Condition Assessment of an Early Thin Reinforced Concrete Vaulted System

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Abstract:

For the analysis and conservation of architectural heritage a multi-disciplinary approach is required. In the specific case of early concrete buildings, survey and experimental investigations constitute a fundamental source of information for verifying the actual structural behavior and the residual safety levels.

This paper reports the direct experience acquired from an extensive experimental campaign conducted on the Paraboloide in Casale Monferrato. The study aims to be an example of how condition assessment of the structural heritage of the early 1900s, with an apparently simple geometric shape and composition, can actually contribute in understanding hidden structural complexity. Moreover, this work may provide useful information to researchers and practitioners who are approaching this specific structural typology (e.g., the industrial heritage represented by parabolic concrete silos). In more details, results are presented regarding the in-situ investigations, and the laboratory tests carried out to analyze the mechanical performance inherent to both (i) local aspects of the structure, such as the quality of the materials and connections, and (ii) global aspects, such as the modal response of the structure. Furthermore, considerations are made on the results of the experimental campaign, also through the corroboration of numerical models.

Keywords:

Reinforced concrete heritage; structural condition assessment; XX century architecture; non-destructive testing; industrial heritage.

Competing interest:

In accordance with Taylor & Francis policy and my ethical obligation as a researcher, I am reporting that I have no *competing interest* to declare.

1. Introduction

The conservation of the architectural heritage of the 20th century is the latest and perhaps one of the most challenging frontiers in the field of preservation. This is due to a variety of factors that ascribe to different reasons. Nowadays, much of the world's heritage built in that period is unrecognized or undervalued and is thus at risk and in need of analysis and protection. While the experts of the period were very aware of those values [1] [2], the lack of recognition of their cultural role has often led along the years to abandonment, lack of maintenance, or even demolitions or alterations that could change the original architecture.

Bridges, industrial buildings, skyscrapers, or sporting facilities are just a portion of a heritage that is temporally very close to us, but that at the same time is witness and depository of the huge technical and social progress of the past century [3].

The present use of this particular heritage requires a proper design of maintenance or strengthening interventions that take into account the necessity of fulfilling the new functions to host, maintaining an adequate level of structural performance, while preserving the spirit of the original characters of this particular heritage.

In fact, most of the masterpieces built in this period are unique examples of their types, whose characteristics sometimes prevent a general classification and thus representing a source of weakness and vulnerability. Furthermore, the materials and construction techniques employed present serious durability issues. Modern materials, such as reinforced concrete, were extensively employed during the 20th century, together with other experimental construction systems that, in most cases, showed their weaknesses over the years. Moreover, contrary to what happens with traditional historic buildings, the effects of material aging such as the weathering (patina) in modern buildings may ruin the perception originally intended by the designer [4], or it may even cause strength loss and dangerous deteriorations of the structural elements.

Currently, the definition of protocols about the principles of conservation that should be applied to 20th century sites and places is in progress and enriched periodically based on first-hand experience by researchers, practitioners, and institutions [2] [5] [6].

When dealing with 20th century architectural heritage, it is fundamental to assess its significance. This is particularly true in case of minor architecture or in case of a poor state of preservation, since it helps to plan the best strategies for both its assessment and conservation plan. As highlighted in the Madrid Document [6], cultural significance may rest in its tangible attributes (e.g., form and spatial relationships; color schemes and cultural plantings; construction systems, fabric, technical equipment, as well as aesthetic qualities), or in its intangible values, usually connected to its use, historical, social, scientific or spiritual associations, or even evidence of creative genius. In general, assessing the significance of a building is the first step of its protection, and it helps in recognizing the elements of value.

A solid starting point in the preservation is constituted by the process of anamnesis [7], especially in the case both for a reliable assessment of current safety and for the choice of effective improvement measures.

The former clinker warehouse, also known as the “Paraboloide” of Casale Monferrato (in Piedmont, Italy) is part of this endangered heritage. The Paraboloide was built in 1922 as a clinker warehouse for the Italcementi factory, and according to [8] it represents the first example in Italy of a construction typology that would have spread throughout the whole country. The rehabilitation of the building is under evaluation by the Municipality of Casale Monferrato for a possible transformation into a “cultural pole”.

The present paper reports the structural condition assessment and actions carried out on the Paraboloide in Casale Monferrato. In fact, in order to evaluate the current state of the structure and to assess its compatibility with the foreseen uses, the building was investigated by means of both mechanical and dynamic tests. This thorough testing campaign is the starting point for the preservation and rehabilitation guidelines of this daring structure.

The paper starts by identifying the significance of the building (Section 2), which is listed both for the cultural value it carries for being a witness of the industrial heritage of the Casale Monferrato area. Section 3 reports the description of the building and its current state of conservation. Section 4 describes the structural investigations and testing campaign carried out for assessing the mechanical properties of the structural elements and materials, which are fundamental information for the corroboration of the numerical model useful for the global structural assessment of the building.

The paper then continues, in Section 5, where the numerical model is corroborated on the basis of the behavior observed during the tests. The underlying goal is to analyze the health condition of the Paraboloide, as well as understanding his actual structural behavior. Finally, in Section 6, the discussion of the results is reported, and the main conclusions are outlined.

2. Identifying the values of the industrial heritage of the early XX century

2.1. Parabolic vaulted systems in concrete: features and elements of an industrial heritage

Structures presenting a large parabolic vault in concrete represent an architectural typology commonly used for decades. This arched geometric shape is one of the most representative examples of synthesis between the structural optimization and the formal research behind the application of reinforced concrete in the roofing of industrial spaces since the beginning of the 20th century [9]. With the introduction of reinforced concrete, in the second half of the 19th century, it became possible to build large roofing systems without the use of intermediate supports, which led to the use of the new construction technique in a wide variety of applications, such as hangars, theatres, swimming pools, religious and industrial buildings, and many other solutions.

Parabolic-covered warehouses are horizontal silos born as a solution to the industry's needs to process or store large quantities of raw materials or products. A parabolic cylindrical shell constituted the silos with a parabola as a directrix. This form was adopted because, contrary to traditional buildings, it allowed the storage of a larger amount of materials considering the same area covered. The structural configuration generated by the parabolic form, in fact, permits a unified interior space of considerable height, without intermediate floors, ensuring the large spaces needed for storage or the manufacturing of materials. Moreover, it was especially suited to the storage of raw materials in powder or granules, which accumulation would cause significant thrusts along the load-bearing walls; this would have forced a costly strengthening of the structures or to limit the quantity of stored material. In both cases, traditional buildings represented an economic disadvantage compared to parabolic silos. But these were not the only aspects to consider; in fact, the shape allowed more efficient management of storing and collection operations. A gallery (or catwalk) is generally positioned along the key of the vault, usually housing a conveyor belt that would transport the product, even directly from the production plants, and distribute it along the length of the warehouse. The hoppers at the base of the silo would then collect the falling material. This scheme was extremely successful, and it would spread throughout the country in the following decades, especially for industrial facilities buildings [8].

The cylindrical vaulted roof of the parabolic silo is supported by parabolic arches and/or ribs, usually designed adopting a three hinges statically determinate scheme. Depending on the structural configuration, the two supporting hinges can be found at the level of the foundations or at the level of the arch impost if the arches rise above special lateral buttresses, while the third hinge is located in the keystone. The scheme was preferred instead of the single or double hinges ones, to avoid the arising of internal stresses potentially caused by differential settlements of the foundations. At the level of the foundation were usually placed steel or reinforced concrete tie-rods to counteract the thrust of the arches.

Other characteristic elements of parabolic warehouses are the towers and cantilever roofing systems, which sheltered the arrival of the material through rail tracks or trucks.

In Italy, there are many examples of parabolic roofed warehouses, most of which are now abandoned; the census work of Modica and Santarella [8], counted 85 warehouses of this kind that survived demolition, and which construction spread especially between the twenties and seventies of the 20th century, during the period of maximum industrial development of Italy, and have become part of the industrial heritage of the country.

A thorough typological classification of parabolic silos by cataloging the various configurations of their main elements (Figure 1) was carried out by [8], and it represented a first and valuable step for the enhancement and recognition of this large heritage that has survived thanks to the local listing.

