Palazzo delle Esposizioni. View of the interior of Hall C.

Understanding the structures of Pier Luigi Nervi: a multidisciplinary approach

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Abstract: The paper describes the strategies adopted to carry out the knowledge campaign on Hall C built by Pier Luigi Nervi at Torino Esposizioni, between 1949 and 1950, and belonging to the architectural heritage of the 20th century. The structure was built by combining reinforced concrete and ferrocement elements, thus implementing what for Nervi would later become the distinctive construction system of his artwork, which combined the use of precast in situ and cast-in-place elements.

The extensive review of the historical documentation allowed the identification of the distinctive features and material differences of all structural elements in order to formulate the least invasive testing campaign possible, combining sample extraction with non-destructive testing. The paper aims to illustrate the problems and challenges associated with the creation of interpretive models of the built heritage through the relationship between historical critical investigations and structural diagnosis and is intended to serve as an example for an appropriate phase of investigation aimed at developing guidelines for the conservation of a complex and iconic work.

Keywords: diagnosis; preservation; structural assessment; historical concrete structures.

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1. Introduction

The preservation of 20th century architecture, with its various forms and types of construction, is a challenge in several respects, imposing a multidisciplinary approach from the very beginning of the analysis.

The main risk factor is often the failure of communities to recognize the cultural value of these works. This condition in many cases has led over the years to abandonment, lack of maintenance, or even material-constructive transformations due to changes of use that have modified if not compromised the architectural and structural consistency of the initial design.

The lack of recognition is due to two main factors such as the apparent non-historicity of the works, which are characterized by a design language perceived as contemporary and temporally close to the present, and the effect of aging of the materials, which soon made them acquire a decadent and brutal appearance, consisting of corroded reinforcement, stains and efflorescence, and disintegration of concrete.

The materials and construction techniques used, contrary to what was believed at the time, suffer from serious durability problems, often showing a fragility associated with technologies that for a long time have been developed empirically and with experimental solutions often applied directly on buildings without adequate preliminary theoretical verification.

This condition has led, abetted by the absence of maintenance inherent with the consideration of unlimited durability over time, to states of obvious surface degradation associated with damage and reduction of structural capacity not directly appreciable by visual reconnaissance and therefore triggering an underestimation of damage. Not secondary is, as mentioned, the time lag between implementation, testing and theoretical apparatus, which has generated some issues particularly concerning seismic safety.

The language of modern architecture (built between the late 19th and mid-20th centuries) is in sharp contrast to the past (Curtis, 2006), thanks in part to the use of new building materials and increasingly high-performance construction techniques; this rupture allowed the basic principles of architecture to be rethought in new methods, forms, and languages.

In an approach that guarantees the expression “safely preservation”, these considerations make central the definition of diagnostic plans that must be related to the delineation of the critical historical aspects, with a focus not only on the genesis of the project and its implementation, but also on a detailed assessment of the technical background of the period.

The integration of knowledge regarding the engineering aspect, through the use of advanced structural diagnostic procedures for assessing structural health, and the historical-critical sensibility, through an in-depth understanding of the archival apparatus, constitute the multidisciplinary palimpsest underlying responsible conservation.

In this context, the present contribution aims to illustrate the problems and challenges related to the diagnosis and conservation of a particular heritage, such as the one represented by the Turin Exposition halls, designed and built by Pier Luigi Nervi, masterpieces bridging technology and science, where new construction techniques and materials were combined in an innovative and daring architectural solution.

In particular, the contribution illustrates the strategies adopted to carry out the experimental campaign on Hall C built by Pier Luigi Nervi between 1949 and 1950. The objective of the work, funded by the Getty foundation’s Keeping It Modern initiative (Ceravolo, *et al.*, 2021), is the development of an appropriate conservation plan, through the collective effort and multidisciplinary collaboration of the various research groups, where condition assessment and diagnosis of the structures turns out to be one of the main focuses.

2. Description of the case study

The Turin Exposition complex (or Palazzo delle Esposizioni) was built in 1948 to host the International Motor Show. The design by Nervi and Bartoli proposed a new construction system that combined, for the first time to a considerable extent, the use of prefabrication and ferrocement. The complex consisted of several buildings that were designed to house different functions; among them, Hall B (1947-48, with subsequent enlargement in 1952-53) and the adjoining Hall C (1949-50) together with the underground pavilion (called Pavilion V), designed by Riccardo Morandi, constituted the main pavilions of the complex.

