and 2 MPa for the mortar. From these two values it is possible to obtain a characteristic compressive strength of the masonry equal to 3.92 MPa according to standard NBE FL-90 and 3.88 MPa according to Eurocode 6 (EC-6). Considering again those standards, the tensile strength of the masonry is equal to 0.19 MPa (NBE FL-90) or 0.39 MPa (EC-6). The elastic modulus is between 2.94 and 3.73 GPa according to NBE FL-90 and 3.88 GPa if one considers the EC-2. The Poisson's ratio is considered equal to 0.25. To develop the numerical model, the most unfavorable values of the material properties were considered, as shown in Table 1.

The current structure of the tower still includes some of the underpinnings and insertions made of Alfacar travertine, although some of them were removed during the restoration works carried out by Torres Balbás in the first half of the 20th century. This travertine, obtained from a quarry at Alfacar (Granada), is a carbonate rock that has been frequently used as a construction material within the region of eastern Andalusia (Spain) due to its great strength and durability (28, 29). It is mainly composed of calcite (> 84 %) and quartz (ca. 14 %), with presence of dolomite (< 5 %) and feldspar (<1 %) (29).

The studies undertaken by Suarez and Bravo (28) at the aqueduct of the Royal Ditch of the Alhambra, made of the same material, indicate a density of the Alfacar travertine equal to 2140 kg/m^3, an elastic modulus of 23.67 GPa and a Poisson's ratio of 0.35. Other study considering the same rock (5) obtained similar results for the elastic modulus and Poisson's ratio, and defined a compressive strength of 29.4 MPa and a tensile strength of 1 MPa.

The beams and reinforcements in the concrete slab introduced by Torres Balbás in 1932 are made of carbon steel. Taking into account the characteristics of the steel used in construction in Spain until 1960, the mechanical properties of this material are considered equivalent to category A7 (carbon steel) as defined in standard ASTM A36. To define the mechanical properties of the concrete used in that slab, reference is made to the first Spanish standard regarding structural concrete (30), approved in 1944 but written in 1939, so it is reasonable to consider that the concrete used by Torres Balbás in 1932 was similar to the one indicated in this standard.

Together with the steel found in the beams and reinforcements, the other metallic material present in the tower is the wrought iron used for the braces that help supporting the south wall between the fifth and the sixth floor of the tower. The mechanical characteristics of this material are also shown in Table 1.

Also wood is present as a construction material in the Tower of Comares. Cedar wood was used for the vault covering the Chamber of the Ambassadors, while pine wood was chosen for the beams and boards conforming the floor slabs, most of them in the south wall. To define their mechanical properties, the values offered by Rodríguez Rodríguez (31) for Atlas cedar and stone pine have been considered, as shown in Table 1.

3.2. Analysis of geometry

A thorough analysis to define the geometry of the building is essential to develop an accurate model and to obtain reliable results. Due to the geometrical complexity of the Tower of Comares, the present study aims to create a highly-detailed 3D model of the structure that can represent with precision its mechanical behavior.

To define the geometry of the building, diverse references have been consulted and analyzed. The most exhaustive and accurate geometrical description of the tower, together

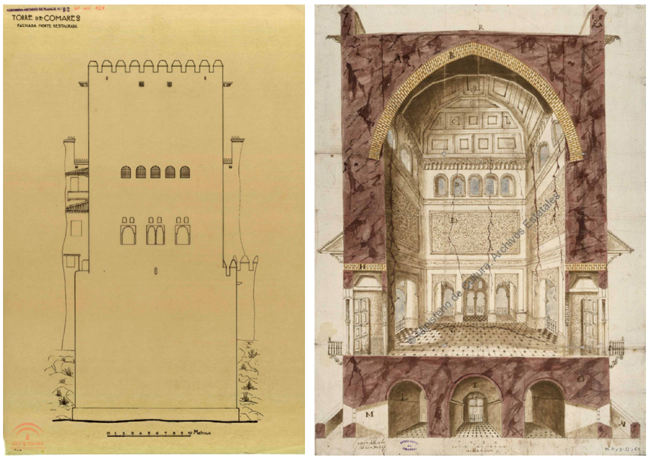


Figure 2. Architectural documentation from restoration projects at the Tower of Comares: north facade (left) (33) and West-East vertical section (right) (34).

