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Pier Luigi Nervi: His construction system for Shell and Spatial Structures

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Summary: Pier Luigi Nervi invented the so-called "Nervi System": an entirely new way of building large structures that the engineer developed over his lengthy, uninterrupted experiments with statics and construction. With the intention of minimising cost and time, the System was based on authentic inventions, such as structural prefabrication, ferrocement special pieces and a series of original technical solutions. The paper presents this system of construction, explaining its application in some major works by Nervi and presenting two recent restorations conducted by the authors.

Keywords: *Nervi, ferrocement, structural prefabrication, construction system, autarchy, made in Italy*

1. INTRODUCTION

Between the end of the Thirties and the end of the Sixties, during his "second life" [1][2], Pier Luigi Nervi invented the so-called "Nervi System", a completely new way of designing and constructing reinforced concrete structures, and applied it to the marvellous masterpieces of his maturity. It was an extraordinarily effective, quick and economic method whose stamp would be unmistakably seen in the original architectural design of his vaults and domes.

Nervi's works were closely related to the cultural and social conditions both domestically and worldwide, which considerably changed during his long productive life (from Twenties to Seventies): from World War One through the Fascist era to the enthusiastic second post-war reconstruction period, and on to the booming years of economic euphoria up to the financial crisis of the Seventies. For this reason, upon reviewing his works, it seems that Pier Luigi Nervi lived three lives, not just one: in the first life he was a modern architect, in the second an ingenious creator of a new building method, and in the last an international starchitect. Three equally intense lives that coexisted, overlapped and interacted but remained independent of each other.

2. NERVI'S FIRST LIFE

During his first life Nervi had already become a famous designer in Italy: some of his works in reinforced concrete (especially the Berta Stadium in Florence) had been published in architectural and engineering international journals, accompanied by flattering comments. He participated in the debate about renewal in architecture and published important articles in avant-garde magazines when requested by the most prestigious contemporary critics (especially Pier Maria Bardi). Together with his cousin, Giovanni Bartoli, he ran a busy construction company which was very competitive on the market [3]. And yet, like for many other of his engineer-entrepreneur colleagues, dark clouds were gathering on the horizon.

After the sanctions imposed by Geneva when Italy invaded Ethiopia, the autarchic regime Mussolini established sowed havoc in the construction business. Of all the materials imported from abroad, and now rationed, steel was top of the list; over and above its cost in gold, steel had to be reserved exclusively for the war effort. Reinforced concrete, which requires steel for the reinforcement, suddenly became an anti-autarchic, anti-national construction material. Despite the fact that this construction system was still the most popular in both small and large-scale construction in Italy, restrictions began to be imposed, starting in 1937: the system was completely banned in 1939. So what did the designers and constructors who used reinforced concrete do (and Pier Luigi Nervi was one of the most important figures in both categories)? Waiting for better times, they began to experiment with alternative solutions.[4]

Based on this approach research led to the development of two new materials which can be considered genetic mutations of reinforced concrete: "prestressed concrete" and "ferrocement". Although they still used steel and concrete, the static role and mechanical properties of the two materials were very different to those of ordinary reinforced concrete. While Gustavo Colonnetti promoted the former material, developed in France by Freyssinet, Arturo Danusso was the main sponsor of the latter (and Nervi was the first, very generous, supporter). Back in 1934 Danusso wrote: "when man develops and uses natural elements he doesn't get his best results from the elements themselves, but from the clever way in which he combines them; he often realises that by constantly varying the ratio between those elements, he can create special, extremely useful mixtures. It's very likely that the combination of steel and concrete should not be limited to a ratio between a few units or percentage fractions of units (used so far); instead, between the two extremes (only concrete or only iron) there will be a whole range of combinations between the two materials which, on a case by case basis, will provide the best solution" [5]. Nervi accepted the challenge.

3. THE SECOND LIFE

Due to the ongoing autarchic restrictions, Nervi began his research, which led him to focus on two important issues. The first was that to save on steel it was important to reduce the amount of concrete: thin layers of thickly reinforced concrete are more efficient — and therefore cheaper — than larger sections of weakly reinforced concrete. The second was that greater savings were obtained by reducing the amount of wooden formwork used for onsite casting: this not only was extremely wasteful, it also severely hampered the shaping potential of reinforced concrete. To eliminate wood from his building sites, he experimented a prefabrication technique he called "structural prefabrication". [6][7]

3.1. Structural prefabrication

The opportunity to test the system arose when he was asked to build the so-called "second series" of airplane hangars for the Italian Air-Force: between 1939 and 1942 six pairs of identical hangars were built in Orvieto, Orbetello, and Torre del Lago. Nervi adopted the same structural plan he had used in Orvieto in 1936 to build two innovative reinforced concrete airplane hangars: to calculate their stability he had used simplified hypotheses which he had carefully verified using a model. This was the first time a model, tested in the laboratory run by Danusso at the Polytechnic of Milan, had produced tangible results. So, while he maintained the same static system, Nervi made crucial changes to the building system: he abandoned the complex and very expensive wooden formwork required to build the great ribbed vault. How did he do this?