Nervi’s halls constitute one of the greatest examples of modern Italian architecture in the immediate post-war period. Nervi adopted solutions for both halls that were statically efficient and economical, while creating thin-shell roofs with large spans. To achieve these results, Nervi had to solve several problems, including the stringent timelines required by the client.

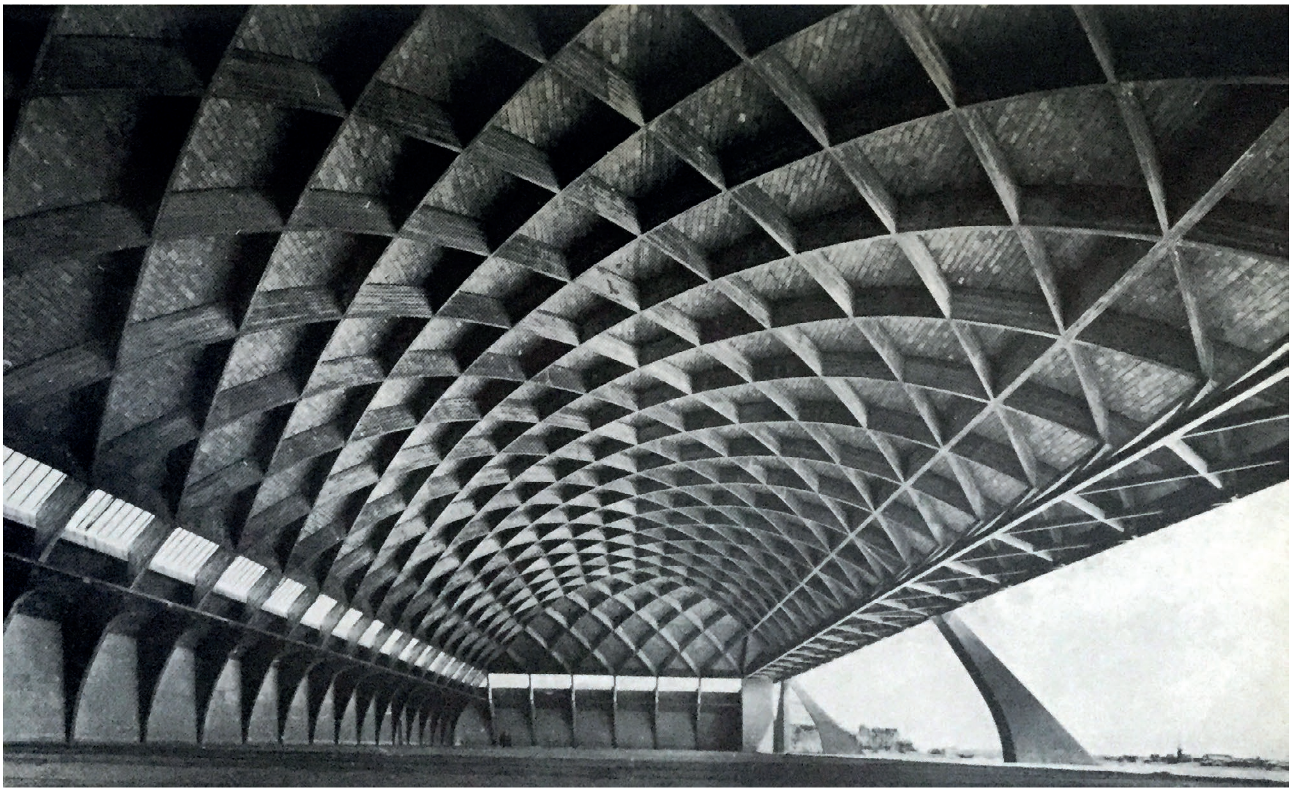

Figure 1 | Structure of the Orvieto hangar. Photographic negative preserved at CSAC Archives in Parma, courtesy of the Pier Luigi Nervi Foundation.