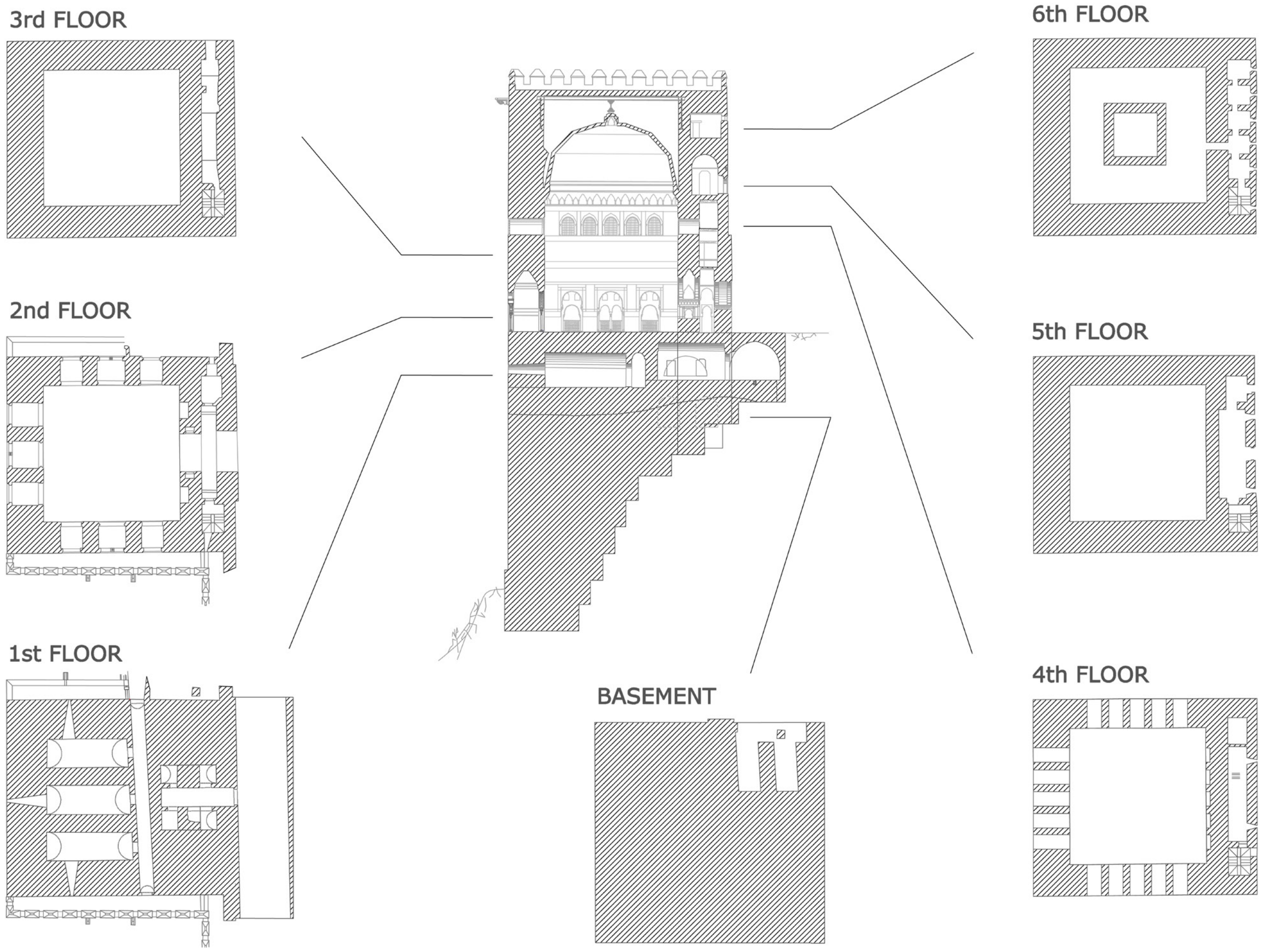


Figure 3. North-South vertical section and horizontal sections of the Tower of Comares. Adapted from (15).

