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Damage scenario-driven strategies for the seismic monitoring of XX century spatial structures with application to Pier Luigi Nervi's Turin Exhibition Centre

Erica Lenticchia [a], Rosario Ceravolo [a,*], Cristiana Chiorino [b]

[a] Politecnico di Torino, Department of Structural, Geotechnical and Building Engineering, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
[b] Pier Luigi Nervi Project Association, Belgium

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ABSTRACT

Damage and stiffness degradation in non-structural elements are known to strongly affect the global dynamic response of buildings subject to seismic excitation. This is particularly true for complex structural schemes, such as those characterizing XX century shell and spatial architectures. Moreover, degrading behaviours will strongly influence the design of seismic monitoring systems, which are deemed to be a non-invasive protection strategy for cultural heritage. This paper concerns the optimal sensor placement for vibration-based monitoring of one of the vaulted structures realized by Pier Luigi Nervi in the Turin Exhibition Centre. Based on finite element numerical models and optimization algorithms, the sensor placement in such peculiar structures should also take into account the possible effects of non-structural elements. The objective function used for optimizing sensor placement has been modified in order to account for the progressive damage in infill walls. The final scope of this work was, thus, to propose a damage scenario-driven sensor placement strategy accounting for concurrent damage scenarios, as those affecting spatial architectures.

1. Introduction

In recent years there has been an increase in the recognition of the cultural significance of modern architecture [1–3]. However, there are still challenges to secure its protection and conservation. In fact, many of the characteristics of modern architecture – such as the use of new and innovative construction methods and materials, the role of architecture in social reform, and the development of new building types and forms – challenge traditional conservation approaches and raise new methodological and philosophical issues [1,4]. An area of conservation that requires attention is seismic provision. In fact, modern architecture buildings were designed and built with no, or very limited, seismic provisions, due to the lack of reference technical standards at the time of their construction [5]. With a view to the restoration and renewal of these buildings, a careful assessment of the performance of their structures is a priority, especially when they are situated in a seismic risk area.

There is a growing body of literature that recognises the importance of the Modern Architectural Heritage [1,2,4], especially in the case of modern masters such as Pier Luigi Nervi. Recently the works of Pier Luigi Nervi have been the object of special attention: various papers and books have analysed his work [6–9], a special double issue of an international journal dedicated to Nervi [10], and the itinerant international exhibition "Pier Luigi Nervi. Architecture as challenge" has been set up since 2010 [11].

However, there remains a paucity of detailed studies on the structural behaviour and dynamic response of spatial of the 20th century. In the case of Pier Luigi Nervi there is very little information about effects of seismic loads on his structures, although they were realized mostly in seismic risk areas. In fact, the existing studies focus mainly on stylistic and architectural aspects, and much less on structural behaviour. The only studies addressing structural aspects concern the Palazzo del Lavoro in Turin (1961) [5,12], and the Palazzetto dello Sport in Rome (1960) [13,14].

In this paper an iconic building realized by Pier Luigi Nervi will be examined. Turin Exhibition Centre is a spatial structure masterpiece, admired for its daring and innovative conception. Nonetheless it has sadly been abandoned for a long time. This lack of maintenance is starting to induce serious preservation problems. The Municipality of Turin, that owns the building, is considering the assignment of a new function for the complex.

* Corresponding author.
E-mail address: rosario.ceravolo@polito.it (R. Ceravolo).

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The building consists of different blocks, including two famous halls: Hall B and Hall C. For the largest hall, known as Hall B, there is a relevant body of literature [6,15–17]. However, few studies have investigated the smaller Hall C [6]. Consequently, very little is known about its construction and how Nervi conceived its structure. Furthermore, no studies have to date analysed its structural behaviour or its response to ground motions.

This paper reports on the placement of sensors in a seismic monitoring system for Hall C in Turin Exhibition Centre. The authors examined the original design documents and the information from previous surveys. Subsequently, it was created a Finite Element (FE) model of Hall C to evaluate the vibration modes and to calculate the Modal Assurance Criterion (MAC) matrix [18,19]. The concept of MAC was used to define a general methodology for sensor placement in complex spatial structures.

Another issue addressed in this paper concerns the possible effects of non-structural elements (infill walls) on the seismic behaviour of spatial structures. In fact, both halls in Turin Exhibition Centre (Hall B and C) were realized without accounting for seismic action, but only for static configurations, in accordance with the technical standards of the time. The results of the numerical analysis demonstrate that infill walls undergoing seismic damage or degradation [20,21] may significantly affect the global dynamic response of these spatial structures, and consequently the optimal monitoring configurations. These observations led to the development of a novel numerical method to take into account different seismic damage configurations. This sensor placement strategy consists in an extension of the form of an objective function to be minimized in a penalty procedure and is presented in this paper.