Although the phenomenon of silos with a parabolic coverage finds its origin in the Italian context, starting from the thirties of the 20th century, their construction interested many other European countries. Modica and Santarella [8] underline that the construction of the first silos outside Italy started in countries that were culturally closer to Italy and were also historically characterized by the use of reinforced concrete in industrial construction, namely Spain, France, and Belgium. The first parabolic silos built outside Italy were built thanks to the technical contribution of the Montecatini and the Ammonia Casale companies, who owned two different patents.

Regarding parabolic silos, many of them are nowadays completely abandoned, their value is poorly recognized, and several of them have been demolished. Currently, the awareness of the value as a heritage of these objects is still under discussion. Usually, it strongly depends on the will of a local community to preserve a recent past that had characterized an area. An example is the parabolic silo for stocking sugar in Liverpool, designed by Tate and Lyle's Engineering Department between 1955-57; the building is currently listed as a legacy of the city; however, it is still abandoned. Some of these artifacts are recognized as architectural and engineering works of the highest value, and many of them have been protected. However, only a few have been rehabilitated and re-used with a new function (a fine example is represented by the Embarcadero of Caceres in Spain, rehabilitated with a project by Aldea Moret).

***Figure 1: Scheme reporting the classification of the parabolic silos typologies gathered and classified by** [8]**.*

2.2. An industrial heritage of concrete manufacturing

The town of Casale Monferrato (in Piedmont, Italy), see Figure 2, has long been linked to the cement production industry, from the extraction of raw materials to their refining. The lime in the area has been extracted since ancient times, during the 2nd century AD by the Romans, and the mining of the materials continued during the Middle Ages. Although it is only with the industrial revolution, in the 19th century, that cement manufacturing had a strong development. The industry of concrete production started to develop rapidly in the small town and soon became the main industrial activity of the area. During the first decade of the XX century, the Italian cement sector, therefore, went through a phase of intense expansion. In Casale Monferrato, production, which had already increased from 104,000 tons in 1890 to over 198,000 tons in 1900, rose to around 390,000 tons in 1906 and tripled in the following years, reaching 1,360,000 tons on the eve of the First World War [10].

Figure 2: (a) View of Casale Monferrato from the Sant'Anna hill in 1893 *[11]* ***where it can be noticed the baroque city center together with the massive presence and extent of the industrial facilities of concrete manufacturing. (b) a photo showing the construction of the clinker warehouse named Paraboloide, the object of the present study*** *[12]****.***

Over the course of a century (the main activities ended in the 70s of the last century), in Casale Monferrato area there were dozens of quarries and mines, more than 70 plants for more than 20 manufacturing companies.

The building analyzed in the present paper is a former clinker warehouse, also known as the "Paraboloide" of Casale, which was built at the beginning of the past century and it is the only survived building of this larger industrial complex. It was built during the production peak at the beginning of the 1920s by Engineer Luigi Radici, who first conceived the design idea of the industrial warehouse with parabolic roofing [8]. The complex was located near the railway station on the edge of the historic center and, in its original configuration, occupied an area of 6,500 square meters and was an expansion of the production plants of the Italcementi company of Bergamo.

The building is considered a milestone of Italian industrial architecture, both for its particular architectural features as well as for the construction techniques used in the period in which it was built. According to [8], the Paraboloide represents the first example in Italy of a reinforced concrete building built with a thin parabolic-shaped reinforced concrete vault. After the end of Italcementi's activity in Casale Monferrato (in 1948), most of the company's structures were demolished over the years, apart from the Paraboloide, which was used as a timber warehouse from the 1950s onwards. From the 1980s, the Paraboloide remained unused and then fell into disuse and, in 1995, the complex was acquired by the Municipality of Casale Monferrato.

The significance as a cultural heritage of the Paraboloide can be read on two levels: i) as evidence of the industrial past of Casale Monferrato, which is identified with the cement production, i.e., intangible values; ii) as a brilliant example of a novel building typology built in reinforced concrete, i.e., tangible attributes linked to its novel form and construction systems, which would have spread as a technical solution for decades, rising to a canonical form of industrial concrete architecture also dear to great designers like Pier Luigi Nervi.

In fact, Pier Luigi Nervi employed the parabolic-shaped configuration for many industrial buildings in Italy [9] [13]; Figure *3* reports a comparison of the Paraboloide in Casale Monferrato, built by Luigi Radici, and two different warehouses built by Nervi. The Salt warehouse in Tortona is located less than 50 km from Casale Monferrato and the similarities, although the design of Nervi is evident, are striking.

Figure 3: Comparison between the (a) interior of the Paraboloide of Casale Monferrato, built in 1922 and (b) the Salt Warehouse in Tortona built by Pier Luigi Nervi in 1954 (less than 50 Km from Casale Monferrato) (c) Margherita di Savoia (Foggia). Salts adulteration warehouse built by Pier Luigi Nervi (photo courtesy of PLN Project) *[9]*.

3. Description of the case study

The Paraboloide presents a rectangular shaped plan of about 23x51 meters, a height of 12.6 meters; by considering the open gallery placed at the top of the structure, the overall height of the building measures a total of 16.1 meters. On the north-east side of the Paraboloide there is a concrete tower 16.8 meters high (Figure 4). The ground floor consists of a single space marked in bays by pillars in reinforced concrete, connected by tie-rod beams located the height of 3.5 meters.

Figure 4: Current state of the building: exterior seen from the north side (a), interior view (b).

The Paraboloide was entirely built by employing only elements in concrete or reinforced concrete. The main structure consists of a parabolic roofing system in concrete, composed of 8 arches. A system of joists, supported by the arches, sustains the 5 cm thin RC shell panels. The arches lie on trapezoidal-concrete panels (large buttresses) whose thrust is counter-acted by 6 tie-rod beams in reinforced concrete, supported at the midspan by reinforced concrete pillars with a square profile of 30x30 cm (Figure 4b).

On the longer sides of the building, the main buttresses are connected by longitudinal beams whose spans are divided by thinner panels (Secondary Buttresses) (Figure 5), which delimit the holes for the discharge of the material to the underlying floor of a system of tunnels. Moreover, the buttresses are connected by rather massive conglomerate concrete components that have an arched shape and serve as a perimetral connection between the various buttresses. These elements are called edge beam.

Figure 5: Scheme reporting the main elements of the Parabolide, which would have become the distinctive elements of the parabolic silo building typology.

Two drawings of this innovative construction solution were reported in a popular construction textbook written by Professor Luigi Santarella in 1926 [12]. In the drawings (Figure 6), the cross-section and the façade are represented; in both, it is possible to notice the particular regarding the covered railways with the shape of the train carrying the raw material to the silo. The drawings also report the details of the main structural elements of the silo and their reinforcements.

Figure 6: One of the two original drawings reported by Santarella in his manual** [12]**, in which he reported the silos project for clinker warehouse in Casal Monferrato. Client: Fabbriche Riunite Cemento e Calce, Bergamo. Designer ing. Radici.

Given the particular configuration of the building and the lack of original documentation (apart from two drawings reported in [12], there was no information on the design), it was considered necessary to conduct an accurate metric survey. The metric survey was carried out by [14] [15] using high-resolution terrestrial laser scanning technology (TLS), also known as LiDAR (Laser Imaging Detection and Ranging), in order to obtain an accurate 3D model with a uniform level of detail and precision, in addition to continuous metric information for each portion and elements of the structure. This procedure allowed detailed geometric information, which provided a proper reading of the structural typology of the building and the recognition of possible design and construction principles. In [7] [16], the results of a preliminary dynamic investigation have been presented to evaluate the main seismic structural criticalities. While, in [17], a section of the building was used to develop and validate an integrated procedure for HBIM-FE model transition. In continuity to these previous works, the present paper extends the analyses of the structure by thoroughly investigating the whole building and structural elements by analyzing critically the results of various experimental campaigns. The study aims to be an example of how condition assessment of the structural heritage of the early 1900s, with an apparently simple geometric shape and composition, can actually contribute in understanding hidden structural complexity. In particular:

- The structural condition assessment of the building is performed by employing the results of the mechanical tests, which have been used to inform an advanced numerical model of the whole building.
- The tests were carried out to analyze the dynamic and mechanical performance inherent to both (i) local aspects of the structure, such as the quality of the materials and connections, and (ii) global aspects, such as the modal response of the structure.

- Furthermore, the degree of connectivity between the macro components of the structure has been extensively studied thanks to the results of the dynamic testing campaign and the corroboration of numerical models.