Nervi divided the ribs into pieces, as identical as possible; he prepared them in series on the ground in formworks (simple side planks) that could be reused dozens of times. Then the pieces (their weight and size were calibrated to facilitate transportation) were lifted into place on a light scaffolding system and joined to the neighbouring elements by welding their protruding rods and casting the node with high strength concrete. Once the work was completed, there was no trace of this fragmentation and the resulting structure proved to be statically monolithic. In November 1939, this procedure was patented (patent n. 377969, Fig. 1).

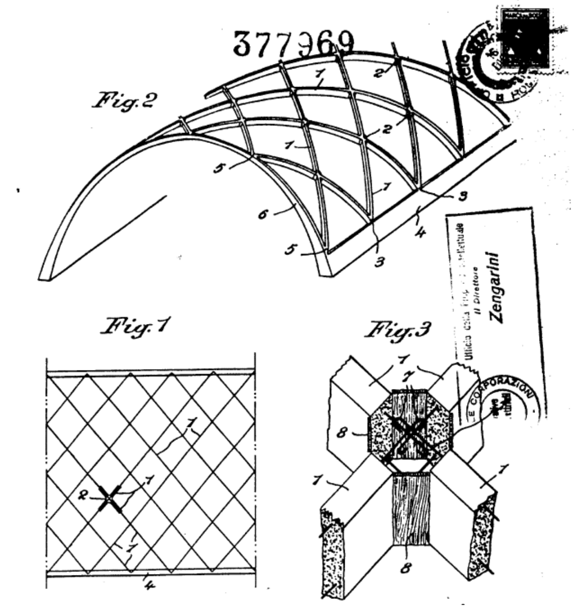

Fig. 1. Italian patent n. 377969, "Structural prefabrication technique", 1939 (Archivio Centrale dello Stato, Roma: Fondo Brevetti).

3.2. Ferrocement slabs

In the same years, Nervi began to experiment with thin steel-reinforced concrete slabs. At this point, his experiments were hardly scientific. Due to the war, they had to be conducted in makeshift labs, often in his own home. (Carlo Cestelli Guidi reports that Nervi kept his slabs on his home's balcony, to check how they weathered). Only after the war, Nervi was able to verify his findings thanks to load tests carried out in Danusso's laboratory.

Nervi first referred to these slabs as "evenly wired", "evenly reinforced" and then "ferrocement felt". But how were they made? Nervi superimposed several layers of metal mesh and then pressed cement and sand mortar into them using a trowel or float (the metal mesh had to be a few millimetres thinner than the slab once it was finished, generally 3 cm thick). By pressing the mortar on one side of the mesh the cement came out on the other side after having filled the entire reinforcement. Of course the operation also required the mortar to be correctly plastic, so it had to be carefully moulded (even with additives such as diatomaceous earth or bentonite). Wooden formwork to shape the mortar until it hardened was no longer needed to make either a horizontal or vertical slab. The extreme subdivision of the reinforcements, the very thin wires and the uniform distribution created a material very different to ordinary reinforced concrete. Ferrocement was homogeneous, isotropic, elastic, ductile. It is midway between "only concrete" and "only iron" on the scale proposed by Danusso. Although Nervi patented his material in April 1943 (Italian patent n. 406296, Fig. 2), things took a turn for the worse. After the collapse of the Fascist regime, in September Italy was subjected to the post-armistice invasion of the Nazi forces during which Nervi wisely decided to shut down his company. In June 1944 Rome was liberated and in September he had already improved his own patent (continuing patent n. 429331, Fig. 3) and was ready to start creating the first prototypes, actually some fishing boats.

