Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Knowledge path and analysis of the Binishell structures. The case study of villa La Cupola in Paradise Coast (Sardinia)

Giorgia MELLONE*, Diego A. TALLEDO, Luisa BERTO, Sara DI RESTA

* Università Iuav di Venezia
Dorsoduro 2206, 30123 Venice (Italy)
gmellone@iuav.it

Abstract

The Binishell construction, introduced in the early 1960s by architect Dante Bini, is a patented system realized by inflating and shaping a reinforced concrete membrane to form large, efficient domes. This technology gained great interest, as testified by the construction of more than 1500 structures worldwide since 1964. Efficiency, cost-effectiveness and structural stability were the main features of a system that embodies an innovative approach in the field of construction. From the preservationists' point of view, Binishells represent a research and operational challenge for the conservation of unconventional concrete structures, important examples of 20th-century heritage. The research analyzes the case-study of the villa 'La Cupola' of director Michelangelo Antonioni, a Binishell structure located in Sardinia (Italy). In-depth information on the building has emerged from the analysis of the original patents, the photogrammetric survey and some information about materials of the dome. Linear finite element analyses also provided an understanding of the structural behavior of the Binishell structure. The research contributes to the understating of the safety level needed to define an informed conservation strategy, opening up innovative methodological scenarios for other similar examples of Modern heritage.

Keywords: Binishell, Dante Bini, Villa La Cupola, concrete, shell, analysis, conservation, structural behaviour

1. Introduction

Born in Castelfranco Emilia (Modena) in 1932, Dante Bini stands as an internationally renowned architect celebrated for his pioneering contribution to architectural innovation. Throughout his career, he dedicated himself to pioneering studies focused on dynamic pneumatic formwork, known as 'pneumoforms', and the integration of automation within construction processes.

Among his notable projects, including Binistar and Binix, Binishell emerges as a seminal achievement, embodying Bini's vision for utilizing pneumoforms alongside construction automation. Binishell is precisely a method (Figure 1) for building concrete structures by inflation [1]. The idea of employing air as a tool for construction occurred during a tennis match: the architect has disclosed that the inspiration for concrete domes utilizing air struck him when he found himself trapped within a pressostatic structure due to heavy snowfall [2]. Despite 40 centimeters of snow accumulating during the match, neither Bini nor his opponent had been aware of the conditions outside. Remarkably, the geometry of the pressostatic structure remained unaffected. This event prompted the architect to recognize the potential of membranes to bear the weight of concrete, thus catalyzing his groundbreaking approach to architectural construction.

Thanks to the efficiency, cost-effectiveness and structural stability, of this innovative patented system it is estimated that more than 1500 domes have been built all over the world. Among the countries in which

Binishells were built are Australia, United States, England, Spain, France, Switzerland, Austria, Saudi Arabia, Iraq, Venezuela, Brazil, Peru, Canada, Japan, Pakistan and many others.

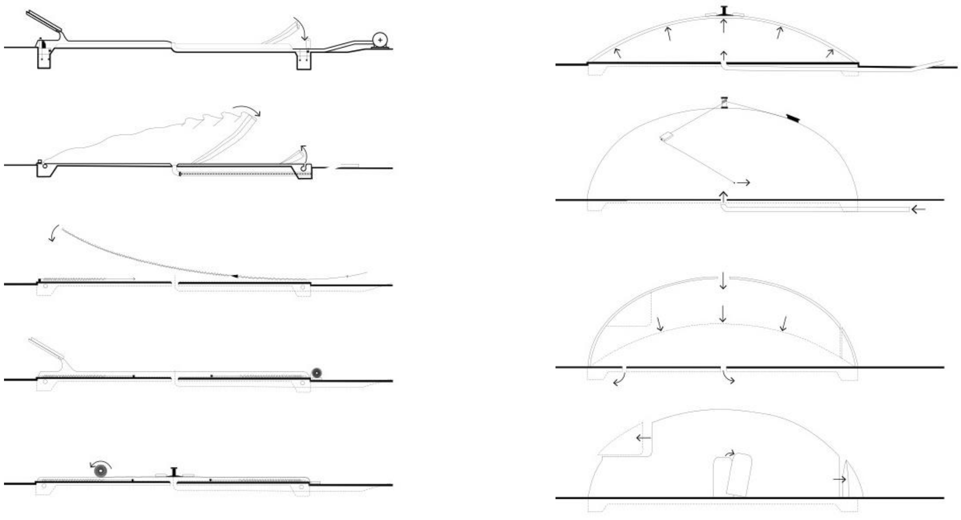


Figure 1: Schematic representation of Binishell construction phases. Redrawn from original drawings of Dante Bini, Mellone [6]

