Proceedings of the First International Congress on Construction History, Madrid, 20th-24th January 2003,
ed. S. Huerta, Madrid: I. Juan de Herrera, SEdHC, ETSAM, A. E. Benvenuto, COAM, F. Dragados, 2003.

Structural invention and production process in the Pier Luigi Nervi's work

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Pier Luigi Nervi (1891–1979), a structural engineer, also called the «Constructor» or the «Architect», started his practice in the late years Twenties and continued till the early Seventies. This long, fruitful period includes the development of his structures and the studies and testings about the structural precasting. At the same time, he designs several buildings, from the first realizations as Stadium Berta in Florence (1929–1932) and the Hangar in Orvieto (1935), Figure 1, to the followings of '40s and '50' (Exposition Palace in Turin, the Small Sport Palace in Rome, the Pirelli Skyscraper in Milan), until the american projects (St. Mary's Cathedral, San Francisco, Cultural and Convention Centre of Norfolk, Virginia).

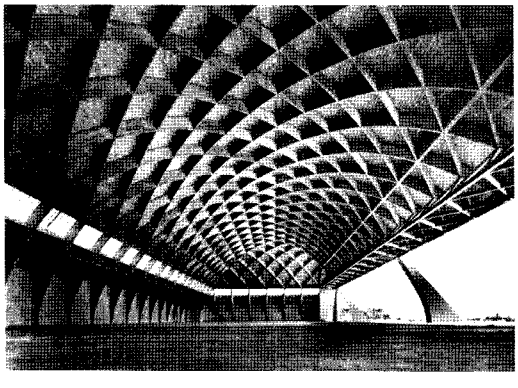

Figure 1
Hangar in Orvieto (1935)

The Nervi's approach to the building process is global.

This extraordinary achievement is reached by mastering all the factors which condition the building process, namely the experimentation of new structural configurations and of building process, the planning and the realization of specific constructions, the production of structural elements, the same building process meant as studies for a logical economical progression of the building activity and the planning of the provisional works, the aesthetic aspects, the economics of the construction.

The systematic survey of these factors, chosen as key to the interpretation of the Nervi's work, is the aim of the present paper.

The structural invention

The essential factor in the Nervi's practice is the constant attitude to conceive, experiment and realize innovative structural complexes.

In the important planning appointments or in occasion of calls for bids for large architectural buildings, especially where the presence of large vaulted halls is requested, Nervi does not plan his construction in the traditional way: on the contrary, the whole building is conceived from the foundation, also

in the vertical supports, even in anyone of the structural elements, as a rational composition of parts principal and secondary of the covering vault or floor. In the case of vaults, the research is carried out following the method of prefabrication of thin, light, strong elements, flat or grooved, which are placed in the final position and later connected by ribs of reinforced concrete cast in the empty spaces left on purpose between the same elements, this way producing a network of members which are oriented in two main directions and kept in their position by the prefabricated elements, a kind of warp of knitted tissue. Nervi shows to follow the great, noble constructional tradition in the research and realization of large-span, thin, light vaults as it has been manifested by the western architecture since the ancient roman time and continued in Europe and in the Near East, namely in Iran; to a very large extent, in fact, the research on vault planning is the most peculiar feature of the architecture of these constructional civilizations.

The researches on structural types are supported by those on building materials and especially on the reinforced concrete and on the *ferro-cemento* etc.

The first idea of the *fer-ciment* is due to Lambot and Monier in the XIX c.; Monier in 1855 got a patent for the construction of boats where the product is used in place of the wood, in 1867 an other patent for *caisse-bassins mobiles* to be used in gardening. Wayss and Koenen in Germany modified the original idea using boxing and a simplified reinforcement and opened the way to the modern reinforced concrete. The Cottancin system, 1886, using boxing and a very dense net of iron wires, was later used in a systematic way by Anatole de Baudot for his architectures like, for instance, the Church of St. Jean in Montmartre.

