Pneumatic concrete laminar structures revisited. A singular architectural structural type

Estructuras laminares neumáticas de hormigón. Revisitando un tipo arquitectónico estructural singular

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Abstract: The 20th century was a time for architectural change, technical innovation and the search for affordable construction and prefabrication. In this context, pneumatic concrete laminar structures represent the advances towards a new architecture that could give answers to the challenges of the century. This work identifies the systems that were explored during that period and describes the experimental designs developed by W. Neff, H. Heifetz, H. Isler, D. B. South and D. Bini. In addition, the adaptation capability of this singular type and the reasons that caused the abandonment of these structures are also analysed.

Keywords: pneumatic structures; concrete laminar structures; architectural structures; structures and heritage; structural type.

Resumen: El siglo XX estuvo marcado por los cambios arquitectónicos, la innovación tecnológica y la búsqueda de técnicas de prefabricación y construcción asequibles. En este contexto, las estructuras neumáticas laminares de hormigón representan los avances hacia una nueva arquitectura que pueda dar respuesta a los desafíos de la época. El presente trabajo identifica los sistemas creados durante este período y describe los prototipos experimentales desarrollados por W. Neff, H. Heifetz, H. Isler, D. B. South y D. Bini. Por otra parte, se analiza también la adaptabilidad de este tipo estructural singular y los motivos que causaron el abandono de su aplicación.

Palabras clave: estructuras neumáticas; estructuras laminares de hormigón; estructuras arquitectónicas; estructuras y patrimonio; tipología estructural.

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PNEUMATIC CONCRETE LAMINAR STRUCTURES: ARCHITECTURAL AND TECHNICAL EVOLUTION

The search for an architectural construction that responds to the concepts of adaptability, quick assembly and, building and economic efficiency has been the base for investigating and exploring new structural forms. This interest, and the necessities of the second half of the 20th century, were the starting point for the development of pneumatic concrete laminar structures. The type unifies the characteristics of air prestressed membranes designed to work in tension and, the tectonic properties of concrete laminar structures (Figure 1).

From theory to practice

During and after the World War I, building hospitals, accommodation and different temporary constructions quickly was paramount. In that period, architects and engineers explored lightweight constructions using pre-stressed concrete, steel bars or textile.[1] In this context, it is considered that the first attempt to use inflatable structures to this purpose was made by Frederick Lanchester. The first conceptual prototype was patented in 1917 and, although it was never built, it provides the basis for later pneumatic structures. The design consists of tents that can be erected by adding air that is maintained at a certain pressure. Since there was no need for poles or other building supports, both the materials and labour needed for their construction were reduced. This allowed for a more cost-effective construction.[2]

It was not until 1946 when Walter Bird experimented with the concept of these pneumatic structures and developed the first prototypes. This first construction consisted of an air supported radome, the first of its kind, to protect antennas from extreme climate conditions.[3] After this experience, Bird focused on exploring the feasibility of these pneumatic system and its application to large-scale projects.

While Bird manufactured his designs, Wallace Neff was also introducing the use of these "bubble" structures for the construction of homes and public buildings. However, his system introduced the use of these pneumatic membranes as formworks on which metallic reinforcement was placed and concrete sprayed. This method reduces the cost and systematise its production.[4] Neff provided improvements to the prototype, presenting two new patents in 1945 and 1952.[5]

In the early 1960s, the architect Dante Bini started developing an innovative design for pneumatic structures. This innovative type was patented in 1969, and it represented an important difference respects the previous systems: the "bubble" construction was executed on a flat surface and then, while the sprawled concrete hardened, it was lifted by means of air at a certain pressure.[6]

Following the structural type patented and developed by Neff, many architects and designers experimented with new materials and changes in the way of building the structures. Thus, while Bini worked on his Binishells, in 1972 H. Heifetz implemented changes to the proposals of Neff. He added a base ring, in which tensioned cables were anchored transversely, to prevent deformations in the structure that may affect load distribution.[7] In 1975, the designers Isler and F. Prouvost presented new innovative solutions. Isler's first contact with pneumatic shells was their use as rooftops of industrial or large-scale buildings.[8] However, Isler began to explore the feasibility of assembling the base of the construction without anchorages. Prouvost shared that same interest, and his patented system was used in some of Isler's project, developing and improving it.[9]

In 1979, D. B. South focuses on the materiality of the pneumatic structures and tested the differences between materials and their layering location within the construction.[10] Moreover, in the 1990s, South