3.1. Damage state

Although both the Municipality and the Ministry of Cultural Heritage have recently recognized the historical and documentary value of the Paraboloide, unfortunately, it has been in a state of neglect for several decades. The asbestos decontamination works in the underground tunnels have not been accompanied by proper maintenance interventions, so the Paraboloide has always been directly exposed to the weather and the actions of the time.

Currently, the building is affected by widespread degradation and marked damage phenomena, extended over the entire surface of the structure. The decay interested all the structural elements and, in particular, those located on the north side of the building.

The poor state of conservation can be attributed both to aging phenomena and to deterioration due to constructive reasons related to the productive context with which the structure was built. At the beginning of the 20th century, in fact, the knowledge regarding the preparation of the concrete mixtures was at an early stage yet, as well as the development of proper tools and apparatus. Moreover, the Paraboloide was intended to be a warehouse and not a prominent building, which could explain the general lack of quality in the realization that arose since its construction.

The visual investigations detected a diffuse degradation of the concrete, moisture stains, bio growth, rust stains, cracks, delamination and detachments, and consequent corrosion of the reinforcements. Moreover, pronounced and widespread cracks and high degrees of corrosion of the reinforcements are present in the whole body of the building, often accompanied by the complete detachment of the concrete cover. The degradation is mainly due to physical causes, linked to frost and defrost cycles, and corrosion phenomena, due to the lack of maintenance of the building, that favored infiltration and percolation of rainwater.

The decay was observed during the high-resolution metric survey by combining the laser survey information with a series of terrestrial photogrammetric pictures. The results are reported in [14] and show both the distribution and extent of the decay of the Paraboloide.

The decay is particularly noticeable on the intrados of the building and especially on the elements constituting the parabolic vault: the arches, the joists, and the panels (Figure 7) where Invernizzi et al. [14] highlighted that water staining and bio-growth cover the 40% of the area of the roofing.

A combination of both destructive and non-destructive tests has been carried out to investigate how the extension of damage affects the structural behavior. The following section describes the choices behind the design and implementation of the experimental tests.

Figure 7: Damage and degradation on the building: (a) exposed rebars on the** arches**; (b-c) exposed rebars and detachments of concrete of the joists and roofing panels; (d) water staining and bio growth on the elements of the outdoors shelter; (e) a general view of the interior of the Paraboloide showing water staining and bio growth on the roofing panels; (f) a detail of the exposed rebars of a parabolic arch.

4. Structural condition assessment

4.1. Mechanical tests

In order to investigate the state of health of the structure, different types of mechanical tests were carried out. The test comprehends non-destructive, semi-destructive, and destructive tests, distributed on the main structural elements; in particular: 17 core drillings, 21 pull-out tests, 14 ultrasonic tests, and 21 cover meter scans.

The tests have been extended on the main structural elements in order to have a uniformly distributed and representative overview of the whole structure (Figure 8) and at the same time to analyze the individual structural elements and their role in the mechanical response of the

Paraboloide basing on the scheme reported in Figure 5. The result is a relatively uneven picture of concrete quality.

Figure 8: plan of the Parabolide showing the position of the tests carried out.

The analysis of the cores extracted denotes, at best, a concrete of modest mechanical characteristics (essentially at the level of the reinforced elements, the arches in particular) and poor in the lower part of the building (buttresses and edge beams). Based on the original documentation, it is not possible to estimate of the mechanical characteristics of the concrete used; in addition to the two mentioned design drawings, no documentation was found that contained information on the materials used. Considering the fact that the building was built in the early 1920s, we can estimate the mechanical characteristics (which are then used as a benchmark for comparison with the results obtained from laboratory tests) based on a study of the mechanical characteristics of the concrete of the period. In [18], a database has been reported of certifications attesting the compressive strength values of specimens created between 1915 and the early 2000s in the archives of the Politecnico di Torino. By examining four time intervals (from 1915 to 1935, from 1936 to 1955, from 1956 to 1975, from 1976 to 2002), the authors of [18] report the probability density curves obtained for each of these periods. Based on this study, the expected characteristic resistance of the concrete of the Paraboloide is around 18.3 MPa (value μ of the real distribution) [18].

With reference to the tests carried out in the laboratory on the sample cores, the mean values of compressive strength and elastic moduli are reported in Table 1.

Table 1: Mean values determined in terms of compressive strength and elastic moduli of the main structural elements:

Based on the results of the mechanical tests, it is possible to affirm the substantial consistency of the results with those reported in the above mentioned study [18]. It is further possible to state the significant difference in terms of compressive strength and elastic modulus between the reinforced elements (arches, tie-rods, and joists) and the elements that do not present rebars (buttresses and edge beams). It can be stated that elements without reinforcement present values, in terms of compressive strength and modulus of elasticity, that are about half of those with reinforcement. The aggregates' size also differs between the two configurations: the elements without reinforcement, in fact, have larger aggregates than the reinforced ones (Figure 9).

Figure 9: Differences in the aggregate's size of different structural elements: (a) Segregation in concrete in the buttresses elements; (b) a complete carbonated element in a passing core drill of a secondary buttress; (c) the core drill of a parabolic arch and the results of the phenolphthalein test. It is possible to notice the smaller size of the aggregates in the parabolic arch.

It is worth underlying that, the structural engineering standards of the time did not explicitly contemplate seismic actions. In this scenario, some of the main structural elements of the Paraboloide suffer from insufficient reinforcement for bending (e.g. buttresses) or shear (tie-rods with pillars in the middle).

4.2. Dynamic tests

Experimental dynamic investigations have long been used in flexible structures, such as bridges and buildings, to characterize their overall structural properties and better understand the influence of external factors on their dynamic behavior, e.g., see [19], [20], [21], [22].

In the case of the Paraboloide, the dynamic tests have been designed taking into account three main objectives: (i) clarifying the influence of the interaction between the main hall and the tower by ad hoc designed test setup; (ii) completing the information on mechanical properties acquired by mechanical tests; (iii) investigating the nature of the connections between arches and buttresses. The information from dynamic tests is typically used for the corroboration of a FE model, which becomes a powerful diagnostic and prediction tool.

Dynamic testing of shell and spatial structures is often challenging due to the complexity of the dynamic behavior and the difficulties in optimizing the positioning of the sensors to extract useful information [23] [24].

Typically, experimental setups depend on the specific scope of the investigations. For instance, setups designed to capture low frequency global modes of a building will provide information on the global condition of the building and will help in predicting its seismic response. On the contrary, higher frequency modes are more sensitive to changes in local conditions or localized damage. Accordingly, the preliminary FE model was used to identify the structural portions and elements that mainly affects the dynamic behavior of the structure (both in terms of local and global behavior).

The dynamic tests on the Paraboloide aimed at capturing the main vibration modes of the parabolic vaults and investigate the behavior of the tower in relation with the rest of the building. In particular, the main purposes were to maximize: a) the spatial resolution of the experimental modal shapes; b) the number of modal parameters (modal frequencies, damping ratios) to be employed for calibrating the mechanical model.

Based on the FE vibration modes, two measuring setups were defined, taking into account the constraints in terms of the employable number of sensors and the accessibility of the building due to safety concerns. Figure 10 reports the assumed testing setups. The sensors used for the dynamic tests are uniaxial PCB Piezoeletronics capacitive accelerometers, with a sensitivity of 1V/g and a resolution of 30 μg. The signals acquired correspond to the structure response to ambient noise excitation, produced by external stochastic forces such as wind and vehicular traffic, and by hitting the structure by using an instrumented sledge. The signals have been acquired adopting a sampling frequency of 256 Hz, whilst the main modes were confined in the first 20 Hz.

Figure 10: Axonometry scheme of the building showing with sensor positioning in Setup 1(a) and Setup 2 for the tower (b).

Setup 1

The design of the first setup aimed at measuring the vibrations of the central portion of the parabolic vault. In fact, the analyses conducted on a preliminary Finite Element (FE) model showed that the most relevant modal components mainly involve the central part of the building along the transverse direction (Figure 4).

The accelerometers were installed by using a platform in order to reach the points on the vault. The acquisition setup is composed of 19 accelerometers: 1 in the X direction, 14 channels in the Y direction, and 4 channels in the Z direction (Figure 10). The sensors have been distributed mainly on three arches at different heights. The 30 min signals have been preprocessed to roughly define the energy content interval in the frequency domain and then conditioning by subsampling, mean removal, and detrending through a polynomial fitting. The signals were split into a sequence of 180 s recordings, with a superimposition lag of 20 s, and the modal parameters repeatedly estimated adopting the Stochastic Subspace Identification (CVA-SSI) algorithm. The adopted identification technique is broadly described in the literature [25], [26] and a rigorous discussion of its formulation is out of the scope of this paper. Figure 11 depicts the first 2 main modes identified and reports the identified frequency with the corresponding clustering diagram.