Hall B was opened in September 1948 and is characterized by the large space crowned by the undulating vaulted roof that stretches without interruption of continuity. The striking vault is composed of the juxtaposition of waves of ferrocement, a few centimetres thick, connected transversely by diaphragms; at the base of the vault, fan-shaped elements collect the thrusts and transmit them to the pillars sloping down to the foundation. The strong modularity of the architectural and structural system allowed a later expansion of the hall by another 5 bays. On the other hand, the Hall C, built a short time later, in only 6 months, presents a rectangular plan configuration of 50×65 m surmounted by a ribbed pavilion vaulted roof supported by four inclined arches, a form layout that can be traced back to the one already experimented by Nervi in the hangars of Orvieto (Fig. 1), destroyed during World War II, but which in Torino Esposizioni is further developed through the use of new technological solutions.

The static scheme of the solution adopted by Nervi is of striking straightforwardness (Nervi, 1950): the four inclined reinforced concrete arches support not only the large vault but also the perimeter slab made of precast

Figure 2 | View of the interior of Hall C, where it is also possible to appreciate the detail of the inclination of the arches supporting the vault and perimeter slabs.

ferrocement corrugated beams (Fig. 2), the insertion of which is useful in correcting the horizontal thrust of the vault. Finally, the inclination of the arches is determined by the resultant of the loads of the various supported elements, corresponding to the sum of the thrust of the arch and the perimeter floors.

3. Historical and archival information

Heritage buildings require a thorough documentation process aimed at gathering as much information about the building as possible. In the case of 20th-century architectural heritage, it is often possible to trace a much wider range of sources than is the case with older architecture.

In fact, frequently, drawings, letters, and specifications are encapsulated and preserved in multiple archives: not only the municipal building archives, but also those of the commissioner or even in the archives of the designer himself.

In addition, it is possible to take advantage of the source constituted by photos and videos from the construction site, during the construction of the building itself.

The latter constitute invaluable documents that make it possible to capture phases or solutions that may not emerge from the design drawings.

We can categorize the sources into direct, those referable to the object of study, and indirect, those that belong to the technical historical field of the period along with materials that do not specifically describe the architecture.

The availability of such sources is essential for the correct history of the work, as well as for the classification of the elements and materials used. Moreover, they are fundamental to the creation of interpretive models that will serve to refine the understanding through diagnostic paths and subsequent assessment of residual structural capacity.

As for Hall C, the sources are multiple and from numerous archives; in addition, the writings of Nervi, a prolific promoter of his work, were used, as well as the original calculation reports.

The data from such heterogeneous and complementary sources made it possible to outline the optimal strategy for the campaign of diagnostic tests on the structural elements of the pavilion, which would be as minimally invasive as possible for a work designed pursuing the goal of structural optimum, where the elements are often characterized by extremely thin thicknesses. The sequencing of the construction phases made it possible to highlight varying mechanical characteristics depending on the mode and period of execution of the members, thus optimizing the number and type of sampling.

3.1. Identifying the main structural elements

3.1.1. The pavilion vault

The pavilion vault is developed on a rectangular plan of 45.8×30.8 m and is characterized by ribs arranged at 45°. The vault was built through the use of prefabricated ferrocement elements, used as a disposable formwork in which to cast the ribs and the roof slab (Fig. 3). In the lower part of the vault, the solid elements leave room for openings to allow natural lighting of the interior.

Figure 3 | Detail of the site during the construction phase of the ribbed pavilion vault. In the image it is possible to see the hollows for the casting of the ribs. Università di Firenze, Biblioteca di Scienze Tecnologiche (BST) - Archivi di Architettura, Fondo Pier Luigi Nervi (024-2783).

3.1.2. The undulated slab

The corrugated slab at the impost of the vault consists of prefabricated ferrocement elements of 9.5 m span with a wave section, then completed by in-situ casting to give