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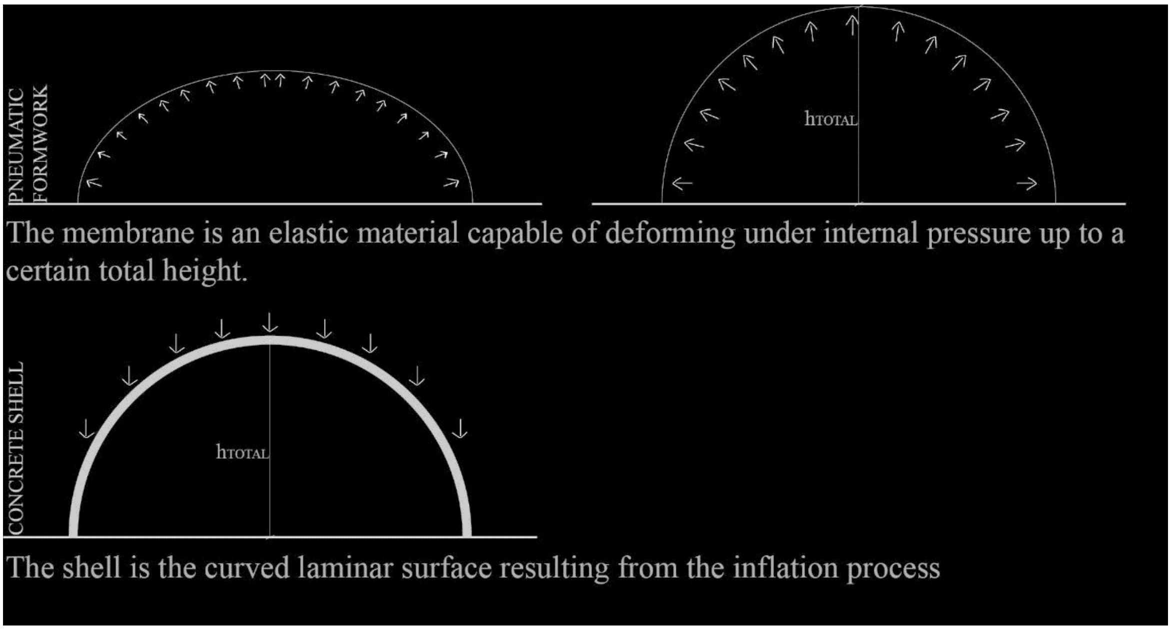

Figure 1. Pneumatic formwork and concrete shells, scheme system definition.

analysed the feasibility of using pneumatic concrete laminar structures for the construction of laboratories and research facilities.[11]

Since 1980s, many of the prototypes and patents have focused on improving many of the previous designs, thus innovating in the materials and building techniques of the pneumatic structures. Robert L. Nicholls worked in 1981 on the system designed and patented by Dante Bini. He changed the formwork reinforcement to textile components and simplified the lifting system of the structures.[12] Focusing on the classical pneumatic structures developed by Wallace Neff, Schlaich and Bergermann, in 1985, and T. Thoeny, in 2005, have presented new advances on the technical aspects of the building process. These changes solve the shape deformation problems and the loading distribution.[13]

Some of the most recent systems have integrated inventions that reflect today's technological advances. One example is the application of TRC (Textile-Reinforced Concrete) as a material used in these pneumatic laminar concrete structures; the innovation, made in 2010, is being analysed by E. Verwimp.[14] Regarding the use of new materials, the building systems named as Concrete Canvas Shelter are the result of applying the patented material Concrete Canvas. The material combines concrete fibres that, after spraying it with water, it hardens.[15] The design allows for standardisation and the use of the elastic membrane as a lost mould. The combination of Dante Bini's lifting pneumatic structures and the advances made in the optimisation and parameterisation of structures have resulted in a new pneumatic laminar type called *PFHC* (Pneumatic Forming of Hardened Concrete). The form of the

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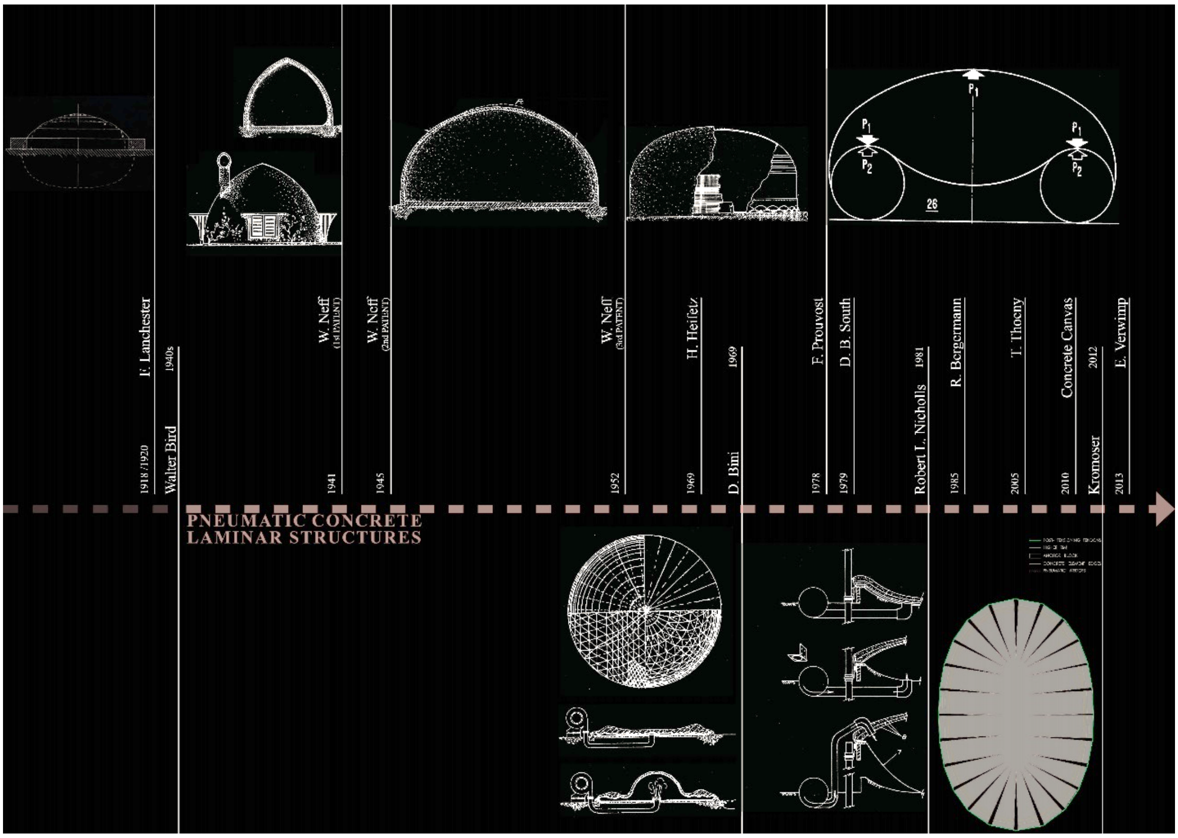