Figure 11: Identified modes of the Paraboloide by plotting only the horizontal components: (a) first mode; (b) second mode; (c) clustering diagram; and (d) identified natural frequencies and damping ratio obtained after the clustering analysis.

<u>Setup 2</u>

The second run of tests (setup 2) aimed to investigate the effectiveness of the connection between the tower and the hall (the test setups are shown in Figure 10). Two pairs of accelerometers were placed in adjacent positions on the tower and on the roof along the main horizontal axes of the tower, to compare the frequency content and possibly observe their relative movements. The time histories and the power densities reported in Figure 12 show the vibration responses along X and Y directions induced by hitting the corner of the tower by a sledgehammer. The different energy distributions and amplitudes along both directions measured by adjacent sensors clearly indicate that the mutual influence is negligible.

Figure 12: Impact test: (a) and (b) X direction. Comparison between the records in 3X (black) and 4X (red); (c) and (d) Y direction. Comparison between the records in 3Y (black) and 4Y (red).

5. Numerical and experimental investigations to support the structural diagnosis

This section reports the description and corroboration of the numerical models supporting structural considerations on the health conditions of the Paraboloide. The criticalities highlighted by the experimental campaign are then addressed, as supported by the updated FE model of the structure.

5.1. Description of the baseline FE model

The geometric model of the Paraboloide is based on the high-resolution laser scanner survey [27]. The model was partitioned in macro-components with assumed uniform material characteristics. Each macro-component was finally assembled in the FE software to obtain the mechanical FE model. The linear elastic FE model of the Paraboloide is constituted by mono- and bi-dimensional elements: a 2-node beam element with 6 Degree of Freedom (DoF) in each node, which implements the Timoshenko theory, is used for the reinforced/regular concrete beams and columns; an 8-node 48 DoFs thick shell element with bilinear shape functions is used for the slabs of the roof and the buttresses [28]. The connection between the tower and the Paraboloide is modeled with elastic spring elements. The numerical model counts 47822 nodes and 19247 elements, having an average dimension of 0.5 m for both the shell and beam elements. The structure was assumed to be clamped at the base of the buttresses, thus neglecting the deformability of the foundation.

5.2. Corroboration of the FE model

The FE model has been sequentially corroborated by the information coming from the experimental tests to interpret the current structural condition. A first attempt model assumes the material properties from current standards and regulations. In this scenario, the elastic moduli are set to 30000 MPa, the Poisson's ratio of 0.2, and the density of the concrete is assumed 2500 kg/m^3. The connection between the tower and the main structure is supposed to be rigid. The result of the eigenvalues problem reveals a discrepancy with respect to the principal identified frequency of 28%, whereas good accordance with respect of the first modal shape is found. None of the numerical modes found in the frequency range between 0 and 10 Hz fits well with the second experimental mode.

The second model has been corroborated with data obtained by mechanical tests and with information coming from the dynamic testing campaign (Setup 1, referred to the main structure). The mean experimental Young's moduli have been adopted for the macro-elements for which tests on cores or ultrasonic were available.

To incorporate consistent values in the numerical analyses, the values obtained from the tests on cores have been increased to account for the discrepancy between the evaluated static data, that refer to secant static moduli, and the tangent dynamic moduli, estimated by ultrasonic tests and which is used in the FE model.

The relation that links the static secant Young's modulus of concrete, E_{sta}, to the dynamic tangent modulus, E_{dyn}, has been obtained by averaging the ratio between the moduli evaluated with ultrasonic tests and the values obtained by cylindric compression tests in laboratory, on the same elements: $E_{dyn} \approx 1.10 \cdot E_{sta}$. This simplified relation is consistent with common laws reported in the literature [29], [30], [31]. Table 2 reports the values of the mechanical parameters obtained from experimental tests.

Table 2: Material parameters assumed for the macro-components of the FE model corroborated with static data only. The elastic moduli reported in the table represent dynamic values.

Regarding the density, several tests to measure its value on regular concrete specimens have brought to an average value of about 2300 kg/m^3. Since no data were available on reinforced concrete specimens, the density of these macro-components was supposed in accordance with

National and European regulations equal to 2500 [kg/m^3]. The Poisson's ratio was reasonably assumed to be 0.20 for every macro-component. In this way, the natural frequencies of the corroborated FE model begin to approach the experimental ones, but a certain degree of uncertainty remains in comparing the modal shapes, especially on higher modes.

The next step was to include in the model the results of the Setup 2 dynamic test described in § Section 4.2 in order to proper modelling the degree of connection between the tower and the main structure. As reported before, the experimental findings showed that the connection between the tower and the main structure can be considered negligible. The model was consequently modified by omitting the tower; then, the eigenvalue analysis allowed extracting the natural frequencies and mode shapes of the isolated main structure of the Paraboloide. The analysis results show a small (negligible) reduction in the values of the natural frequencies. Concerning the mode shapes, the absence of the tower (in the numerical model) led to a better correlation of the first mode of the structure with the first experimental one. This is due to the fact that, in the FE model, the mode shape of the tower is highly correlated to the first mode shape of the main structure, and thus rise problems in the automatic coupling with the first identified experimental mode. In addition, the detachment of the tower from the main body was experimentally verified. Following these observations, the model without the tower has been adopted in the analyses performed in the next sections.

5.3. Considerations on structural criticalities and modal model updating

The experimental investigations highlighted several aspects of the structural behavior of the Paraboloide, which need careful analysis. Two main criticalities emerged: the behavior of the buttresses/tie-rods nodes connection and the consistency of the tie-rods.

5.3.1. Role of the tie-rods

The investigation performed on the main structural elements showed a lack of reinforcements in the edge beam elements (TR) and thus in the buttresses/tie-rods nodes, which are placed at the same height along the perimeter. Another component worth a more in-depth study is the tie-rod. The presence of tie-rods is a peculiarity of the Paraboloide, being one of the few parabolic silos presenting these structural elements.

While the global dynamic response of the Paraboloide is not importantly affected by the tie-rods, the static and seismic assessment performed with current standards [32] show that a removal of these elements would result in an important reduction in safety levels, especially due to excessive shear forces in the buttresses. While the effectiveness of these elements is difficult to demonstrate through non-invasive tests, is necessary to verify the reinforcement at the nodes with dedicated tests. Besides, the structural importance of these elements, especially to resist wind or earthquake actions, is such that it is suggested to ensure and preserve their efficacy.

5.3.2. Assessing the degree of connection between buttresses, tie-rods, and arches via Model Updating

While in-situ mechanical tests were able to clarify some aspects on the geometry, structural details and materials that constitute the Paraboloide, uncertainties remain about efficacy of some elements, such as the edge beams and the node between buttresses, tie-rods and arches, located at the same height of the edge beams. The mechanical parameters of these components were estimated from laboratory tests, however, the experimental campaigns showed widespread cracks and high carbonation levels (Figure 13). In order to bring further elements to the structural condition assessment, a model updating was performed, relying essentially on natural frequencies and mode shapes. No information on damping has been used in the calibration procedure because of the high dispersion experimentally observed (see Figure 11c). For the model updating, the optimization algorithm reported in [33] has been adopted. It is a semi-heuristic method based on: (i) the well-known Singular Value Decomposition algorithm, which is used to invert the matrix of the model prediction of measurements, and (ii) a random perturbation of the model parameters, to provide heuristics in the process.

Figure 13: Pass-through vertical cracks identified on some edge beam elements.

Since the node component constitutes part of the edge beams, in the FE model updating the multiplicative factors of the elastic moduli of nodes and edge beams were supposed the same (this is also supported by a negligible difference of their experimental values), thus a linear constraint has been imposed between these two model parameters during the updating.

The first five modes identified were used to update the model parameters (elastic moduli) by minimizing the difference in natural frequencies and modal shapes (for details see [34]). The resulting parameter values must be considered as equivalent elastic characteristics of the entire macro-elements (for example of the entire edge curb, which would consist of edge beams and nodes) that consider not only the actual material state but also macroscopic conditions such as widespread or localized cracks.

