



THE PROCESS OF DIGITAL FABRICATION AND 3D PRINTING AS A TOOL IN THE STUDY OF HERITAGE PATHOLOGIES: CARCABUEY CASTLE (CORDOBA)

EL PROCESO DE FABRICACIÓN DIGITAL E IMPRESIÓN 3D COMO HERRAMIENTA EN EL ESTUDIO DE PATOLOGÍAS PATRIMONIALES: EL CASTILLO DE CARCABUEY (CÓRDOBA)

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Highlights:

- High-definition scanning and 3D printing have been used as tools in the detection of heritage pathologies, as well as in the study of materials.
- The Carcabuey castle has been digitized and the volumetric data recovered from the study of its materials typology and its stereotomy, obtained with laser scanning.
- The study of construction and material phases, and the pathologies produced by them, has been carried out from the 3D printing of the heritage structure parts.

Abstract:

Precise documentation is essential to carry out the restoration and enhancement processes of protected heritage contexts. Data collection has been increasingly perfected, to the point of being able to perform virtual recreations of complex historical sites, in order to carry out in-depth studies and analyses. An example is Carcabuey Castle (Cordoba, Andalusia), a large fortress with important medieval structures. It is a monumental site of the so-called "Frontier Castles", which were located between the Kingdom of Aragon, and the Nasrid Kingdom of Granada. With the aim of restoring it and highlighting its value, an in-depth study was developed for its conservation and subsequent intervention. The data collection included terrestrial laser scanning and vectorising all the structures, as well as a complex and complete photogrammetric survey. From these previous data and carrying out a deductive analytical methodology, a model was generated which, after being printed in 3D (different models at different scales of detail), would allow the volumes, materials and textures which make up the castle, to be studied. The multidisciplinary team, composed of architects, archaeologists, historians and engineers, made it possible to provide multifaceted and inclusive character to all the work, both in the study of pathologies based on the models, and in the construction phases, detected by the stereotomy of the ashlar, or chemical composition of mortars. Since then, with all the data obtained in the research, summarised in this article, it has been possible to carry out a correct diagnosis for the restoration and enhancement of the heritage site.

Keywords: 3D volumetry; heritage; digitisation; laser scanning; alterations; survey

Resumen:

La documentación precisa es fundamental para poder llevar a cabo los procesos de restauración y puesta en valor de los contextos patrimoniales protegidos. La toma de datos cada vez se ha ido perfeccionando más hasta el punto de poder realizar de forma virtual recreaciones de conjuntos históricos complejos para poder llevar a cabo profundos estudios y análisis. Un ejemplo de ello es el Castillo de Carcabuey (Córdoba, Andalucía), una gran fortaleza con importantes estructuras emergentes de época medieval. Se trata de un conjunto monumental de los llamados "Castillos de Frontera" que se ubicaban entre el reino de Aragón y el reino nazarí de Granada. Con el objetivo de restaurarlo y realzar su valor, se llevó a cabo un profundo estudio para su conservación y posterior intervención. La toma de datos consistió en el escaneado láser terrestre y vectorizado de todas las estructuras, así como en un complejo y completo levantamiento fotogramétrico. A partir de estos datos previos y llevando a cabo una metodología analítico-deductiva, se generó un modelado que permitiría, tras ser impreso en 3D (diferentes modelos a diferentes escalas de detalle), estudiar los volúmenes, materiales y texturas que configuran el castillo. El equipo multidisciplinar compuesto por arquitectos, arqueólogos, historiadores e ingenieros, permitió dar un carácter poliédrico e inclusivo a todo el trabajo, tanto de estudio de patologías a partir de los modelos, como de las fases constructivas detectadas por la estereotomía de los sillares o composición química de morteros. A partir de este momento, con todos los datos obtenidos en la investigación

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sintetizada en este artículo, se ha podido llevar a cabo una correcta diagnosis para la restauración y puesta en valor del conjunto patrimonial.

Palabras clave: volumetría 3D; patrimonio; digitalización; escaneado láser; alteraciones; levantamiento

1. Introduction

In recent years, Carcabuey Castle has had interventions due to urgent consolidation processes. These small, decontextualised incursions, promoted by the local Council, have been undertaken as an unavoidable necessity, due to the state of conservation of the building. These interventions are in addition to those previously carried out, which have led to a complicated reading of the history of the site. Faced with this situation, a request was made for a draft of the global restoration project, in phases, a Master Plan. Given the lack of documentation and prior information on the state of conservation of the monument, it was decided to focus on the first phase of in-depth data collection, which would allow the launch of the different working lines and hypotheses. For this, a very dense point cloud was generated, which would allow the generation of a digital elevation model (DEM), and a subsequent detailed 3D printing. It was possible to identify the most deteriorated and critical areas of the castle to directly focus the material study. It was planned that team members would undertake the work that was most appropriate to their discipline, and that the architect would integrate the work of the field and study teams, attempting to ensure that all the work was transversely synchronized (Fig. 1).

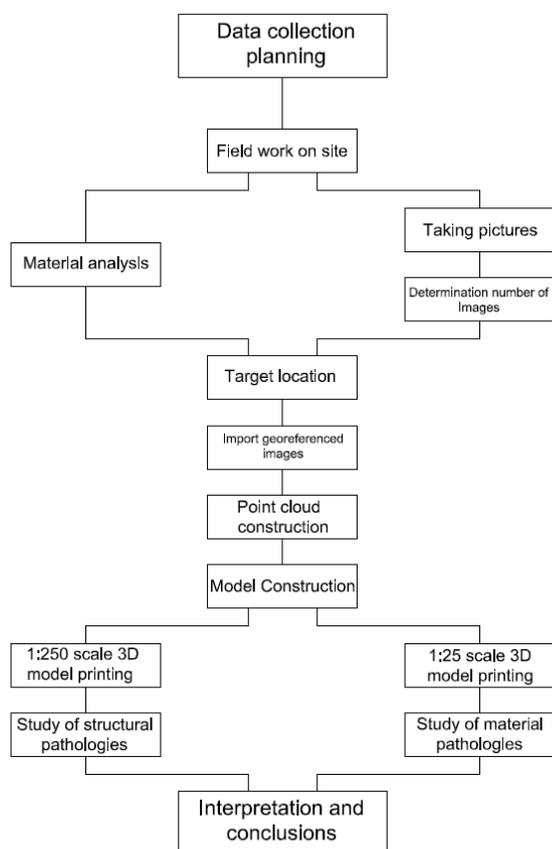


Figure 1: Research work scheme.