The Binishell domes represent significant examples of 20th century 'serial' architectural heritage. However, among these many buildings, one stands out not only as a document of constructive innovation and experimentation, but for its values connected to the memory of two important personalities of Italian cinema of the second half of the 20th century: the Italian director Michelangelo Antonioni and the actress Monica Vitti, who commissioned Dante Bini to design their summer residence in Costa Paradiso (SS) in Sardinia in 1969.

The fame of this dome returned to the center of attention at the 14th International Architecture Exhibition at the Venice Biennale, in 2014. The curator, Rem Koolhaas, mixed architecture and cinema by presenting the exhibition *Monditalia* within *Fundamentals*, the 2014 14th International Architecture Exhibition curated by Koolhaas, a scan of Italy through 82 films and 41 architectural projects. Villa 'La Cupola' was one of these buildings, described as "a thin symmetrical carapace perforated asymmetrically, an artists' house built like a work of art set in the crushed rocks of the Red Desert. Chamomile grows on the terrace floor; a cavity made not to see, but to feel the sea and 'tuned' cantilevered stone stairs are part of the visceral performance of the house. The project was commissioned to Bini on the condition that he would not reveal the names of the clients until they had owned the house. The agreement was respected and only now, years after Antonioni's death, can this singular collaboration receive its worthy tribute" [3].

Presently, the degradation phenomena of the dome surfaces urgently require a conservation plan and protection work to guarantee its preservation over time.

This work is part of a broader research aimed to develop maintenance and monitoring strategies important for extending the life of concrete-made buildings. Interventions and repairs should enhance and sustain the cultural significance of the place and be designed to consider the existing character, scale, form, siting, landscape, materials, colour, patina and detailing. Reference for defining the research approach is the Cádiz Document on the conservation of concrete heritage: "It is important to establish the limits of acceptable change at the project outset. It should also be understood that while the goal is to make the needed repairs in the best way possible now, it is highly likely that further repairs and continued maintenance will be needed in the future even if it will be decades away" [4].

Following this approach the study of the Villa "La Cupola" is carried out, with the aim to understand aspects related to heritage place, cultural value, and structural behaviour helpful to define an informed conservation strategy.

2. The first dome

In 1964, Dante Bini built the first reinforced concrete dome on the road that connected Bologna to the small town of Crespellano. Over the years, he has continuously perfected this type of construction. In particular, in San Cesario sul Panaro, near Modena, there is a field in which there is a concentration of Binishell, all its experiments (Figure 2). The experimental construction site of San Gallo is described as "a place with a very high historical documentary value within which it is still possible to see the compositional archetypes which later had the opportunity to express their formal evolution in the various architectures scattered around the world" [5]. Among these experiments, there is the first dome of 30 meters in diameter and 7 meters high, which is a very interesting experimental architecture because helical spring reinforcement had not yet been used. Bini thought of using a series of "large continuous inclined enveloping steel circles" [2].

3. Binishell's Patent and construction process

The construction process involves the use of a pneumatic formwork, a reinforced neoprene membrane which is inflated to lift both the concrete and its reinforcement from the ground. Once the ground is levelled, the pneumatic neoprene and reinforced nylon formwork are laid out on it and fixed to the foundation beam. Above it, a special reinforcement is arranged, consisting of helical springs containing steel bars.