The updating strategy was based on two stages. In the first stage, a single multiplying factor acting on the elastic moduli of all the model elements was updated. This allowed to reduce the initial uncertainties related to the law used to move from static to dynamic moduli. The results of the first run highlighted a global reduction of the initial parameter values of 12%.

In the second stage, the knowledge acquired by the in-situ inspections was used to reduce the number of variables to be updated. To this aim, the attention was focused on the edge curb. The second run resulted in a reduction of the elastic moduli of 38% for edge beams and nodes, with respect to those obtained by experiments. The results of the updating procedure are reported in Table 3 (modal frequencies and residual errors) and Table 4 (corresponding elastic moduli and densities), together with the initial values for comparison, while the two first updated mode shapes are depicted in Figure 14. The Modal Assurance Criterion (MAC) has been adopted to compare the numerical and experimental mode shapes. Ultimately, the resulting model shows that it reflects the experimental results well.

Table 3: Results of the model updating runs in terms of modal parameters.

Table 4: Initial and updated mechanical parameters.

Figure 14: First 2 updated numerical mode shapes: (a) first mode; (b) second mode; (c) first mode compared with the experimental identified; (b) second mode compared with the experimental identified.

The most evident result is that the global elastic characteristics of the final model have values considerably lower than those determined in the laboratory on intact samples. In particular, elastic moduli values are about 10-40% lower than the ones measured on core samples, due to geometric and/or mechanical discrepancies (e.g. material dislocations), this being detected even under very weak (ambient) excitation. Therefore, it is fair to note that since the initial damage state was not considered in the model updating, the obtained elastic parameters must be taken as representative of entire macro-elements (i.e., representative of all the geometrical nonlinearities such as existing cracks and defects).

Referring to one of the investigated elements of the Paraboloide, the presence of conspicuous cracking phenomena in the perimeter arched beams (Figure 13) almost leads to a halving of the equivalent elastic modulus of the corresponding model components.

6. Conclusions

As underlined by the current national and international regulations, anamnesis is a paramount phase of the condition assessment of cultural heritage structures. For industrial heritage buildings, in particular, information such as original characteristics of the factory, changes made over time, damage resulting from transformations, aging of materials and calamitous events, etc., take on great importance.

Knowledge can be achieved with different levels of detail, depending on the accuracy of the surveying operations, historical research, and experimental investigations; and the knowledge of the characteristics of the construction is useful to define an interpretative model that allows, in the different phases of its calibration, both a qualitative interpretation of the structural behaviour and the structural analysis for quantitative evaluation.

The numerical investigations on the Paraboloide of Casale Monferrato were useful for interpreting the results of the experimental campaigns, both for the mechanical and dynamic tests. Test results were used to corroborate the numerical model in terms of elastic and mass parameters. Then, several model configurations were explored, bringing to some conclusions regarding the linear response:

- The absence of connection between the tower and the main structure highlighted with the dynamic tests was confirmed by the best fit of the FE model without tower, with experimental data;
- While the influence of the-tie rods on the behavior of the Paraboloide in the linear elastic phase was confirmed to be rather low, the evident importance of these elements shows how the condition assessment requires the joint use of different types of investigations;

Because the integration of the findings of the mechanical tests was not able to explain the modal behavior of the Paraboloide (as evaluated by the FE model), especially for what concern the second mode shape, that is affected by the deformability of the nodes, a model updating strategy was pursued. In the updating, the in-situ investigations, the mechanical tests and the findings of the dynamic campaign were extremely useful to reduce the number of updating parameters as well as to focalize the attention on the main uncertain components of the structure. The result of the updating strategy can be summarized in the following points:

- The dynamic elastic moduli, after the FE updating process, resulted in being on average 90% of the static values obtained in laboratory from compression tests on core samples.

- Similarly, the updating procedure revealed a severe reduction in equivalent elastic modulus of non-reinforced concrete elements of the Paraboloide affected by important cracking phenomena. Specifically, the cracks in the arched beams of the edge curb component nearly halved the equivalent elastic modulus.

The most important conclusion, however, is that in this kind of structures non-monolithic behavior and material dislocations lead to appreciable stiffness reductions, which can be detected even under ambient excitation. Future works will focus on nonlinear analyses aimed to better understand the potential effects of the collapse of the tie-rod elements on the statics (in terms of stresses) and the dynamic global behavior of the Paraboloide.

Acknowledgments

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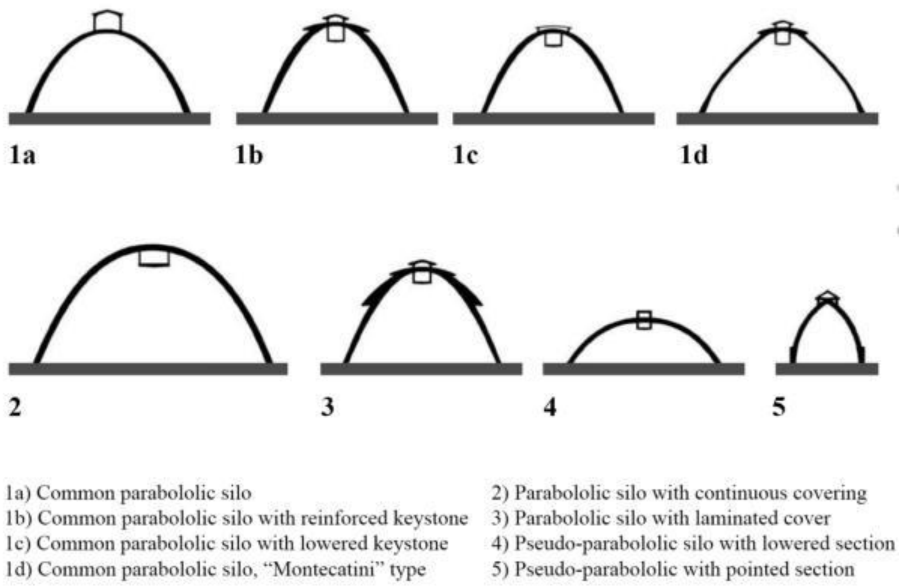
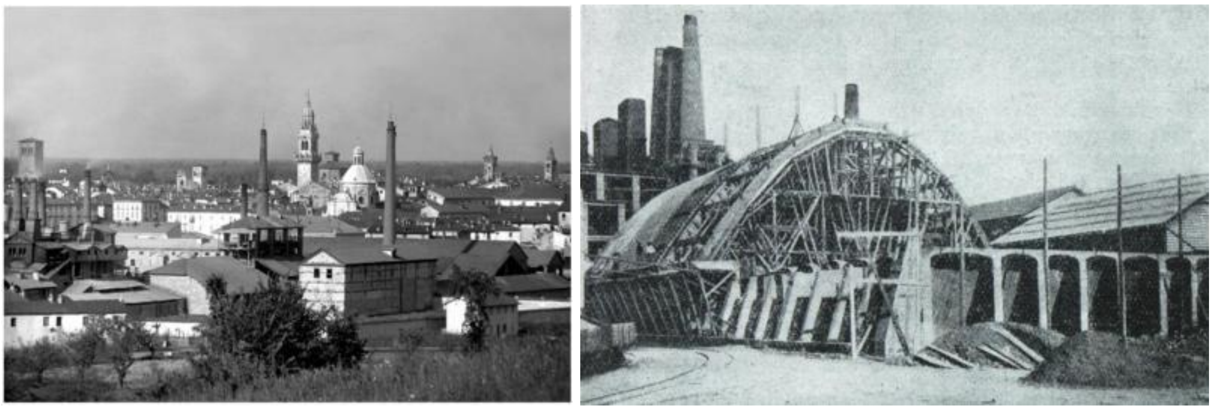


Figure 1: Scheme reporting the classification of the parabolic silos typologies gathered and classified by [8].



(a) (b)

Figure 2: (a) View of Casale Monferrato from the Sant'Anna hill in 1893 [11] where it can be noticed the baroque city center together with the massive presence and extent of the industrial facilities of concrete manufacturing. (b) a photo showing the construction of the clinker warehouse named Paraboloide, the object of the present study [12].

