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Lightweight structures applied for the conservation of cultural heritage: two case studies in Pompeii, Italy

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Abstract

The paper focuses on applying ultra-lightweight structures to conserve and recover built heritage through interventions designed to reinforce its cultural significance and preserve its delicate conditions for the benefit of future generations. Analyzing the technical requirements of heritage coverings, membrane structures emerge as widely used technological solutions due to their employability, transformability, adaptability, and lightness. These characteristics make them suitable and innovative systems for applications to buildings and ruins with delicate and highly valued structures.

Keywords: cultural heritage, lightweight structure, membrane architecture, modular design.

1. Introduction

Cultural heritage requires interventions that must respect and keep the character of the place and its tangible and intangible values, recognizing and enhancing its cultural value. Working on historical structures calls for minimum contact of the existing buildings and ruins to keep the tangible value and integrity of its elements. The fragile state of the structure requires light interventions in both appearance and load bearing systems. Exhibition and preservation are the central pillars of this study, around which each aspect of the proposal is carefully constructed.

Two specific case studies, 'Casa di Orione' and 'Casa del Giardino', situated inside the archaeological site of Pompeii, Italy, stand as examples of built heritage requiring an integral intervention that recognizes its historical value while ensuring its usability. Within the planned interventions from the Pompeii Superintendence for the conservation of the site, this research initiative exploits the fundamental qualities of membrane systems to protect and conserve the Roman ruins and provide spaces with ideal physical and spatial conditions.

The innovative cover systems create a symbiotic relationship between technological advancement and preserving historical and cultural values. In both projects, the technological aspects aim to minimize the impact on the historical asset by proposing modular design solutions that are fast to assemble and completely reversible. The membrane layers reflect the direct sun radiation and spreads diffused light into the atriums.

The objective of the presented design research is to demonstrate how adaptability and transformability capacities of the membrane systems can generate rapid solutions to preserve the cultural heritage. Due to their lightness and reversibility, these solutions are adaptable to protect both temporary excavation and permanent exhibitions. Due to the standardized modularity, the design kits can be implemented in the adjacent domus, following the progressive restoration of the site.

2. Casa di Orione

2.1. History and State of the Art of the Ruins

2.2.1. Historical Context

'Casa di Orione', situated inside the archaeological site of Pompeii, Italy, takes its name after the two mosaics found inside the house during the last excavation in December 2018. [1] Its architecture corresponds to the historical Roman typology of a 'domus' with an atrium, of the type 'cavaedium tuscanicum', which presented a central opening on the roof called 'compluvium' situated exactly on top of a basin on the floor, that collected rainwater, called 'impluvium'. [1]

The atrium, the most public and important space of the house, held the public affairs of the Roman family (social, political and business). [2] The hierarchy and importance of this space were highlighted by its decoration. The decoration is of the first style, with stucco frames and paintings. The floors present decorations of high historical value. [3] Among the decorations uncovered, there are two mosaics, representing the myths of Orion, and three geometric cryptographs [1] (Fig.1).

Figure 1: Wall paintings, mosaics and ceramics found in 'Casa di Orione'. [3]

2.2.2. Current Situation

Despite the high cultural and historical value of 'Casa di Orione', the state of the art of the ruins does not reflect its importance. The lack of preparation has led to choosing a temporary structure, a metallic roof supported on scaffolding, that has become permanent with time and lacks any consideration of design, integration with the built heritage, and optimization of the internal conditions.

The invasive scaffolding structure has taken attention from the decorative elements and prevented a proper exhibition of the heritage, resulting in an improvised, unattractive, and risky exhibition space (Fig. 2). The metallic roof is not the proper cover for a site situated in the south of Italy with elevated levels of radiation. It accumulates radiation, which is transmitted inside, preventing any enclosing of the ruins to avoid elevated levels of temperature in the interior spaces.

Figure 2: Current situation of 'Casa di Orione'. [3]

2.2. Design process

2.2.1. Conceptual Approach and Objectives

The lightweight system focuses on the protection of the built heritage while enhancing its historic geometry and typology [4]. The atrium will be emphasized as the hierarchical multifunctional space of the house, welcoming visitors, performers, and archaeologists. The atrium of 8,93 meters long and 7,44 meters wide, will 'rise' from the ruins forming a higher central space in comparison with the surrounding rooms. However, it will not reach the maximum height according to Vitruvian rules of proportion, to respect the height of the surrounding built heritage in the urban context (Fig. 3).