Amongst the many Nervi's inventions and realizations, one of the most interesting is the so called «*strutture cementizie ondulate*», Figure 2, (patent of industrial invention 1948), i.e. the corrugated vaults.

The invention consists in the use of thin prefabricated elements long from 2 to 3 m of *ferro-cemento*, with the cross section shaped as a semi-wave, Figure 3, (in some versions with square corners); steel bars come out of the body of the elements in order to realize an efficient transversal connection between the single pieces.

To avoid instability of the long, thin elements during the transfer and when in situ, triangular,

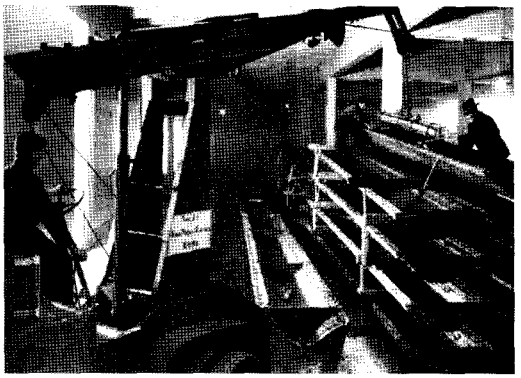

Figure 2
Main Hall of the Exposition Palace in Turin (1950). Prefabricated beam

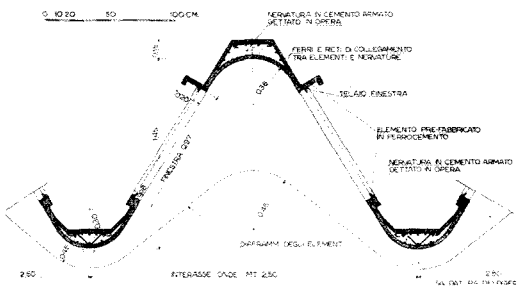

Figure 3
Main Hall of the Exposition Palace, Turin (1950). Drawing of the pre-fabricated cover element

therefore indeformable, meshes of braces prefabricated in the same way, are added to the elements; in some versions these are completed with smart undulated transversal diaphragms which have the same function of the bracing. The triangular bracings and the diaphragms are used as stiffenings during the transfer in the site of the yard, when are in situ become part of horizontal rings —like parallels of the globe— which are connected with the radial elements —half-meridians— of the waves.

A parallel can be started with the early Brunelleschi's idea and realization of the dome of Santa Maria del Fiore in Florence, which was provided with one stone collar tie at the base and with a timber one in the middle and with the

Michelangelo's dome in St. Peter in Rome which was provided in construction with five iron «cerchioni» (some more were added later by Vanvitelli, on Poleni's instigation, as consolidation device).

By means of temporary supports, the elements are put close to the adjacent ones in order to form a succession of waves to define a covering having the chosen shape; they are later connected (see the chapter on Prefabrication) by ribs in reinforced concrete, put at the bottom and at the top of the waves along the radial direction, cast on the spot, Figure 4.

An important role is played in the planning of the Nervi's structures by experimentation also because, as the Author says, it was impossible for the time to calculate the kind of structural systems he was conceiving.

The planning and the realization of specific constructions

This invention of shapes and procedures was extremely fruitful of important realizations:

Swimming Pool of the Accademia Navale in Livorno, 1947–49, the Exposition Palace «B», Torino, 1947–49, the Canopy for Milano Fiera, 1953, Project for the Sport Palace, Wien 1953, Sport palace, Rome, 1958–59, Figure 9, Viaduct Corso Francia, Rome, 1958–59, Papal Hall, Città del Vaticano, 1966–71.

Later Nervi perfectioned the structural conception and got the patent «*Perfezionamento nella costruzione di solette, lastre e d altre strutture cementizie armate*», 455750, 1950, with the realization of the Tobacco factory, Bologna, 1949, Figure 5.