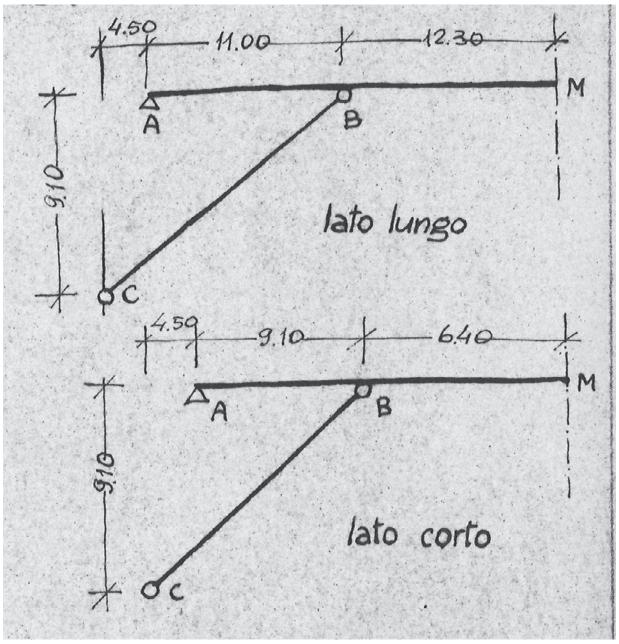

Figure 4 | Hall C Calculation Report, long and short side frame scheme (Nervi, 1950).

continuity. Its main static function is to correct the horizontal thrust of the vault so that it is transmitted to the inclined arches and combining with the vertical forces, thus stressing them in their plane. In his calculation report, Nervi verified the element by calculating both its resistance against vertical and for horizontal actions.

The corrugated beam is composed of a precise combination of reinforcement and wire mesh and high-quality cement mortar. Its cross-sectional area is not constant but increases from the outside inward toward the arches, where it reaches its maximum size. The element has dimensions of 0.94 m wide, 9.5 m long, as mentioned before, and a height ranging from 0.26 m to 0.44 m at the largest part. It is a modular element so made has remarkable strength characteristics, despite its small thickness (2 to 4 cm). The internal reinforcement of the corrugated beam in Hall C consists of three layers of wire mesh weighing 0.600 kg per square meter, both above and below, forming the characteristic curved shape.

3.1.3. The inclined arches

The inclined arches constitute the main load-bearing element of the hall. As has already been pointed out, these are inclined at an angle approximately equal to the composition of the combined thrust of the vault and the perimeter slabs. The static schemes used by Nervi for the calculation of these elements are depicted in Fig. 4 where for sections CB and BM, only the compressive stresses are considered, since the effective curvature of the axes absorbs the bending stresses, produced in CB by its own weight alone and in BM by its own weight plus the applied load. Sections AB can be considered as simply supported in A and interlocked in B (Nervi, 1950). The foundation apparatus consists of 4 isolated plinths at the impost of the arches. Each plinth is designed so that the resultant of forces falls in the middle third.

An interesting issue that emerged during the documentation phase is the idea schematized by Nervi in a portion of a table of different types and dosages of conglomerate to be used in different portions of the

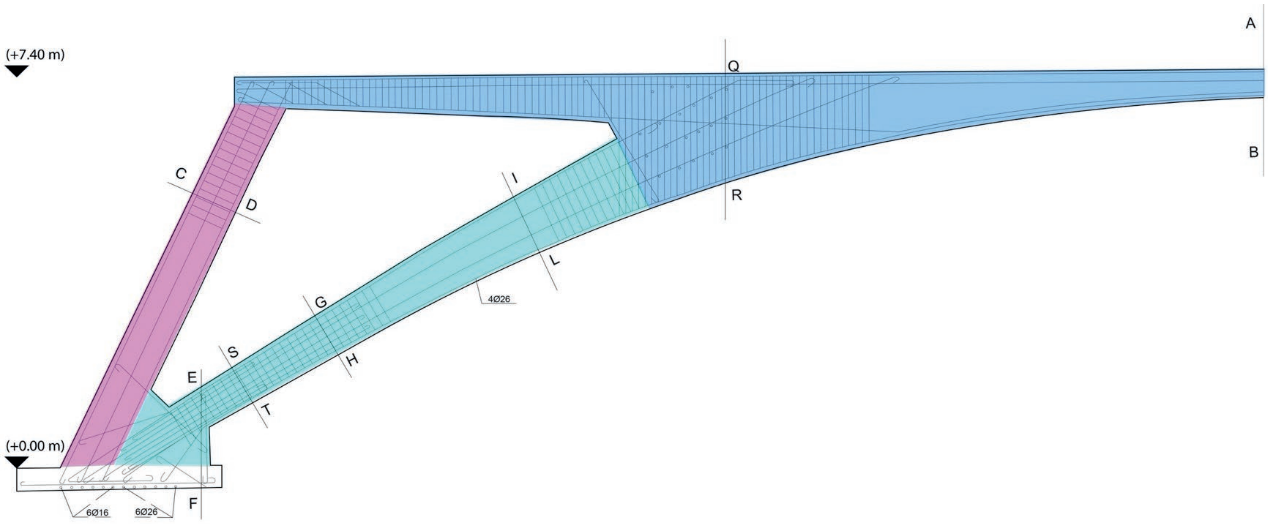

Figure 5 | Identification of different dosages of conglomerate of the arches. The different types of concrete were reported by Nervi in a drawing preserved at the CSAC Parma Archives (Nervi, 1948-53).