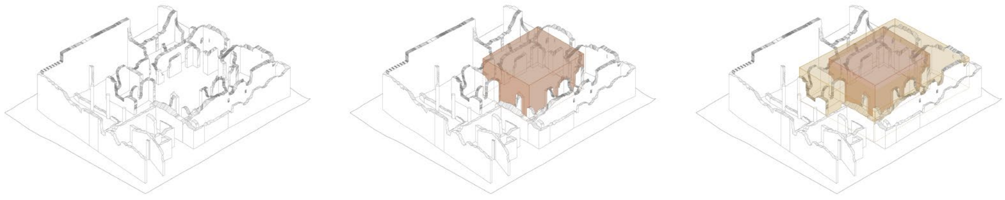

Figure 3: Volumetric approach. [4]

The new cover has four main objectives: 1. Present no intermediate supports and anchoring points reaching the ground. 2. Lightweight non-invasive system with minimum impact on the masonry structures. 3. A fast assembly system with a long-lasting lifespan, but completely reversible if needed, leaving no trace of intervention. 4. High reflecting material capacities, to protect from direct radiation and achieving interior spaces with high thermal comfort in terms of temperature, humidity, and illuminance for both conservation and exhibition of the heritage value.

The atrium and adjacent rooms will present different lightweight systems exploiting their specific performances. The atrium will be covered with a hybrid lightweight structure known as tensegrity system, a self-standing structure composed of compression members (flying masts) and tensile members (cables and membranes) [5]. The adjacent rooms will be covered by a hybrid active-bending system with flexible aluminum profiles that achieve stiffness due to the curved shape acquired by the flexural force applied on the fixed points of support [6]. The hybrid system is composed of flexible curved frames and membranes that creates homogeneous internal microclimate that aims solely on the preservation of the heritage found inside.

2.2.2. Form-Finding: A Reflection on the Historical Typological Roofs of Ancient Rome

The form-finding process for the lightweight cover of the atrium starts with a mono-module tensegrity system creating a 'basilica' shaped roof. By duplicating the base structural configuration, the 'cavaedium tuscanicum' typological form is achieved. Following the tripartition axis of the existing walls, a segmented roof that recovers the ancient geometric form is achieved by implementing a secondary tensegrity structure. The secondary tensegrity structure is then replicated into smaller segments creating a multi-module cover reflecting on the 'cassettonato' composition of the ancient Roman roofs. The cover keeps the central segment open recovering the ancient function of the 'compluvium', reinforcing the vertical axis of the atrium (Fig. 4).

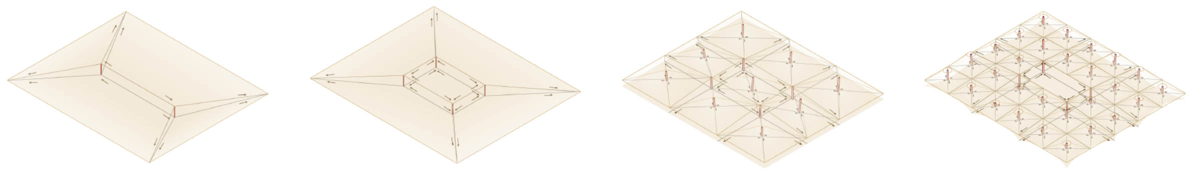

Figure 4: Form-Finding iterations for the atrium cover. [4]

The different iterations are explored in a parallel process between parametric software (Rhino and Grasshopper) and the fabrication of scaled maquettes made of nylon mesh and nylon fishing line. This experimental process verifies the structural behavior and feasibility of the tensile system.

2.2.3. Performance-Driven Generative Design: Energy Performance and Solar Design

By means of different Grasshopper parametric tools (Ladybug, Honeybee and Galapagos) the form achieved on the typological study is improved considering different thermal and environmental parameters such as radiation levels, temperature, humidity and illuminance levels. The design process follows an innovative framework in which performance-driven analysis and design are proposed in an initial step in the form-finding process.

The cover system for the atrium is composed of independent 'flying masts' that extrude each segment of the membrane upwards (Fig. 9). By implementing a ring of polycarbonate at the end of the 'flying masts', each quadrant has the capacity to bring beams of light inside for sensorial purposes (Fig. 5). The central opening allows for natural ventilation of the atrium which will provide a natural interior micro-climate, adequate for the conservation of the heritage.