Figure 2. Pneumatic concrete laminar structures evolution timeline; elaborated by the authors from geometric data obtained from the patents.

pneumatic building adapts to the requirements of the project and the loads following the form finding method and the finite element method.[16]

Architectural characterisation: materiality, and form

Following the historical evolution of the pneumatic concrete laminar structures, this work focuses on the characterisation of different singular types and projects that went beyond theoretical proposals and were built from the 1940s to the 1990s.

1. Wallace Neff. This architect was the first one to explore the possibilities of combining pneumatic and concrete laminar structures. His three patents are evidence of his interest in advancing and improving this type. The following epigraphs described Neff's designs for: Airform houses and international buildings.

- Airform houses: *(i)General data.* The Airform houses were built in USA from 1942-1953 following the patents designed by W. Neff in 1942 and 1945. The location of these construction covers Virgina and California, although many of them were demolished in the 1960s and the 1980s due to their abandonment and lack of conservation.[17] The only extant house is in South Pasadena (California), and it maintains the singular

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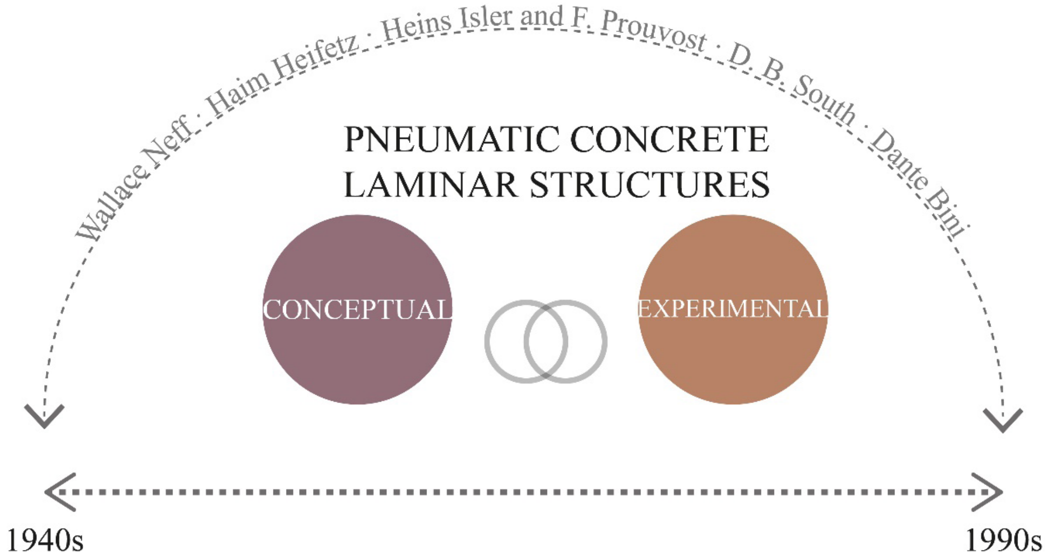

Figure 3. Type characterisation, authors and temporal range.

shape and characteristics of the original design.[18] *(ii)Structural elements/system.* The patented system consists of an inflatable membrane made of synthetic material on which, after being inflated at a certain air-pressure, metal reinforcement is placed, and concrete is projected. The membrane is anchored to the concrete mat foundation and, after the shell concrete hardens, this membrane is removed and could be re-used.[19] *(iii)Morphology.* These first constructions were developed as semi-spherical or dome structures, acquiring their singular name: bubble shells. Projects such as the Falls Church houses followed modular dimensions. Thus, with a 6'70-metre diameter membrane there were two types of houses: single or double (Figure 4). *(iv)Materials.* The structural materials used were elastic membranes made of neoprene, and gunite. The non-structural material applied were fiberglass as insulation layers and mixed gunite and white paint for external finishing coat (in most of the houses). Moreover, as the patent indicates, these first buildings did not include reinforcements.