The first application of the new material to building construction was a warehouse at the Magliana Nervi & Bartoli place, in Rome: made entirely of ferrocement, including the roof, three centimetres thick, it was designed in waves, getting the most out of the inherent shape-resistant solution. [3]

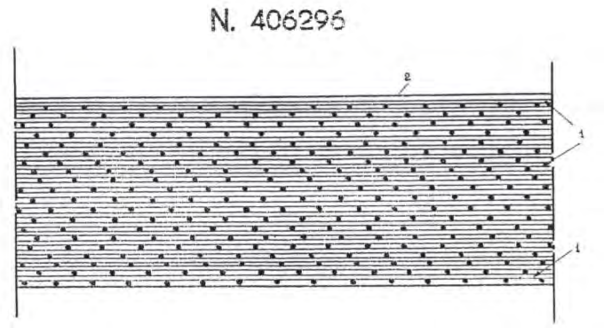

Fig. 2. Italian patent n. 406296, "Ferrocement", 1943 (Archivio Centrale dello Stato, Roma: Fondo Brevetti).

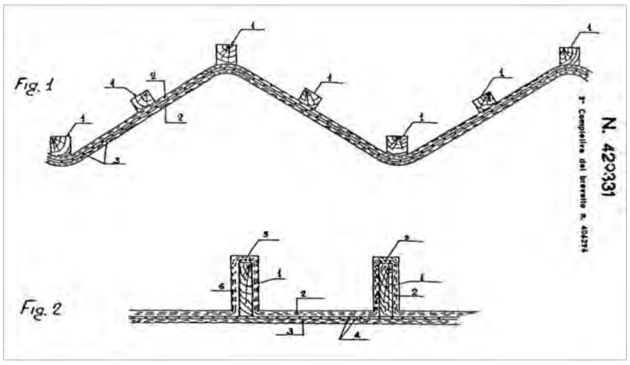

Fig. 3. Italian patent n. 429331, “Ferrocement warehouse”, 1944 (Archivio Centrale dello Stato, Roma: Fondo Brevetti).

The recent restorations conducted by the authors allowed to reveal some secrets of ferrocement. In fact, also in the very first use, ferrocement was strongly simplified: the multiple layers of steel mesh were soon discarded. In the Magliana warehouse's curly slabs (Fig. 4), the steel inner weave was prepared with few 8 mm diameter vertical bars and couples of 6 mm diameter shaped horizontal bars (20 cm spaced): within these rebars, multiple wooden squared strips made more stable the composition and helped to support only two layer of mesh, one for each side. Notwithstanding, on site manufacturing of the entire building was long and difficult: to fix problems while putting dense concrete on the mesh required several attempts. Magliana warehouse was the first and only building entirely conceived in this way. Hereafter, prefabrication of ferrocement smaller pieces was preferred for the roof and ordinary reinforced concrete for vertical structures.

The all-on-site solution was saved only for the boats, definitely with a simpler shape. "La Giuseppa" last motorboat was created by Nervi inside the Magliana warehouse in 1972, immediately after the construction of two fishing boats ordered by FAO. Its ferrocement curved slabs, 14mm thick, are reinforced with 4mm longitudinal bars intersected by 3mm transversal bars. On each side of this frame, two layers of welded wire mesh (12x12 mm opening, 1 mm diameter) helped to hold pozzolanic cement mixed with sand. Extensive conservation works were carried out on La Giuseppa motorboat and Magliana building in 2010 and in 2013, respectively, by a Rome Tor Vergata University group, under the guidance of the authors. Italcementi Group provided the financial and technical support. A new premix concrete was developed for this specific purpose, named Effix DesignST. [8] (Figs. 5, 6, 7)

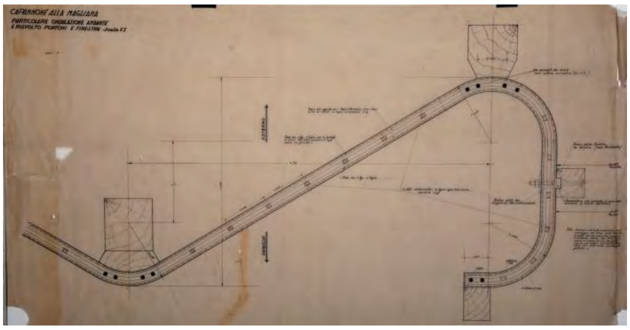

Fig. 4. Magliana Warehouse. Ferrocement slab details, s.d. [1944] (CSAC, Centro Studi e Archivio della Comunicazione, Parma: Fondo P.L. Nervi).

Fig. 5. Full size model of a portion of the Magliana Warehouse's curly wall, 2013 (Photo Sergio Poretti, SIXXI Project).