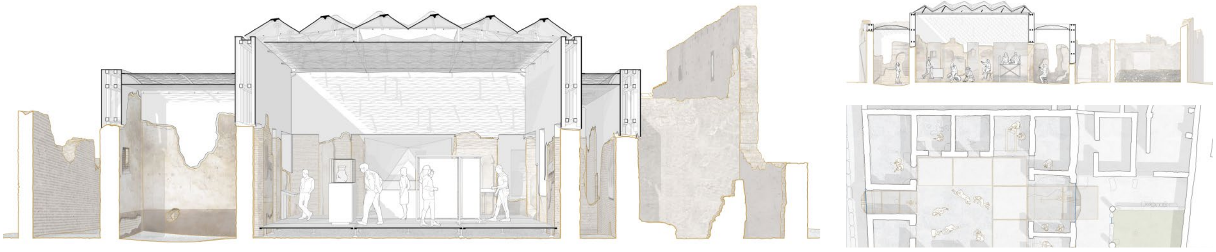

Figure 5: Tensegrity and bending-active cover systems. [Designed by author Endara Vargas]

One of the main objectives of the new cover is to control the direct solar incidence to protect the frescoes and mosaics inside as well as the visitor's comfort. The tensegrity system again provides the solution. By controlling the orientation of the 'flying masts', through algorithmic analysis, natural light can enter the atrium without compromising its thermal comfort levels. Using Grasshopper parametric tools, the orientation of the 'flying masts' is studied, selecting all the possible orientations with adequate thresholds of temperature (18-20 °C) [7] and humidity (40-60%) [7]. By cross-referencing these results with annual radiation, a deeper selection is achieved (Fig. 6). Finally, the study of the solar path provides the definite orientation which achieves adequate levels of comfort without compromising the form and functionality of the mesh (Fig. 7). The rotation of each 'flying mast' in relation to the sun's direction to define the final form of the lightweight system combines the benefits of both the tensegrity structure and the membrane physical attributes.

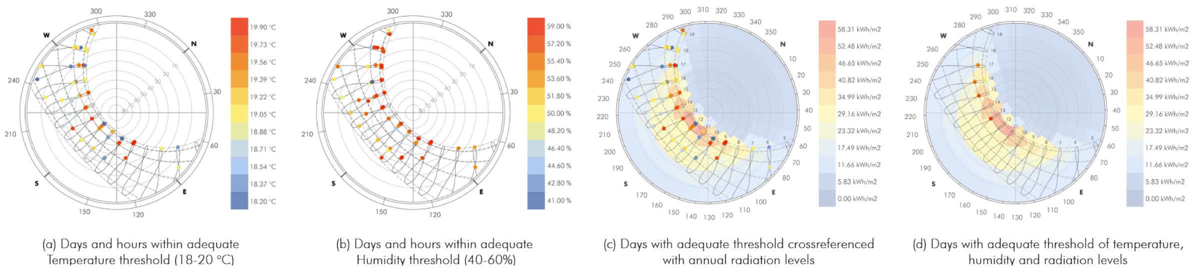

Figure 6: Thermal comfort thresholds analysis using Ladybug. [4]

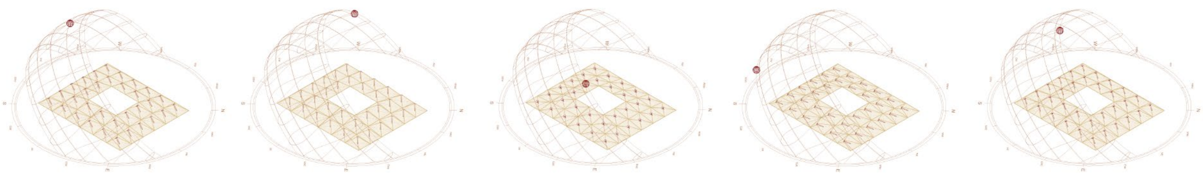

Figure 7: Solar path analysis using Ladybug. [4]

The central opening and the levels of illuminance in all the rooms still need to be controlled. To achieve correct levels of illuminance (50-150 lux) [8] and protect the atrium from the sun incidence coming from the central opening, the combination of double membranes is studied using Grasshopper, Honeybee and Galapagos parametric tools. At this step, the combination of PTFE Type II, with a reflectance of 78% and a transmittance of 15%, and ETFE foil, with 80% pattern printed, [9] are studied in different combinations to achieve adequate levels of solar protection and illuminance for the preservation of the heritage (Fig. 8). The double-layered membrane systems, combining PTFE membranes and ETFE foils, permits the application of different, yet complementary physical capabilities.