Figure 2: D. Bini, the Binishell experimental field in San Cesario sul Panaro (Bologna), Mellone [6]

The reinforcement pattern is very unusual, not only because of the single elements which compose it, but also because of their disposition along the curves created underneath by the organic 'bubble' shape. Bini explains that the idea occurred to him during a casual observation when superimposing two segments of a helical telephone cord. After the reinforcement is superimposed on the membrane follows the cast of a thin layer of concrete and retarding and plasticizing additives. The last layer placed above the casting is made out of a PVC cover, anchored to the foundation beam. Above this layering of elements, a vibrator is placed and the structure begins to rise. Air blows inside passing through many pipes arranged under the foundation beam. All of these steps, from casting to inflation, take from one to four hours. When the dome reaches the design height, the vibrators are operated for an hour more, compacting the concrete and the air pressure is kept constant until the concrete hardens. This step can last from one to three days more. Finally, the dome gets dismantled and the membrane, together with the pneumatic formwork, can be used again [7]. The last step of the process consists in cutting the openings foreseen by the project with hammer drills and circular saws. Being an easy system to build with, which did not require particular specialization and above all being very rapid in construction, it was very successful as proved by the number of Binishells build around the world.

4. Villa "La Cupola": a document of building experimentation and film history

1964 represents an important date to understand the genesis of the construction of the villa La Cupola by Michelangelo Antonioni and Monica Vitti. This year Dante Bini built the first Binishell prototype in the Emilian countryside. Michelangelo Antonioni, on the other hand, was making as director the final Red Desert, a film that marks his venture into color filmmaking. In the gloom and melancholy backdrop of an Emilian countryside barred by billowing pollutants, a scene emerged that transports viewer to distant, idyllic setting, filmed in Budelli Island, in the north of Sardinia. In this period, Antonioni and Monica Vitti, the film's protagonist and the director's partner, encountered Pierino Tizzoni. As a leading building contractor, he inspired the couple to envision their dream holiday retreat to the right of Costa Paradiso.

Four years later, in 1968 Dante Bini met Monica Vitti. Engaged in conversation, Bini unveiled his revolutionary building concept, explaining about the swift construction of the dome at Columbia University in New York. Bini recounted Vitti's palpable astonishment for the rapid construction powered by air, prompting her immediate discussion with Antonioni [8]. The architect was then called to Rome by Antonioni and invited in Sardinia to build a Binishell. During the flight, the director asked the architect to keep the entire project secret.

On the still-empty ground, the director provided specific instructions to the architect for the design of his new home. Antonioni described his desires with these words: "when I open the door, I still want to see the sea, appreciate its smell, its sound, the perfume of this Sardinian land and yes, even perceive the sensual pleasure of the lukewarm raindrops on my hands…inside the house! By the time I get home, I also want to smell the time and space" [8]

It took several months to finalize the design of a home that would embody the master's spatial and three-dimensional vision. Antonioni requested only a few drawings and a three-dimensional model to be observed and left on-site during construction. The house was built on the red rocks of Costa Paradiso, among the shrubby vegetation and is facing the sea (Figure 3).

The project signed by Dante Bini obtained the landscape authorization by the local Superintendency on May 25, 1970; work began after August 20 and was completed before December 21, 1970. In the realization of the house, Bini was surrounded by professional figures such as architects Maria Miniero and Eros Parmeggiani, then his studio collaborators [9].

a) *b)*

Figure 3: D. Bini, 'La Cupola', Costa Paradiso (Sassari), 1969: a) top view; b) side view from south-west

Multiple entrances allow access to the villa: one from an elevated structure, another immediately below. There are two more entrances, one from the sea side and another one from north-east. The shell is pierced by windows in facts "the openings define the visual and physical communication pathways between indoors and outdoors, radicating the building to the site" [10]. Upstairs there is also a lookout. A circular opening, through which rain water could enter and wet a small internal garden, is placed on the top of the dome. The interior walls have organic shapes and the furniture was custom-made for the villa.

The space unfolds from a circular layout and spans across two levels. On the lower level, an inner garden nestles beneath the oculus, serving as the focal point around which the living room, kitchen, bathroom, services, and additional rooms are arranged. Ascending via an aerial bridge, one reaches the entrance on the upper level, granting access to the bedrooms. The internal partitions follow the dome's shape. Moreover, the corridor connecting the bedrooms boasts an inner balcony overlooking the garden below. The garden's design evokes an organic flowerbed, likely adorned with local flora such as grass and bushes, devoid of any tree roots. The building looks like a sculptural landscape within the lush vegetation of Costa Paradiso, where windows and openings help connect inhabitants with the surrounding landscape.