- Airform buildings internationally. *(i)General data.* Wallace Neff expanded his work to other international locations from 1946 onwards. Most of the projects were aimed at building affordable dwellings (in Brazil, South Africa, Egypt, Angola, Senegal, Pakistan and the Middle East); there are also some examples of school combined with restaurants and residential buildings in Mexico, company's facilities in Nicaragua, resorts housing in the Bahamas and Cuba, and wine storage tanks and houses in Portugal.[20] Nowadays, many of them have been demolished or have been modified to the point of losing some of their singular characteristics. *(ii)Structural elements/ system.* Neff patented a new design in 1952, with new changes and advances to his system, and it was materialised in buildings around that year. A new cylindrical form that could improve the load distribution and reduce the number of cracks that appeared during the

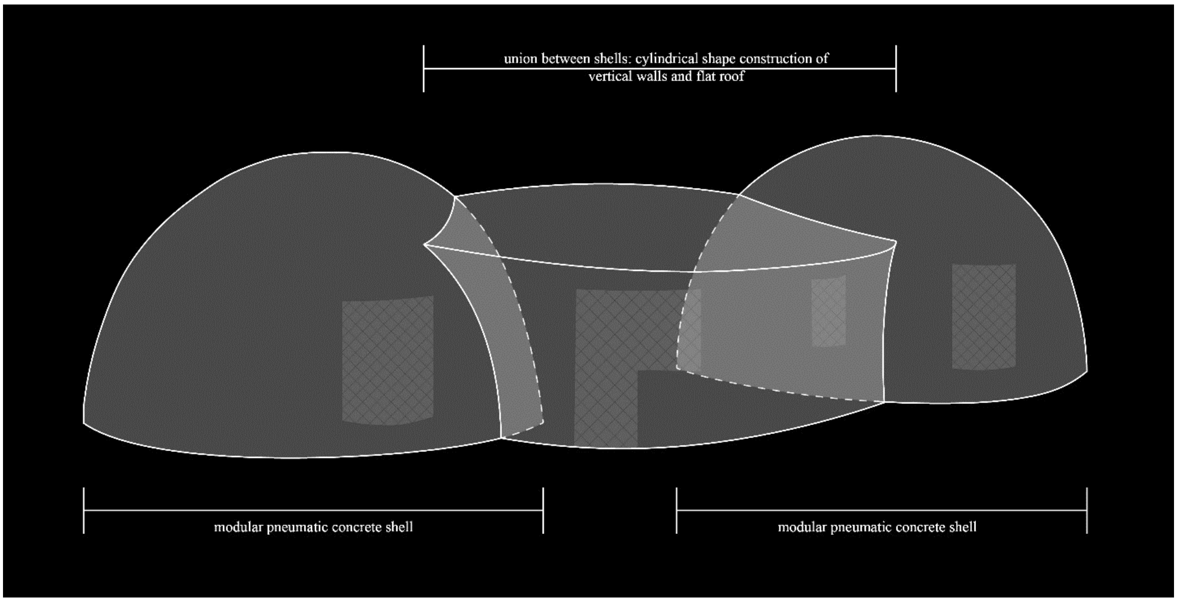

Figure 4. Neff's first double types of dwellings (elaborated by the authors from data by (Head 2011)).

building process was proposed.[21] The phases of construction were the same. *(iii)Morphology.* The shape varies from semi-spherical to cylindrical forms, depending on the application. The designs provide a series of modular houses that shared the same dimensions. This allowed re-using the elastic membrane for the construction of different buildings. *(iv)Materials.* Neff replaced the application of gunite as a structural material for concrete (or insulcrete, a cementitious coating, in the case of the houses located in Pakistan). This change was made due to the available work force and the previous tested projects. The other structural materials were neoprene for the membrane, and wire mesh and steel bars reinforcement. He probably added an insulation layer made of fiberglass in most of the projects.

2. H. Heifetz. This architect improved the system previously developed by Neff, providing new insights in the design of pneumatic concrete laminar structures. The available information regarding the state of his designs is scarce, although he presented two patents, in 1972 and 1978. The following paragraph focus on the application of his patented Domecrete Building System in the development of small-scale buildings.

- Domecrete religious buildings: *(i)General data.* The religious constructions were built in 1984 and 1987 in two distinct locations of the West Bank. In each one there were two or three modular Domecrete buildings that shared the same materials and dimensions. Currently, there is only two extant buildings. *(ii)Structural elements/system.* These religious buildings followed the Domecrete patented system presented in 1972. The proposal consists of an inflatable membrane anchored to a metallic base ring that, given air pressures ranging from 4-10 kN/m^2 is erected.[22] Then, steel bars are placed, and concrete is poured. The use of high air pressure and a base ring ensure that the form maintained its shape

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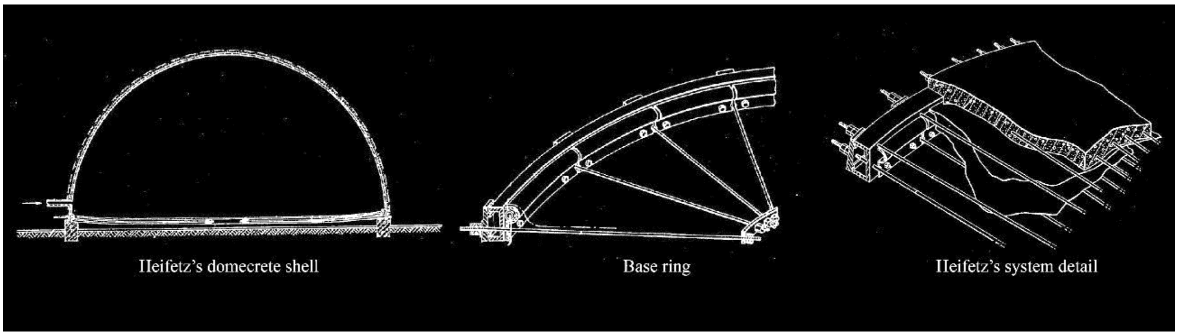

Figure 5. Heifetz's system details; geometric data obtained from the 1972 US3643910 patent.

during the building process, resulting in a better distribution of loads (figure 5). That base ring can be anchored to the concrete foundation or be detached from it to facilitate the transportation of prefabricated shells.[23] *(iii)Morphology.* All the buildings were hemispherical and, according to the available photographs, have the same dimensions. *(iv)Materials.* The structural materials are concrete foundation, metallic base ring with transverse cables

- or struts, anchored to a cotton/nylon membrane covered with synthetic rubber, metallic reinforcement and poured concrete. The available photographs indicate that the building's exterior finishing coating was probably white painting.