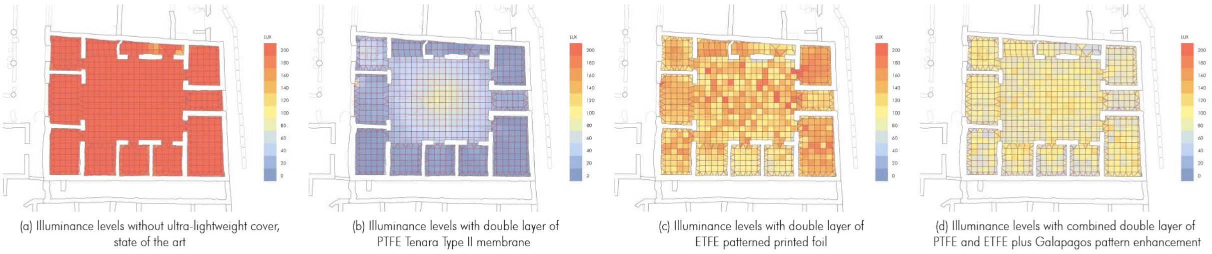

Figure 8: Illuminance analysis using Honeybee and Galapagos. [4]

2.2.4. Fast Assembly and Reversibility Anchoring System

The reversibility of the lightweight structure proposes the least possible contact with the existing walls. The tensegrity system is anchored on a perimetral steel profile through plates and turnbuckles hidden from the ground view, so the system is 'floating' over the atrium (Fig. 9). The perimetral profile also works as a rain collector along the perimeter. This steel ring is supported by four pillars on the corners of the atrium, connected to the existing masonry by steel plates (Fig. 9). These are the only points where the new structure meets the existing walls (Fig. 9). The bending-active structure of the adjacent rooms has a simpler anchoring system composed of flexible aluminum profiles connected to steel plates and fixed keder clamps (Fig. 9). The lack of adequate working space for the installation and maintenance is the main design premise in choosing this anchoring system.

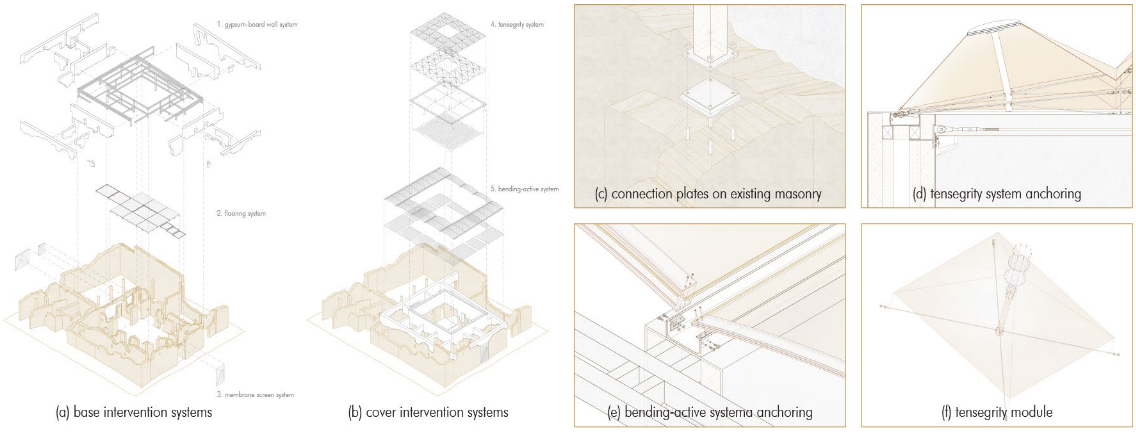

Figure 9: Assembly, anchoring and connection details of the tensegrity-membrane and bending-active systems. [4]

2.2.5. Spatiality and Interior Design

Every design aspect of the lightweight cover systems for 'Casa di Orione' focuses on creating deep connections with the history of the ruins, enhancing it in the process. The interventions consider 'Casa di Orione' as a 'living knowledge system' intervening the built heritage without harming the authenticity of the site. The lightness, flexibility, and physical capabilities of the novel structures improves the state of the built heritage with long-term and fast-assembly solutions, and with 'superficial' physical interventions.