The steps of the staircase, along with all the flooring are crafted from granite slabs sourced from nearby quarries. Granite is used not only for flooring, but also as the aggregate of the exterior finishing of the dome: the architect decided to mix the cement with local red granite grit to make the house harmonize seamlessly with the surrounding landscape. The materiality of Villa La Cupola distinguishes this building as a unique example among Binishells, setting it apart from all the other buildings constructed with this technique.

After his relationship with Vitti ended, Antonioni would only return to the villa sporadically. Despite 'La Cupola' being the result of a serial construction system, its presence remained exceptional until the 1980s. During that period, numerous detached villas emerged as part of the development of Costa Paradiso. This new residential area featured constructions with shared orientations, colors, and materials, aimed at integrating with the landscape while maintaining quality standards. Therefore, in the context of urban development in the area, Villa La Cupola stands as a unique example rather than a typical prototype, despite being a Shell structure that is part of a serial architecture system.

Today, fifty years after its construction and after passing through many owners, the building shows serious degradation problems related to abandonment. Increased public and scholarly attention to the state of the villa La cupola and the risk of loss, has fortunately led, in 2015, to the recognition as a cultural heritage. The dome is now listed according to the Italian Cultural Heritage and Landscape Code (D.Lgs. 42/2004), a key step that prevents owners from demolishing or altering the building. In the text of the declaration of cultural interest, the building is described as follows: "the villa is of particularly important interest due to its reference to the history of technology, in the sense of construction technology: a unique creation where an original construction system has generated a space of surprising architectural quality" [11].

Since the beginning of the new century, when the building returned to the center of attention in architecture magazines, many people went to see it although the villa is a private property. While in the past the main source of danger was abandonment, today there are also cases of anthropic degradation and damage. In recent years, the interior furniture has been stolen and graffiti has been painted on the walls. Instead of providing a path of care and preservation, the growing fame of the building is endangering its permanence.

5. Geometric and degradation survey

A drone survey with an RGB camera enabled the creation of a photogrammetric model (Figure 4a). The drone survey permitted also to check areas of the surface of the dome that otherwise would not be visible. Among these areas, there is the summit part of the dome. The photogrammetric model provides an overall view of the building through the integral representation of its geometry and material characteristics of the surface, thus enabling the acquisition of essential data for the conservation project. Furthermore, the photogrammetric model was the base for the realization of plan and side views of the construction (e.g. see Figure 4b for the plan view) and for defining the finite element model adopted for the structural analyses. The diameter of the dome is about 20 m, while its height is about 7 m.

Furthermore, a detailed degradation survey was performed starting from the in-situ survey and with the aid of the drone survey for inspecting the unreachable portions. The degradation survey results were collected in degradation maps; an example of a part of the dome is reported in Figure 5a. The structure of the dome is in good condition despite long abandonment. However, the building's location near the sea has triggered inevitable degradation phenomena over time. The most compromised elements are the exterior surfaces and finishing mortar layer which currently has gaps due to atmospheric agents (Figure

5b). Corrosive processes due to the presence of chlorides caused concrete cover expulsion particularly along the edges of the openings. Significant phenomena of deterioration are recognizable on the concrete slab of the access bridge, where the reinforcement is largely exposed to weathering.

6. Structural analysis of the dome

To better understand the structural behaviour of the dome, a preliminary series of linear finite element analyses were carried out. This type of analysis is very useful to obtain a first rough estimation of the dome's behaviour and a first assessment of the entity of stresses in particular in the cases when the material characterization is not available.

Two models of 'La Cupola' were considered: first a model without any opening (named "model 1" hereafter); then a model including the opening retrieved from the geometric survey (named "model 2" hereafter), see Figure 5. The FE-models were realized starting from the photogrammetric model using the software Rhinoceros for generating the geometry and importing it into the software Strand 7 3.1 [12] where it was meshed by adopting triangular elements. All the nodes at the base have been pinned permitting so rotations but constraining displacements in all directions. The acting loads have been assumed according to Italian technical Standard (NTC2018, [13]). In particular, the following load conditions have been considered: self-weight (the weight of the dome is of about 145 ton for model 1 and 123 ton for model 2); permanent load equal to 0.5 kN/m^2; wind load for hemispheric domes [14] that consists of a variable load with a maximum pressure in the upwind part of about 0.6 kN/m^2 and a maximum negative pressure at the top of the dome of about -1.0 kN/m^2; uniform temperature difference of 15°C. All the previous load cases have been used for the definition of load combinations (both at Ultimate and Serviceability Limit States).