3. H. Isler and F. Prouvost. Most of the H. Isler's work focused on minimal concrete laminar structures; however, in 1976 he started to explore the possibilities of applying his knowledge on laminar surfaces to develop pneumatic concrete laminar structures. The following paragraphs describe the Habitat East Village project, a house prototype and the modular houses developed in Ponthierry.
   - Habitat East Village: *(i)General data.* The project consists of developing affordable housing in Moghan, Iran. Isler collaborated with J. Dahinden for the design of the buildings, and applied the system patented by F. Prouvost in 1978.[24] Nowadays, only the prototype built in 1976 is an extant building. *(ii)Structural elements/ system.* Prouvost introduced a new system of double air-pressured membrane chambers. Each of these chambers is inflated with different pressures: 25 kN/m^2 for the torus' shape chamber and 5 kN/m^2 for the bigger chamber. The different pressures and shapes help to stabilise the load distribution and avoid deformations. After inflating these two chambers, a layer of gypsum is applied, metal bars are placed and concrete (neopor type, adding an expansive polystyrene insulation) is sprayed.[25] *(iii)Morphology.* The shape of the building is not hemispherical but a combination of a toroid and spherical form (Figure 6). This result in a singular morphology that distinguishes the building from previous pneumatic concrete laminar structures designs. *(iv)Materials.* The structural materials were the two removable chamber membranes, the metal reinforcement and concrete, which was used as an insulation layer also. The gypsum layer applied after the inflation was also the inner finishing coat. For the exterior, after the concrete, a layer of acrylic rubber was applied.[26]
   - Prototype and houses: *(i)General data.* Isler adapted his experience in Iran and the acquired knowledge to the construction of

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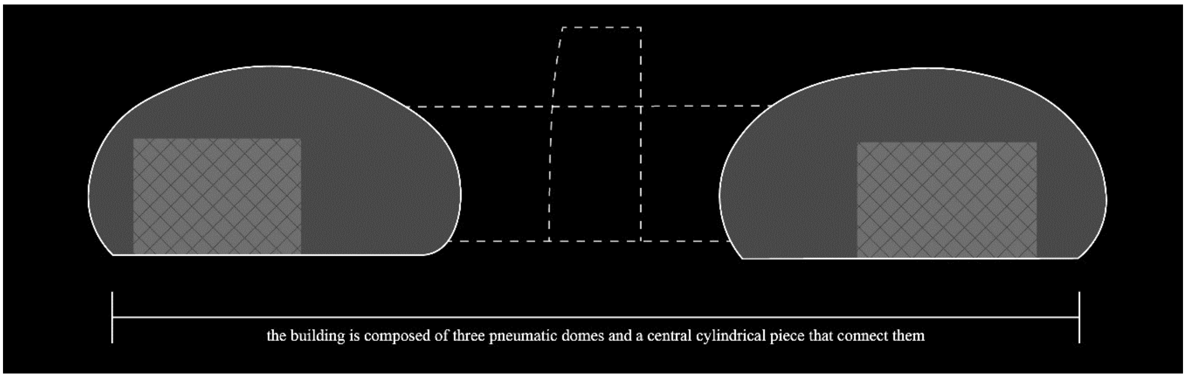

Figure 6. Habitat East Village geometric scheme (elaborated by the authors from data by ('Habitat East-Village (Bubble System) - Contemporary Architecture of Iran', n.d.)).

houses in Europe. He started developing a new design on which he experimented with different materials that could be adapted to European climate conditions.[27] Moreover, he evaluated new solutions and studied the structural behaviour of the pneumatic shell. In 1976 he built a new house prototype in Lyssachschachen (Switzerland) that nowadays is abandoned. In 1980, Isler applied his bubble housing system for the development of affordable housing for craftsmen in Ponthierry (France), which were demolished in 2017. *(ii)Structural elements/system.* The final house prototype exhibits changes with respect the Prouvost's system: the layer of gypsum was thicker, and a plastic mesh grid was added; Isler also added a layer of insulation on which he placed the steel reinforcement and poured the concrete. Thus, the gypsum was used as a formwork for the other layers after the inflatable membrane was removed. Moreover, Isler improved the attachment to the ground designing a one-meter height vertical collar that connected with the ellipsoidal shape of the membrane.[28] *(iii)Morphology.* The prototype house shape design consists of two intersecting cylindrical-dome shells. In Ponthierry, a total of eight houses were built re-using the inflatable membrane. Two of these buildings were single units and the others were double units; *(iv)Materials.* Structural materials: mat concrete foundation, removable elastic membrane, gypsum mixed with plastic mesh grid, steel reinforcement and concrete. The non-structural materials were the sprayed insulation and the exterior painted finishing coat.[29]