The methodological objectives of the process were:

- To obtain all the planimetry and photogrammetry necessary for the study of both the terrain and the enclave in which the Castle is located, and develop a 3D model with the sufficient definition that would allow details of the structures to be printed for the study of the stereotomy and construction systems of the Castle.
- Analysis of the DEM as an archaeological record of both constructive presences and absences/losses.
- Study the stereotomy of the construction systems from the 3D impression of the representative fragments of the castle and, from there, extract the pathologies as well as their evolution over time.
- From the study of the pathological evolution, establish a diagnosis of intervention in the future, anticipating the constructive development of the monument.

The objectives of the research developed in parallel were established as:

- At the pathological and material level: Generate a direct documentation process, linked to the data collection, to obtain constructive and pathological data directly, avoiding interpretations.
- At the level of archaeological and architectural information: Analyse the degree of definition of laser scanning and 3D printing, to obtain sufficient data on the stereotomy of the materials used in the construction process, as well as develop the construction and archaeology hypotheses of the architecture, from an objective basis.
- At the level of future interventions and restoration: Extract the constructive logic for using different materials and establish a constructive logic hypothesis to derive intervention criteria and enhancement.

2. Case study: Carcabuey Castle (Cordoba)

The current municipality of Carcabuey (Fig. 2) has had almost uninterrupted human settlements, believed to be from the Bronze Age, with remains documented both in the 13th and 6th centuries BC. This is evidenced by archaeological elements preserved, both in the British Museum of London (Harrison, 1974) and in the History Museum of Priego de Córdoba (Murillo, 1990).

During the Iberian era and the subsequent Roman conquest, it is believed that the Roman *municipium* of Ipolcobulcuba was established in the vicinity of the Castle. However, there are authors who maintain that this was located in the vicinity of the current Locubín Castle (Bonilla, 2004). This settlement has been identified through epigraphy, thanks to the Latin inscriptions recorded by J. Vives in his works (Vives, 1971), and his later reissues (Stylow, 1998). Similarly, the attribution of the Roman *municipium* is well-founded in a good number of funerary epigraphs (CIL II/2/5, 276 and 277), found both in the current town centre and its surroundings (Osuna, 2002), being expressly named as

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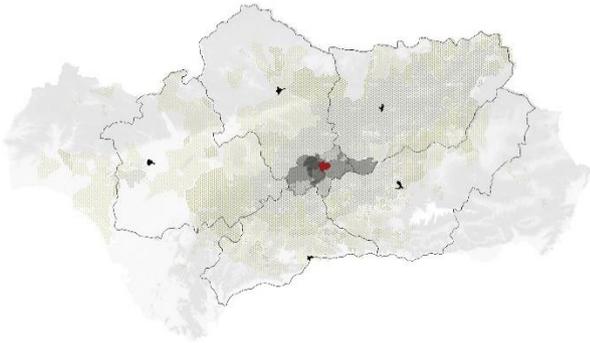


Figure 2: Municipality of Carcabuey in the territorial context of Andalusia.

Municipium Flavium Ipolcobilculensium (Morales, 2002). There are authors (Arjona, 1985) who, due to the wall remains of *opus coementicium*, indicate the existence of a primitive Roman castellum within the medieval fortress of today, as well as its relationship to the cistern that is at their feet. Monturque and Montemayor (Ramírez, 1982) point out that the latter shares a material nature with the ancient settlers of Carcabuey (Alcobitense). However, other authors consider the cistern to be a Muslim work (Córdoba, R et al., 1994), based on the use of the half-barrel vault and brickwork, or even Christian, executed later by order of Calatrava (Raya, 2012). Regarding the cisterns of the Castle, one author points out the existence of a second construction with these characteristics and within the fortified site (Pavón, 1990), which promptly disappeared with no records or citations to be found in that name throughout the occupation of the Castle (Figs. 3 and 4).

Little or nothing is known about the morphology and appearance of the Roman city, except for what is described in writings at the time (CIL II2/55, 276), which, according to later translations (Osuna, 2002), note the building of “a temple, a statue and a forum”. This temple could well have been dedicated to the goddesses Venus or Fortuna (Morales, 2002), according to the epigraphy found, with a base dedicated to Venus and two statue pedestals dedicated to the goddess of good or bad luck.

Advancing towards the late ancient period, a practical abandonment of the place is attributed (Carrillo, 1991). However, the municipality had already been relocated within the Ecclesiae Egabrensis. A funerary stone, later reused as the foot of an altar was found (CIL II2/5, 282), which could indicate there was not a total abandonment of the territory populated by the Romans (Sánchez et al., 2009).

It was in medieval times when the Castle began to take its current form. As indicated in some publications (Arjona, 1982), the construction of a fortress was developed on the top of the hill, which took materials available in its natural surroundings, such as limestone and lime mortar, to build stone walls in irregular rows.

This fortress was used as a base for the uprising, generated in the Cora de Priego by the local, Sa'id Ben Mastana, following the insurgent Umar Ibn Hafsun, against the Cordoban, Emir `Abd Allah. The rebel took control of several nearby castles, thus dominating the entire territory of the Cora, and forcing the Emir to move to the Castle of the then-named Karkabuliya. A quote from the Chronicler, Ibn Hayyan (Hayyan, I. collected in Arjona, 1982), describes how, in 892, the Alcobitense defensive site was demolished, or its functions