arches, depending, evidently on their role in the hierarchy of strengths. From the diagram shown in Fig. 5, two main types of conglomerates, defined as Type 500 and Type 680, emerge. Again, thanks to the documentary phase, we know that the conglomerates used at the Turin Exposition site were produced by Unione Cementi Marchino and that this classification indicated a medium-low-strength mix, for Type 500, and a high-strength mix for Type 680.

The presence of the two different concrete mixture also emerged from the historical certificates of the Experimental Laboratory of Construction Materials of the Politecnico di Torino at the time, which had performed the certifications of compressive strength tests on cubes from the construction site.

One of the main objectives of the experimental campaign is to verify the correspondence of these static patterns and the choices made by the designer in the choice of materials and mixtures.

2. The testing campaign

After analysing the main structural elements and building the finite element mechanical model, the strategy behind the investigation campaign was outlined. Investigations of the reinforced concrete elements are necessary to diagnose the state of preservation and to determine the health of the structures, their residual life, and are the basis for the stability and safety assessments and the design of strengthening interventions.

The investigations of Hall C were carried out in several stages: first, starting from historical sources, a preliminary finite element mechanical model was constructed, which was useful for studying the stress state of the structure. In a second phase, structural investigations were designed to verify the correspondence between the actual state and the original plans and any anomalies. A survey of the existing degradations and their causes was then carried out, and subsequently the investigations concerning the mechanical characterization of the materials were performed, by means of both destructive and non-destructive investigations, depending on the element under analysis.

The location and the number of tests were defined on the basis of the preliminary assessments mentioned above, in relation to the static performance of the different elements, their role with respect to the safety of the structure, and the degree of homogeneity detected in the analysis phase, as recommended by both the Circular (Consiglio Superiore dei LLPP, Il 17 gennaio 2019) and the Guidelines for the Evaluation of the Characteristics of Concrete (Consiglio Superiore dei Lavori Pubblici Servizio Tecnico Centrale, Settembre 2017).

The experimental tests were planned with the aim of identifying the actual correspondence with the original design drawings, as well as to identify their critical elements. Careful planning of the investigations is essential, above all, to establish an adequate level of knowledge of the structure under consideration, considering the gaps in the original drawings of some structural elements, or transformations and/or damage that have occurred over the years, as well as to have a clearer understanding of the construction and implementation choices applied by the designer.

2.1. Structural and damage survey

Along with an initial phase of metric surveying (Sammartano, *et al.*, 2021), structural surveying was carried out, which aims at verifying the correspondence of the actual construction in terms of construction details to the blueprints. This verification is of particular importance, considering Nervi's construction approach, characterized by an experimental and innovative flair, which could have led him to make decisions on site that differed from what was reported in the design phases.

For elements having a structural function, the external geometry has been described in order to obtain a reliable calculation model, while details, such as the arrangement of reinforcement, have been surveyed on a sample basis, also because of the presence of structural elements made in series.

The survey of construction details is aimed at achieving the following information: i) amount of longitudinal reinforcement in beams, columns, and walls and its arrangement; ii) amount of reinforcing bars contributing to shear strength; (iii) constraint conditions of horizontal elements; (iv) thickness of cover meters; (v) the length of overlapping areas of bars and their anchorages. Investigations revealed a good correspondence with the original drawings, both in terms of the quantity of bars used, their diameter and the thickness of the cover. Slight differences were found in the layout, especially in the spacing of shear reinforcement.

Regarding the damage survey, apart from the stagnation phenomena in some elements of the corrugated slab and water infiltration on a few vertical perimeter elements, cracks were found at the base of the various arches as well as in the keystone. These cracks, considering their limited size and their distribution, are physiological, due to thermal coercion states, moreover some of them are located in correspondence of the different casting phases.

