12th INTERNATIONAL CONFERENCE ON STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS

SAHC 2021

Online event, 29 Sep - 1 Oct, 2021

P. Roca, L. Pelà and C. Molins (Eds.)

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PREFACE

The International Conference on Structural Analysis of Historical Constructions (SAHC) was first celebrated in Barcelona in 1995, followed by a second edition also in Barcelona in 1998. Since then, nine subsequent editions have been organized in different countries of Europe, America and Asia. The SAHC conference series is intended to offer a forum allowing engineers, architects and all experts to share and disseminate state-of-art knowledge and novel contributions on principles, methods and technologies for the study and conservation of heritage structures. Through all its successful past editions, the SAHC conference has become one of the topmost periodical opportunities for scientific exchange, dissemination and networking in the field.

During the last decades the study and conservation of historical structures has attained high technological and scientific standards. Today's practice involves the combination of innovative non-destructive inspection technologies, sophisticated monitoring systems and advanced numerical models for structural analysis. More than ever, it is understood that the studies must be performed by interdisciplinary teams integrating wide expertise (engineering, architecture, history, archeology, geophysics, chemistry…). Moreover, the holistic nature of the studies, and the need to encompass and combine the different scales of the problem –the materials, the structures, the building aggregates, and the territory – are now increasingly acknowledged. Due to all this, the study of historical structures is still facing very strong challenges that can only be addressed through sound international scientific cooperation.

Taking these ideas in mind, the 12th edition of the SAHC conference aimed at creating a new opportunity for the exchange and discussion of novel concepts, technologies and practical experiences on the study, conservation and management of historical constructions.

The present proceedings include the papers presented to the conference, which was finally celebrated on September 29-30 and October 1, 2021, in an on-line mode due to the word sanitary emergency situation created by the Covid-19 pandemic.

The conference included the following topics: history of construction and building technology; inspection methods, non-destructive techniques and laboratory testing; numerical modeling and structural analysis; structural health monitoring; repair and strengthening strategies and techniques; conservation of 20th c. architectural heritage; seismic analysis and retrofit; vulnerability and risk analysis and interdisciplinary projects and case studies.

The SAHC 2021 conference has been possible thanks to the large contribution of the scientific committee and reviewer panel who took care of selecting and review the papers submitted. The contribution of the different sponsors and supporting organizations is also acknowledged. Above all, the conference has been possible thanks to all the authors who have contributed with very valuable papers despite the difficulties caused by the world pandemic. New editions of the conference are already planned in normal face-to-face formats which, in the upcoming years, will provide new opportunities for sharing valuable knowledge and experience on structural conservation, as well as for keeping alive and fulfilling the purpose and aims of the SAHC conference series.

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CHALLENGES IN THE REUSE AND UPGRADE OF PIER LUIGI NERVI'S STRUCTURES

R. CERAVOLO[1], G. DE LUCIA[1], E. LENTICCHIA[1*], G. MIRAGLIA[1], A. QUATTRONE[1], F. TONDOLO[1], E. MATTA[2], G. SAMMARTANO[2], A. SPANÒ[2], C. CHIORINO[3], G. BRUSCHI[4], P. FACCIO[4], A. NANNI[5]

[1] Department of Structural, Geotechnical and Building Engineering,
Politecnico di Torino, Turin, Italy.
e-mail: rosario.ceravolo@polito.it; giulia.delucia@polito.it; *erica.lenticchia@polito.it; gaetano.miraglia@polito.it; antonino.quattrone@polito.it; francesco.tondolo@polito.it

[2] Department of Architecture and Design
Politecnico di Torino, Turin, Italy.
e-mail: emiliano.matta@polito.it; giulia.sammartano@polito.it; antonia.spano@polito.it

[3] Pier Luigi Nervi Project Association, Brussel, Belgium
e-mail: cristiana.chiorino@gmail.com

[4] Dipartimento di Architettura, Costruzione e Conservazione
IUAV University of Venice, Venice, Italy.
e-mail: faccio@iuav.it

