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Structural assessment of the Roman wall and vaults of the cloister of Tarragona Cathedral

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ABSTRACT

The Mediterranean city of Tarragona was a capital city in Roman times. Nowadays, the remains of the ancient constructions coexist with many subsequent buildings. This is the case of the Gothic Cathedral cloister, whose walls partially take advantage of the remains of the *temenos*'s wall. This paper focuses on the assessment of that unique overlapping of construction phases. The investigation is performed through an unprecedented topographical survey by means of massive data capture techniques. This information is the basis for the mechanical assessment of the equilibrium conditions of the northern corner of the gallery, which is performed on the well-known theoretical framework of limit analysis by means of thrust lines. The study allowed to enhance the understanding about the equilibrium conditions and the deformation processes of the gallery masonry elements, where the mechanical relation between the Roman and Gothic walls is essential.

1. Introduction

The city of Tarragona is located at the Mediterranean coast of Catalunya (Spain). Known as Tarraco, it was a capital city in Roman times and until eighth century. The city lived a second period of splendour which began at the end of eleventh century. Then the construction of the Gothic Cathedral started at the location of the temenos, where it was built the temple dedicated to Emperor Augustus.

Medieval builders took advantage of the existence of the remains of Roman times, and adapted their project to the location. Thus, both Roman and Gothic structures coexisted, defining a structural continuum with mechanical interaction. It is one of several singularities of the Cathedral enclosure, and its current management and preservation are a challenge of the present times.

The Roman wall of the temenos was 0.90 m thick and 12 m high, and its structural role was limited to supporting the porch and its own weight. Subsequently, a medieval vaulted gallery was added, together with a building known as the 'Casa dels Canonges' (Canons' House). At the same time, when the construction of the perimeter gallery of the cloister was planned, it took into account the existence of the Roman wall, which worked as a lateral reinforcement to support the thrusts of the vaults.

This situation raises several questions: How did the additions in later periods alter the Roman wall? What is the mechanical behaviour of the cloister's gallery?, Are the observed geometric deviations relevant?, Could the gallery collapse, either totally or partially? There is also a desire and need to deepen knowledge of a structure that is over 2000 years old.

Heritage documentation techniques are currently very varied, and international conservation and restoration specialists recommend undertaking surveys accurately and rigorously [1–3]. The use of massive data capture techniques (MDC), such as terrestrial laser scanning and digital photogrammetry, enable to obtain highly accurate topographic bases in a short period of time. This is particularly relevant in the assessment of historic buildings, as it is difficult to perform surveys with other techniques.

Numerous investigations have addressed during the last years the assessment of masonry constructions using these techniques. Beyond the most obvious applications for surveying and modelling complex structures [4,5], it is possible to study in depth the displacements suffered by the masonry [6–8]. In addition, these 3D surveys can be the base to perform structural analysis using techniques such as finite elements [9], or limit analysis by means of thrust lines. The theory is well developed nowadays, and is a sound procedure for assessing the stability of masonry structures [10–13]. These techniques have been used for masonry buildings [14–16] and other arched structures, such as masonry bridges [17–19].

The paper deals with the geometric survey and the mechanical

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assessment of this unique overlapping of construction phases, where Roman and Medieval masonry works together. The study is focused on the northern corner of the cloister, and the new topographical documentation of the cloister is unprecedented, as well as the structural analysis of equilibrium conditions. Most studies about this location are focused on artistic or historical matters [20]. Present investigation goes one-step beyond common references about the cloister of Tarragona, focusing on the masonry construction stability.

1.1. Brief historical background of Tarraco

A cathedral is a key element in many cities as it is often the community's main religious building and has a place in a city's history. In Tarragona, this symbolic role is enhanced by the topographical situation of the cathedral and the historical relevance of the city. Consequently, Tarragona Cathedral is a singular masterpiece. It has a great scenographic effect since it is located in the highest part of the city, and defines the skyline. It could be said that it is the city of Tarragona's reason for being and existing [21].

The diocese of Tarragona can be considered one of the oldest documented. There is evidence of the life and martyrdom of Saint Fructuous, who was bishop in 249 BCE and was considered the first saint of the Iberian Peninsula. Tarraco was a capital city in Roman times. It was quickly transformed into an ecclesiastical metropolis that was one of the important religious capital cities of the Peninsula. This position was lost after the Islamic invasion of 711 BCE, especially when the bishop Saint Prosper fled to Italy [22].