(a) (b) (c)

Figure 3*: Comparison between the (a) interior of the Paraboloide of Casale Monferrato, built in 1922 and (b) the Salt Warehouse in Tortona built by Pier Luigi Nervi in 1954 (less than 50 Km from Casale Monferrato) (c) Margherita di Savoia (Foggia). Salts adulteration warehouse built by Pier Luigi Nervi (photo courtesy of PLN Project) [9].*

(a) (b)

Figure 4: Current state of the building: exterior seen from the north side (a), interior view (b).

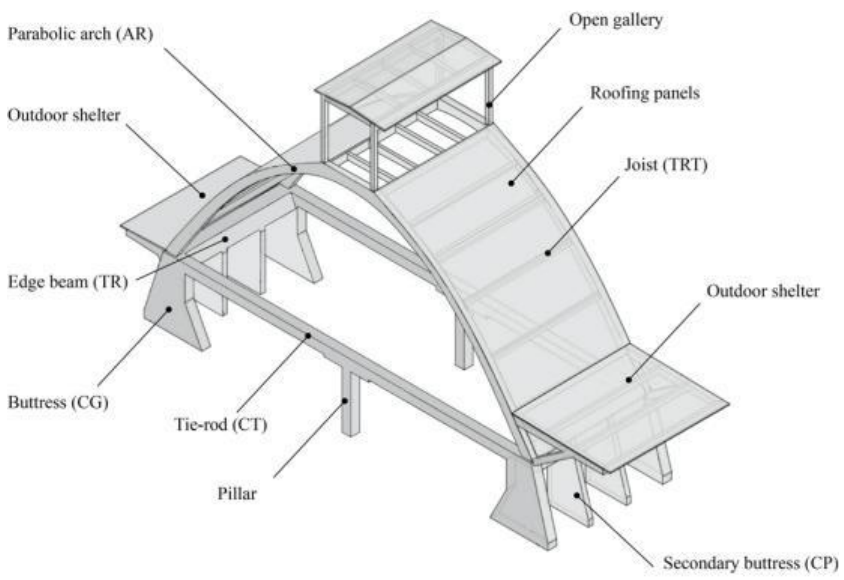


Figure 5: Scheme reporting the main elements of the Parabolide, which would have become the distinctive elements of the parabolic silo building typology.

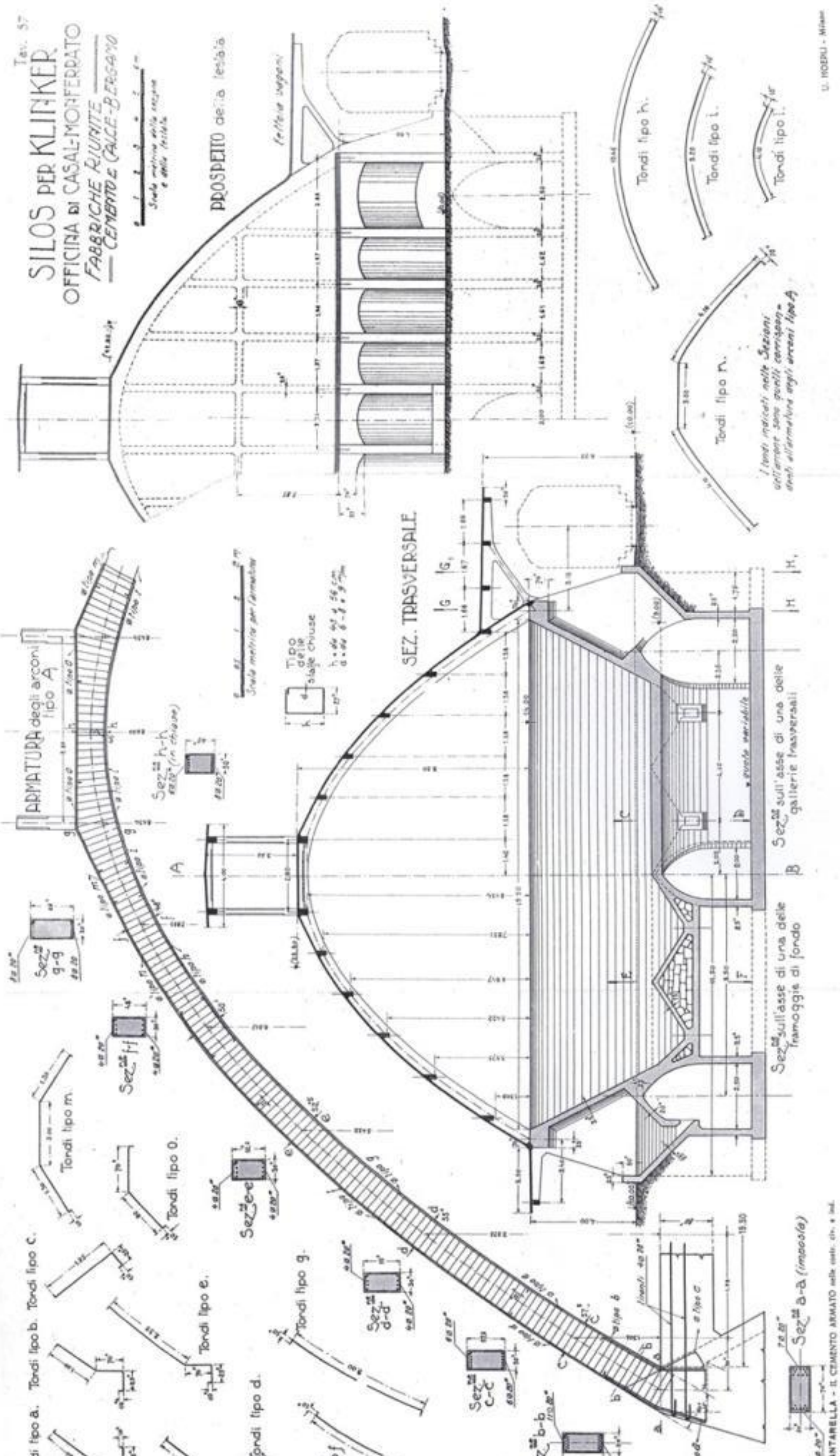


Figure 6: One of the two original drawings reported by Santarella in his manual [12], in which he reported the silos project for clinker warehouse in Casal Monferrato. Client: Fabbriche Riunite Cemento e Calce, Bergamo. Designer ing. Radici.

(a) (b) (c)

(d) (e) (f)

Figure 7: Damage and degradation on the building: (a) exposed rebars on the AR; (b-c) exposed rebars and detachments of concrete of the joists and roofing panels; (d) water staining and bio growth on the elements of the outdoors shelter; (e) a general view of the interior of the Paraboloide showing water staining and bio growth on the roofing panels; (f) a detail of the exposed rebars of a parabolic arch.