An other very interesting patent, 455678, 1950, is concerned about the disposition of the structural ribs along the isostatic lines of a covering or a vault, Figure 6.

Realizations are the Wool Factory Gatti, Rome, 1951–53, Entrance Canopy at the UNESCO Palace, Paris, 1953–58, Sport Palace, Rome, 1958–59, Labour Palace, Turin, 1959–60, Entrance to the Papal Hall, Città del Vaticano, 1966–71, Figure 7.

With the patent on «*Procedimento di costruzione per la realizzazione di superfici resistenti piane o curve costituite da reticolati di nervature in cemento armato, completate o meno da solette di collegamento tra le nervature*», n° 465636, 1951, Nervi realized the following works: the semi-spherical dome of Exposition Palace «B», Turin,

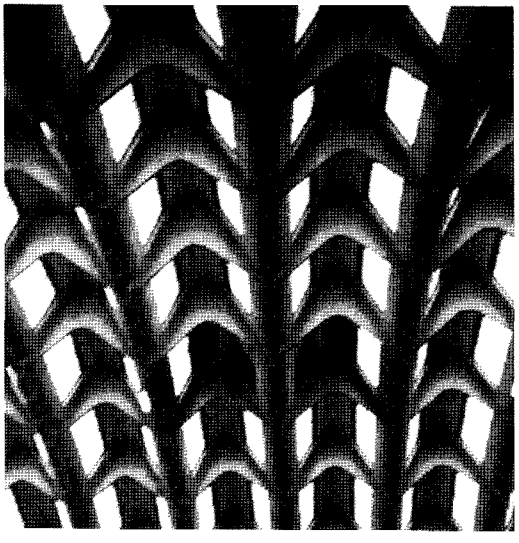

Figure 4
Main Hall of the Exposition Palace in Turin (1950). A view of the prefabricated cover beam