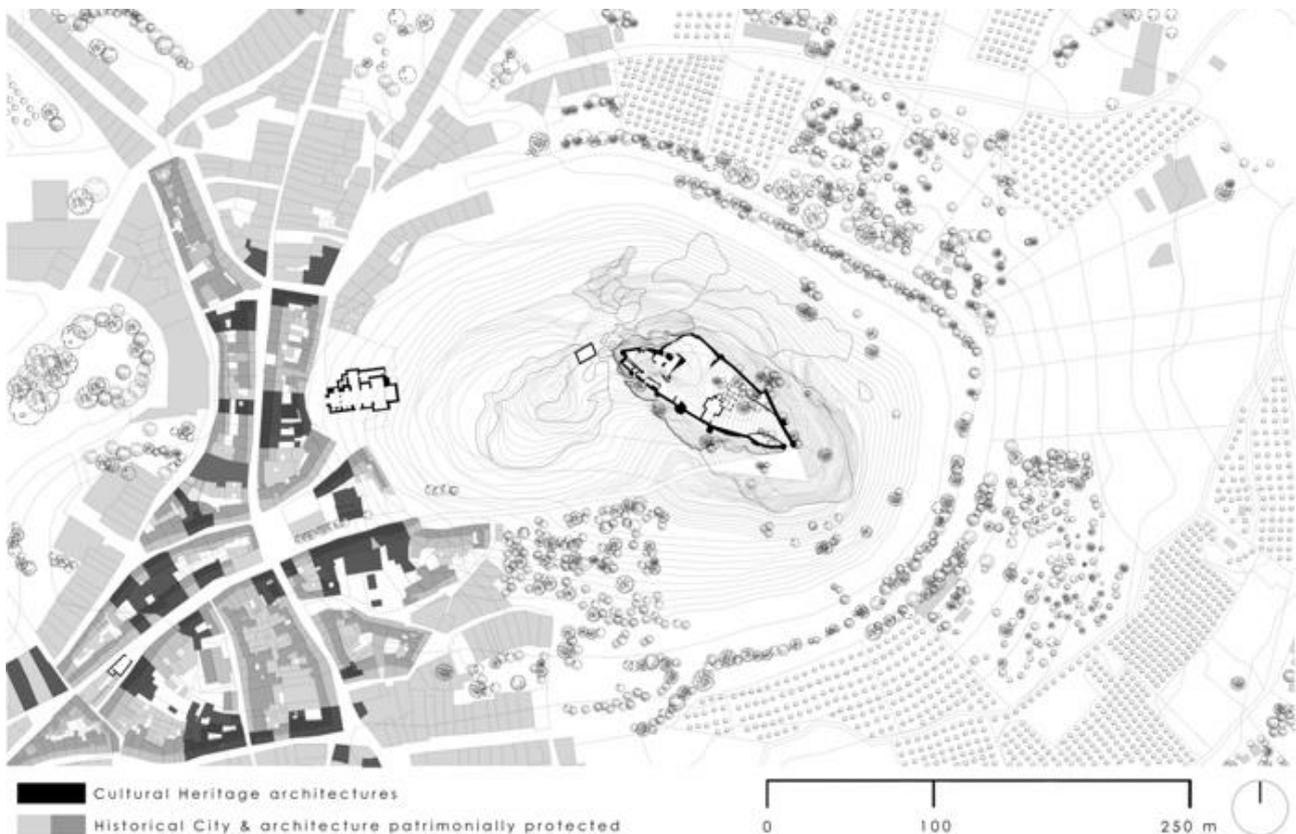


Figure 3: Plan of the patrimonial context of the castle of Carcabuey.

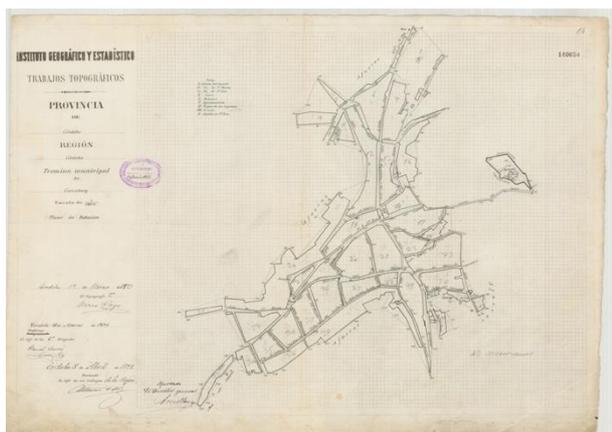


Figure 4: Historical map of Carcabuey. 1893. National Historical Archive.

abandoned. This was a result of a pact between the combatants, following fighting in the area, which demanded the demolition of the fortification walls as a condition of peace, at least until 894.

During the remaining Muslim domination, and until the restoration of Christianity by the Crown of Castile, in the first third of the 13th century, seizures took place in which the neighbouring towns of Priego (1225) and Cabra were taken (1240). However, there are no indications or citations about the ancient settlement of Karkabul, its Castle, or the conquest of both.

It is in the years after these dates that Carcabuey reappears with the name it still bears today. As the domain of order of Calatrava (Nieto, 1979, 472), and, under the Ecclesiastical jurisdiction of the Bishopric of Jaén, the population of Egabra (Qabra / Cabra) disappeared under the new structure of the Cordoban church (Flórez, 1754). In all probability, the Castle was rebuilt and the town was repopulated during the 40s or 50s of the 13th century. The Castle appeared in documents of King Alfonso X, known as the Wise, from the year 1262 (Nieto, 1979, 637), and in a document held in the Cathedral of Cordoba, dated from 6 May 1256, as a district with its own Council, together with other surrounding villages. It is also referenced by several authors (García, A *et al.*, 1976). There are no other references to Carcabuey until 1339 (Rubiera, 1982), when it is noted that it passed into the hands of Sultan Yusuf I, and therefore of Islam. It finally separated from Islam in 1341 (Anonymous, 1787), a period during which the town was uninhabited, the Castle surviving with only a small number of troops to avoid it returning to the hands of Granada. From that year until 1851, it belonged to the Abbey of Alcalá la Real (Rodríguez, 1975). From the 14th century, both the Castle and the town that was reborn within it were definitively Christianised, with evidence of a primitive church dedicated to Saint Mary Magdalene, within the fortified enclosure (Díaz, 1383).

With the disappearance of the Nasrid Kingdom of Granada, the Castle lost its status as a border watchtower and thus began its material decline (Figs. 5 and 6). However, this did not occur until at least the second half of the 16th century, a period during which it was considered a fortress of special interest, for the defence and protection of the Lordship, and the recently created Marquisate of Priego. This is evidenced by an

inventory of the year 1518, which gives an account of the military apparatus kept there (Quintanilla, 1979). It was during the nominal reign of Juana of Castile, when the town's small population began to grow and settled outside the Castle on its southern slope (Osuna, 2002).

During the 17th and 18th centuries, no citations or documentation of the Castle are recorded, only the renovation of the Hermitage of the Virgen del Castillo towards the end of the 18th century, noting a baroque design and a new altarpiece by Francisco Javier de Pedrajas from Priego, dated 1770 (Osuna, 2002). At the beginning of the 20th century, there were a series of repairs to the walls of the Castle, attributed to Rafael Ramírez Arellano in his descriptions of the fortified site (Ramírez, 1982) (Figs. 7 and 8).



Figure 5: Historical engraving of the castle of Carcabuey. 1814, Municipal Historical Archive.