4. D. B. South. The patent presented in 1982 by D. B. South explored a new system that provided a new distribution of layers. South started the development of pneumatic concrete shells in 1976. The following paragraphs focus on the description of his first houses.
   - Houses: *(i)General data.* The first two dome houses were built in Idaho in 1978 and 1979.[30] Nowadays both are extant buildings. *(ii)Structural elements/system.* Both houses applied the system that would be later patented by D.B. South and that had been previously used for the construction of potato storage buildings. The system comprises a non-removable elastic membrane inflated under a specific air pressure. In this case the metal bars reinforcement is placed in the

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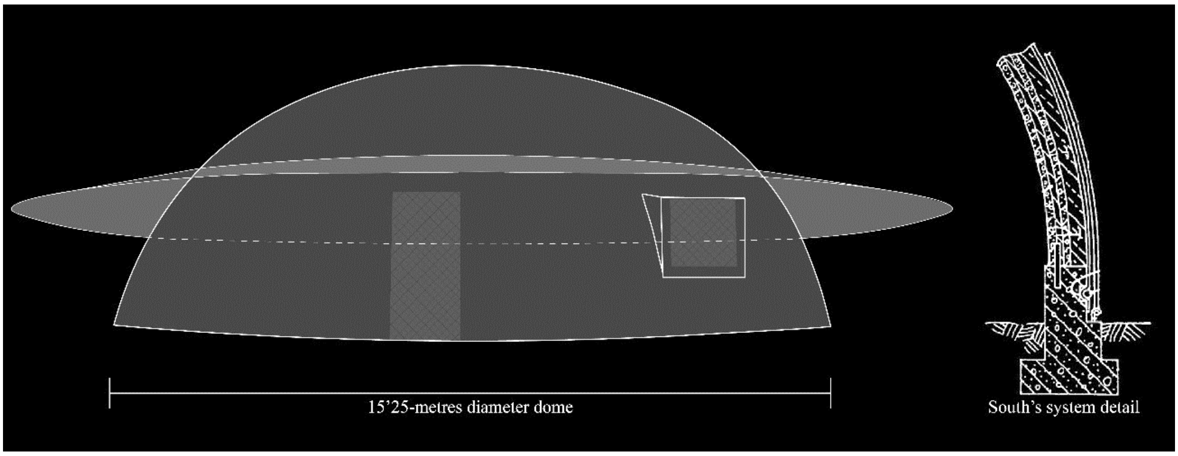

Figure 7. D. B. South's first house -left- (elaborated by the authors from data by ('Marjorie South and the First Monolithic Dome Home - Monolithic Dome Institute', n.d.)); South's building section -right- (geometric data obtained from (South 1999)).

interior of the dome, and, after that, concrete is sprayed in the interior surface. *(iii)Morphology.* The first house designed in 1978 had a semi-spherical shape of 15'25 metres diameter (Figure 7). The second house shared the same shape but the dimensions were larger: 22'9 metres diameter and 8'50 metres height.[31] *(iv) Materials.* The structural materials used were sprayed concrete and steel bars reinforcement; PVC membrane was used both as a formwork and as an external layer. The non-structural materials were urethane as an insulation layer and metal cladding or hand-split cedar pieces as the external finishing coat.

5. Dante Bini. The Italian architect started working on pneumatic concrete laminar structures in the 1960s. His patented system presented a new building process, in which the concrete is poured before the membrane is inflated. The following paragraphs describe designs built between 1964-1980: Binishells building prototypes and house, schools, and Malvern Sports Hall.
   - Binishells houses: *(i)General data.* Between the 1960s and the early 1970s, Bini patented in Italy his first system and worked on experimenting and studying its structural behaviour. The first buildings were erected in Crespellano, Pegola, Castelfranco Emilia and San Cesario sul Panaro, and they were private commissions or Bini's own experimental tests.[32] These last two construction are now abandoned. In 1969, Bini started building his first house in Gallura which nowadays is also abandoned. *(ii)Structural elements/ system.* The Binishells system, patented in 1962 in Italy, consists of a footing ring beam in which an elastic membrane is anchored. On the membrane, metal reinforcement is placed and then concrete is poured. Before the concrete hardened, the shell is inflated with a specific air-pressure. The concrete was restrained during this process by a net fence at first and, later, with a second membrane.[33] *(iii)Morphology.* The first Binishells were semi-spherical buildings with diameters that range from the 12 metres to 30 metres (in San Cesario sul Panaro's prototypes).[34] Thus, Binishells could be modular pieces systematically built or adapted to specific designs. *(iv)Materials.* The structural materials were concrete footing ring, PVC elastic membrane, steel