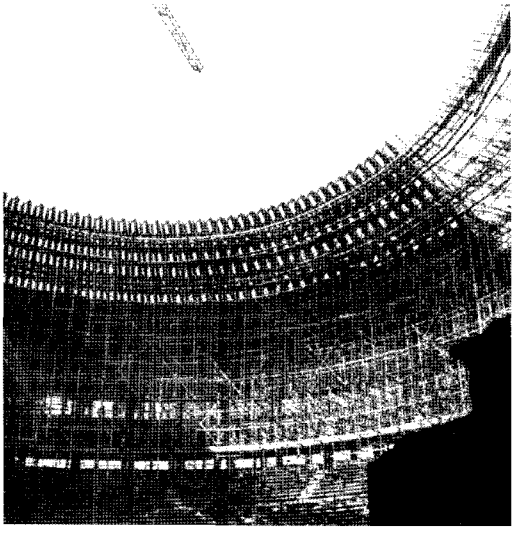

Figure 5
Sport Palace in Rome (1959). Assembly of the prefabricated elements

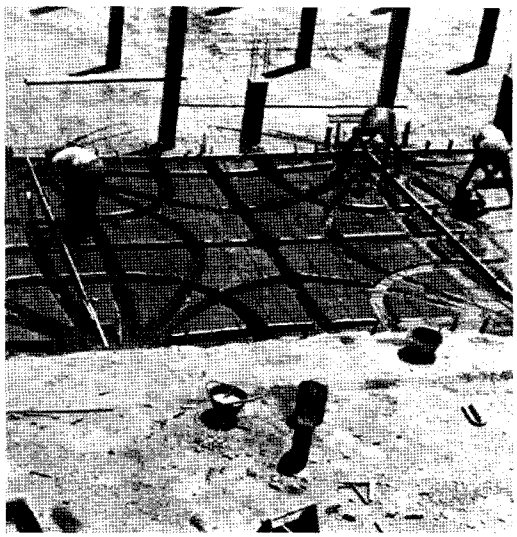

Figure 6
Tobacco Factory, Bologna (1949). *Ferro cemento* boxing

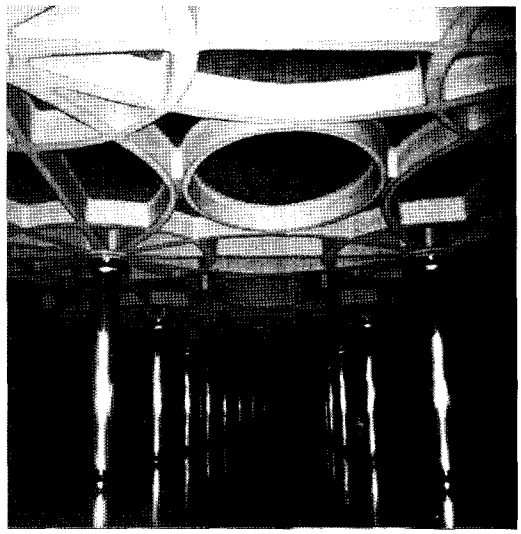

Figure 8
Papal Auditorium in Rome (1971). A view of the entrance floor.

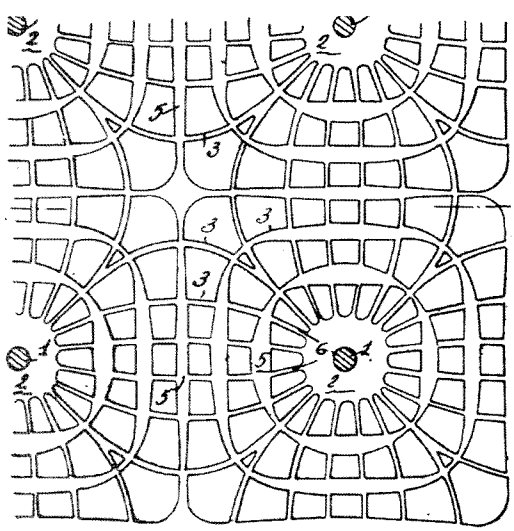

Figure 7
Floor with the ribs positioned along the isostatic lines of the moments

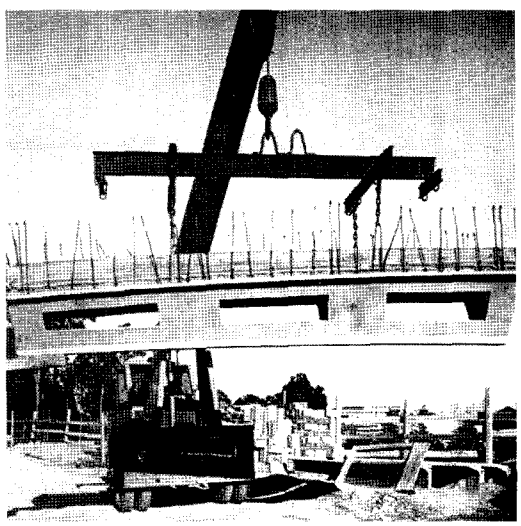

Figure 9
Small Sport Palace, Rome (1959). Cover pre-fabricated element

1947–49, the vault and covering of the entrance gallery to the Exposition Palace «C», Turin, 1949–50, covering of the Restaurant Kursaal, Lido di Roma, 1950, Storage for the salt, Tortona, 1950–51, covering of the Fests Hall of the Thermae, Chianciano, 1952, Small Sport Palace, Roma 1956–57, Figure 8, project for the Benedictine Cathedral, New Norcia, Australia, 1958, vault of the

Field House of the Dartmouth College, Hanover, USA, 1960–61, Bus Station, New York, 1960–62, Building Australia Square, Sidney, 1961–67, St. Mary's Cathedral, San Francisco, 1966–71, Culture and Sport Centre, Norfolk, USA,1966–68.

These researches on materials and on methods of vault planning are announced in the two hangars Nervi planned in Orvieto in 1935, organized as an only coved vault starting with its supports from the very ground and developing as a network of ribs diagonally moving from one to the other of the longest sides of the building. The entire building, the ribs and the other portions, allow to get over a span of 50 m.