with the one developed by Jiménez Martín in 1996 (35), was carried out by Torres Balbás between 1927 and 1932 (16) on the occasion of the restoration project that was developed during the 1930s. Also some drawings by Juan de Rueda for the restoration project carried out in 1688 are still preserved. An example of the blueprints and drawings from these two projects are shown in Figure 2. The geometrical information obtained from literature was complemented with some measurements in-situ.

Externally, the Tower of Comares is a 16.75 × 19.15 m rectangular prism with a height of 22.60 m above the floor level of the Chamber of the Ambassadors (1.30 m-tall battlements included) and between 6 and 26 m below the ground level, foundations included. The basements of the tower consist of several vaulted tunnels covered with brick masonry, among which stands out the Hall of the Nymphs.

The main body of the tower has 2.5 to 3.0 m-thick walls and is dominated by the Chamber of the Ambassadors, also referred to as Hall of Comares or Throne Room, which is considered the most majestic room of the whole palace. The room has a 11.30 m-side square plan and is 18.20 m high, crowned by the Cedar wood dome. A staircase at the southwest corner gives access to the upper rooms, most of them placed at the south side of the tower.

This south wall has, at the level of the fifth and sixth floors, the wrought iron braces placed in the 17th century to contain the pressure generated by the wooden roof. These braces have square section of side 2.5 cm and 2 m free span (8).

The tower is topped by the roof constructed in 1932, composed of an 8 cm-thick reinforced concrete slab resting on I-joists that rest, in turn, on a 12.30 m-long I-beam. This main beam is embedded in the east and west walls of the tower, which are the best preserved ones (16).

As a result of the architectural and geometrical analysis, the geometry of the building, used to create the model, can be defined as shown in Figure 3.

3.3. FEM modeling analysis

Considering the information obtained from the historical and geometrical analysis, it was possible to create a three-dimensional model of the Tower of Comares. This model was generated as a combination between several sub-models defined according to the characteristics of the construction materials and the building period of each part of the structure. In this regard, the following sub-models were identified:

- RE foundations.
- Primitive tower from the 13th century, made of RE and whose walls are now composing part of the foundations and the ramparts passing under the tower.
- Basements under the Chamber of the Ambassadors, made of RE.