Figure 10: Spatial qualities of 'Casa di Orione'. [4]

3. Casa del Giardino

3.1. History and State of the Art of the Ruins

The second case study focuses on 'Casa del Giardino', another Roman house in Vicolo dei Balconi as 'Casa di Orione', brought to light during recent excavation works between 2018-2020. The design focuses on 'Casa del Giardino' since it is an accurate example of an archeological building with historical, cultural, and architectural significance that needs conservation and preservation interventions [11]. 'Casa del Giardino' is an irregular house with a rectangular atrium eccentric in relation to the entrance and a porch decorated with a floral pattern that blends in the passage from a closed environment to the big open garden, from which the Domus takes its name. It was supposed that in the second century BC its plan was more established with an 'atrio tuscanico', that was successively removed. The atrium became smaller to host a frescoed tablinum with a refined female portrait showing the domina of the house [10]. Another important feature of the house is an inscription in the atrium, a tangible trace of ancient Roman daily life that was particularly interesting since it supports the theory that Vesuvius erupted in October and not in August. The inscription reported a date corresponding to the sixteenth day before the calends of November, the 17th of October. Since the graffiti was written using charcoal, a fragile and evanescent material which could not have been able to last long, it is highly probable that Vesuvius' eruption occurred on the 24th of October in 79 AD. The house was undergoing renovation works at that time, so the inscription cannot be related to the previous year [10].

3.2. Design process

3.2.1. Conceptual Approach and Objectives

The project consists of a lightweight protective canopy over the space of the atrium, a boardroom for the guests which usually was open-air and elegantly decorated to fulfill its public and representative soul. In this extraordinary architectural and historical context, the novel canopy of 'Casa del Giardino' is conceived as a non-reconstructive partial coverage. As Minissi explained, non-reconstructive partial coverages use modern or traditional materials, the elevations are permeable, and they respect the museological requirements for tourists' enjoyment [12]. From the preservation point of view, the satisfaction of the protection requirement results one of the main objectives since protection is useful to respect the character of the place and its tangible and intangible values; the ruin lasts to be a "semiophoric truth" [13], and continues to convey a message to society so that future generations will endure having access to the full richness of cultural heritage in the archeological site.

Other criteria that followed during the design process are the idea of the minimum intervention, without a significant impact on the ruin regarding weight and visual perception, and the reversibility, as suggested by ICOMOS ethical and technical guidance [14]. The Athens Charter of the CIAM appeals to the contrast value to seek a new perception and mutual dialectic within ancient and modern not only in colors and construction materials but also in the different shape and arrangement of the new elements, thus differentiating from the original while safeguarding its "patina", its stratified sign of time [15]. Following these objectives, the choice of juxtaposing a lightweight structure, with translucent textile, to the massive structure of the ancient ruins, emerges as particularly suitable for meeting the criteria for a new protective structure in an archeological site [16,17].

From the architectural point of view, given the extraordinary context of Pompeii, the design focuses on the capture of its classic soul made of architecture, proportions, visual relationships and shadows, and to reinterpret it with the design of a contemporary lightweight structure. The first reference recalled is the Neue Nationalgalerie by Mies Van der Rohe, whose structure can be interpreted as a classic pavilion for its proportions and composition. Phyllis Lambert, in his book Mies in America, recognized its ties to the classical language, calling it "a modern temple, whose monumental simplicity evinces the immense skill behind its design and conception" [18]. Thus, the canopy reinterprets the structural composition of a classical temple, whose main elements are the columns and the trabeation. A grid made of beams is laid on 8 pillars arranged on the ruins of the two domus symmetrically but keeping the angles free.

Since the aim is to design a new ceiling without any purpose of philological reconstruction, but trying to dialogue with classicism, another reference is the citation of a typical classical element, the lacunaria, also called a coffered ceiling. This architectonic feature must have been a rather common solution in medium and high class homes to hide the structural beams, as it is suggested by the collection of visual and written reconstructions of a roman atrium, including a chromolithographic plate from the Essais de restaurations des principaux monuments de Pompéi (1900) or a fresco from Villa dei Misteri located in Pompeii, both depicting a coffered ceiling covering an atrium. Recalling it, we used textile elements shaped and composed to form a coffered ceiling, to give the suggestion of the interior of a roman atrium.