Another roof system, tested by Nervi, is the mushroom floor, used in the Labour Palace in Turin, where the reinforced concrete pillars show a variable section, and are covered by metallic elements placed along the radius, Figure 10, Figure 11.

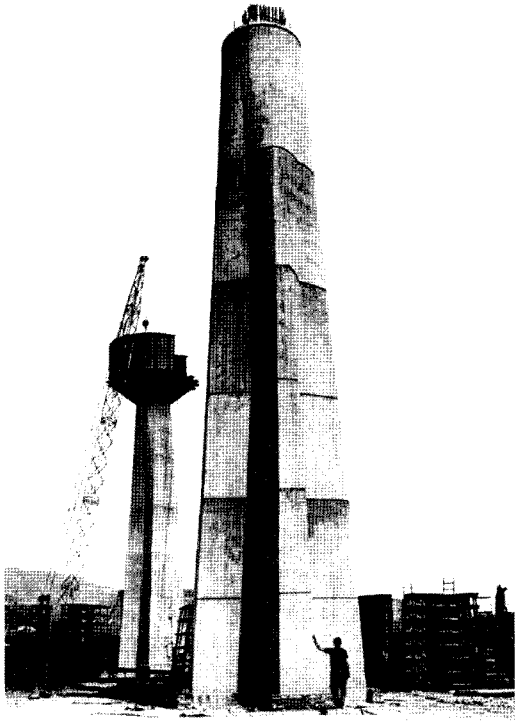

Figure 10
Labour Palace in Turin, (1960). Execution of the pillars with a variable section

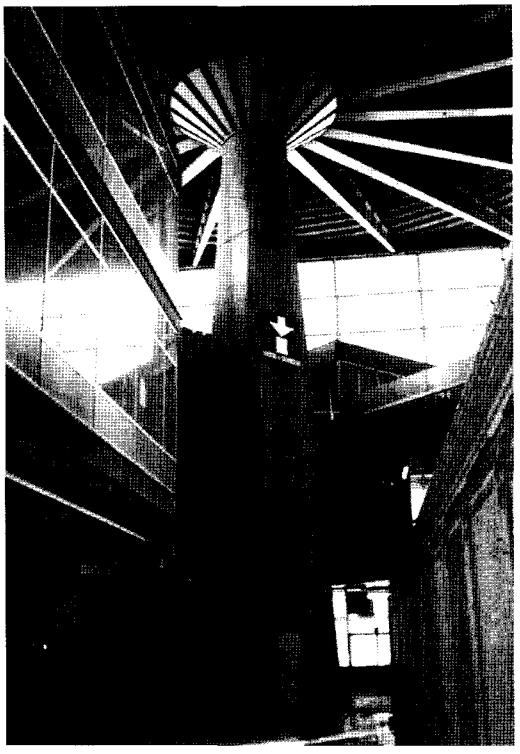

Figure 11
Labour Palace in Turin, (1960). A view of the pillar with a variable section

The very large number of realizations of vaulted buildings proves the fulfilment of this task.

The production of structural elements, the prefabrication

«*La prefabbricazione apre ai progettisti i più ampi e promettenti campi della vera e grande architettura*» profetically said Pier Luigi Nervi in 1955. The *ferro-cemento* in the version for which Nervi got a patent in 1943, is constituted by several layers of iron net (thickness inferior to the millimetre and meshes of about one centimetre), connected by thin iron wires; this skeleton is later covered by concrete of plastic consistence, with modest mechanical properties, made with high quality, high percentage cement melt with water and sand. The composite *ferro-cemento*

has very peculiar properties such as: perfect structural isotropy, due to the homogenous distribution of the reinforcement; an excellent behaviour both to tension and compression; high elongability and, at the same time, high superficial tension, properties which prevent it from cracking, «*inrompibile*» as Nervi defined it with an Italian neologism. The boxing, made of wood or metal or chalk, to be used an indefinite number of times, is laying on the soil during the positioning of the reinforcement and the cast of the concrete; bottom and side surfaces can be smooth or dressed according to the refinement quality and level requested for the final product. The prefabrication allows to realize elements with a curved surface and the presence of material only where really needed for the structural function, something which is rather difficult and anyhow very expensive with the traditional reinforced concrete. The possibility of connecting all the elements prefabricated in the said way by means of a network allows the monolithicity of the work.