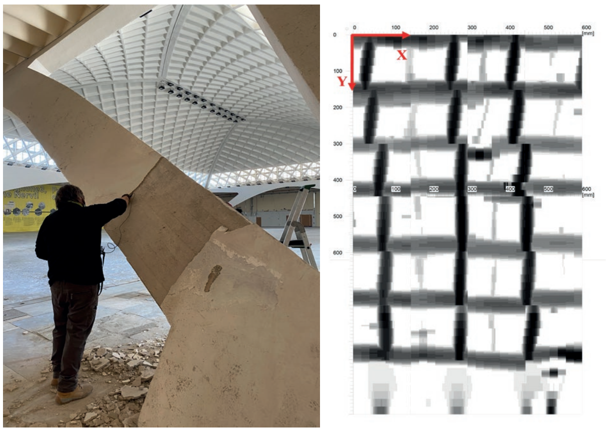

Figure 6 | Rebar survey using pacometer.

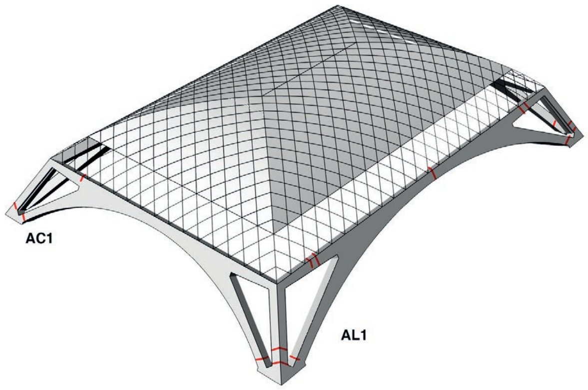

Figure 7 | Schematic showing the qualitative survey of the cracks identified.

Of particular interest is the development of the material-constructive and degradation characterization, performed by means of stratigraphy of the surface layers and which allowed the appreciation of the presence of polychrome finishes. These aspects, combined with the investigations mentioned above, constitutes a fundamental moment of synthesis between the architectural and structural aspects, inseparable for this type of work.

2.2. Non-destructive tests

Considering the particular configuration of the structure under analysis, it was decided to employ the use of non-destructive investigations as much as possible; these were used especially to analyse elements of reduced thickness, such as the ribs, or to limit the use of core drilling.

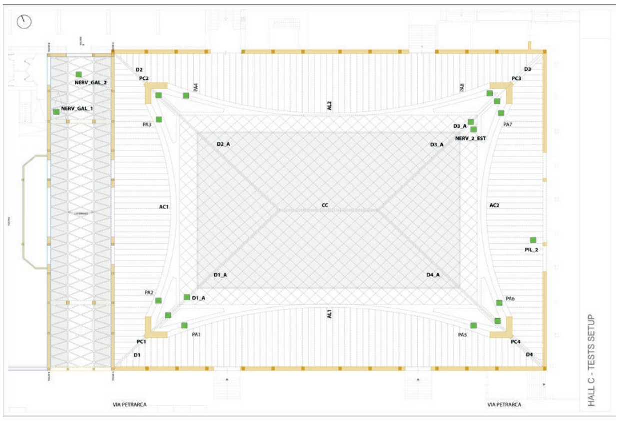

Figure 8 | Floor plan of the hall with the main locations of testing by means of non-destructive measurements.

The schematic in Fig. 8, shows the floor plan of the hall with identified nondestructive tests useful for the materials characterization, such as acoustic emission tests and SONic REBound tests, the latter achievable through the integrated use of ultrasonic and sclerometer surveys. Non-destructive measurements have the advantage of being both straightforward and quick to perform; however, they have a low degree of accuracy. Therefore, in order to achieve better reliability of the tests, they have, where possible, been coupled with the removal of specimens for mechanical characterization tests.

In addition to the investigations just listed, thermal camera acquisitions were carried out, which complemented the structural surveys, and corrosion potential measurements were performed especially on those elements where cracking phenomena had been identified and which could presumably activate corrosive phenomena. A total of 22 areas (mainly the arches, and perimeter pillars) were analysed with measurements of corrosion potential, concrete resistivity, and corrosion rate. The results of the analyses showed the overall good health of the analyzed elements against corrosion, apart from the perimeter piers and the base of the PC1 arches (Fig. 8). It is important to note that the main load-bearing structures of the pavilion, the arches, are protected from corrosive phenomena, such as weathering, and have a rather important layer of plaster (2 cm) that slowed down phenomena that can trigger corrosion of the reinforcement.