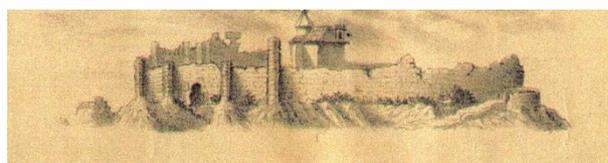


Figure 6: Historical engraving of the castle of Carcabuey. 1877, Municipal Historical Archive.



Figure 7: Historical photograph of the castle of Carcabuey. 1914, Municipal Historical Archive.



Figure 8: Current state of the Carcabuey castle (2022).

3. Methodology

The work carried out has been the support for the drafting of an intervention project divided into several phases of execution. For this reason, the methodology used in the research can be divided into two parts. The first is focused on the documentation, and the second is dedicated to the study of the restoration and enhancement of the Castle.

3.1. Research methodology

The complex material reality of Carcabuey Castle required a particular methodology. When working with heritage institutions, whether archaeological or architectural, their precise and rigorous knowledge is vital to understanding and studying the material assets. In recent decades, historical architectural surveys have given way to other realities, with more precise techniques for two-dimensional (2D) and three-dimensional (3D) representations of the object being studied, and their subsequent interventions.

There are already many works that have used photogrammetry to obtain good prior knowledge of a material asset and for its subsequent dissemination (Ruiz et al., 2017; Grilli et al., 2019; Zlot et al., 2014; Núñez et al., 2012), and identification of the nature and severity of its deterioration (Alshawabkeh, et al., 2020; Pesci et al., 2012). All these methods are highly recommended for the study of superficial and structural pathologies of architectural elements as they have developed models and simulations able to anticipate any response or serious pathological situation. Such is the case found in (Napolitano et al., 2019; Alfio et al., 2022) combining laser scanning and structural modelling.

The use of these techniques has been an important aid in understanding the development of structures with important hidden and diffuse pathologies. They provide precise knowledge of the structural evolution of the building, in-depth knowledge of the construction system used (Andreu et al., 2019, Millán et al., 2021) and aid diagnoses of these pathologies of construction.

The application of this methodology was focussed on Carcabuey Castle, a complex defensive enclosure composed of a series of perimeter lines of towers and walls and the remains of the old quarters and their respective towers. It was declared an Asset of Cultural Interest, according to the decree of 29 June 1985, enjoying the greatest protection contemplated by current Spanish legislation. To date, the fortified enclosure has only had small interventions of greater or lesser depth,

to improve accessibility, as well as some consolidation interventions on some walls of the southwest flank. The lack of an orderly intervention plan has generated a gradual loss of homogeneity in the site, with different criteria applied to the same cultural asset. This, together with the abandonment and lack of use of the complex itself, with the exception of the Virgen del Castillo Hermitage, has contributed to the population's detachment from the Castle, accelerating the degradation of the complex.

To achieve the heritage requalification of the enclosure and the determination of the heritage elements that have survived to this day, as well as their state of conservation, the following stages of the investigation were established:

- Stage 1: Gather all the existing historical documentation on the Carcabuey defensive complex: chronicles, quotations and historical references that can help to understand the different construction stages, as well as its historical transformations and phases of settlement and abandonment.
- Stage 2: Carry out a new georeferencing, photogrammetric survey and 3D laser scanning of the entire fortified area. It was possible to build a network of geodesic points, a cloud of points, and a 3D model that allowed millimetre definition measurements. These enabled an exhaustive analysis of the different superficial and structural pathologies that the Castle has been developing over the last centuries, as well as the production of a planimetric set of the whole heritage asset (Figs. 9 and 10).



Figure 9: Data collection in situ.



Figure 10: 3D model of the castle with the point cloud and mapping of high-resolution photos.

- Stage 3: Analyse the Castle by printing the 3D scan at two scales: One of the whole complex, and another of particular elements, to be able to analyse all the construction phases and material incursions that the Castle has had throughout its history. This enabled the determination of bonds, stone morphologies, brick infills and original elements, as well as a profound analyse of the material layers that make up the wall sections. These are composed mostly of a rammed earth interior, lined on both sides with limestone masonry from the quarries of the Subbetica of Cordoba, and material brought from previous constructions (Figs. 11 and 12).
- Stage 4: Study the current topography and the settlement of the enclosure within its natural terrain by making a territorial model that includes the heritage asset in the orographic context of the hill upon which it stands. This model also assists in foreseeing possible points of settlement, runoff and future washings of the fillings that can cause structural pathologies in the walls and towers that directly rest upon the hill.
- Stage 5: Use the 3D printed physical medium to make a study and in-depth analysis of all the superficial and structural pathologies from which the Castle currently suffers, supported by the photogrammetric surveys carried out and the partial impressions of each part of the protected complex. This support material will provide the necessary rigor when documenting and planning the necessary interventions to alleviate all existing pathologies, as well as to anticipate others that are still very difficult to record and delimit due to their degree of development (Fig. 13).

3.2. Data collection

The data collection process was separated into two areas, obtaining data in situ, and obtaining data from the analysis of results:

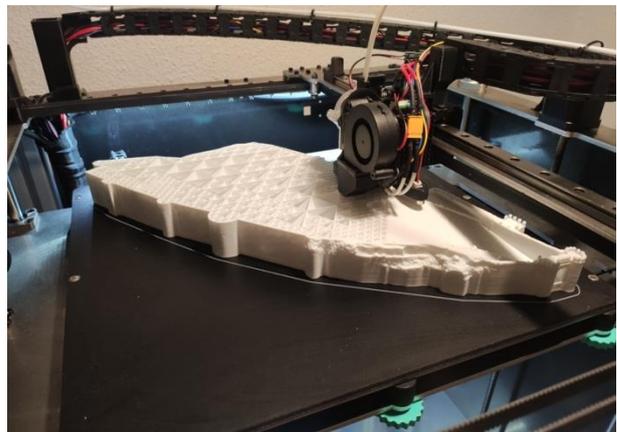
Field work:

The data collection and survey work on the site were firstly carried out using Global Navigation Satellite System (GNSS) georeferencing techniques (Jiménez *et al.*, 2010) and laser scanning (Arcifa *et al.*, 2010). Subsequently, vectorization and digital photogrammetry were performed to obtain all the necessary documentation in true magnitude and with real measurements, and always with precise quality for subsequent analysis. Although the use of GNSS could introduce inaccuracies, points have been taken with caution for their geolocation, including reflectorless laser measurements (Fig. 14). The survey work was carried out using convergent photogrammetry, with two drones (Ulvi, 2021) (a Phantom and the other a Mavic mini). The survey was completed with 3D modelling (Giuffrida *et al.*, 2022; Scopigno, 2012; García *et al.*, 2021), made from a 3D point cloud to obtain the orthophotos.