In the case of the grooved vaults, a steel reinforcement of longitudinal bars (high resistance steel if a pre-tension is planned) is placed, from the extrados, at the bottom of the wave and at the crest; concrete is poured on both reinforcement to form radial ribs from the top of the vault to the springings. The resistant masses of steel bars, being placed at the maximum distance from the neutral axe, as Nervi says in the patent request, exploit the maximum efficacy. It is clear therefore that the waves have the function to keep the steel reinforcement, in a way they act as distancers even if they co-operate to the bearing function; in fact they can have voids for windows at one or at both sides, as Nervi says, besides they realize the closing of the building and do not need further protection against weather because they are water-proof and «*infessurabile*» an other nervian neologism like «*inrompibile*» .

Prefabrication, coupled with seriality, is in fact present in almost everyone of the Nervi's work. Already in the early realization of the Hangars in Orbetello, Figure 12, Tuscany, the ribs of the coverings are prefabricated on the ground of the yard.

The boxing was put lying on the soil. The maximum care was put in the design and execution of the joints, Figure 13, Figure 14.

The same building process was meant also as a series of studies for a logical economical progression

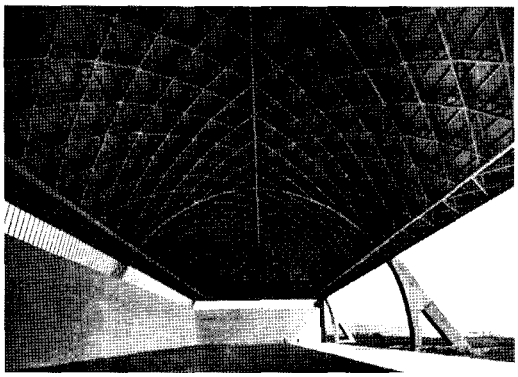

Figure 12
Hangar in Orbetello (1940)

Figure 13
Hangar in Orbetello (1940). Pre-fabrication yard

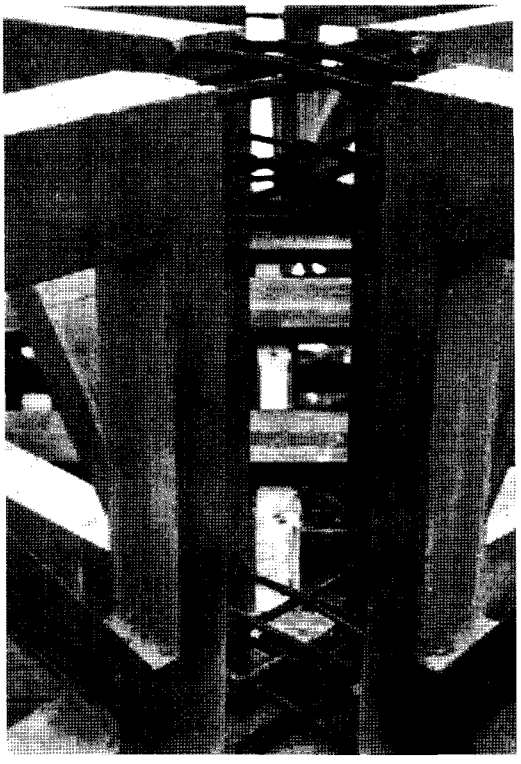

Figure 14
Hangar in Orbetello (1940). A view of the pre-fabricated element node

of the building activity and the planning of the provisional work.