Proportions and modularity have also been the subject of the research. The module of the covering is based on the golden ratio proportions of the atrium by subdividing its width by 12, as in the ancient roman period, an integer number of feet was preferably divided by 6 or by 12 to return more easily through proportional submultiples [19]. Modularity is a good criterion to consider since the design of pieces assembled in modular sails allows different configurations based on the identified needs and optimizes the packaging and transportation on the site. A common denominator can make the new architectural system reproducible and eventually extend this approach to future roman excavations [20]. Following this mathematical and geometrical criteria is interesting because in this way the new structural frame converses with the ancient structure of the domus and with the partition of its frescoes. The result is a squared module of 0,97 x 0,94 meters that constitutes a grid of 8 x 12 meters for the atrium of 'Casa del Giardino'.

Another important choice is the color for the canopy that derives from the reading of Francesco dal Co's book Francesco Venezia e Pompei: l'architettura come arte del porgere in which the staging for the Neapolitan section of the exhibition Pompei e l' Europa in the Sala della Meridiana was described. One of the blow-ups exposed was Paul Klee's Urnenbild considered by Francesco dal Co "Conseguenza del riaffiorare di un ricordo maturato da Klee diciannove anni prima" when he visited Pompeii [21]. Klee used colors that remember Pompeian paintings and those colors were used by Francesco Venezia for the linoleum panels of the exhibition. Therefore, shades of pink are proposed which remember cocciopesto, a mixture of lime and ceramic fragments that was accurately smoothed, used in 'Casa del Giardino' on the coverings of the atrium (Fig. 11).

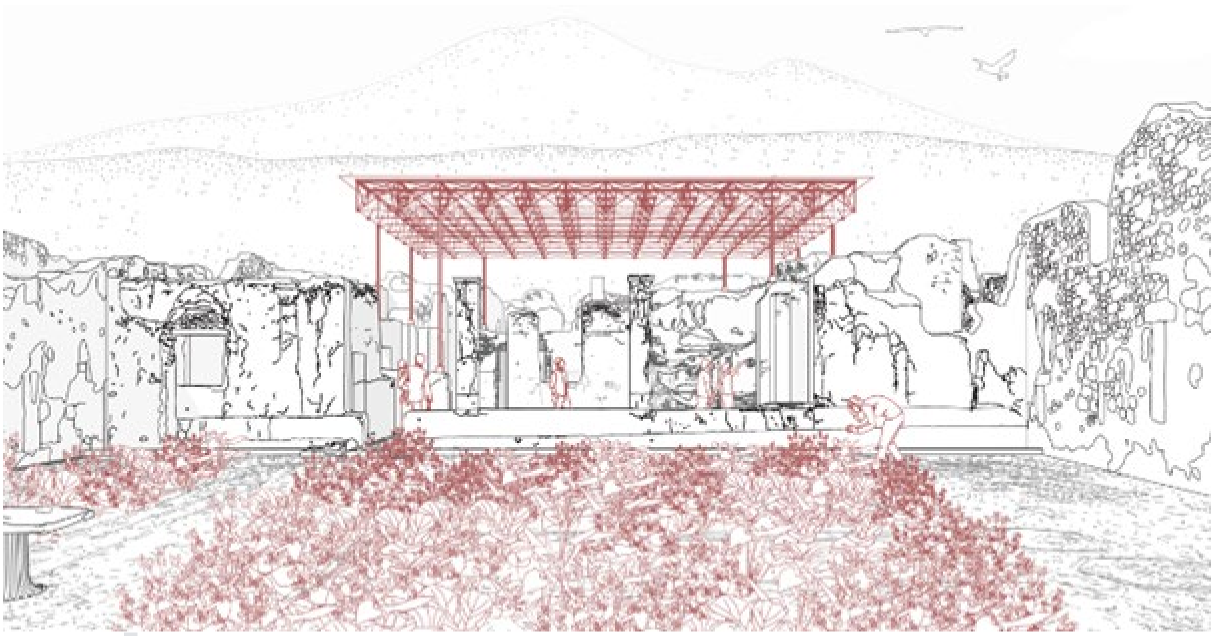

Figure 11: Perspective view of 'Casa del Giardino' from the garden, showing the protective canopy upon the atrium [11]