4. THE NERVI SYSTEM

To celebrate the end of the war, in May 1945 Nervi published a book titled *Scienza o arte del costruire?*[6]. The text recounted his experience with construction: one chapter (6 pages) is devoted to explain potential applications of ferrocement. Ferrocement is a very poor material and an unskilled labourer can easily prepare it using very simple equipment. Moreover, structural prefabrication is an artisanal technique that requires careful and much more complex planning than an ordinary technique; however it can easily be implemented on a traditional worksite. Nervi did not suggest factory-made standard construction elements; in each building he simply used prefab elements, made onsite. Despite its pompous and misleading name (prefabrication) it is just a very old technique, in continuity with the tradition of stereometry and the art of scribing. It was a perfect technique for post-war Italian construction worksites. Nervi tested his inventions on various minor works in the years leading from reconstruction to the economic boom.

Fig. 6. Magliana Warehouse. Restoration works, 2013 (Photo Sergio Poretti, SIXXI Project).

Fig. 7. Magliana Warehouse. Interior after restoration works, 2013 (Photo Sergio Poretti, SIXXI Project).

The best chance he had to test ferrocement and structural prefabrication together was the construction of the exhibition halls at the Turin Expo (Hall B and Hall C). During the very rapid construction of this building (construction on Hall B began in June 1947 and inauguration took place on September 1948; Hall C began in early November 1949 and ended on 15 April 1950), Nervi was able to fine tune all the construction processes he would use in his future works: the so-called "Nervi System". The system is both economical and rapid. Economical because it eliminates the wooden formwork required to pour reinforced concrete, both costly and difficult to reuse, and because it reduces the costs of materials, limiting the thicknesses of the load bearing elements (and thus diminishing dead loads).

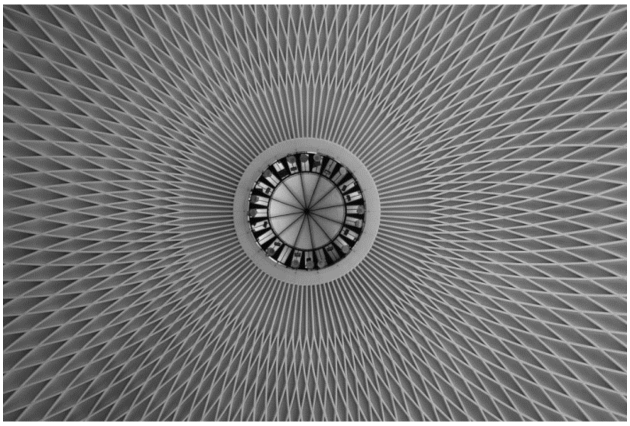

Fig. 8. Palazzetto dello Sport. Interior view of the dome, 2010 (Photo Sergio Poretti, SIXXI Project).

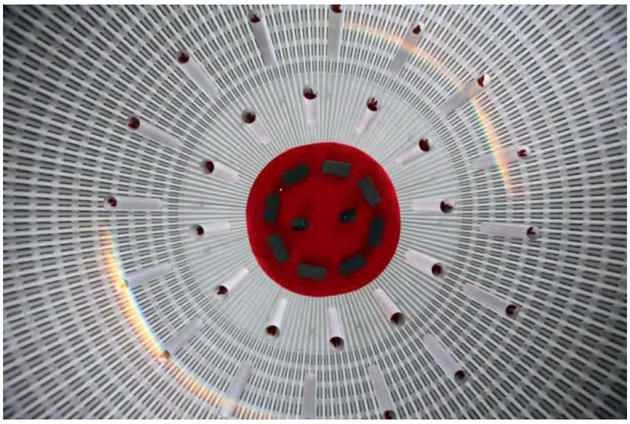

Fig. 9. Palazzo dello Sport. Interior view of the dome, 2009 (Photo Sergio Poretti, SIXXI Project).

Rapid because it divides the building yard into two autonomous sectors, where labourers can operate in parallel: on the one hand the building site, home to the realization of excavations, foundations, columns and all site-cast elements; on the other, the prefabrication yard, used to prepare the pieces used to assembly the structure.

In 1951 one of the most famous ceiling in the world, the isostatic ribbed slab of the Gatti Wool Factory in Rome, was built, using ferrocement to simply prefabricate the complex reusable formworks. The final capricious arabesque was severely dictated by the wisdom of nature.[9]

In his works for the 1960 Rome Olympics the system evolved to perfection [10][11]. The Nervi & Bartoli Company realized four masterpieces: the Palazzetto dello Sport, with its flat, 60 meter span dome supported by a carousel of 36 trestles and internally criss-crossed with lozenge-shaped pattern (Fig. 8); the Palazzo dello Sport at Eur, roofed with a finely undulating dome of 100 meter in diameter (Fig. 9); the Flaminio Stadium with its elegant pleated cantilever roof; the Corso Francia viaduct, with its characteristic variable- section pillars. Nervi was sixty-nine years old when he completed these four structures. He only took four years (since 1956 to the early months of 1960) to design and erect them. A true miracle, whose explanation is to be sought in the Nervi system.