[5] Civil, Architectural and Environmental Engineering Department
University of Miami, Miami, Florida, USA.
e-mail: nanni@miami.edu

Keywords: Historical Structure, 20th century architectural heritage, Conservation Plan

Abstract. *The paper presents the overall objectives of a funded research program for the development of a Conservation Plan (CP) for the two halls by Pier Luigi Nervi of the Turin Exhibition Center. The Turin Exhibition Center was conceived immediately after the Second World War to host primarily the annual Automobile Show, in connection with the presence in Turin of the FIAT motor company. The two main pavilions of the Center (Halls B and C) are outstanding examples of a pioneering use, of new advanced methods in reinforced concrete construction, combining innovative prefabrication procedures and the re-invention by Nervi of ferrocement, used to form extremely thin elements. The CP is expected to push and contribute to the preservation of the halls designed and built by Nervi, with special emphasis on structural and seismic vulnerability aspects, also due to concerns raised on the durability of concrete materials and technologies. Re-using these buildings entails the challenge to guarantee new extended service life to concrete structures built many decades ago and faces the need for a seismic assessment of these structures, in compliance to recent Italian standards.*

1 INTRODUCTION

The present work is part of a topical line regarding the analysis and structural diagnosis aimed at the conservation of 20th century architectural heritage. A heritage of great importance which is however characterized by several problems, first of all the scarce recognition of their historical-documental value. In fact, the preservation of 20th century architecture has fully entered the wider disciplinary of conservation. However, in practice, this cultural awareness clashes with the difficulties involved in adapting recent buildings to current building regulations. Moreover, many of the characteristics of modern architecture - such as the use of advanced construction methods and materials and the development of new building types and forms - challenge traditional conservation approaches and raise new methodological issues. In fact, the assessment of the twentieth century architectures poses new problems in terms of material preservation, structural analysis and reuse [1] [2]. Addressing these challenges will require convergent contributions from experts of different fields. From the point of view of their seismic improvement, 20th century buildings present specific issues, connected to the materials and techniques used for the construction, as well as to the complex and innovative spatiality; the continuous experimentations in all these areas have been among the characteristic features of architectural and engineering research of the past century [3]. For these reasons, in view of a restoration and re-functionalization of these buildings, it is a priority to carry out a careful evaluation of the structural performances, both as regards the level of safety in static conditions and from the point of view of seismic behavior. Experimental activities, including dynamic tests, are part of those operations aimed at identifying the structural characteristics, determining the state of health of the structure and predicting the response to seismic actions.
One of the reasons of the current abandonment of the Turin Exhibition Center, as well as of other Italian Nervi's buildings (e.g. Palazzo del Lavoro, Stadio Flaminio), is the lack of virtuous examples for guiding the renovation and/or reuse projects of the Modern architectural heritage in Italy. The contribution will address the issues regarding the preservation of modern heritage architecture as seen from the perspective of a country exposed to seismic risk. The paper presents the overall objectives of a funded research program for the development of a Conservation Plan (CP) for the two halls by Pier Luigi Nervi of the Turin Exhibition Center.

2 THE CASE STUDY

The monumental complex of Turin Exhibition Center represents a milestone in the history of modern engineering and architecture. The complex was designed and built between the 1948 and 1950 by Pier Luigi Nervi, one of the greatest and most inventive structural engineers of the 20th century [4] [5], as a public space to host primarily the annual Automobile Show, in connection with the presence in Turin of the FIAT motor company. In the construction of both halls of Turin Exhibition Centre, Nervi used new construction procedures that he studied for some years before this project. In fact, he had already successfully used these procedures with his engineering firm Nervi and Bartoli, though on smaller experimental buildings, such as the small storehouse in the Magliana area in Rome (1946) [6], the wharf Conte Trossi in San Michele di Pagana (1947) and the ceiling of the pavilion at the Milan Fair (1947) [7]. Reference to this celebrated and iconic masterpiece, as one of the most skillful examples of structural art, is very frequent in the literature on contemporary architecture. This combined use of two different technologies for the construction of large concrete shells, would become one of the distinctive trait of Nervi's work.