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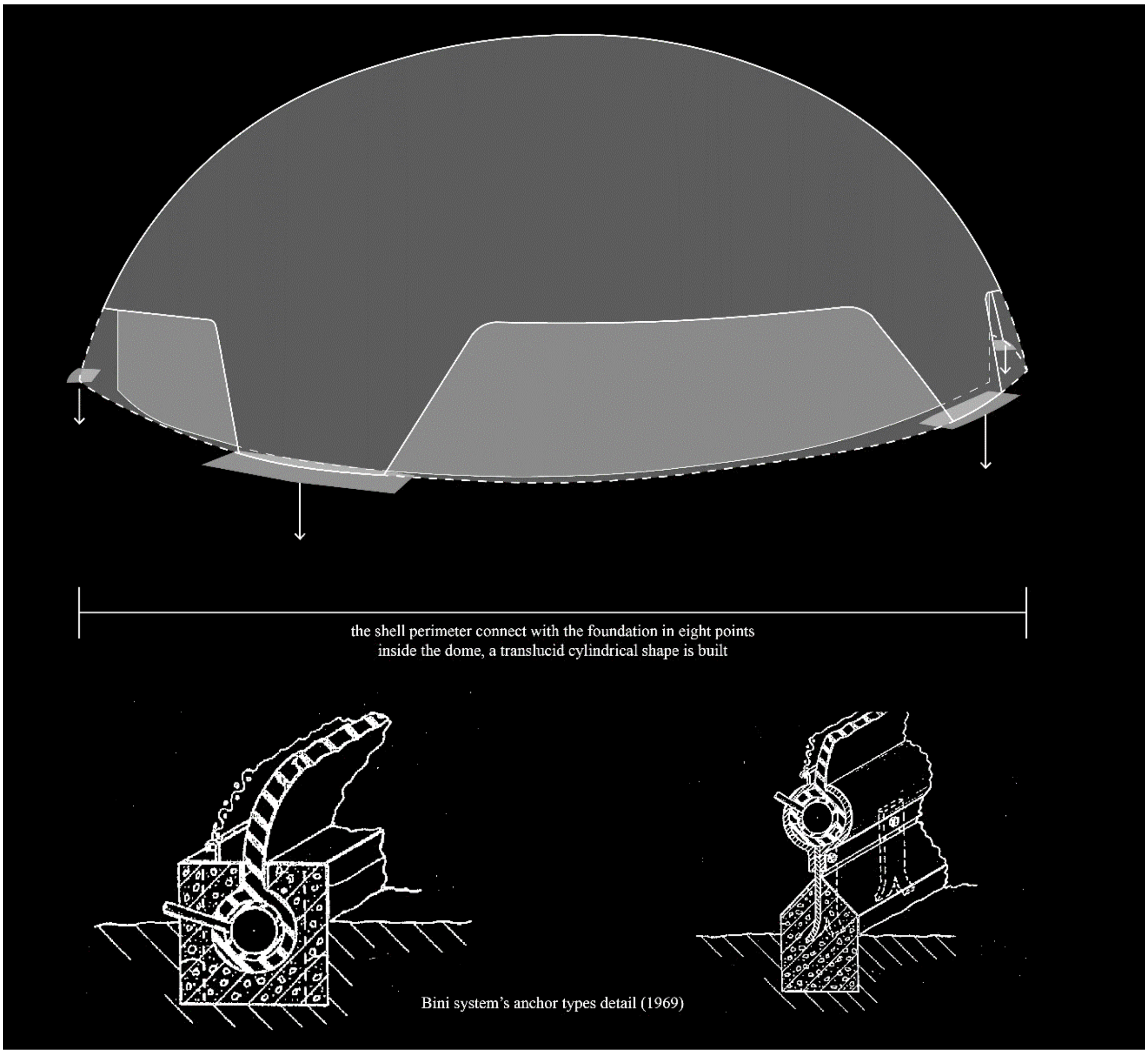

Figure 8. Malvern Sports Dome geometric scheme -top- (elaborated by the authors from data by ('The Edinburgh Dome a Concrete Parashell Imperial Road Malvern Worcestershire The Building Is a Sports Hall Belongs to Malvern St James Girls School Stock Photo - Alamy', n.d.)); Binishell's types of anchor systems -bottom- (geometric data obtained from (Bini, 1969)).

rods and chains and galvanised steel chain link reinforcement and poured concrete. In the prototypes, Bini tried prefabricated insulation elements, placed after the reinforcement. The material of these elements could be triangular shape panels of fibres according to the available images.[35]

- Binishells schools and teaching facilities: *(i) General data.* Dante Bini worked in Australia to build many schools applying his patented system from 1974 to 1980. Most of them were

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demolished between the 1980s and the 1990s.[36] These large-scale projects tested the behaviour of the system and the deformation problems that could appear.[37] *(ii)Structural elements/ system.* The patented system applied is the one tested previously in his Italian prototypes and buildings. *(iii)Morphology.* The buildings were hemispherical, and their diameter dimensions vary between 18 metres and 36 metres. Bini varies the dimensions following proportional measurements; however, the 36 m diameter domes were the ones with most of the structural behaviour problems. *(iv)Materials.* The structural materials were concrete footing ring, PVC elastic membrane, steel rods and chains and galvanised steel chain link reinforcement and poured concrete.[38]

- Malvern Sports Dome: *(i)General data.* In 1978 the Binishell's system was applied for the construction of a sports hall in Malvern (UK). The building, which remain extant, was designed by Michael Godwin and John Faber.[39] *(ii)Structural elements/system.* The system followed the Binishell system patent.[40] Because of the building design and location, the architects decided to build the sport hall over eight pilotis and a ring-beam. *(iii)Morphology.* The semi-spherical building's dimensions are: 36-metre diameter and 11-metre height (Pugnale and Bologna 2015). The architects used the same geometrical proportions as Dante Bini; however, the circular perimeter only connect with the ground in eight specific points, related to the pilotis (Figure 8). *(iv)Materials.* The structural materials were concrete footing ring, PVC elastic membrane, steel rods and chains and galvanised steel chain link reinforcement and poured concrete.[41]