In designing these sports facilities, Nervi opted for rather traditional architectural solutions and clearly preferred symmetrical curved forms. However, Nervi's domes and vaults are visibly different to classical models due to their extremely complex surfaces which were either ridged, wavy, pleated, or ribbed. His structures are enriched by a minute superficial design that is not found in any other contemporary reinforced concrete works. The shells are often no thicker than 3 centimeters, but the complexity of the movement prevents one from perceiving their thinness, which can only be discovered by consulting the executive plans. Why did Nervi adopt these complicated surfaces which others had discarded due to the construction and calculation problems involved? Why were these complex surface patterns reserved for symmetrical or even circular structures? The answer lies in the uniqueness of Nervi's worksites.

Nervi's concept of structural prefabrication meant that structures had to be broken down and each element had to be prepared on the ground. Every element had to be small enough and light enough to be lifted and easily assembled. The thinness of each section was functional not only in terms of weight but also helped streamline material costs; the minute surface design depended on the scale of the prefabricated elements. Each piece had to have a shape that which would allow it to have enough strength during assembly. Finally, each piece had to be duplicated as many times as possible. This meant that only surfaces of revolution and translation were suitable.

4.1. Waves and *Tavelloni*

What type of elements were used to break down the complex surfaces? When was ferrocement used? The complex surface, the minute design of the ribbing, the thick folds of the domes and floors, were created - albeit with different results - by using only two different elements: the "wave ashlars" and the "rhomboidal hollow blocks", called "Tavelloni".

The "wave ashlars" were patented in August 1948 just before the inauguration of Hall B (Patent n. 445781, Fig. 10). The idea was to shape the prefab elements using a geometry that would guarantee a high moment of inertia with a minimum amount of material. Obviously it was the ferrocement that made this modelling economical: it was just a matter of bending the wire meshes around a brick mould and then filling the mesh with cement and sand.

The result was an element that was only a few centimetres thick, lightweight (roughly 1,500 kg every 4 meters), and safely transportable due to its high moment of inertia. The wave ashlars were closed at either end by non-deformable headers and stiffened by two or three internal diaphragms that stabilize the wavy shape (often lightened by wide openings). When the wave ashlars were mounted on the scaffolding, their shape made it possible to cast concrete ribs both along the top and bottom of the wave. The reinforced ribs were connected to the precast element via the rebars protruding from the ashlar itself.

The "wave ashlars" were used for the dome of the Palazzo dello Sport: six V-shaped ashlars, approximately five metres in length, forming 144 identical waves; they have large openings on the sides and perforated diaphragms to allow the passage of the lighting system and other installations.

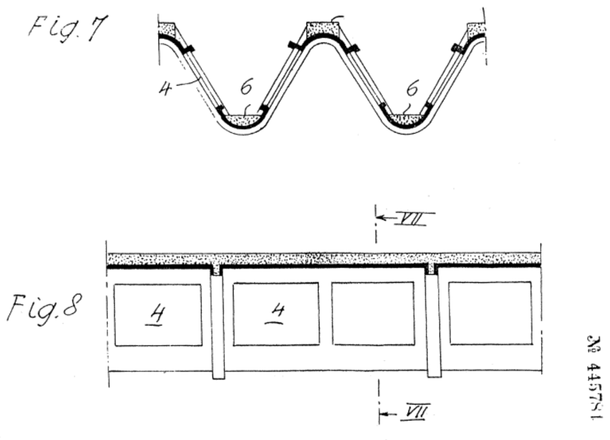

Fig. 10. Italian patent n. 445781, Ferrocement wave, 1948 (Archivio Centrale dello Stato, Roma: Fondo Brevetti).

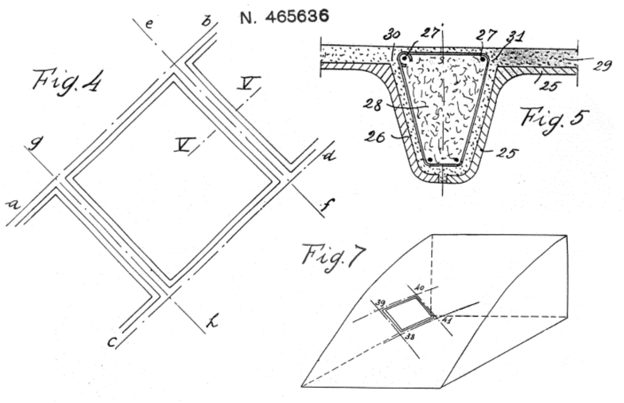

Fig. 11. Italian patent n. 465636, Ferrocement "Tavellone", 1950 (Archivio Centrale dello Stato, Roma: Fondo Brevetti).