Figure 1: Turin Exhibition Center, Pavilions by Pier Luigi Nervi: Hall B (left and center) and Hall C (right).

The roofing systems, in particular, are outstanding examples of a pioneering use, at the intersection between inspiration and technique, of new advanced methods in reinforced concrete construction, combining extensive use of innovative prefabrication procedures and reinvention by Nervi of ferrocement, as an extremely malleable building material. As in the large majority of his works, Nervi was both the designer and, through its construction company, the builder of the Exhibition Center. In the fifties Nervi will be asked to design a second pavilion (Hall C) and to enlarge the Hall B. Figure 1 shows the interiors of the two halls built by Nervi. Shaped like a fascinating modern cathedral, Hall B (1947-1948) consists of an imposing wide nave covered by a cylindrical barrel vault, and an elegant apse with ribbed hemispherical dome. For the realization of the arches of the vault, Nervi conceived wave-like prefabricated ferrocement elements joined by cast on site reinforced concrete ribs. Stylish fans connect the arches to the inclined columns. The apsidal semi-dome was built using lozenge-shaped ferrocement tiles connected by reinforced concrete cast in the lateral ribs and on their tops. Hall C (1950) is characterized by a captivating ribbed vault, constructed with the same system of ferrocement tiles and resting on four sculpturally shaped inclined arches. A clear proof on how significant the design and construction of both pavilions had been in the growth as a builder for Pier Luigi Nervi, is the fact that after the completion of both halls he immediately registered the patents of the solutions he employed during the construction site. In fact, Nervi registered various patents: patent no. 445781 in Rome on August 26th 1948, entitled "Ferrocement wave" and patent no. 465636 in on 19 May 1950, entitled "Building procedure for creating flat or curved load-resisting surfaces consisting of grids of reinforced concrete ribbing, possibly finished with connecting concrete slabs between the ribs" [8]. These patents would be adopted by Pier Luigi Nervi in the following decades until becoming a typical feature of the globally recognized Nervi's style [8] [9]. Moreover the experimentation of this new solutions was accompanied by the structural prefabrication, that Nervi already developed during the construction of a series of hangars for the Italian Air Force in the late 30s. It is important to note that Nervi's prefabrication did not concern factory-made standard construction elements. In fact, in each building he simply used prefab elements, made onsite. Nervi' s concept of structural prefabrication meant that structures had to be broken down and each element had to be prepared on the ground (Figure 2). Every element had to be small enough and light enough to be lifted and easily assembled. Despite its misleading name (prefabrication) it is just a very old technique, in continuity with the tradition of stereometry.