3.2.2. Reversible Design System

After discussing the preliminary design and exploring the architectural choices of the canopy, it is necessary to examine the technological and detailed aspects to achieve the lightness of the structure using fiberglass as the main structural material and textile membranes for the coverings. It is important to underline that the analysis, diagnosis, restoration and consolidation activities will not be discussed in this paper, as well as the project engineering. Starting from the joint between the existing walls and the vertical supports, the detailed design focuses on a reversible base made of a removable cast-in-situ lime cube, to which a stainless-steel plate is anchored via anchor bolts. The stainless-steel plate is welded to a circular stainless-steel tubular profile with a threaded anchor rod, which is the connection with the vertical supports. Between the existing masonry and the removable lime nut, a leveling plan is needed because of the extremely rough surfaces. Compatibility, removability, and reversibility of an intervention are additional aspects to consider to the greatest possible degree. The use of removable lime, namely a cement-free lime, allows interventions on archaeological structures without attacking them and allowing the layer to be removed when needed.

The vertical pillars have a square T-slot section and are made of fiberglass. The T-slot section is taken from the aluminum profile manufacturing industry, and it is chosen to achieve the highest level of adaptability, flexibility, and reversibility. This type of profile permits all vertical elements to be prefabricated without holes or welding allowing versatile dry connections. This is possible thanks to the grooves, which enable the connections to be bolted and hidden inside of them. The hiding of the connection between elements is also possible thanks to the shadow generated by the grooves. This is interesting because columns' flutes and fillets are highlighted in classical architecture by shadow. T-slot frames also allow for quick assembly, disassembly, and reuse, being easy to move or modify as needed. These types of profiles are also used for the struts and the upper two-dimensional grid, but in different shapes and sizes. Concerning the material, fiberglass is a type of fiber-reinforced plastic made of glass fiber (GFRPs). Fiberglass-reinforced Polymer is preferred compared to stainless steel because of the better material qualities. The most important characteristic to consider is that fiberglass is almost four times lighter than steel, more precisely fiberglass density is 2000 kg/m3 while steel density is 7800 kg/m3 [9]. At the same time fiberglass is stronger than steel, and it has a high strength to weight ratio. Another important characteristic to observe is the corrosion resistance, fiberglass is more resistant to corrosion if compared to steel, a material predisposed to corrosion. In addition, we must underline the predisposition of fiberglass to manufacture complex shapes, which is the right characteristic to produce T-slot aluminum-derived profiles in GFRP. Lastly, fiberglass has an average life span longer than steel. A significant detail is the element that connects T-slot profiles between each other: the component designed is an anchor nut connector which can allow from two up to six fixing ways according to the needs, being extremely flexible and adaptable. These connection elements, together with all the other joint components, are made of stainless steel.

The struts and the two-dimensional grid are the elements that compose the upper layer of the roof and they are the anchoring bases for the coffered membrane system. This small textile module is pulled at the upper points by stainless steel tie rode cables, and at the lower points by polyester webbing belts, until reaching the coffered shape desired. The membrane is translucent elastane, also called Lycra, a highly elastic synthetic fabric. The upper layer of the roof is covered by a second layer of textile membrane to meet the water-tight feature, along with more positive microclimatic conditions given by a double-layered system. This second film presents a single central pole solution, which allows the membrane to have the minimum slope for the water to flow to the gutter system that runs along all the sides of the roof and where the perimeter of the membrane is anchored. Because of the characteristics required, the material of the second membrane chosen is a translucent PVC-coated polyester fabric. Polyester-PVC is commonly used for tensile architectures because of its mechanical strength and flexing resistance. It is also one of the least expensive membrane materials available on the market [9]. The water drains through gargoyles that protrude from the structure and they are positioned in points considered adequate for the fallout of the water. Since they are placed in rooms that were undergoing renovation activities at the time of the eruption, no coatings are present on the pavements, therefore the terrain is permeable. The protrusion of the gargoyles is camouflaged by a strip of membrane material along all the sides of the structure, which hides both the gargoyles and the gutter system. To obtain a higher level of safety, the entire structure is stiffened by a bracing system made of stainless-steel crosses along the entire perimeter, both vertically and horizontally (Figg 12-13).