The aims of this investigation were (i) to assess the vulnerability of historical spatial structures to seismic actions, with special attention to Nervi's structures; (ii) to propose efficient solutions for the optimal sensor placement (OSP) configurations in such complex architectures. This paper also seeks to contribute to increase existing knowledge about the great legacy of Pier Luigi Nervi. To this end, the present study is aligned with similar studies carried out by other authors on the work of great structural engineers such as Eduardo Torroja [22–24], Félix Candela [8,25,26], Robert Maillart [27], Eladio Dieste [28], Rafael Guastavino [29] thus contributing to the development of the discipline of structural criticism [23,30].

The paper begins with an overview of Turin Exhibition Centre and its construction innovations (Section 2). It then focuses on Hall C, describing the design and the structural conception conceived by Pier Luigi Nervi. Section 3 regards a seismic assessment of the structure, considering the potential seismic damage to non-structural elements. Section 4 describes the application of an optimal sensor placement strategy to two different cases: a first one corresponding to the undamaged structure, and a second scenario that considers a possible damage of the infill walls. Section 5 concerns the application of the novel sensor placement strategy. Finally, the main conclusions are presented in Section 6.

2. Turin Exhibition Centre

Pier Luigi Nervi (1891–1979) was one of the greatest and most inventive structural engineers of the 20th century [10]. With his masterpieces, scattered the world over, Nervi contributed to create a glorious period for structural architecture [11]. Nikolaus Pevsner, the distinguished historian of architecture, described him as "the most brilliant artist in reinforced concrete of our time" [31].

Considering the importance and the peculiarity of this legacy, a cross-fertilization is needed between engineers on one side and historians and architects on the other side, to lay the base for an advanced scientific approach to the documentation and conservation of the 20th century architectural heritage [6,32]. Currently the *Pier Luigi Nervi Project Association* contributes to keep track and knowledge about the life and work of Pier Luigi Nervi. At present the halls built by Pier Luigi Nervi are used occasionally for short exhibition events. This state of abandonment is inducing some preservation problems, in particular in the Hall B, caused by moisture and infiltrations [6]. In the past the building was interested by works of ordinary maintenance [32], and the only inspections were done in 2002 and interested the larger Hall B [33], while the Hall C was only visually inspected. The Turin Exhibition Centre (Palazzo di Torino Esposizioni) was built in 1948 for the 31st international Auto Show. The masterplan prepared by Roberto Biscaretti di Ruffia planned for a large complex on the remains of the Palazzo della Moda, damaged during World War II. The tender was committed to Nervi and Bartoli, whose project proposed a new construction system that combined prefabrication and the use of ferrocement. The building consists of the main Hall B and the smaller adjacent Hall C, both designed and constructed by Nervi (1947–1948, and 1950). In Fig. 1(a) it is reported the Turin Exhibition plan with the Hall C coloured in red[1].

2.1. Design and construction innovations

Nervi pointed out how the limited amount of time allotted for construction and the unusual size of the building created a series of uncommon construction problems that were difficult to resolve using traditional building systems. Nervi employed 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, although only with the realization of experimental buildings. Some of these are the small storehouse in the Magliana area in Rome (1946) [34], the wharf Conte Trossi in San Michele di Pagana (1947) and the ceiling of the pavilion at the Milan Fair (1947) [15].

For Pier Luigi Nervi, the Turin Exhibition represented the first concrete possibility to apply the principle of structural prefabrication, which united in a single large-scale vaulted structure his highly personal use of ferrocement with the extensive use of prefabricated elements. 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. In fact, in the fifties concrete prefabricated elements were especially used in simple buildings, and the precast industry and standardization was not as advanced and broad as in the following decades [35].

Dating back from the thirties, thin shell roofs in concrete were seen as "the starting point for the specific solution of the vaulting problems" [36]. Vaulting forms were created taking inspiration by simple ideas grounded in the laws of nature [37] both empirically and mathematically. After World War II, structural research, particularly into thin concrete shells for vaulted structures, achieved extraordinary results. Researchers and designers of the time adopted a highly pragmatic approach to the industrialisation of construction systems, optimal use of materials, and structural analysis [38]. Nervi was one of the leading structural designers of the period together with Eduardo Torroja, Anton Tedesko, Nicolas Esquillan, and many others.

Turin Exhibition Centre is one among many spatial buildings that were built at the time. In the same decade other daring and innovative vaulted buildings were constructed all over the world. In the U.S.A., Eero Saarinen designed the Kresge Auditorium for the Massachusetts Institute of Technology (1953–1956), while in

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.