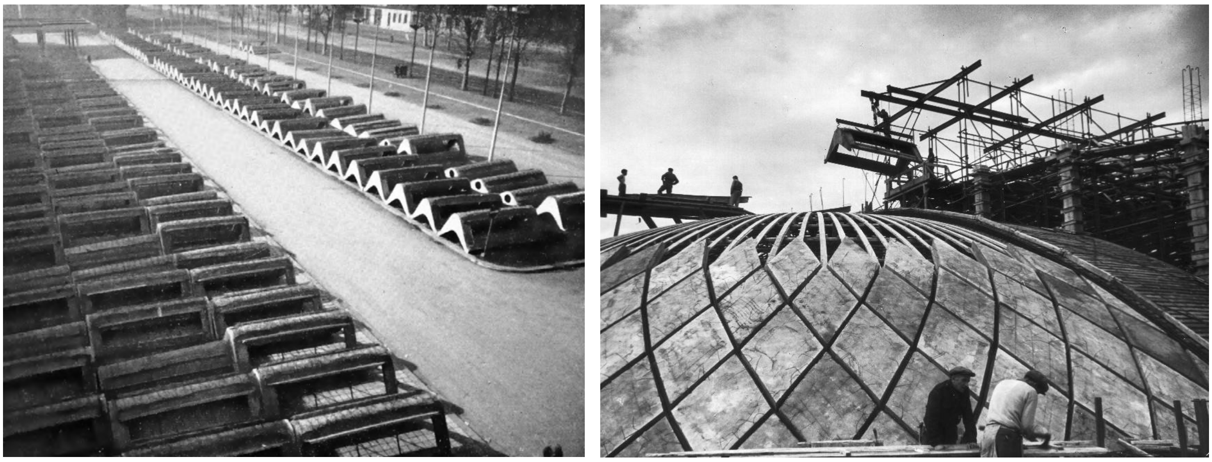

Figure 2: The onsite prefabrication procedure of the undulated ferrocement elements of Hall B and their positioning.

The building is protected with a Landscape protection by the City Masterplan and since 2018 is listed in the National Heritage by the Ministry of Culture (*Codice dei beni culturali e del paesaggio,* D. Lgs. 42/2004) because it's a public building of 70 years old.
Despite its remarkable historical and architectural relevance, the Turin Exhibition Centre has been abandoned for a long time and the lack of maintenance is starting to induce serious preservation problems. In fact, after the transfer in the late 1980s of the Automobile Show to another location, the Center was used for sporadic exhibitions and events and progressive abandon followed. Even more so, these buildings were designed and built with no, or very limited, seismic provisions, due to the lack of technical standards at the time. The CP will issue guidelines to reconcile structural requirements and conservation criteria.

3 THE CONSERVATION PLAN

The conservation of the architectural heritage of the modern movement is the latest and perhaps one of the most contentious frontiers in the field of architectural preservation. Long-standing prejudices and a persistent public lethargy often overcome objective analysis when Modern buildings are faced with demolition or disfiguring renovations [2] [3].
The first act in defining approaches related to the preservation of modern architecture is aimed at recognizing the object as a monument, document, or material testimony, having the value of civilization, which implies a conservative need or a slowing down of the processes of degradation. Criteria, principles and postulates of the modern restoration critically and scientifically understood (distinctiveness, minimal intervention, potential reversibility, respect for authenticity and ancient matter, physical-chemical compatibility of additions, recognition under the double aesthetic and historical requirement of the work) correspond to those developed for the now shared actions of restoration of monuments. These statements find a first

difficulty in the specific disciplines related to the conservation project, but will be overcome thanks to a holistic approach that focuses not on individual scientific contributions but the object as a central element of research in the unity of architecture and structure.
Also the ICOMOS20 groups states that "*There is also some confusion about the basic principles of conservation that should be applied to twentieth-century sites and places*" [10]. The difficulty, or even lack, of communication between architects and engineers has always been one of the main obstacles in the analysis and conservation of the architectural heritage. In fact international guidelines states that the conservation, reinforcement and restoration of the architectural heritage require a multidisciplinary approach. A typical example of interdisciplinary approach is the interaction that has to occur between historical research and structural diagnosis: historical research can discover particular phenomena involving structural behavior whilst historical questions may be answered by considering the structural behavior.

3.1 Scope and challenges of the project

More generally, the research project may be ascribed to the structural assessment and retrofit of 20th century architectural heritage, characterized by a complex 3D structural design. The service life of civil and Cultural Heritage (CH) concrete spatial structures is typically thought to range from 10 to 200 years, but in practice, the service environment plays a pivotal role in sustained durability. We address the challenge of monitoring, conserving and rehabilitating 20th concrete CH because: concrete has become a 20th century emblem; consequently, specific studies are needed that contribute to the successful reuse of modern concrete built heritage. More specifically, large spatial concrete structures, conceived by 20th century European architects and engineers, represent a powerful common world background. Moreover, such structures are plagued by significant deterioration and most of them are in urgent need of retrofitting and/or radical refurbishment. There is a need to bring some of these buildings back to life, while respecting the spirit of their original characters, through new technologies for long-term conservation that can maintain an adequate level of structural and seismic performance. Achieving this goal would produce substantial economic impacts through activities such as tourism, restoration, maintenance, and cultural industry.
The scope of the research project is to develop a Conservation Plan for the two Halls designed and built by Pier Luigi Nervi in Turin Exhibition Center, with emphasis on structural and seismic issues. The project will be a mean to promote, support and guide the successive executive project of the building. An analytical investigation of Nervi's architecture, structures, materials and construction techniques will be supported by:

i) experimental tests on the building and its materials
ii) dynamic vibration-based tests
iii) historic and archival documents and direct observation
iv) accurate geometric survey through lidar and 3D restitution.

These activities will provide clear indications and recommendations for the conservation and restoration of the building's original characteristics, carried out by active experts of architectural heritage preservation. A special concern will be the correct modelling of the unconventional prefabricated ferrocement elements, a peculiarity of Nervi's vaulted structures which finds in these two halls a wide spectrum of constructive variants: in Hall B the wave-like elements of the undulated vault (interestingly interfering with the glass window panels); in Hall

C the diamond panels in the central portion of the vault and the undulated beams in the perimeter area. The unique features of these components make their mechanical behavior largely uncertain and their modelling a fundamental challenge to a reliable estimation of the present and future seismic safety of Turin Exhibition Center.

4. WORKPLAN

In order to overcome the difficulties in the diagnosis and the definition of a proper conservation strategy, the research propaedeutic to the Conservation Plan for the halls in Turin Exhibition Center will be centered different work streams. The various team will work together in order to carry out this main objectives:

1. Historical analysis of the building, investigating its design and construction process, with a particular focus on its technological features and characteristics.
2. Moreover a 3D dense clouds modelling derived from 3D sensing technologies (integrated and fused image and range based methods) will be produced;
3. Structural analysis of the building, considering the construction techniques and materials. Vibration-based dynamic tests will be carried out to investigate the global behavior and the health state of the two main halls and to define guidelines for possible interventions;
4. Analysis of the materials and their durability by means of experimental investigations on structural elements and laboratory mockups. These analysis will be fundamental in the definition of guidance criteria for the materials conservation and rehabilitation
5. Definition of the overall conservation and management plan for the future renovation of the halls.

Figure 3 reports a timeline of the activities of the project. A more detailed description of the activities of the various groups can be found in the following paragraphs.

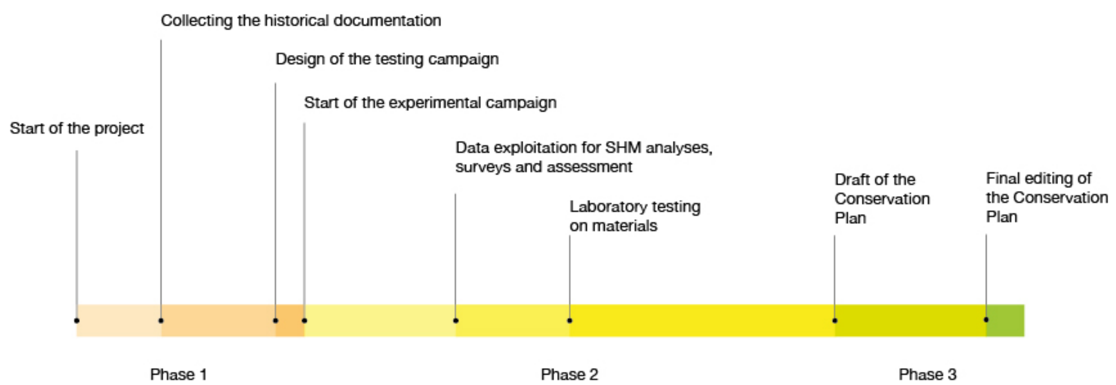

Figure 3: timeline of the project activities.