The same operational progression of the building activity is quicker because several elements can be done contemporaneously, for instance whilst foundations are prepared the pre-fabricated elements can be cast.

The aesthetic aspects

To discover the essence of the Nervi's aesthetical theories and at the same time to find a key to the interpretation of his works we need to recall some of his most important statements.

«L'indipendenza di spirito . . . è una condizione assolutamente indispensabile per quanto riguarda il lato estetico.»

«Il carattere di una costruzione non dipende dalla sagoma delle modanature, dalla dimensione delle finestre, o da qualche particolare carattere decorativo, ma fondamentalmente dai rapporti di volumi, di forme, dalle caratteristiche delle strutture portanti, da quel complesso, insomma, di elementi che riguardano non la rifinitura ma lo scheletro e l'organismo strutturale dell'edificio.»

The pilasters of the large halls, for instance, like those of the Papal Hall in Vatican, are shaped by a dynamic conception of the supports: they are very few, dynamically inclined to meet the covering, establishing in a natural way the connection with the soil and starting the very vault, in some cases continued in the covering as arched ribs; they are faceted to reflect the light in different tonalities as sculptures, oriented at the top in the opposite direction of that at the base to meet different orientation of the internal tensions therefore showing the stresses they are facing.

In the coverings, an important aesthetic factor capable to produce patterns of extreme interest, is the seriality of the elements and the alternation of voids and nervures, as it was to be assumed as the dominant motive in the Calatrava's architectural expressions. Precious interesting effects of vibration are produced by the undulation of the elements and the wise use of openings in the lateral sides, the less stressed.

The large halls reach an impressive monumentality by means of the absence of intermediate supports and the same very wide span of the structure.

The most interesting effect is given by the complete integration between architecture, function and structure. Architecture and Structure as nerves and sculpture are to be seen in many of the Nervi's works as the many Halls he planned and in this attitude the Constructor follows or starts, a trend which was also followed by Mallart, Le Corbusier, Marcel Breuer, Morandi etc. The structure, in a period when it is, at least in Italy, generally hided by marble or more traditional materials, in the constructor's conception, on the contrary, is exalted and proudly shown.

Fortunately, the Nervi's ideas and conception in architecture with experimentation, new materials, new structural conceptions, prefabrication etc. therefore large span halls, daring overhangs, expressive members and structures, met the requirements of the new Italian industrial leading

class which thought to be well represented by architectures which were a challenge to the traditional materials and execution techniques as well to the laws of the static; this explains, at least partially, the Builder's fortune.

The economics of the construction

Low cost of the labour in comparison with that of the building materials therefore the optimization of the process is one of the more important targets in the period Nervi was operating.

Many economies came from self-construction because Nervi also acted as Contractor, i.e. easiness, speed and precision when assembling: every piece's end is inserted in the apposite hollows of the other or there is a final cast of reinforced concrete to connect all the elements. Besides: minor incidence of the transportation, stocking in the same yard of the production, the possibility of reducing the execution time by means of contemporary working of the different parts of the construction, finish of the outside surfaces of the elements by means of suitable boxing, preparation of the concrete suitable also for insulation, superficial waterproofing, eventually clear and programmable budget were the main economic factors of success, especially in the offerings presented in the calls for bids.

Conclusions

Nervi introduces an original conception of the load bearing structure which goes far beyond the traditional articulation, in a building, of the different constituting elements such as structural members and curtain walls or internal partitions, i.e. bearing elements and supported parts: he reaches, by means of the building process, a global organization where every element plays a role in supplying, even in different proportions and ways, a contribution to resistance, equilibrium, stiffness, impediment to deformation, in order to ensure the general efficiency and stability of the whole system. In a period in which the load bearing structure is essentially meant as a well defined resistant skeleton separate from the other parts and, especially in Italy, the reinforced concrete is the material deputed to realize it —also steel but only to a minor extent—, the Nervi's structural conception is closer to the attitude of the classic period, when the architect was the protagonist of every building phase or activity, but of course on completely new bases; these are the possibility of using a material resistant to both tension and compression other than wood, the possibility of casting it in the desired shape and the monolithic quality i.e. the effective connection of all the members.