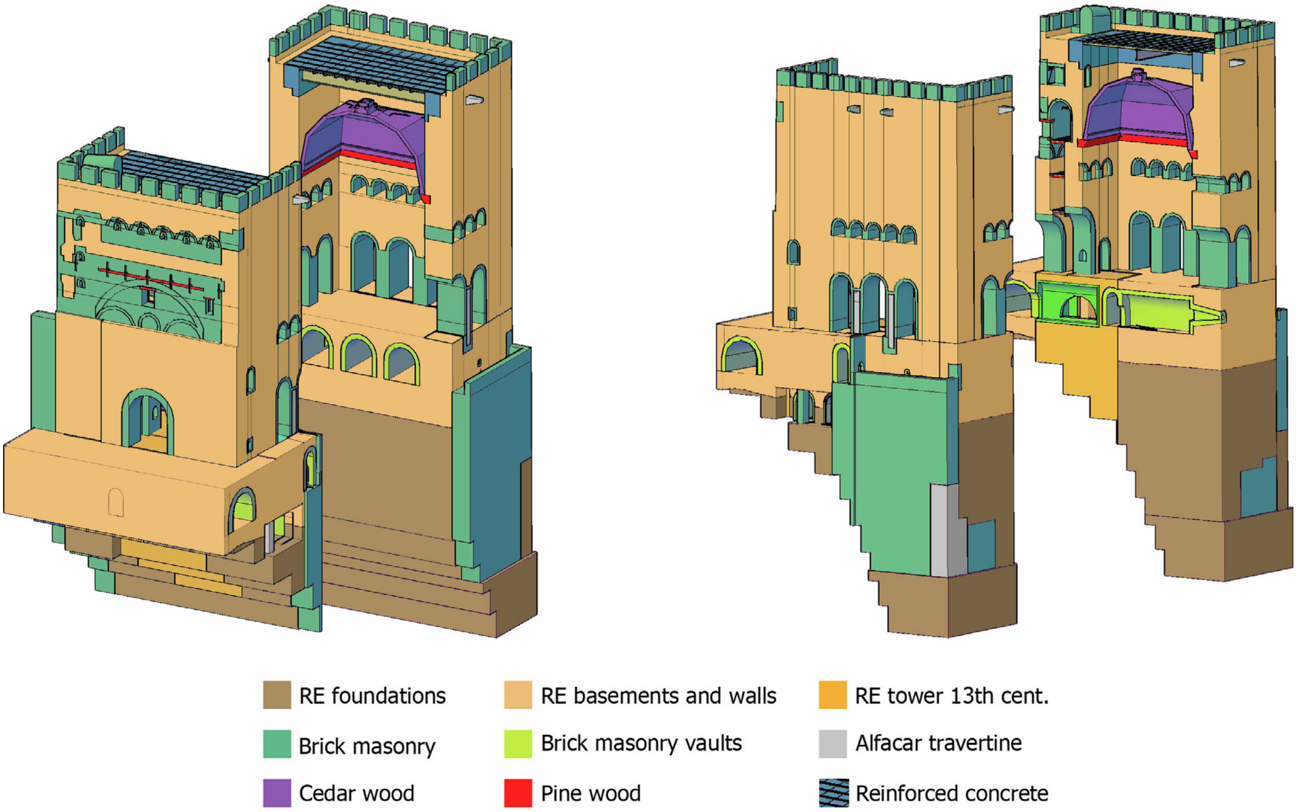


Figure 4. 3D model of the Tower of Comares. East-West (left) and South-North (right) vertical sections.

- Brick masonry vaults of the tunnels and Hall of the Nymphs in the basements of the tower.
- RE walls at the main body of the tower.
- Brick masonry at walls, arches and battlements.
- Alfacar travertine insertions and underpinning.
- Cedar wood main dome.
- Pine wood beams and floor slabs.
- Wrought iron braces in the south wall.
- Reinforced concrete slab at the roof.
- Steel joists and I-beam supporting the roof.

Figure 4 shows the 3D model of the building, identifying the parts and materials that compose it.

This geometry was introduced in a FEM software in order to perform the structural analysis. For the purposes of the present study, only the elastic material properties were included. The behavior of the materials was represented via macro-modeling, a common procedure when analyzing large structural members or full structures, as it requires lower computing times and offers an adequate approach for the characterization of the structural response (3, 5).

The parts of the model were meshed mainly with linear 4-nodes tetrahedral elements, in order to properly fit with the complex geometry of the building. The model has a total of 480128 elements, 143888 nodes and 431664 degrees of freedom. The mesh size was defined computing the first three natural frequencies using meshes with increasing element density until reaching convergence.

Once the FEM model was defined, it was first subjected to a full modal analysis including the first ten modes of vibration, in order to validate its behavior, and then to linear static analysis. The loads considered for the static analysis were the self-weight of the building, live load, snow load and wind load, according to the values indicated by the Spanish Building Code (CTE-DB-SE-AE) (36) for the city of Granada, as shown in Table 2. The live load was considered applied on the passable zones (corridors, basements, rooms and walkable roof) and the snow load was applied on the roof and other exterior horizontal surfaces. The static wind load includes a pressure that was applied on the north and west walls, oriented to the exterior of the fortress and therefore more exposed to the action of the wind, and a suction effect applied on the opposite facades. Regarding the boundary conditions, the foundations of the tower were considered fixed in the hillside where it is placed.