In 1089, Pope Urban II gave the mitre of Tarragona to the bishop of Vic, Seniofred de Lluçà, and encouraged the Count of Barcelona to reconquer the city, which was still under Islamic control. Count Ramón Berenguer III wanted to recover the ecclesiastical metropolis of Tarragona to gain independence from Carcassonne and break with the political dependence on the French Crown. He recovered the city and the bishopric in 1091. Then, the construction of the current Cathedral began [23,24].

It could be said that the city was reborn due to the will of the Pope and the need to recover the diocese of Tarragona. This led to the construction of the cathedral, around which the new city was built. The new medieval city occupied the site of the ancient Roman Tarraco and used its visible remains. This is especially true in the case of the Cathedral, since it is placed in exactly the same location as the Temple of Augustus, as ascertained in recent archaeological works [25] (Fig. 1).

Most of the Roman architectural structures from the area of worship dedicated to Emperor Augustus were still standing in the twelfth century. They included the temple, the temenos and the surrounding monumental portico, which is now known to have been 115 m in length, with an average height of 12 m.

Its monumental character and state of preservation determined the planning of the medieval Cathedral enclosure. It affected the specific location of the temple and the anomalous position of the cloister [26] (Fig. 1), which is located between the western transept and the apse, when its natural position would be at the feet of the eastern transept. This position was chosen due to the remains of the northwest corner of the enclosing wall of the temenos, which currently coincides exactly with the corner of the cloister.

2. Methods and theoretical framework

The study was based on two main procedures. First, topographical documentation provided relevant geometric information about the shape and deformations suffered by the gallery and the perimeter wall. Second, the structural assessment focused on the mechanical behaviour of the buttressing system and the equilibrium conditions of the masonry.

Metric information was obtained by geomatic procedures, and was then used to perform the structural analysis, based on the premise that the Roman wall was built with large stone blocks, on which other structures were built.

The masonry structure's equilibrium conditions were assessed using the theoretical framework of limit analysis, through the layout of thrust lines. It was established that the masonry has infinite compressive strength, no tensile strength, and sliding of the blocks is impossible. These assumptions are the basis of the lower bound theorem: if a combination of hypotheses can be found that result in a line of thrusts contained in the masonry, the structure will be stable and will not collapse. Furthermore, the position of the thrust line can be used to evaluate the safety of the structure.

The analysis of the equilibrium of the cloister's vaults was based on the premise that the structure was in good condition, since there was no severe pathology to indicate otherwise. Nevertheless, a certain loss of verticality was observed in some sections of the cloister's inner wall, which indicates that there was movement at some point. The cloister is a low-rise structure without large loads; the kind of structure that tends to be stable. In addition, the pointed shapes of the vaults and arches need less buttressing, since the horizontal thrust values tend to be lower.

Thus, the analytical procedure consisted of determining the thrust caused by the vaults and assessing the capacity of the buttresses to support this thrust. The closer the line of thrust to the limit of the section, the less safety margin the structure will have. This provides information about the equilibrium conditions governing the design of the structure.

3. Documentation techniques

Heritage documentation techniques are currently very varied, and international conservation and restoration specialists recommend undertaking surveys accurately and rigorously [1–3]. The graphic documentation of heritage can be performed in many ways: by sketching, through photographs in combination with measurements made with tape measures or hand-held laser distance measures, or rigorously by topographic and photogrammetric techniques. Due to their scope and rigour, the use of photogrammetric procedures has been prominent. In the last decade, photogrammetry has been used to supplement or replace terrestrial laser scanning thanks to significant advances like Structure-from- Motion (SfM). Usually, several of these techniques are used at the same time to supplement the documentation in the survey, but not all of them are valid procedures to obtain appropriate 3D model for a structural assessment.

In many cases, the possibility of computing in an accurate way is due to the availability of quality 3d information. Furthermore, the runtime of the procedure must be taken into account, as well as the provided information, the financial cost of the work, and the accuracy (Table 1). Massive data capture techniques (terrestrial laser scanning and digital photogrammetry) allow fast results to be obtained in the field, and the entire process of exploitation of results is performed in the office.

Current surveying technologies play an important role in the process of increasing awareness of cultural heritage. They enable us to analyse and evaluate the geometry of monuments, and to discover their state of preservation and aesthetic properties [27].

From an analytical point of view, architectural heritage structures need to be calculated and assessed by mathematical models. To achieve this, we need to know the geometry in detail, as well as the displacements and damages suffered over time. Approximate or schematic geometries are not sufficient in many cases.

The metric information that is obtained can be used by many professionals who work in the fields of restoration and rehabilitation of monuments. One application is described in [28], where it is used to examine in detail the cracks, deformation, collapse and geometry of Alcántara Bridge and the Cathedral of Coria. Another interesting study is the use of terrestrial laser scanning (TLS) to determine differential