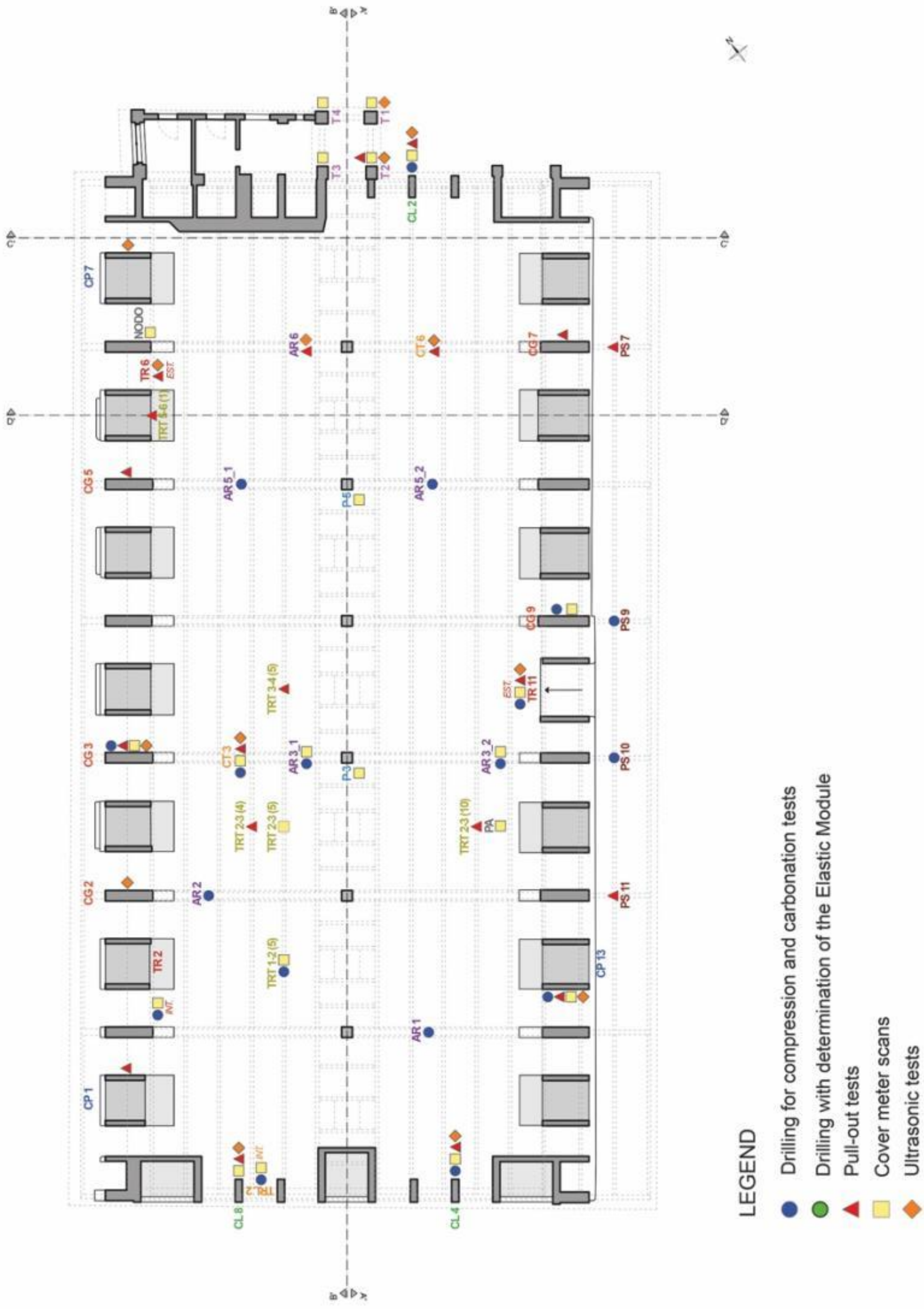
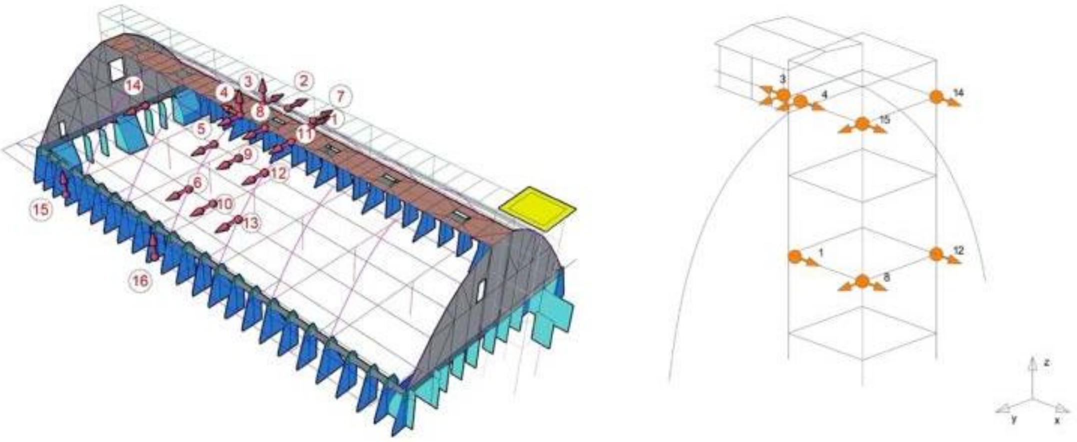


Figure 8: plan of the Paraboloide showing the position of the tests carried out.

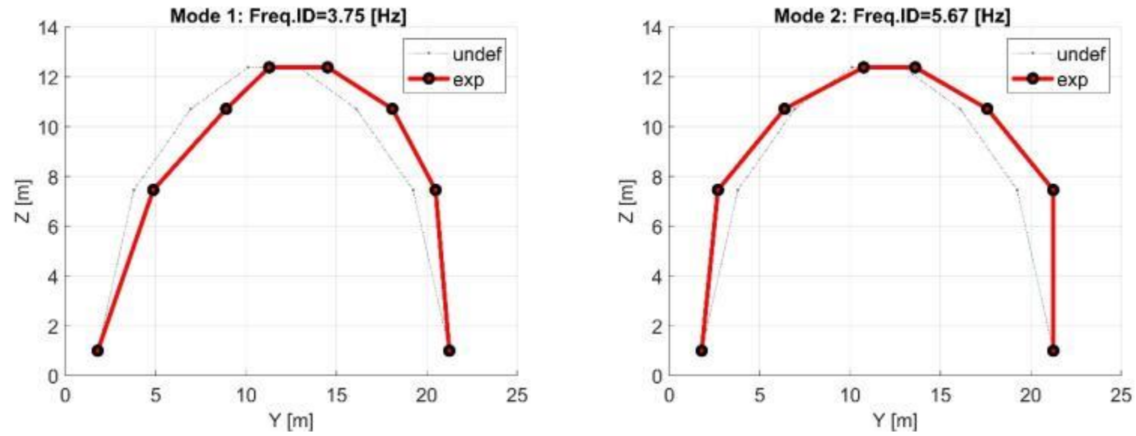
(a) (b) (c)

Figure 9: Differences in the aggregate's size of different structural elements: (a) Segregation in concrete in the buttresses elements; (b) a complete carbonated element in a passing core drill of a secondary buttress; (c) the core drill of a parabolic arch and the results of the phenolphthalein test. It is possible to notice the smaller size of the aggregates in the parabolic arch.

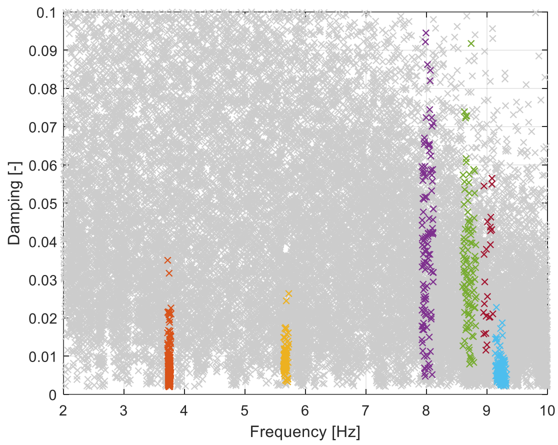


(a) (b)

Figure 10: Axonometry scheme of the building showing with sensor positioning in Setup 1(a) and Setup 2 for the tower (b).



(a) (b)

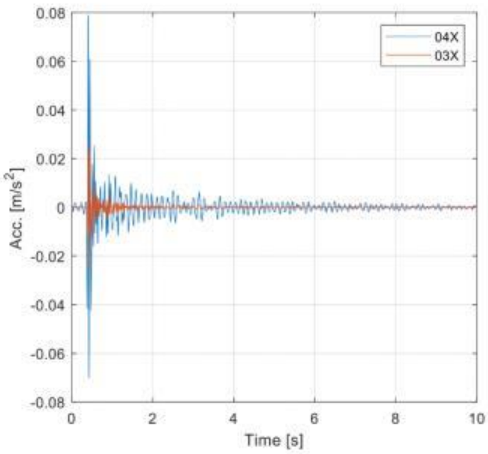


(c)

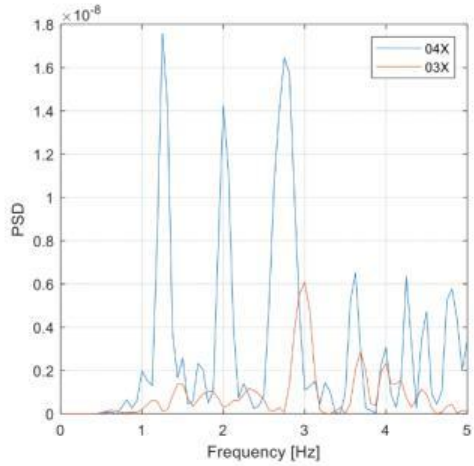
Frequency [Hz]	Damping ratio [-]
3.747	0.006
5.668	0.009
8.008	0.040
8.702	0.034
9.015	0.032
9.227	0.006

(d)

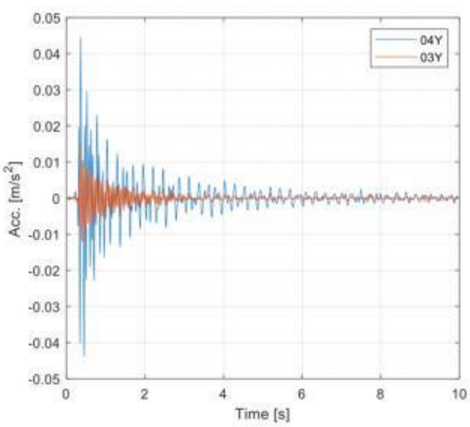
Figure 11: Identified modes of the Paraboloide by plotting only the horizontal components: (a) first mode; (b) second mode; (c) clustering diagram; and (d) identified natural frequencies and damping ratio obtained after the clustering analysis.