4.2 Structural Health Monitoring and Seismic assessment of the building

The first work stream is responsible for vibration-based tests and dynamic analysis in order to evaluate the response of the building to earthquakes and perform a seismic assessment of the two Halls of the building. One of the main objective of this unit is the diagnosis of the health state of the halls. It involves a multi-scale approach based on the integration of experimental investigations carried out on-site and in the laboratory. Indeed, the conservation and rehabilitation of heritage buildings can be successfully accomplished only if a correct diagnosis has been formulated. Vibration-based structural health monitoring techniques have now become an important tool for the preservation of either antique or modern architectural heritage [11]. Dynamic tests are particularly appreciated in this field because they are a non-destructive technique and provide information about the whole-body response of the structure and its overall structural integrity. Accordingly, these techniques can in turn be undertaken for: i) understanding the structural behavior of a building; ii) assessing the response to specific events, by measuring some sensitive parameters and comparing them to typical threshold values.; iii) assessing the efficacy of structural or seismic interventions. The investigations of the structures in the dynamic and seismic domain are particularly important for this kind of structures, especially because they were designed and built to withstand only the gravity loads, accordingly to the technical standards of the time. An in-depth analysis of both hall C and B was carried out through several numerical investigations aimed at investigating the dynamic and structural response of the structures. The objective of this phase was to highlight the main criticalities of the structure and to evaluate the best strategy for the experimental campaign. An investigation of Hall C is reported in [12], while the more complex Hall B was analyzed in different steps: a preliminary model is reported in [13] and was implemented by adding the adjacent Hall A, in order to take into account the influence of an annexed structure. In the case of Hall B, the main critical aspects are connected to the large number of structural elements that govern the dynamic behavior of the structure. These macro-elements and their influence on the dynamic response of the building were described in [13]. In particular, it was pointed out that the most critical responses are those related to the undulated thin shell vault, the out-of-plane movements of the tympanums, and the presence of the apse, which cause a complex and potential vulnerable interaction with the main body of the hall. Similarly to Hall C, in Hall B bending and shear assessments were carried out on the main structural elements. Most elements, in particular the inclined pillars, are unsafe with respect to shear. Moreover, the infill walls of the tympanums are subjected to out-of-plane overturning (Figure 4).

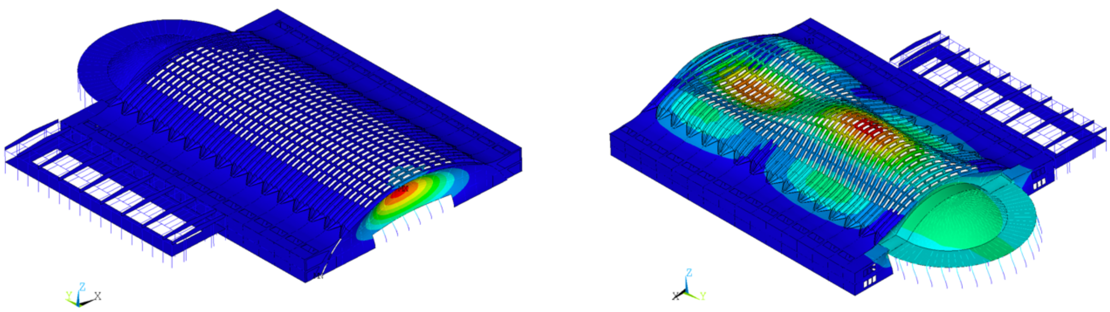

Figure 4: On the left, the out of plane movements of the front tympanum of Hall B; on the right, the interaction movements of the apse and the undulated vault.

The structure of Hall C consists of a vaulted roof supported by four inclined arches. It is completed by a perimetral slab of about 10 meters in length, sustained by a series of slim pillars and infill walls. The analysis started in [12] highlighted that the most vulnerable elements were constituted by the dynamics of the inclined arches. These movements are amplified by their inertial mass, which is proportionally very high compared to the other elements of the hall, especially in comparison with the thin ribbed vault. Another critical aspect lies in the translation of the rigid cap of the roof with respect to the deformable contour ribs. Also due to the low ductility associated with these mechanisms, in case of moderate seismic events, the ribs may be affected by local interaction with the roof. Moreover, the main structural elements (arches, ferrocement elements, and pillars) were assessed with respect to bending and shear. In particular, results show that the arches are not verified with respect to shear loads. As a matter of fact, the shear reinforcement is weak if compared to current standards, as at the time designers were very confident about the resistance of concrete (Figure **5**). Accordingly, the standards of the time only required a shear assessment for beam elements.