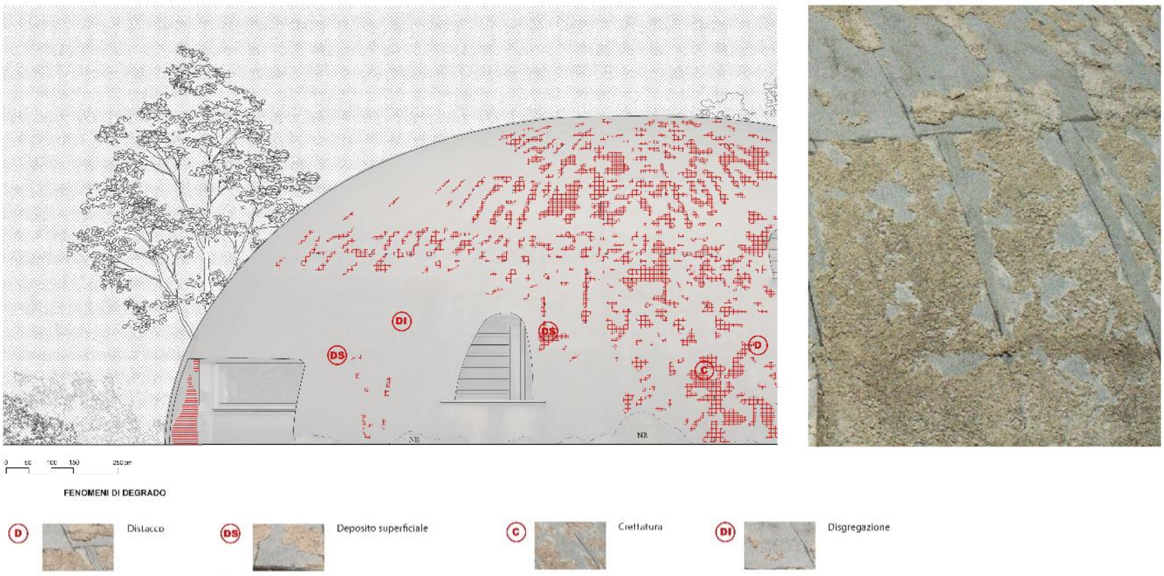
a)

b)

Figure 4: a) 3D model of the Binishell 'La Cupola' obtained from a drone survey with photogrammetric technique; b) Plan view of the ground floor.

As expected, model 1 (i.e. without openings), for the conditions of vertical load, shows results represented in (Figure 6) with compressive stresses generated radially, while circumferential stresses varying along the height with maximum tensile stress towards the base (approximately at one-fourth / one-third of the dome height), matching the analytical predictions The values of maximum tension recorded for all Ultimate Limit State combinations is of about 1 MPa, while maximum compressions are in the order of 0.5 MPa.

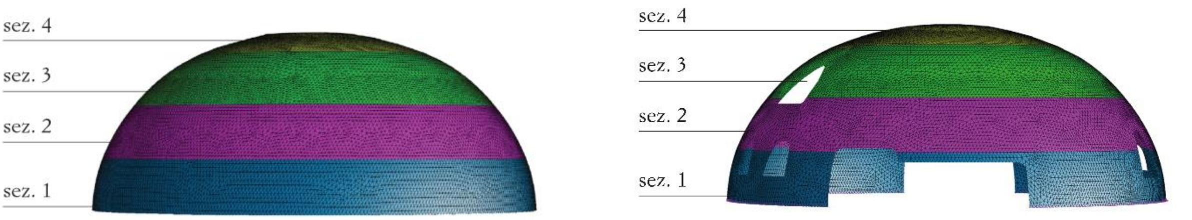
In model 2 (i.e. with the various openings present in the real dome) the results show a significant change in the stress pattern (Figure 7), since tensile and compressive stresses must deviate due to the openings made in the reinforced concrete shell of the Binishell.