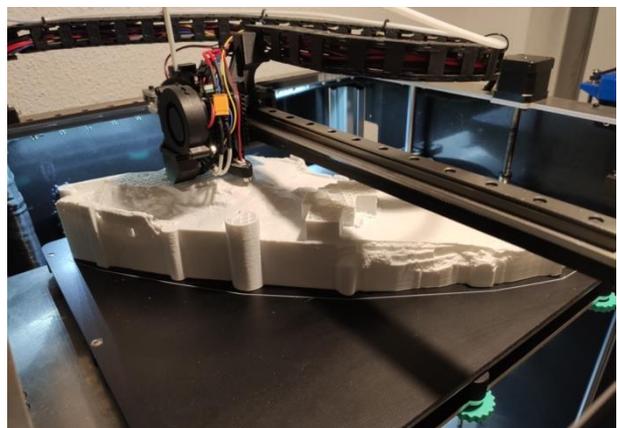
The orthophotos obtained, and especially the 3D printings have provided the pertinent keys to elaborate the subsequent study of pathologies and construction phases (Millán, 2021; Aguirre *et al.*, 2020; Martín *et al.*, 2018).



Figure 11: Photograph of the archaeological excavation for the documentation of construction elements.



(a)



(b)

Figure 12: Photographs when the first model was being printed in resin with an experimental high-resolution printer: a) View of the lightened grid of the model and b) impression of details.

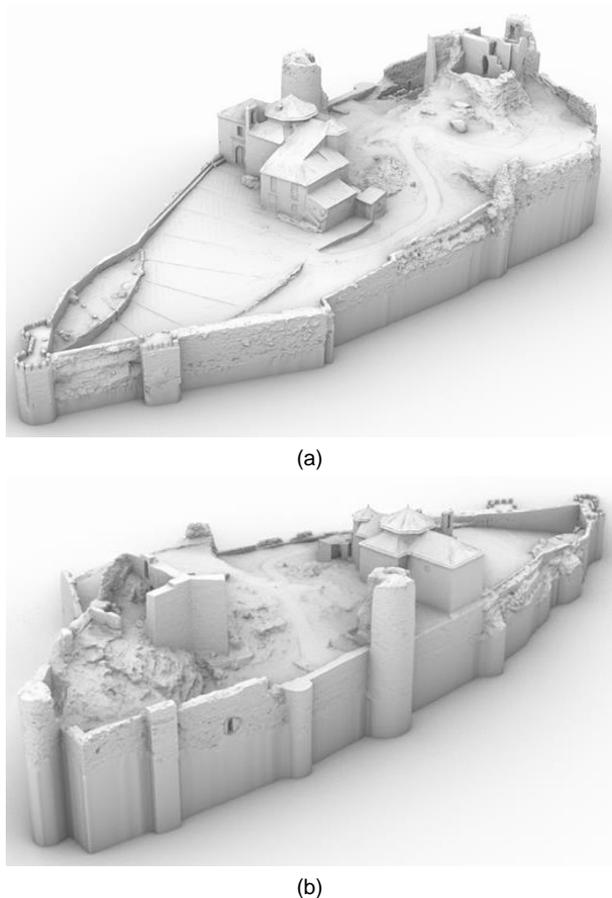


Figure 13: Digital model ready to be printed without photography assignment: a) north view; b) south view.

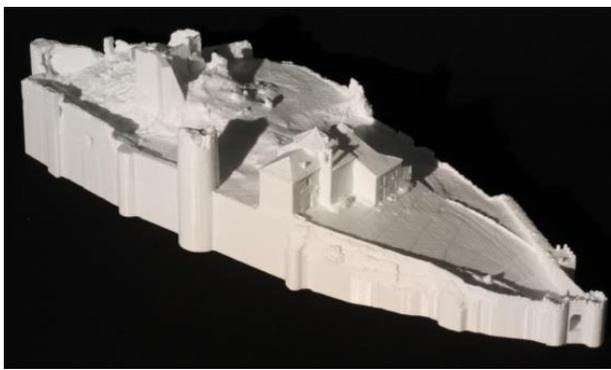


Figure 14: Initial 3D model of the castle of Carcabuey printed in high-resolution for the study of pathologies.

For the data acquisition, the following equipment and software was used: Leica TCR 407 total station; Topcal 21 software, TCP v. 4 software; GPS Trimble 5800; Canon 80D (24.2 MP) calibrated camera; Canon G7X (20.1 MP); DJI Phantom 4 Pro; DJI GS Pro flight programming software, and Agisoft Metashape v. 1.7 software.

Laboratory work:

It was developed with the idea of integrating two conceptual analyses in the same work: the topographic study of the land (Fig. 15) and the heritage unit of the Castle itself (Fig. 16), two elements of different natures but which, in combination constitute the majority of the heritage values of the complex. The model of the hill was made with pressed paper pulp at a scale of 1:250,

following the contour lines obtained from the survey with the georeferencing of the entire natural complex. The model of the fortified enclosure, devoid of colour for maximum contrast, was superimposed on this model of the hill, with the maximum level of detail.

Once processed by Rhinoceros 3D software, the application of an edge closure treatment, elimination of the null vertices and all those elements that hindered the global understanding of the element (luminaires, vegetation at height, etc.), the polygonal mesh was finally closed and, together with the PrusaSlicer software, was left ready for subsequent transfer to the printing machine. The printer used for the global model of the Castle was a Fused Deposition Modeling (FDM) printer CoreXY, assembled expressly and tailored for this work, with dimensions of 32x32x40 centimetres, using PLA (Polylactic Acid) material (plastic of vegetable origin, composed of corn starch and sugar cane), manufactured in Jaen (Andalusia, Spain). The printing process took over 48 h, finally removing impurities and excess pieces with a specifically produced fine-toothed brass brush.

This relationship of contrasts and external appearances, allowed a physical and global reading of the heritage entity to be obtained with a very high level of rigour, and provided the necessary keys to order the actions to be carried out, while discerning the possible flaws in the wall structures in direct contact with the natural karstic terrain.