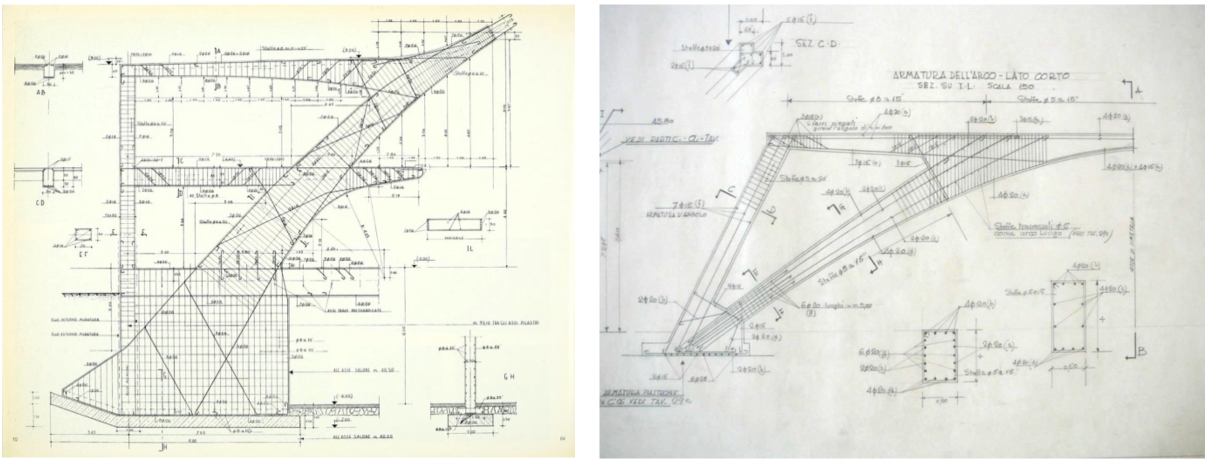

Figure 5: Original drawings reporting the details of the reinforcements of the slanted pillars of Hall B (on the left) **[14]**, and shorter inclined arch of Hall C (on the right) **[15]**.

4.3 Durability

This research stream will carry out the investigation, diagnosis and testing of the materials, by means of on-site inspections, and experimental investigations on materials and mockups on the ferrocement elements. The characterization of the structural materials employed in Hall B and C will be used to reproduce, with the help of the documentation of the construction procedures used by Pier Luigi Nervi (e.g. cement type and content, aggregate dimension, etc.), laboratory mockups to be subjected to an accelerated corrosion procedure. This phase of the experimental investigation is aimed to forecast the structural damage evolution of the main elements of the Turin Exhibition Center once the initiation period is over and the propagation period for corrosion of the reinforcing bar becomes effective. Once some reference level of corrosion will be over, mockups will be tested to compare their structures performances with undamaged reference specimens. Therefore, the evolution of the damage will be directly associated, to the loss of bearing capacity with safety reduction both in service and at ultimate conditions. Rehabilitation techniques as the use of FRCM (Fiber Reinforced Cementitious Matrix) or the use of other thin protective layers and of materials with effects on the cement mortar at the nanoscale will be also employed to explore their effectiveness with deteriorated ferrocement elements.