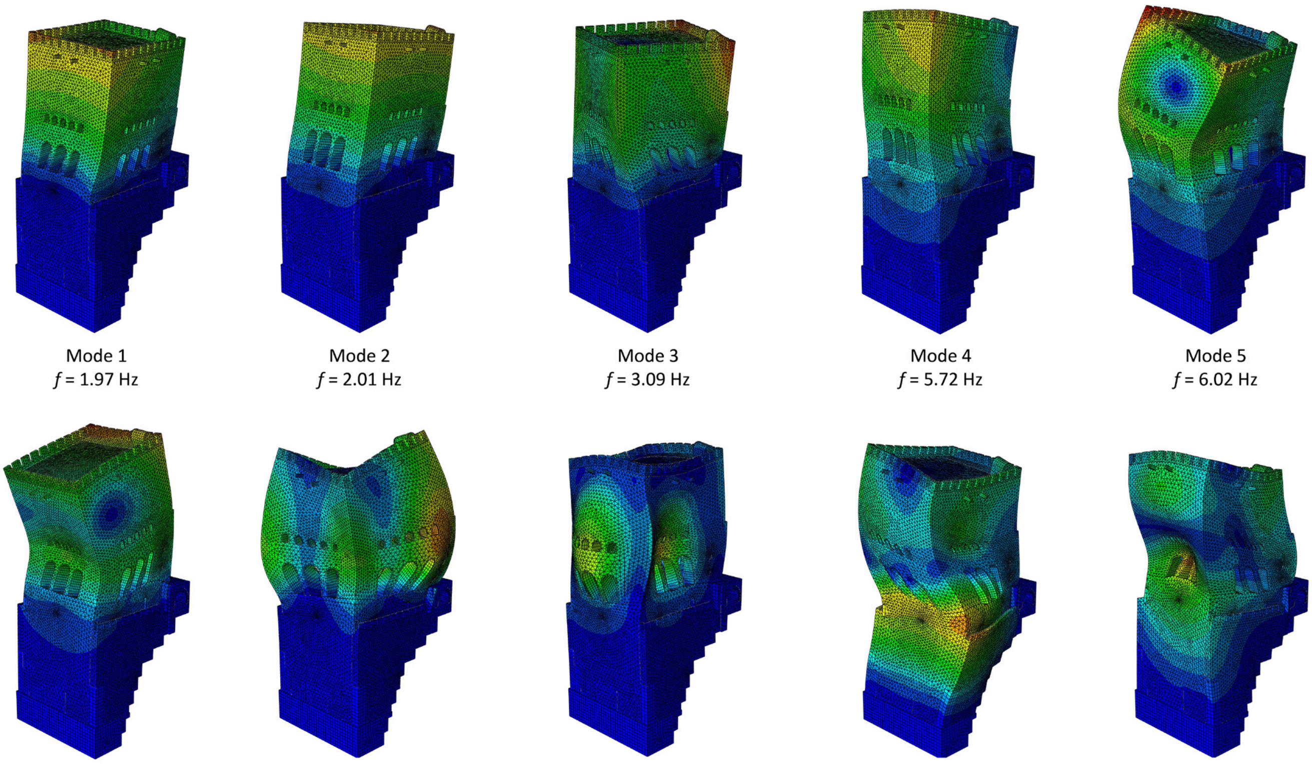
Table 2. Loads applied on the model, according to Spanish Building Code (36).

Load	**Value [kN/m²]**
Self-weight	*(depending on the material)*
Live load	2.00
Snow	0.50
Wind (pressure)	1.00
Wind (suction)	0.50

4. RESULTS AND DISCUSSION

4.1. Modal analysis

The first ten modes of vibration and natural frequencies of the Tower of Comares obtained from the modal analysis are



Mode 1
f = 1.97 Hz
Mode 2
f = 2.01 Hz
Mode 3
f = 3.09 Hz
Mode 4
f = 5.72 Hz
Mode 5
f = 6.02 Hz
Mode 6
f = 6.44 Hz
Mode 7
f = 7.15 Hz
Mode 8
f = 7.97 Hz
Mode 9
f = 8.46 Hz
Mode 10
f = 9.82 Hz

Figure 5. First ten modes of vibration and natural frequencies of the tower.

shown in Figure 5. First ten modes of vibration and natural frequencies of the tower. The modal analysis is a useful tool to have a first validation of the correctness of the model and to forecast its seismic response.