In addition to the 1:250 scale model of the hill and Castle complex, and after an initial analysis of the casuistry and general structuring of the pathologies and construction phases observed, a series of partial models of various specific parts of the fortress were made at a 1:25 scale. In order to make this model on a larger scale, the model was worked using vector modelling software, eliminating inaccuracies obtained in the scan. After that, the points were selected where the greatest number of general problems converged, and where the entire construction sequence could be found repeated throughout the enclosure (Fig. 16).

Printing this section on a large scale has allowed a repeated pattern of pathology to be detected throughout the Castle (Fig. 17). The first to be detected were those due to the general washing of mortar and the volumetric losses of the capping, with similar rates in all the joints between walls and towers. There were cracks due to material joints between elements of a different nature (towers and adjoining walls) and, due to contact between different construction phases, with different compositions of stones and mortars.

4. Results

To carry out this work, a workstation was required mainly for image processing and volumetric modelling. Although the entire procedure took two years from the beginning of the data collection campaign, processing of the point cloud required most of the time. Sometimes low resolution was required to obtain faster volume results, then, once verified, high-resolution was allocated.

The point cloud showed the different types of ashlar, which are coarser in the lower part and better cut above. It also showed the different construction periods, from the Almohad mud wall, the first stone masonry as a protection of the mud wall, or the most recent

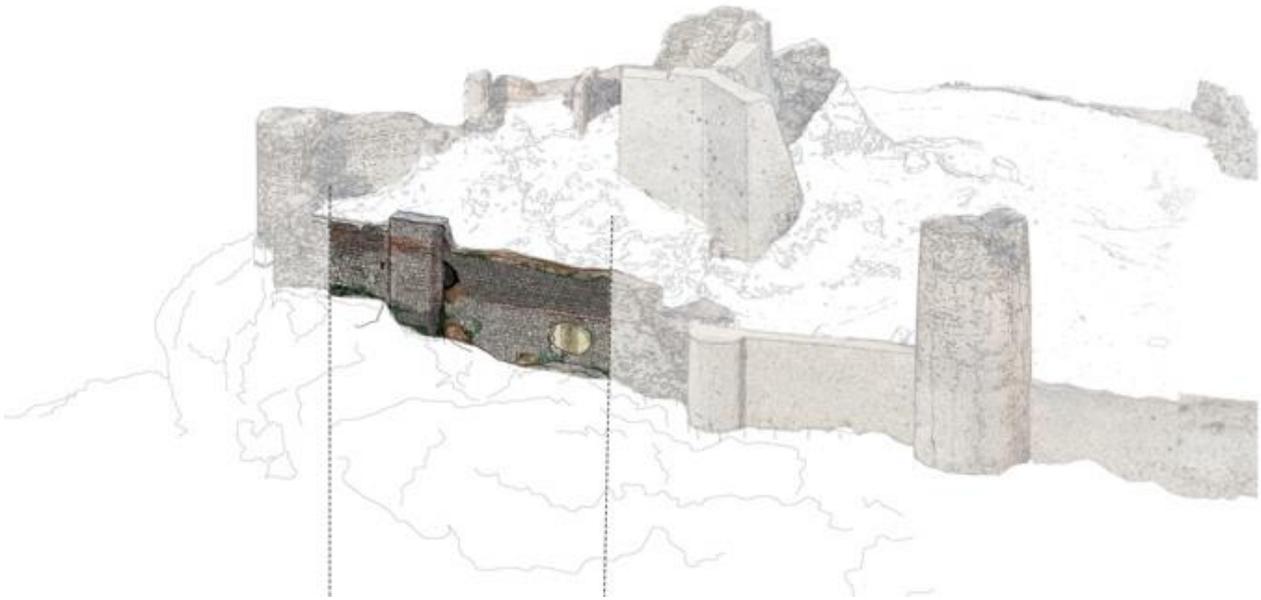


Figure 15: 3D volumetry with the study of pathologies and the location of the study area.



Figure 16: Orthophotos for the location of the study area in detail (plan and elevation).



(a)



(b)

Figure 17: High-resolution 3D printing :a) perspective view; b) front view.

interventions, all with the simple analysis of the stereotomy of the stone or granulometric analysis of the mortars.

Given the high level of detail, it has been possible to analyse the material and structural pathologies. The most notable thing has been to detect active cracks and measure their evolution. Some are of seasonal origin (the Castle is based on calcarenite limestone rock), and others are pathology based which will now be monitored with sensor systems and controlled.

High resolution orthophotographs (1 mm/pixel) can be extracted. These results allowed moving from printing on paper at a normal survey scale, to post-production with 3D modelling software. This permitted the move to 3D printing, with a millimetre level of detail for the study of pathologies, stone stereotomy or material granulometry. With various models at various scales, it was possible to analyse not only the hypothesis of the evolution of the monument, but also the actual material study of what remains (Fig. 18).

5. Discussion

The complex material reality that currently configures the different structures of the walled enclosure and Castle required a detailed study of which elements were reconstructions (anastyloses) or simply repairs. Given the wide spectrum of types of ashlar, masonry, lime mortars and plasters, a system was required which would allow the evaluation of different periods and incursions to determine what was original and what was a later intervention.

High resolution 3D printing has been a valid tool that has provided many certainties and which has also opened up new questions. Currently, questions about the planning of the interior of the walled enclosure have arisen, as the study provided levels of pavements much lower than those currently assumed. Sampling was carried out by the archaeology team which confirmed the proposed hypothesis (Figs. 19 and 20).



Figure 18: Orthophoto of the elevation of the detail of the study.

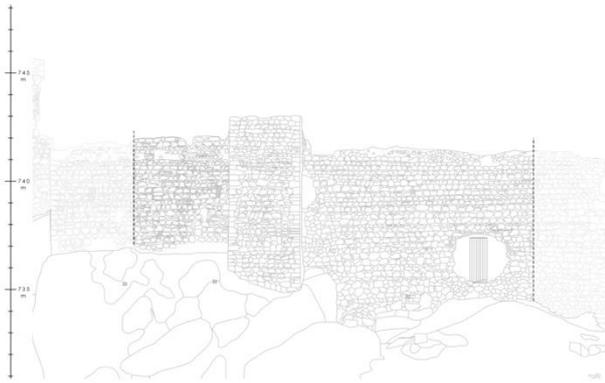


Figure 19: Detailed drawing of each of the elements that make up the chosen wall fragment. First plane for later study of material pathologies.