The experimental analyses will be crucial to define the guidance criteria for the materials conservation and rehabilitation for the CP of the halls, especially since the halls were built with newly patented construction systems and materials by Nervi himself.
The main aspects considered will concern:

- safety checks with respect to durability with a proposal of upgrade of the traditional systems from inspections methodologies to forecast formula of carbonation diffusion to corrosion structural damage for ferrocement construction improving the awareness of the residual safety level of the structures.
- guidelines for remedial actions and structural rehabilitation; a level of intervention priority will be proposed to check the actual conditions, plan the structural conservation activities and to suggest rehabilitations taking into consideration of the sustainability of interventions basically considering the most advanced and less invasive techniques; with reference also to the results of the experimentation on the effects on durability by additional materials as mentioned in the preceding section.

4.4 Historical Analysis and Conservation Recommendations

The conservation plan for the two halls built by Pier Luigi Nervi is an emblematic chance for research studies of structural concrete architectural heritage. The scientific approach implied in this kind of studies reflects the complexity of conservation, restoration and reuse policies requested for great works of modern architecture. This works stream has different objectives: it will closely collaborate with the other units in order to provide the necessary documentations for the first step of their action strategies. It will provide the historical and architectural analysis of the building, including archival researches as well as investigations on the relationship between architecture and construction. Moreover, it will also provide a complete accurate and dense 3D survey, and will define the conservation recommendations also considering the current Italian and European legislation framework. In fact, iconic structures, well known and appreciated and internationally recognized, are difficult examples on which to apply and reconcile any invasive structural retrofitting in terms of conservation.
The main challenges connected to this work stream are connected to various kind of criticalities. In fact, since the building had various owners, and since it has been abandoned for a long time, there is no unified and organized archive related. In particular, archives are located in different cities (Turin, Rome, and Parma), and some documents are in a precarious state of conservation, e.g. the original drawings were realized on tracing papers, which is a very fragile support. Moreover, a precise geometrical survey of the building has never been carried out and maintenance work, that could have caused changes in the interiors of the buildings, has not been adequately documented. The comparative analyses of different historical sources, such as archives, pictures, and videos, can be of great value when analyzing underestimated aspects, such as the use of color. For example some sequences of the film The Italian job, clearly show how the interiors of the building were painted with a cream color (Figure 6) , instead of the current bright white. The use of polychromies combined with the use of natural and artificial light sources, introduce new facets in analyzing the work of Nervi that need careful reflections. This is particularly true if we consider the impact of the interventions carried out up to now, even those that were considered not-invasive, such as the operations of ordinary maintenance and some technological updates.

Figure 6: A frame of the movie The Italian Job, 1969, Peter Collinson in which it is possible to appreciate the different polychromies between the vault (painted in grey) and both the slanted pillars and the walls (painted in dark cream color). On the right, a fragment of the plaster of the hall B showings the various layers of coloring.

5 CONCLUSIONS

After years of abandonment, the celebrated spatial structures built by Nervi in the Turin Exhibition Center will be the object of an in depth analysis in order to recover them. The grant awarded by the Getty Foundation is a remarkable occasion to establish methodological criteria and guidelines for all the steps to be undertaken for an appropriate and virtuous path of structural preservation and rehabilitation. The most challenging issues to be faced in this respect concern *a)* the evaluation of the residual service life of these dated structures and the definition of adequate remedial actions to extend it in line with the new uses foreseen, and *b)* the assessment, in compliance with current Italian standards, of the structural safety and reliability of these structures with respect to seismic actions. As far as concerns item *a)*, advanced research actions are currently being initiated with respect to the assessment and prolongation of the service life of the delicate ferrocement elements of the Pavilions by Nervi. As for item *b)* a modeling and diagnostic investigations in the dynamic and seismic domain have already been performed. These investigations show some seismic vulnerabilities typical of large span shell and spatial structures that were predominantly conceived to withstand static actions and whose behavior in the dynamic domain was not taken into account in their original conception. Appropriate remedial actions, in terms of strengthening and/or damping interventions, shall be properly defined in the final stage of the reuse project.
Finally, the guidelines will have a broad range applicability, so that it will constitute a reference for possible interventions, not only on Nervi's buildings, but also on the concrete shell architectures which at the time were experimented all over the world.

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