If we attend to the first mode of vibration, a first natural frequency of 1.97 Hz was obtained. This value is very close to the 2 Hz determined by Astiz (11) using a model of the tower with simplified geometry and homogeneous material, and calculated by Santos et al. (9) by the installation of seismographs at two levels of the tower. The result is also in agreement with the approximation that can be calculated applying the expression proposed by the Spanish seismic code (NCSE-02) (37) for brick masonry structures:

[1] $$f_F = \sqrt{L}/[0.06H\sqrt{H/(2L+H)}]$$

where f_F [Hz] is the fundamental frequency of vibration of the structure, L [m] is the length of the plan of the building in the direction of the vibration, and H [m] is the height of the building. Considering the total height of the tower (H = 47.30 m) and repeating the calculation for both main directions (L = 16.75 m and L = 19.15 m), an average value of 1.98 Hz is obtained for the first natural frequency of the tower.

According to these results, it is possible to conclude that the outputs of the modal analysis support the accuracy in the behavior of the developed FEM model.

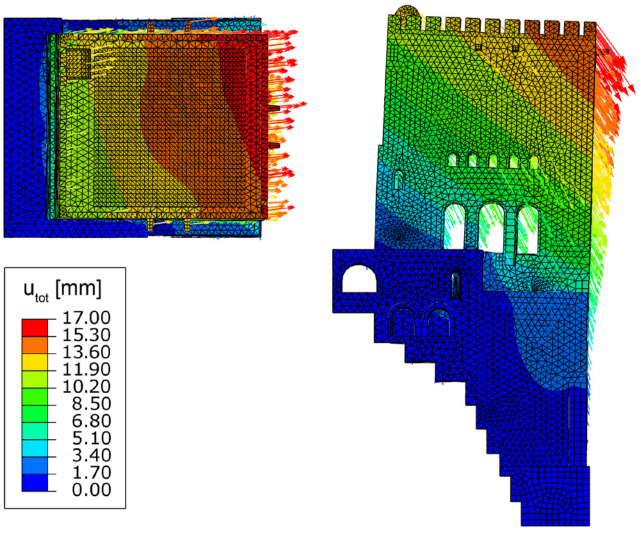


Figure 6. Contour plot of total displacements in the tower under static loads. Plan view (left) and east facade (right).

4.2. Static analysis

The results from the static analysis of the building under gravity and wind loads show that the greatest displacements (Figure 6) occur at the top of the north wall, towards the exterior of the fortress. This is due to the slanted foundations adapting to the shape of hillside where the tower is placed. However, the obtained deformations are very low, with maximum displacements lower than 17 mm, showing the high stiffness of the structure.

Regarding the stresses generated in the structure (Figure 7), it is possible to observe that the RE walls conforming the main body of the tower are subjected to limited stresses (lower than 2 MPa), and the maximum values are reached

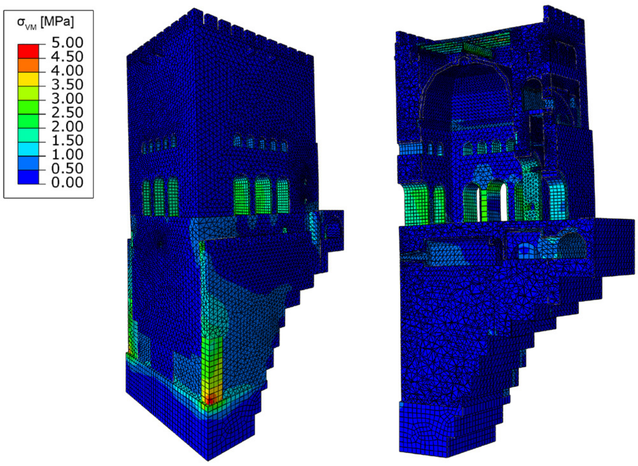


Figure 7. Contour plot of Von Mises stresses in the tower under static loads. North and west facades (left) and North-South vertical section (right).

at the foundations and near the arches of the windows at the Chamber of the Ambassadors.