The results obtained from both the point cloud and the 3D printing have corroborated most of the hypotheses raised about the various construction phases of the complex. The interpretation of the data obtained has allowed classification of the types of ashlar and mortars according to their stereotomy, this was decisive in order to classify the different construction phases. The use of mud walls which seemed relegated exclusively to the Almohad period, has been seen not to be the case, and Christian phases with this type of construction system

have been verified. Similarly, the reinforcements of amorphous masonry did not correspond only to a defensive issue against artillery, but rather a reinforcement operation in the lower levels of the walled enclosure and Castle (Fig. 21). The results obtained from the orthophotos, together with the dense point cloud, show a more complex construction process than previously thought.

In carrying out the detailed printing of various fragments of the heritage complex in a neutral material, the geometry and order that articulates the construction can be observed more clearly. The element when devoid of materiality, colour, place and immediate environment, favours an aseptic reading focused on its organoleptic composition. Thus, for example, it can be observed how some ashlar do not correspond to the courses, or how their volumetry is different from that of the original construction pattern. In this way all the additions have been identified (Fig. 22). The original lime mortars have undergone a process of natural degradation, losing volume in the pointing of the masonry. With the use of cement mortar, the opposite has occurred. The hardness of the material has allowed them to follow a specific pattern of composition of the pointing flush with the ashlar. In this way, although it was complex to read which mortars were from one era or another, with the investigation of their volumetry, it has been possible to date them.

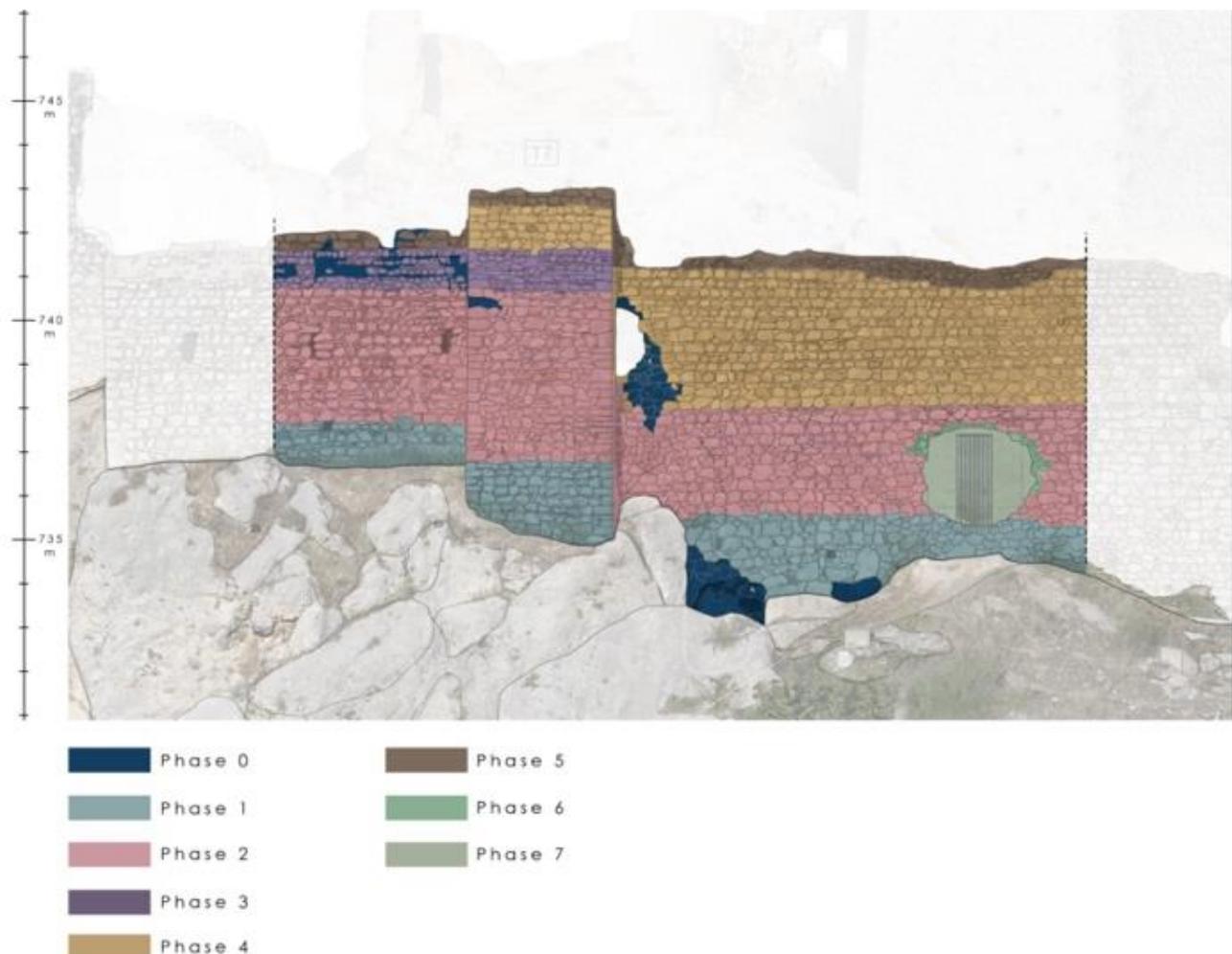


Figure 20: Study of the construction phases of the detail fragment of the wall studied from the model printed in high resolution by the stereotomy of the construction.