To complete the 1008 elements catalog, we have to add 3 elements for each 48 fan-shaped structure, focusing the thrust on the outer, inclined pillars. The V-shape was also repeated in the beams which, next to one another, create the deck of the Corso Francia Viaduct. The beams are 16 metres long and partially prestressed (a procedure Nervi very rarely used, except in foundations).

Also in the canopy over the stands in the Flaminio Stadium, the 15 metres cantilever was built by juxtaposing waves, which section varies along the span. In this case, the casting is limited to the ridge of the wave and joins the prefabricated elements to the back, previously erected structure. The last Nervi's application of the waves has been the Papal Hall in Vatican City, completed some years later, in 1971. In this case Nervi adopted an half-wave in expensive ferrocement, prepared with white cement mixed with fragments and sand of Carrara marble.

The other special elements, the "*Tavelloni*", were patented in May 1950 (Patent n. 465636). In fact they are the main element in the Turin absidal half-dome at Hall B and the entire vault at Hall C. The idea was inspired by the need to solve the problem regarding the construction of a thin curved surface stiffened by ribs; this is one of the most complex solutions to achieve using casting. Nervi solved this problem by inventing a "sacrificial formwork", in other words a precast "shape-element" just a few centimetres thick; this element was not removed when the building was finished, but became an integral part of the completed structure. (Fig. 11)

4.2. 1620 diamonds for the Palazzetto dello Sport

Precast rhomboidal elements were employed to assembly the dome of the Palazzetto dello Sport [12]. In particular, the blocks were obtained by creating a light weave of 6 mm diameter bars (15 cm spaced in the two directions) and one layer of square wire mesh (weight 0,6 kg per sq meter), on which the concrete, only with sand, was applied until a thickness of 2.5 cm was reached. This laborious manual operation was made extraordinarily economical by an ingenious "generational" solution that permitted production of about 30 blocks per day, with the certainty that each piece would fit exactly in the final assembly. (Figs. 12-15)

The first step was the preparation of a wooden template that reproduced, in actual size, a slice (10-degrees) of the spherical cap. Adopting a traditional solution, Nervi used a light "model", which was rotated around two different center points, to generate precisely the template. On this, finished with plaster, the axes were traced by hand and the 13 triangular or rhomboidal forms were constructed in masonry. On each masonry form a block prototype was made in ferrocement. In theory, this last operation could be repeated 108 times for each form, to obtain all the pieces required: but this wou1d have called for uncomfortable work, outdoors, with the workers operating in a tight space, using a support that would be deformed over time, as it was not sufficiently durable.

Fig. 12. The 1:25 scale model of the Palazzetto dello Sport, 2010 (Photo Sergio Poretti, MAXXI Pier Luigi Nervi Exhibition, Roma).

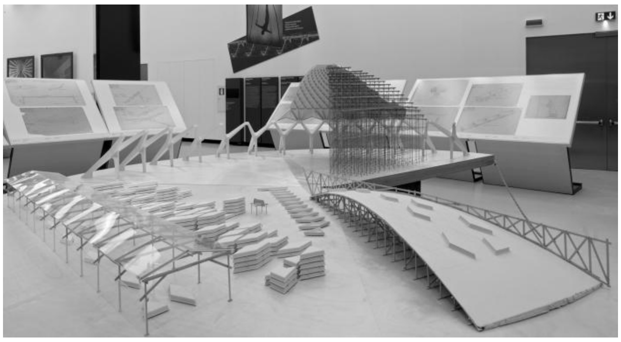

Fig. 13. The 1:25 scale model of the Palazzetto dello Sport. Prefabrication site, 2010 (Photo Sergio Poretti, MAXXI Pier Luigi Nervi Exhibition, Roma).

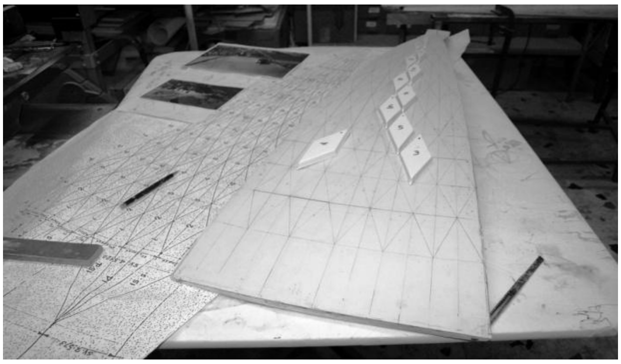

Fig. 14. Generating the model of the Palazzetto dello Sport, 2010 (Photo Sergio Poretti, MAXXI Pier Luigi Nervi Exhibition, Roma).