Stress concentration is found at the brick masonry arches and, especially, at the travertine underpinnings at the corners of the tower, although theses stresses are much lower than the strength of the materials. Also a slight stress concentration is observed at the basements under the south wall, but these stresses are still limited, indicating the correctness of the intervention carried out by Torres Balbás removing the ashlars in that position and allowing the connection between the staircase and the oratory. Also the execution of the concrete slab seems appropriate, as the beams show stresses much lower than their limit load and they are able to transfer that load to the walls without generating excessive stresses to the RE.

The iron braces in the south wall are subjected to tensile stresses much higher than the rest of the structure (up to ca. 18 MPa), as shown in Figure 8, proving the essential role that these elements are playing even today in the global stability of the tower, as indicated by previous studies (8, 11). This stress state, however, is still much lower than the tensile strength of the material, and might be substantially increased when subjecting the structure to a seismic load, which implies significant horizontal forces to be absorbed by the iron rods.

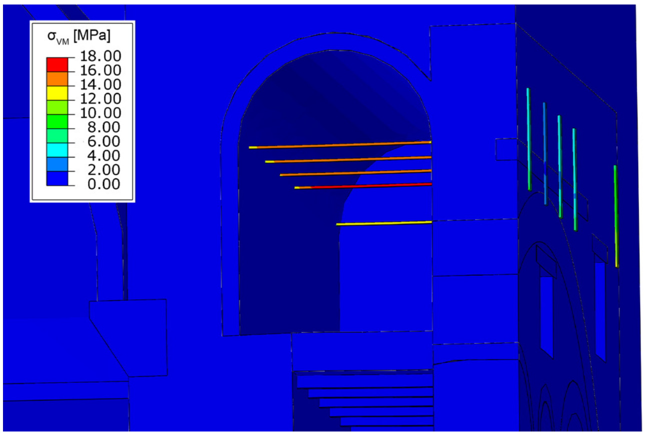


Figure 8. Contour plot of Von Mises stresses in the braces of the south wall under static loads.

These results make it possible to understand the structural behavior of the Tower of Comares under load conditions that are common during its lifetime, as a result of a long history of interventions and restoration works. The behavior shown by the detailed model developed in this study is in agreement with the results obtained by several authors that have previously analyzed the structural state of the tower (8–10, 25).

5. CONCLUSIONS

This work presents a historic and architectural study of a building with a high heritage value, the Tower of Comares at the Alhambra of Granada (Spain), with the aim of creating a numerical FEM model to analyze its structural behavior.

A thorough literature review made it possible to define the geometry and mechanical properties of the diverse elements, construction techniques and materials that compose the structure. With this information, it was possible to develop a highly-detailed three-dimensional FEM model of the tower, reflecting its geometry with a high level of precision. This historical and architectural analysis is essential to create accurate models of heritage buildings that properly represent their structural behavior; and it is also a useful tool to identify which parts of the geometry could be simplified or not included in the model without affecting its structural response in case the computational cost is unacceptably high.

The model is subjected to a modal analysis and a static analysis including gravity and wind loads. The results from the modal analysis, in agreement with previous studies, show a natural frequency of the tower slightly lower than 2 Hz. The static analysis allows to understand the structural behavior of the building under normal load conditions, indicating that the rammed earth making up the majority of the structure is subjected to limited stresses, while the main stresses are located at the brick masonry arches, travertine underpinnings and wrought iron braces. The displacements in the tower under these load conditions are also very limited, showing the high stiffness of the building.

It is worth to mention that the model developed in the present study includes only the elastic mechanical properties of the construction materials, as they are enough for the static evaluation performed. This study, therefore, aims to be the basis for future studies including the plastic behavior of the materials and regarding the dynamic evaluation of the tower oriented to the assessment of its structural vulnerability and reliability.

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