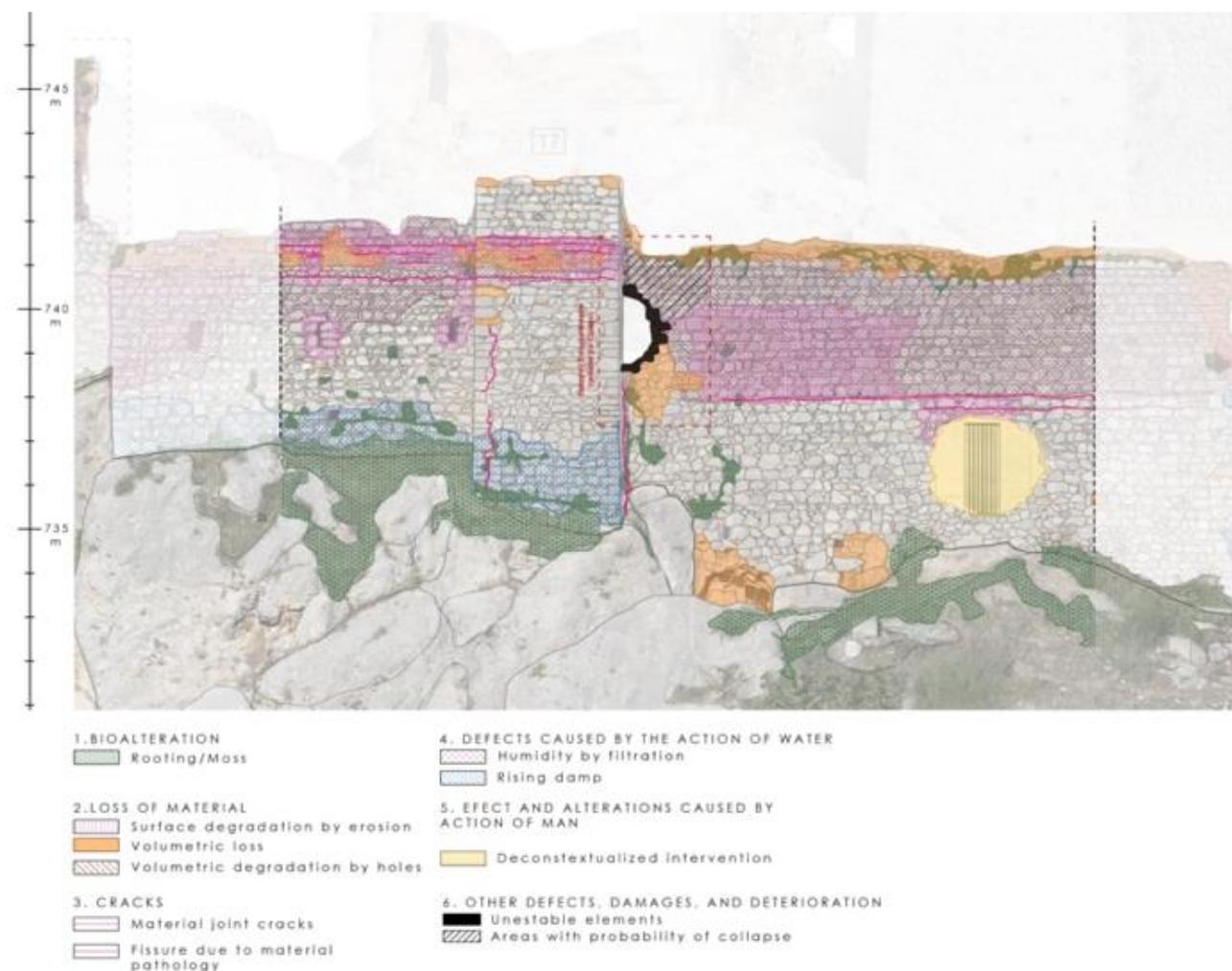


Figure 21: Study of material pathologies of the detail fragment of the wall studied from the model printed in high-resolution by the stereotomy of the construction.

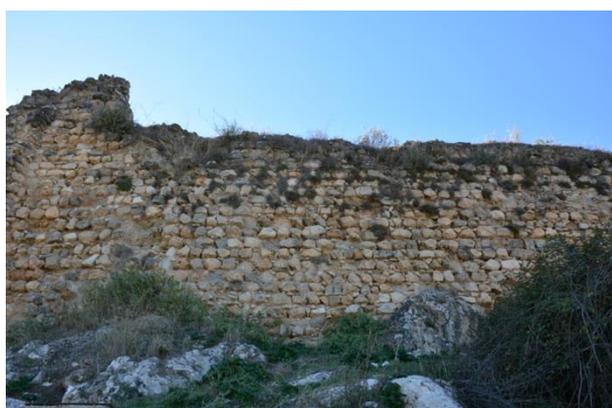


Figure 22: Photograph of the current state in detail of the pathologies suffered by the castle.

According to the volumes, textures and pathologies, the current enclosure of the Castle has an infilled level, currently walkable at the approximate level of the roof of buildings located within the walled enclosure.

This shows that the Castle had two clearly differentiated areas: the interior area of the Castle with the buildings that have remained until today, and the outer plaza area that was occupied by some collapsed buildings, possibly linked to the domestic use of the primitive area. The

study, based on the model, has allowed archaeological surveys to be made which have verified this hypothesis, opening a new horizon for future interventions.

One of the singular elements of the greatest controversy has also been confronted in the investigation. These are the Almohad mud walls. They had always been considered as walls protected, in later times, by limestone masonry. After the analysis of the wall coverings carried out with the point cloud and 3D printing, it has been possible to verify that different tothing stones were from different periods, so the process was not so much for defence as for the conservation of the building itself. Thus, in the interior, it can be observed how the mud walls seen in current times have been preserved, and how, on the façade, some of them have been covered with different types of masonry at different times.

The research leaves several development options for future studies. One of them is the cistern. As it is apparently out of sync with the masonry studied from the Almohad and medieval times.

6. Conclusions

Throughout history, Carcabuey Castle, given its genesis as a building for border defence, has suffered the logical vicissitudes of a place deprived of permanent vocation

and solely thought of for defensive purposes. The conclusions have been defined at three levels: the pathological and material; the architectural and archaeological information on what remains; and, the future actions for a correct value enhancement.

Firstly, the study of the different periods of ruin and decontextualised interventions show a complex reality and a set of structures difficult to understand as a whole. The documentation generated from the digitisation and development of the 3D model, both physical and digital, have allowed us to study a diagnosis of the pathologies currently suffered by the heritage monument and archaeological remains, as well as a detailed study of the construction phases. These data reveal the numerous incursions and abandonments that the complex has had, as well as the various reconstruction works. On the contrary, no large invasive interventions or interventions outside the heritage complex have been detected. The manufacture of the different printed models has helped us to understand the evolution of the topography and the monument.

Secondly, after clarifying the poor state of conservation of the Castle, an exhaustive analysis of the evolution of the pathologies was carried out, anticipating the different, most urgent interventions, all demonstrated by the 3D models. After the study of the materials and the

stereotomy of the masonry, it was possible to determine the previous state of the structures as well as the architectural evolution of the archaeological remains. With the laser scanning and subsequent modelling, it has been possible to determine the advancement of many of the structural cracks and determine which are in a serious state and which are not.

Finally, a detailed study of future actions was carried out to gradually recover the physical and heritage stability of the buildings. All these actions are included in the complete building protection document. With the certainties obtained in the investigation summarised here, the protection document will enable future interventions to be carried out following a united and orderly guideline. After having detected and documented all the archaeological levels, it has been possible to accurately assess the magnitude of the different actions for the conservation of the heritage complex.

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