a) *b)*

Figure 4: a) Example of degradation maps; b) Degradation of the finishing mortar layer, Mellone [4]

Therefore, in the vicinity of the openings, stress concentrations are observed, particularly tensile stresses, which may indicate areas prone to cracking phenomena. The tensile stresses observed are in the order of 5 MPa for the worst load combinations. In the other areas, the stress state reports rather limited values, indicating that the dome, from these preliminary analyses, is in a safe condition. It is important to note that often, in the regions of big openings, a strengthening beam containing additional reinforcing steel was included by Bini's system. It is also worth noting that a sort of slight pre-compression was induced by the deforming of spiral reinforcements during the inflation process [1], this effect was disregarded in this preliminary analysis but it is probably sufficient to avoid tensile state in the dome.



a) *b)*

Figure 5: View of finite element model analyzed: a) complete hemispheric dome; b) dome with openings. Coloured sections are named from 1 to 4 and correspond to variable thickness of the dome from 13 cm at the base to 10 cm at the top.

Finally, considering the wind action, it can be observed that zones characterized by negative pressure (assuming that wind direction is predominantly from the sea) correspond well to the portions where the phenomenon of detachments formation in the superficial layer composed of cement mortar mixed with local granite is most pronounced (see also Figure 5).

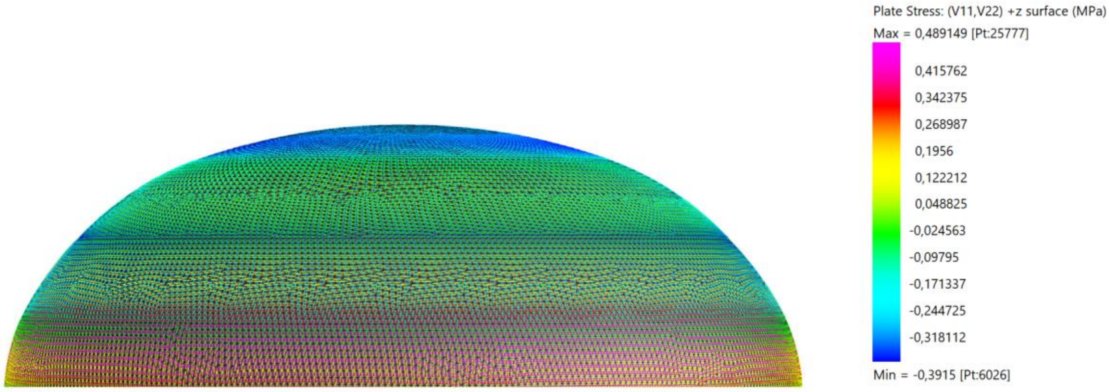


Figure 6: Principal stress distribution for model 1 for ULS combination 1 (only vertical loads) [MPa].

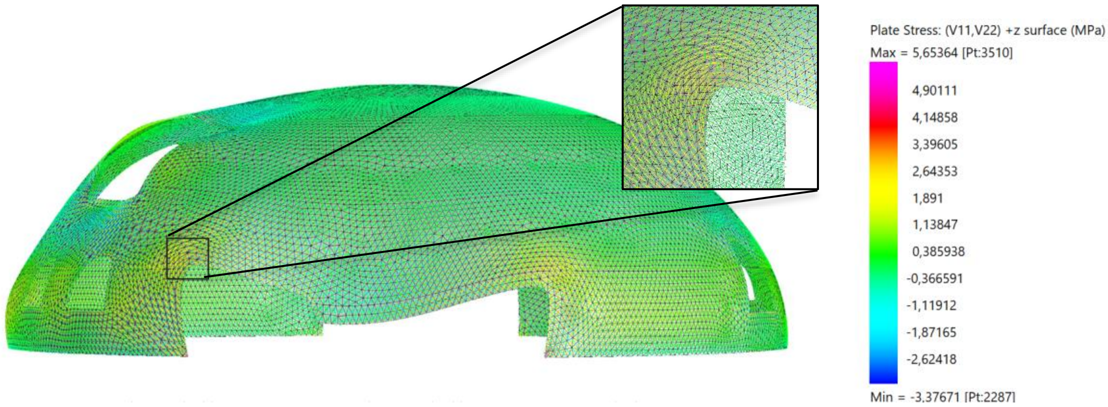


Figure 7: Principal stress distribution for model 2 for ULS combination 1 (only vertical loads) [MPa].