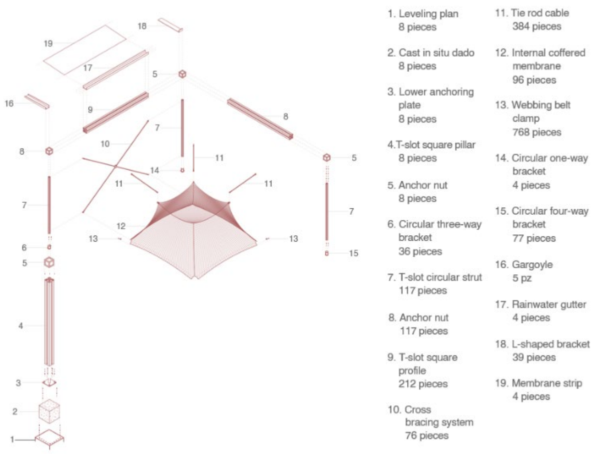

Figure 12: Assembly Kit of the modular structure [11]

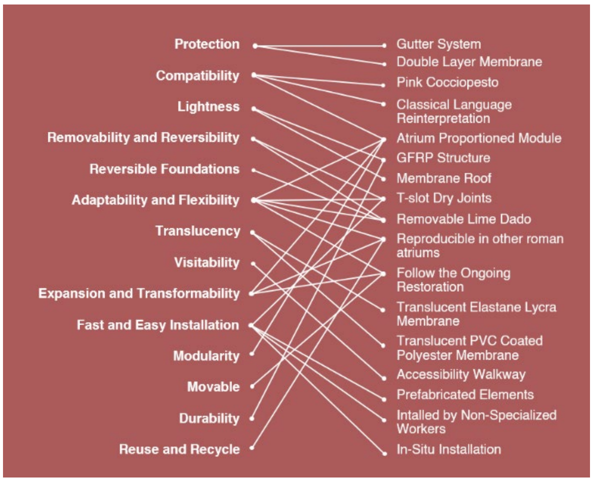

Figure 13: Design Criteria Brief [11]

3.2.3. Fast Assembly Process

Since the design concerns an archeological site, the entire construction process is defined in advance to preserve the archeological remains during the construction phase and to obtain a fast and easy installation. A shelter inside an archeological area should be quick to assemble and dismantle because the structure must follow the future developments of the excavations. Due to their lightweight standard modules, the proposed solution can be directly mounted by unspecialized people, thus permitting a considerable cost reduction.

Most of the elements designed can be assembled outside the archeological site in a previously identified area next to the 'Casa del Giardino' such as the excavation front. To have a general overview, the fabrication process can be analyzed as follows. The first phase for the construction works happens in factories where the fiberglass-reinforced polymer pillars, beams, and struts are extruded, the steel elements are prefabricated, and the membranes are produced. Then all the components are packed and transported, including the membranes, which will be folded or rolled for transport. As said before, the first phase of assembling the main bidimensional components through the appropriate joints will happen in the northern embankment area. First the assembling of the two-dimensional grid made of T-slot square profiles and the anchor nuts, secondly the addition of the cross-bracing system in the horizontal direction, and thirdly the setting up of gutters, gargoyles, and L-shaped brackets, is done. Once the grid components are arranged, the second layer of PVC-coated polyester fabric can be placed in position and then tensioned until anchored to the gutters' system. Immediately after this first phase, the second begins with the preparation of the existing masonry walls, particularly with the setting of the eight support points consisting of the casting of the leveling surface and the removable lime cube. Then, the structure is lifted, using a light-lifting machine positioned over the embankment, moved, and positioned in its correct location upon the pillars. At this point, the third phase can start with assembling the three-dimensional secondary components, first the vertical struts and then the cross-bracing system in the vertical direction. Once arrived at the assemblage of all the components, the last missing piece is the coffered elastane membrane system, first tensioned at the upper points and then at the lower points.

4. Conclusion

This contribution focused on the complex relationship between cultural heritage preservation and the need for additional protective structures. Frequently, the conservation of built heritage buildings and ruins requires design interventions that must respect and keep the character of the place and its tangible and intangible values recognizing and enhancing its cultural and historical value. The research initiative exploited the fundamental qualities of membrane structures to protect and conserve the ruins, and in the process, providing the spaces inside with optimal physical and spatial conditions for flexible functionality. In both design projects, technological aspect meticulously aimed to minimize the impact on the historical asset by proposing a permanent design solution that is both fast to assemble and completely reversible if needed.

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