This turns into a general expressivity of the structure where every member that is co-operating to stability is exactly planned in shape and dimensions in accordance with the distribution of the internal tensions and shows clearly the role it is playing. Strong suggestions came to Nervi by the Futurism, and these are to be recognized in the daring cantilever canopy of the UNESCO Palace in Paris, the Maratona

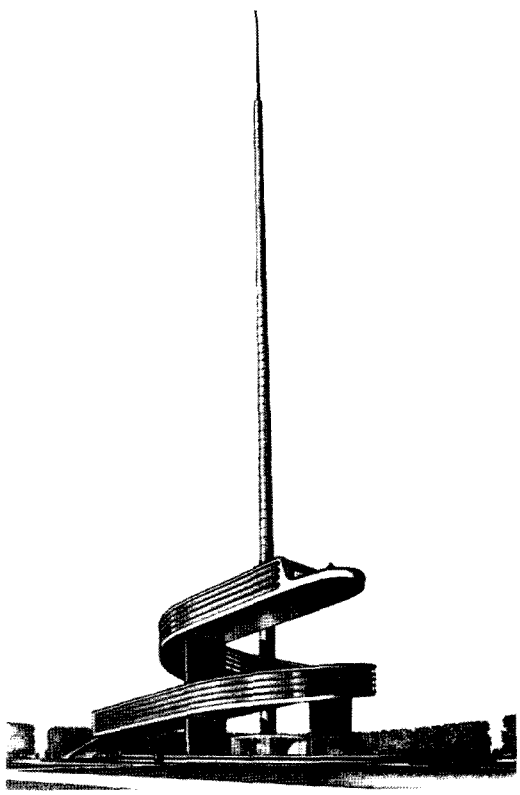

Figure 15
Plan of the *Palazzo dell'acqua e della luce* in Rome (1942)

Tower and the helicoidally shaped staircases of the Gymnasium in Florence, in the graphic rendering of the project for the Palace of the Light and the Water in Rome, Figure 15.

The period of «*autarchia*», i.e. the embargo, very mild in reality (Italy was not, in fact, short of iron and was a middle producer of cement), acted by the European Nations with the consequent shortage of some important building materials, the large use Nervi did of the *ferro-cemento* was in opposition to the trend. The Nervi's ideal and practical experience was concluded with his person, the architecture took later other ways.

An important thought when speaking about the Nervi's practice is the fact that he acted as Planner, Clerk of works, Contractor and Producer, position which gave him the rare possibility of complete control of the building process and of the costs and allowed to experiment structural systems as well as large scale pre-fabrication.

Nervi was in contact with some of the leader planners of his time; Piccinato, Libera, Vaccaro e Ridolfi came to his house in Rome, Bardi, Danusso, De Finetti, Rogers were meeting him in Milan but in architecture he took always an isolated and original position. Nevertheless he is to be considered one of the most important Masters of the Rationalism and Functionalism.

A very interesting contamination and strong analogies for the use of grooved vaults are to be noticed between the reinforced concrete and the use of timber for structural purposes like the pavilions realized in wooden boards by the famous Firm of prefabricated structures Legnami Pasotti, Brescia, and planned by Adalberto Libera and Mario De Renzi, especially the Winter Garden of the National Fascist Party (Libera, De Renzi and Guerrini, 1938).

Also very interesting is the fact that in the timber structures too of the period the pre-fabrication, at an handicraft level, was also pursued and this happened in the same way adopted by Nervi, i.e. the system of designing on the soil the shape of the arches which were to be realized in wooden boards assembled and nailed together. This can be explained by the fact that the cost of labour was very low in comparison with that of the materials.

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