Fig. 15. Generating the Palazzetto dello Sport, 1956 (MAXXI Architettura, Centro Archivi, Roma: Fondo P.L. e A. Nervi).

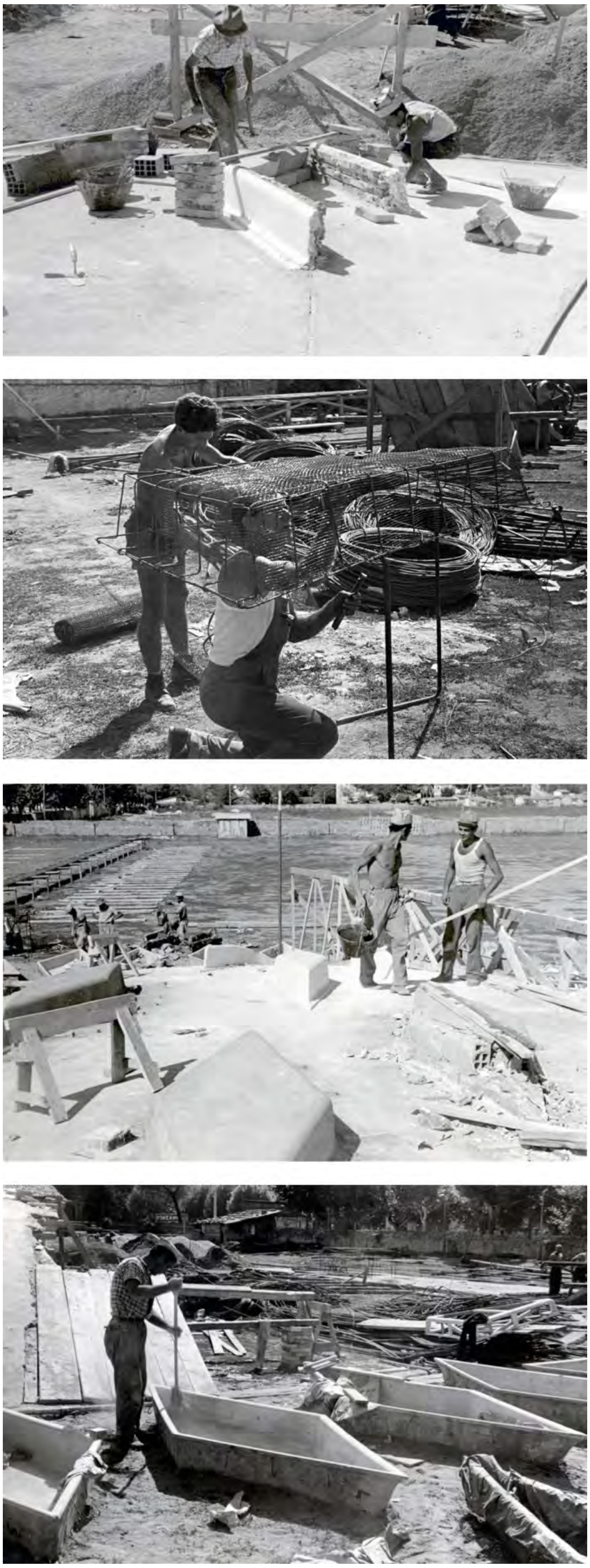

Fig. 16. The grandmothers construction sequence, 1956 (MAXXI Architettura, Centro Archivi, Roma: Fondo P.L. e A. Nervi).

Nervi preferred to organize the sequence in a number of passages: reversing the first block sample, which was called the "grandmother", a small number of "mothers" were made, i.e. forms perfectly identical to the masonry profiles (Fig. 16). On these "mothers", working in the shelter of a shed, multiple teams made dozens and dozens of "daughters", also identical to the "grandmothers", which would effectively be used in the construction (the generational terminology was part of the jargon that was really used on the worksite). Even the outermost rim of the dome, the one connected to the trestles was made with the same technique: three different blocks to compose the fan, and three for the "festoon", whose famous profile, however, was the result of a formal correction obtained thanks to a special, sinuous prefabricated element that modified the interrupted triangular pattern suggested in the initial drawings.