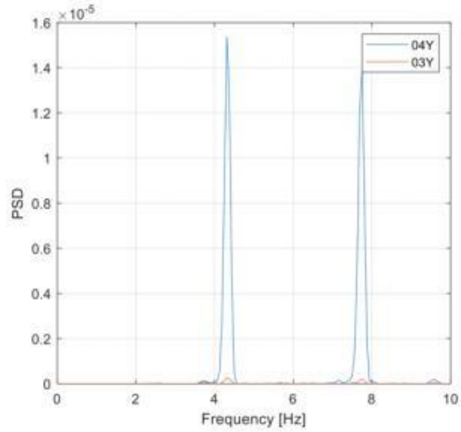
(a)



(b)



(c)



(d)

Figure 12: Impact test: (a) and (b) X direction. Comparison between the records in 3X (black) and 4X (red); (c) and (d) Y direction. Comparison between the records in 3Y (black) and 4Y (red).

(a) (b)

Figure 13: Pass-through vertical cracks identified on some edge beam elements (TR).

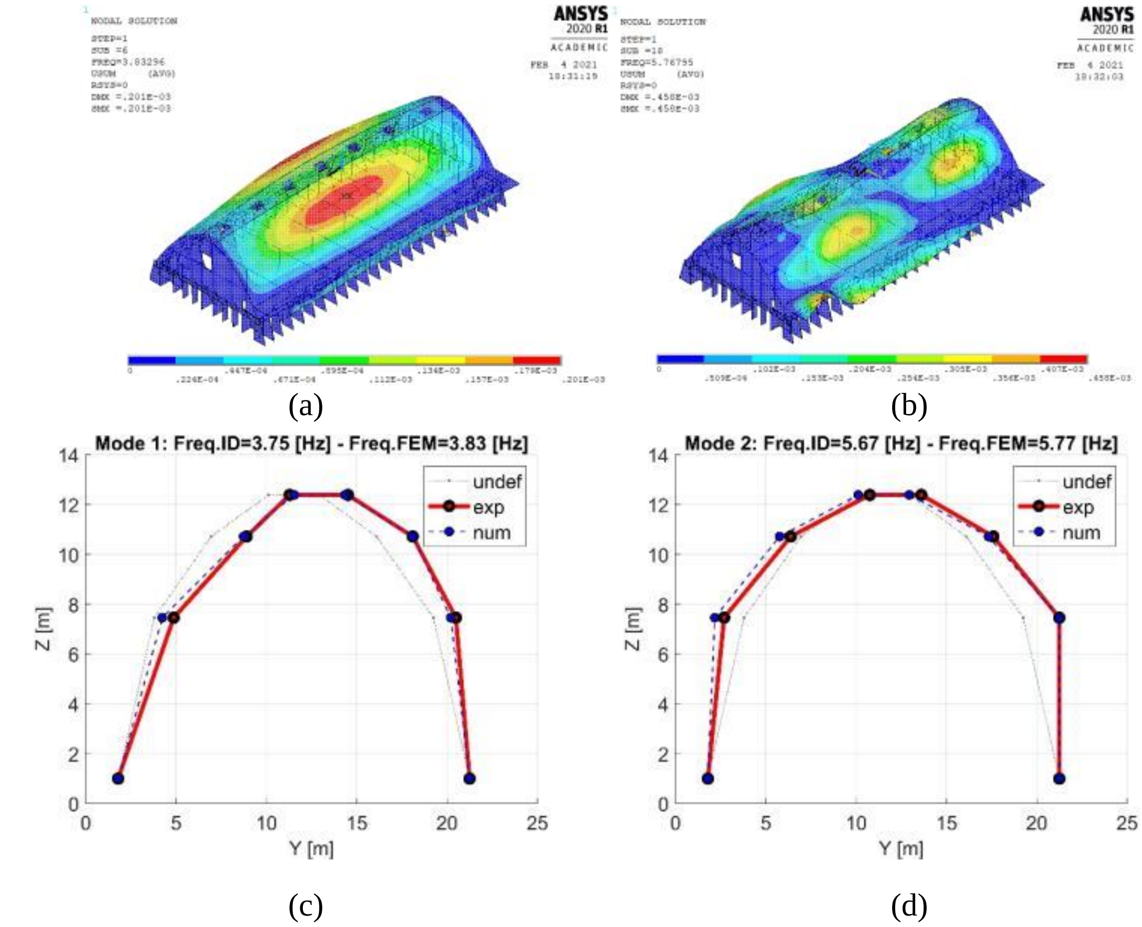


Figure 14: First 2 updated numerical mode shapes: (a) first mode; (b) second mode; (c) first mode compared with the experimental identified; (b) second mode compared with the experimental identified.

Table 1: Mean values determined in terms of compressive strength and elastic moduli of the main structural elements:

Element	Element code	Compressive strength [MPa]	Elastic modulus [GPa]
Parabolic Arches	AR	22.6	25.4
Joists	TRT	22.1	-*
Tie-rod elements	CT	14.8	-*
Buttresses	CG	9	16.6
Secondary Buttresses	CP	12.2	-*
Side Buttresses	CL	12.5	-*
Edge beam elements	TR	16.2	17.8

*Elastic modulus lab tests were not carried out

Table 2:Material parameters assumed for the macro-components of the FE model corroborated with static data only. The elastic moduli reported in the table represent dynamic values.

Id	**Macro-components**	**Young's modulus [MPa]**	**Poisson's ratio [-]**	**Density [kg/m^3]**
1	Buttresses (CG)	18278	0.20	2292
2	Buttresses (CG)/tie-beams (CT) node	18278	0.20	2292
3	Tie-beams (CT) and columns	25500	0.20	2500
4	Arches (AR)	27940	0.20	2500
5	Beams of cantilever roof	24858	0.20	2500
6	Shells of the tympanum and roof	24858	0.20	2500
7	Beams of the tympanum and roof	24858	0.20	2500
8	Edge beams (TR)	19580	0.20	2293
9	Roof of the gallery	24858	0.20	2500
10	Beams and columns of the tower	27200	0.20	2352
11	Beams and columns of the gallery	24858	0.20	2500
12	Walls of the annexed room	18920	0.20	2292

Table 3: Results of the model updating runs in terms of modal parameters.

Updated numerical natural frequencies [Hz]	**Identified natural frequencies [Hz]**	**Residual percentage error [%]**	**MAC matrix between numerical and identified mode shape**					
3.83	3.75	2.13	0.96	0.26	0.54	0.80	0.63	0.65
5.77	5.67	1.76	0.01	0.84	0.03	0.15	0.45	0.05
8.15	8.01	1.74	0.62	0.09	0.91	0.68	0.13	0.71
8.21	8.70	-5.63	0.95	0.36	0.66	0.90	0.66	0.67
9.58	9.02	6.20	0.48	0.90	0.43	0.75	0.87	0.16
10.40	9.23	12.68	0.36	0.01	0.59	0.30	0.01	0.68

Table 4: Initial and updated mechanical parameters.

Id	Macro-components	Initial Young's modulus [MPa]	Updated Young's modulus [MPa]
1	Buttresses (CG)	18278	15987
2	Buttresses (CG)/tie-beams (CT) node	18278	11238
3	Tie-beams (CT) and columns	25500	22304
4	Arches (AR)	27940	24438
5	Beams of cantilever roof	24858	21742
6	Shells of the tympanum and roof	24858	21742
7	Beams of the tympanum and roof	24858	21742
8	Edge beams (TR)	19580	12038
9	Roof of the gallery	24858	21742
11	Beams and columns of the gallery	24858	21742
12	Walls of the annexed room	18920	16548