COMPARATIVE ANALYSIS AND DISCUSSION

As can be deduced from the previous sections, Pneumatic concrete laminar structures are singular systems that have been evolving for decades. A great number (21) of the designs analysed had been demolished and forgotten, despite their importance in the technical structural evolution of 20th century Architecture. The historical review and the type characterisation evince both the experimental work and theoretical research of many architects, especially in terms of adaptability. In the following paragraphs, two of the main issues that should be considered to reappraise this singular type and to promote its possible use in contemporary designs are examined (i) the causes of the abandonment of some of the structures, and (ii) the adaptability potential in terms of form and materials.

i. Neff's designs were abandoned for multiple reasons: its characteristic shape, which was not conventional in the 1940s; the economic loss of not making the most of the surface available to build, and the limitations of adapting and refurbishment the buildings because of the form and materials. The Domecrete system by Heifetz was an opportunity to test the prefabrication and transportation possibilities of these structures. However, this concept of erecting the shell and transporting it hasn't been tested since then, probably because of the economically expenses of the transportation process. Isler experience with pneumatic shells was similar to Neff, as his experimental approach was too expensive for the purpose of building economical dwellings. His work on this type of structures was reduced to his prototypes in Iran and Switzerland, and the houses built in Ponthierry. The collaboration between Isler and Michael Balz was the end of this phase of his work and the return to the design of minimal concrete laminar surfaces.[42] The system patented by D. B. South was the first in reaching large-scale dimensions. The semi-spherical form was no longer a problem because the buildings could have distinct levels and compartmentalized or open spaces. Thus, the design offered flexibility within the form. This feature makes impossible to re-use the material. Bini's explored the feasibility of large domes that could be public spaces or houses; although, many of his buildings had 36-metres diameter,

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most of them were demolished because of structural problems: collapse of part of the domes and deformations.[43] From the 1980s onwards, Bini explored new structures that were related to the Binishells but offered innovative design possibilities and implemented new techniques: the Binix (lattice lightweight construction with reusable moulds and the Binistar (steel frame structures).[44] Nowadays, the only two systems that are being manufactured are those patented by Bini and South. The fabrication is licensed under the companies that they founded: Binishells and Monolithic Domes. Since the first designs, the building process, forms, and materials used have evolved and innovative technologies have been implemented.

ii. Neff experimented with modular dimensions to enable the combination of single domes to build diverse types of dwellings. However, these proposals did not modify the shape, but instead combined the domes with vertical walls that unify them. The international implementation of Neff's system shows the adaptation of the materials used depending on the location of the proposals.[45] The modification consisted of changing the use of gunite for concrete considering which option was the most economically efficient and the available local resources. Regarding Heifetz's designs, the available images show distinct materials applied in different proposals: rigid foam, masonry blocks and sprayed concrete.[46] This variation shows Heifetz's interest in exploring the adaptation of the system and studying its structural behaviour. His proposals were semi-spherical constructions that could be combined to create complex designs. In the case of dwellings, he introduced two types (single or double storey) that shared the same modular proportions. Isler's design shape evolved through his experimental work on prototypes. From his first proposal in Iran, in which the form responded to seismic requirements, the architect tried to enhance the building process and improve the loading distribution. It is worth mentioning his research on the materials that could be adapted from the Habitat East Village to European proposals, considering climate, wind and snow conditions. Thus, Isler worked in solutions that used clay mixed with gypsum, cement mixed with gypsum, neopor or concrete and studied their long-term behaviour.[47] South's design form has not changed since his first proposal, only the dimensions of his designs varied depending on the requirements. One of the main differences between his system and the other patents is the non-removable membrane and its use as part of the finishing layer.[48] The adaptability of the materials used refers specifically to the ones used as finishing coat and that, consequently, protect that membrane and the shell. Lastly, Binishells could be one of the most shape adaptable systems of the analysed work. The modular proportion (18 m / 36 m) of the diameter facilitated the building process and re-using the elastic membranes and, at the same time, enabled different designs and uses.

From the previous analysis and considering the current state and/or use of the different designs, it can be concluded that the reasons of their abandonment as a structural and architectural type could be attributed to the following factors: i) the special form of the design, which contrast to the modern architecture precepts of that period; ii) the inflexibility of the shape that did not facilitate adjustments or extensions. However, towards the 1980s, the development of South's system and the Binishells showed that pneumatic shells could be adaptable structures that create new forms and singular interior spaces.

CONCLUSIONS

The historical and morphological-technical evolution of the pneumatic concrete laminar structures evinces their singularities among the architectural designs of the 20th century. The advances made from the theorical concept of pneumatic structures patented by F. Lanchaster to the lifting pneumatic shells built by Bini allows understanding their adaptability and their potential use for sustainable and economically efficient architecture. Thus, dynamic

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loads such as seismic and wind, and different climate conditions were considered in the design of some of these systems, giving response to these challenges. Nowadays, the possibilities of learning from this structural type and improving it by applying today's technological advances are represented in proposals such as Concrete Canvas or PFHC. This new interest in pneumatic concrete laminar structures reappraise their value and singularity and gives them significance that, during the past century, was lost.

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