The wooden template was finally conceived at the end of August 1956. At the end of December, the 1620 prefabricated pieces were ready, stacked in perfect order near the completed ring of trestles. (Fig. 17) Starting in January, the blocks were rested, one after the other, on the sparce scaffolding of pipes. Then, once the mosaic had been assembled, in the canals created by placing the blocks side by side reinforcement bars were inserted, followed by poured concrete to complete the work. The blocks, with a good finish on the visible inner surface thanks to the use of a smooth counterform, were engulfed by the poured concrete, functioning like sacrificial formwork. In the end, the dome appeared like a monolithic molded block: no one would be able to intuit the sequence of breakdown and recomposition revealed by the drawings or the worksite photographs. The procedures of assembly of the pieces and pouring took just 30 days. helped by a mild winter. So on 24 February 1957 the dome was finished, and it was already time for the first visits for ecstatic participants.

5. THE THIRD LIFE

In the wake of success, Nervi became an ante litteram international starchitect. He established his own architecture and design studio - Studio Nervi - that worked with an international clientele. From a historical point of view, the designs developed by Studio Nervi for buildings to be made in foreign countries have to be distinguished from the works constructed in Italy by Nervi & Bartoli Company. Overall, the Studio's production is more heterogeneous than Nervi's Italian works. That was the natural consequence of many differences: his customer's heterogeneity, his partial role in the design, and the relationships with numerous foreign building firms. [13][14]

However, such heterogeneous production shows also the continuous effort by the Studio's designers to keep the main features of the Nervi system. For instance, ribbed or undulated surfaces: in the oversized dome of St. Mary's Cathedral, in the New York Bus terminal, in the dome of the Norfolk Sport Palace and so on And again the monumental shaped pillars: in the central piers of the Bus Terminal, in the inclined supports to St. Mary's roof, in the plastic columns of the Norfolk dome or in the tetrapod columns of Brasilia Embassy.

However, the Nervi system took on a different connotation: without the construction stage on site, detached from the peculiar situation of the Italian building industry in which it was developed, it underwent an 'encoding' process. On an international scale, the typical building technique of the Nervi system turned into a style: the so-called Nervi Style.

6. CONCLUSION

Studying the works built for the Olympics confirms the innovative nature of Pier Luigi Nervi's experiments; in fact, the novelty lies above all in the unique construction technique. The ingenious intuition of the great structural potentialities of thin vaults, by keeping in mind that their resistant virtues depend on the form, is internationally recognized.

Fig. 17. The Palazzetto dello Sport full worksite: on the left, the prefabrication site; on the right, the cast-on-site and assembly site, 1956 (MAXXI Architettura, Centro Archivi, Roma: Fondo P.L. e A. Nervi).

Since the Thirties it produced a series of masterpieces by Dischinger, Finsterwalder, Torroja, Freyssinet, and in the post-war years, it was the basis for Candela or Isler's hypar shells. The signature feature of Nervi's vaults, domes, ceilings lies essentially in the folded, ribbed, undulated version of the surfaces. That is the distinctive feature of Nervi's architecture, which can, therefore, be seen more clearly from the inside.

Paradoxically, however, the exceptional nature of Nervi's works (and hence their Italianness) lies in their being complex structures made by using a simple and plain method invented by Nervi himself. That is closely related to the year-long technological underdevelopment the Italian building sector would experience from the reconstruction years to the first half of the Sixties. Not only current building but also large-scale infrastructures were still constructed in substantially pre-industrial building sites by small-sized enterprises that used very little automated equipment. Nevertheless, Italian works were recognized as masterpieces of structural engineering. Riccardo Morandi, Silvano Zorzi, Sergio Musmeci bridges won a place in international exhibition, like the famous one in MOMA in 1964. Their sophisticated and bold solutions became the symbols of Italy's rebirth and of valued "Made in Italy" products.

Nervi proved that the full potential of reinforced concrete was still waiting to be discovered. He believed that his work would usher in a new phase of his favourite material. Instead the exact opposite happened: the use of thin shell concrete structures was gradually abandoned and ferrocement - this economic miracle - was to remain forever associated only with Nervi. Why? First and foremost, the inexpensive nature of ferrocement and structural prefabrication ended due to the growing costs of labour and materials which came close on the heels of the economic miracle (much sooner than in more industrialised countries).

What became even more anachronistic was the idea that an individual could control the entire construction process. As a result, Nervi - the great architect, engineer, builder - was the last in line of a long dynasty of Italian master builders, which from Antonelli and Vittone goes back to Brunelleschi.

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