2.3. Coring and collection of samples

Sampling is useful both to obtain reliable results on mechanical properties in terms of compressive strength and elastic modulus of concrete and to measure carbonation phenomena. In this case, the sampling was limited mainly to the arch since they are the most monolithic and massive elements in the entire hall, while two other samples were extracted to characterize a beam and a lateral pillar. One of the main objectives in the choice of sample extraction was to identify the presence of the two types of conglomerates hypothesized by Nervi, so core sampling was carried out at the points where this dissimilarity could be appreciated (Fig. 9). On the basis of the extracted samples, it was possible to state, even from visual inspection alone, the presence of different types of concrete, recognizable by the different size and quality of the aggregates found: samples taken from the struts, such as sample PC1_C5 shown in Fig. 10, generally have a lower quality of aggregates than samples taken from the portions of the arches where Nervi had identified a Type 680 mix, such as sample PA2_AC1_C7, shown in Fig. 10.

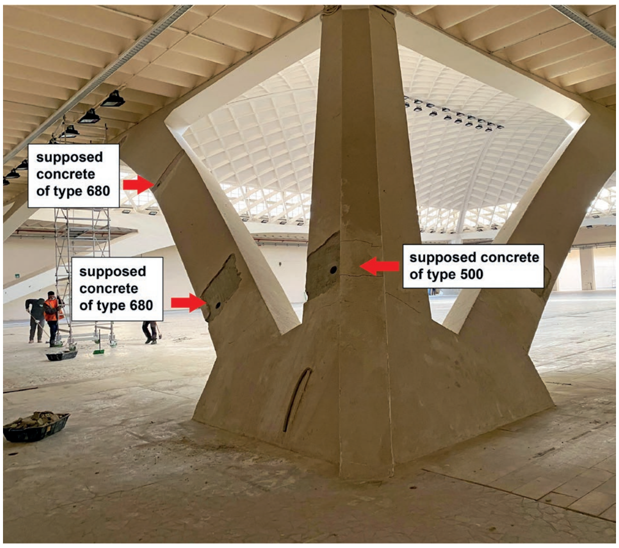

Figure 9 | Identification of the portions of the arches presumably characterized by different types of concrete and different casting phases.

Figure 10 | Sample in the portion of the arch presumably made with Type 680 concrete (on the left), and a sample in the portion of the arch presumably made with Type 500 concrete.

Tests were performed on all extracted samples to determine the depth of carbonation using the phenolphthalein method. Overall, in the case of the elements of the arches, the depth of carbonation was either zero or with a minimal advance front (less than the concrete cover). The element with a higher carbonation level was found in the sample extracted from a perimeter pillar. The results of these tests are in accordance with what was found with the corrosion test results.

2.4. Analyses on the ferrocement elements

As for the ferrocement elements, a construction material present in several elements of the hall, the in-situ investigations were limited to endoscopic surveys and surface scarification to determine the compliance with what the designer designed.

In addition, a specimen of approximately 12 cm×12 cm in size (Fig. 11) was taken to undergo petrographic and physical-chemical analysis for replication. This is due to the extremely small thicknesses of the elements, as well as the fact that substantial portions of the elements would have to be removed to test their mechanical properties. Possible destructive tests on the ferrocements could be carried out through the construction of mock-ups that would be subjected to durability tests and mechanical characterization.

Figure 11 | Sample in the portion of the arch presumably made with Type 680 concrete (on the left), and a sample in the portion of the arch presumably made with Type 500 concrete.

4. Conclusions

It is evident how the multidisciplinary approach is fundamental to pursue the goal of safe conservation, with a particular relevance of the archival reconnaissance and historical-critical observation phase that by means of synthesis in an interpretative model, allows a consequent and appropriate diagnostic campaign. Initial results showed an overall good state of preservation of the main structural elements, with regard to corrosion and carbonation phenomena, with the exception of the most exposed elements.

Moreover, with only a few exceptions, a good correspondence between Nervi's drawings and the actual structure was observed; something that was not taken for granted considering the experimental nature of the designer.

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