7. Surface conservation and protection work: some remarks

The Bini patent contains no references on how to answer the problem of impermeabilization of these buildings. Unlike the other Binishells, the decision to cover the extrados of villa La Cupola with a mortar layer mixed with granite, not only reduced the building's visual impact in the landscape, but also protected the dome from UV degradation, salt weathering and wind erosion. Surface conservation and protection work is then urgently needed to prevent the loss of the outermost layer and the exposure of the bituminous membrane, the most fragile building element to weathering.

To better understand the behavior of the building over time, and in particular the durability and the degradation phenomena of the surfaces, the research extended the investigation to other Binishells built in the Italian territory.

The first case-study is the swimming pool in Prato, completed in 1977 (Figure 9a). Although the dome has no structural damage, the bituminous membrane, not protected, shows an increasingly serious damage due to the exposure to atmospheric agents, particularly UV light.

In 1977, two other Binishells were built in Castelfranco Emilia, near Modena (9b), which have always been used as a sports facility, protected since their construction by a bituminous membrane. In 2017, due to infiltration problems from the roof, a new waterproofing layer was placed on the shells. This intervention consisted of using a thick polyurethane foam that completely hides the original finishing, altering the image of buildings and their relationship to the context.

In the case of villa La Cupola, the loss of the external layer would further compromise its image and identity, as would the addition of new layer to ensure that the membrane does not remain exposed to weathering. The conservation of the cement mortar and red granite finish is crucial for understanding Dante Bini and Michelangelo Antonioni's vision. Whether the waterproofing of the domes in Prato and Castelfranco Emilia responded to technical problems related to rainwater leaking, the conservation project dedicated to a modern monument such as villa La Cupola must contemplate both technical requirements and cultural instances of preservation.

a) *b)*

Figure 8: a) Indoor swimming pool designed with the Binishell construction method in Prato (1977); b) ‘Le Cupole’ sports facility, Castelfranco Emilia (Modena) (1977); pictures from Mellone [4].

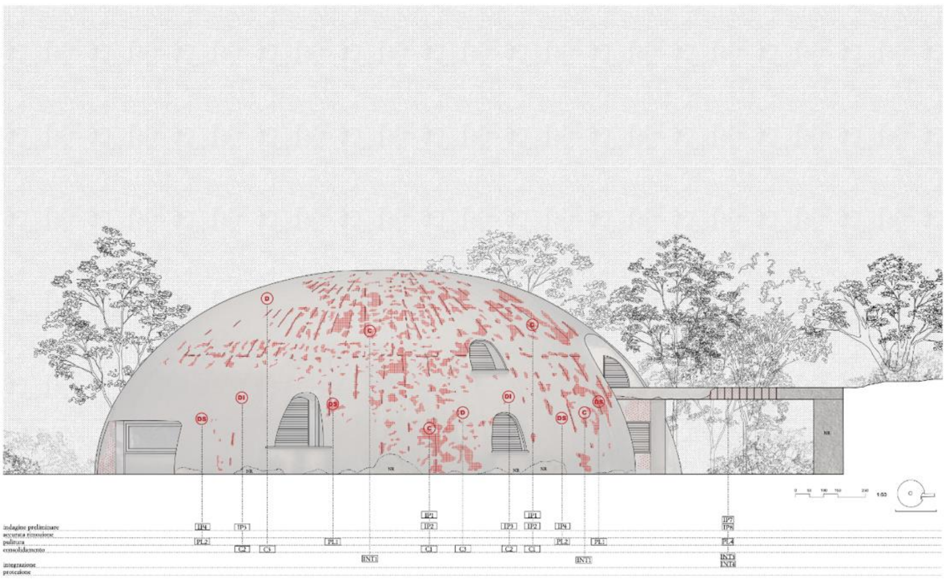


Figure 9: Degradation map and intervention proposal, Mellone [4].

For this reason, the research suggests a multilevel proposal capable of orienting the emergency intervention on the building, also providing the background documentation useful for the drafting of the conservation plan. The first choice is related to the compatibility of the materials used in the conservation work. In some areas, the external mortar layer is completely lacking, leaving the sublayers unprotected. The integration of these gaps requires preliminary investigations aimed at determining the specific hue, clarity, and color saturation of the finishing mortar.

This is followed by integration using a polymer-based mortar. The use of a different material serves to fill where there are gaps in the finishing mortar, improving performance and at the same time also giving a different texture from the original. In this way the different texture is perceived respecting the image of the villa from afar, instead upon closer examination this new polymer-based mortar becomes recognizable. This approach stems from a culture rooted in respect for the ‘materia signata’ [15], meaning that after identifying what should be preserved for the future, every part of original material must be conserved rather than replaced.

8. Conclusions

In this work, a methodological framework is proposed for the analysis of modern dome heritage constructions. Specific reference is made to the Binishell system and a comprehensive knowledge path permitted to obtain some information related to the actual state of the construction analyzed as a case study. Preliminary linear finite element analyses show that the dome maintains a stable structural condition despite its age and exposure to environmental factors, which instead affected much more the surface coating.

The Binishells built around the world represent such a vast heritage that it is unlikely to be fully preserved over time. However, the research outcomes are intended to provide theoretical and operational tools for the analysis and the preservation of other modern domes, part of the legacy of Dante Bini's experimentation in 20th-century architecture.

References

[1] D. Bini, "Expandible reinforcement structure for inflatable domes", patent no. 3686818, USA, June 1972.

[2] D. Bini, "*A cavallo di un soffio d'aria. L'architettura autoformante"*, edited by G. Dioguardi, Guerini e Associati, Milano, 2009 (in Italian)

[3] R. Koolhaas, Monditalia. In: *Fundamentals: Architecture Biennale 2014*. Exhibition catalog, Marsilio, Venice 2014, p. 378 (in Italian)

[4] The Cádiz Document - InnovaConcrete Guidelines for the Conservation of Concrete Heritage, art. 5 Develop Sustainable Repair Approaches and Policies, ICOMOS International, 2021, p. 25.

[5] D. Bini, *Mechatronics*, edited by A. Pennacchio and G. Ricci, Postmedia books, Milan 2016 (in Italian)

[6] G. Mellone, *La Cupola. Conservazione di una Rovina Moderna*, Master Thesis, Venezia, 2022 (in Italian).

[7] G. Morelli, *Cassaforme pneumatiche per la costruzione di cupole in cemento armato*, L'Industria Italiana del Cemento, p. 461, June 1978 (in Italian)

[8] Lecture "*L'architetto e il regista*" (The architect and the director), held on July 22, 2019 at Giardini Margherita in Bologna. Accessed: March 25, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=0FRZ_8KztNo

[9] Ministry of Culture, Superintendence of Fine Arts and Landscape for the Provinces of Sassari and Nuoro, Declaration of Cultural Interest of Villa Antonioni in Costa Paradiso, 2nd September 2015.

[10] A. Pugnale, A. Bologna, *Architecture Beyond the Cupola. Inventions and Designs of Dante Bini*, Birkhauser, Basilea 2023, p. 132.

[11] Ministry of Culture, Superintendence of Fine Arts and Landscape for the Provinces of Sassari and Nuoro, *Declaration of Cultural Interest of Villa Antonioni in Costa Paradiso, pursuant to Italian Cultural Heritage and Landscape Code* (D.Lgs. 42/2004), art. 10, paragraph '3', letter 'd', and artt. 13-14, 2nd September 2015 (in Italian).

[12] Strand7 release 3, Strand7 Ply Lts, Sydney, Australia.

[13] MIT, Aggiornamento delle "Norme Tecniche per le Costruzioni" NTC18, 2018 (in Italian)

[14] National Research Council of Italy, *Guide for the assessment of wind actions and effects on structures*, CNR-DT 207/2008, Rome, 2010

[15] Cf. R. Codello, R. Masiero (edited by), *Materia signata-haecceitas tra restauro e conservazione*, Franco Angeli, Milan 1990.