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Dynamic Identification of Large Thin Shell Structures in Concrete

E. Lenticchia[1][0000-0002-3746-2933], G. Miraglia[1][0000-0002-3611-0215] and R. Ceravolo[1][0000-0001-5880-8457]

[1]Department of Structural, Building and Geotechnical Engineering (DISEG), Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Torino, Italy
erica.lenticchia@polito.it

Abstract. The paper presents the results of a recent testing campaign carried out on the vaulted structures built by Pier Luigi Nervi in Torino Esposizioni. Nervi's halls are a spatial structure masterpiece, admired for their daring and innovative conception. The technological achievements of the 20th century have allowed conceiving unprecedented large scale and complex structures. However, the experimental nature of numerous innovative structural and spatial configurations adopted by the designers of the time have revealed over time intrinsic fragilities that, when neglected, have threatened their long-term structural integrity.

In addition, 20th century's structures were usually conceived without accounting for seismic actions, but only for static configurations, in accordance with the technical standards of the time. Therefore, it is of crucial importance to assess the dynamic behavior of these structures to understand their vulnerability and plan their correct preservation measures.

Due to its complex configuration, the setup of dynamic testing campaign for Hall B built by Nervi presented many challenges, including: i) the complex optimization problems due to the spatial characters of the vaulted structure; ii) the possible effects of damage degradation or anomalies.

The aims of this investigation were to investigate the behavior of historical spatial structures to seismic actions; and to detect the presence of possible structural anomalies.

Keywords: SHM, Dynamic tests, Reinforced concrete, Structural assessment, architectural heritage, NDT, shell structures.

1 Introduction

The technological achievements of the 20th century have allowed conceiving unprecedented large scale and complex structures. However, the experimental nature of numerous innovative structural and spatial configurations adopted by the designers of the time have revealed over time intrinsic fragilities that, when neglected, have threatened their long-term structural integrity [1], [2].

Among the fragilities due to the degradations of materials which durability had never be tested (reinforced concrete was regarded as an eternal material). However, some issues are also connected to the spasmodic and often daring research (developed both mechanically and empirically), perpetuated by engineers, of the materials and shapes optimization, according to a performance-oriented design philosophy (e.g., minimum amount of materials, minimum weight, uniform resistance, maximal ductility etc.)[3]–[5]. The aim was to obtain the most daring and performing structures by using as little amount of material as possible. Nervi was one of the leading structural designers exploring these problems, together with Eduardo Torroja, Sergio Musmeci, Nicolas Esquillan, Heinz Isler, and many others[6]–[8].

Dating back from the thirties, one of the most used solutions allowed by reinforced cementitious materials to cover large spaces was the employment thin shell roofs. Whenever the first ones were built as monolithic shells, soon designers started to explore different solutions in order to maximize the structural performances. As highlighted by [9], corrugated shells structures have been largely employed in civil engineering. In fact, the undulated shape of these structures allows a significant improvement to their structural behavior, increasing the bending stiffness at the edge, thus allowing the designer to reduce its thickness. This remarkable characteristic had not gone unnoticed by Nervi, that inspired by the nature surface resistance structures (e.g., seashells) [10], decided to adopt this shape to cover the large span of Hall B in Torino Esposizioni.

However, it is important to highlight that 20th century's structures were usually conceived without accounting for seismic actions, but only for static configurations, in accordance with the technical standards of the time. Therefore, it is of crucial importance to assess the dynamic behavior of these structures in order to understand their vulnerability and plan their correct preservation measures.

The paper focuses its attention on the dynamic identification of the corrugated thin shell structure of the roofing system built by Pier Luigi Nervi in hall B of Torino Esposizioni, built in 1947. The hall built by Nervi is a spatial structure masterpiece, admired for their daring and innovative conception. Recently both Nervi's halls, which have been abandoned for a long period, apart sporadic and temporary use, have been the object of a thorough investigation campaign to outline the best conservation strategies [11][12], including dynamic tests campaign carried out on the vaulted structure.

Due to their complex configuration, the setup of dynamic testing campaign for the hall built by Pier Luigi Nervi presented many challenges, including: i) the complex optimisation problems due to the spatial characters of the vaulted structure; ii) the possible effects of damage degradation or anomalies.

The aims of this experimental investigation were i) to investigate the behavior of historical spatial structures to seismic actions; ii) to assess the presence of structural anomalies. These investigations will be also a useful tool to better understand the structures as well as designing the optimal structural health monitoring system of the building, in view of its rehabilitation and reuse.

2 Preliminary Analyses

The recent testing campaign is part of a larger project which investigates both the halls built by Pier Luigi Nervi in Torino Esposizioni. The multidisciplinary approach implemented in this monumental site was developed within a Keeping it Modern project – Planning Grant 2019, promoted by the Getty Foundation, whose aim is to identify projects that have strong potential to serve as models for the conservation of other 20th-century buildings [13]–[15]. The aim of the general research work is the development of a conservation plan (CP), through the condition assessment and diagnosis of the structures, finalized to preservation, retrofit and re-use.

With the aim to finalize an exhaustive characterization of the materials and structures, the estimation of the type and number of necessary tests was defined based on preliminary assessments and in relation to the construction phases of the work, the static role of the various structural elements, their function regarding the structural safety and the degree of homogeneity of the results of any preliminary tests.

The construction history and configuration of Hall B is better analyzed in [16]. While the crucial stages of the geometrical documentation, together with a very-high-scale photogrammetric documentation to generate a multi-scale 3D model are reported in [17], [18]. These documentation stages were crucial to define the best strategies to investigate the buildings. In fact, as it emerged in [19][20], the main issues with the seismic response of the halls are related to the large number of structural elements that govern the dynamic behavior of the structures.

With regards to Hall B, the macro-elements influence the dynamic response of the whole building; in [19] it was pointed out that the most critical responses are those related to the undulated thin shell vault, the out-of-the-plane movements of the tympani and the presence of the apse, which cause an interaction with the main body of the hall.

This complexity in the dynamic response also affects sensor placement for a dynamic testing campaign which aims to identify the structure.

3 The Experimental Campaign

3.1 Dynamic Tests

Dynamic tests supply information about the whole-body response and allow extending to the whole structure the outcomes of the local inspections and measures. These techniques are particularly appreciated in architectural heritage because of their usual non-invasiveness and non-destructiveness, and because provide direct information about the seismic response, and in-direct information about structural integrity. Moreover, the dynamic test setups can be easily installed and removed.

The complexity of the structure directly affects the dynamic behavior of the building and the design of the testing setup. This complexity is due to the uncertainties related not only to the behavior of the interconnecting nodes (e.g., stiffness value, connections between subcomponents, etc.), but also to the interaction with soil and non-structural elements or adjacent buildings. Under these conditions, the proper design of the dynamic tests plays a decisive role in the characterization process. A preliminary FE model of the hall provided valuable data to design acquisition setups in order to maximize the content of extractable information and the spatial visualization of the modes. This preliminary study aimed to reconstruct the global and local dynamic behavior of the hall. The dynamic tests were conducted on 11 October 2021. The signals acquired corresponded to the structure response to environmental noise excitation, produced by external, stochastic forces, such as wind and vehicular traffic. The acquisitions lasted for a maximum of one hour. The acceleration signals were acquired using a sampling frequency of 512 Hz. The acquisition system consisted of 34 monoaxial, piezoelectric accelerometers (PCB Piezotronics, a sensitivity of 1 V/g and 10 V/g was used), positioned on the wavy vault and in the area of the apse and the rear tympanum. Overall, one setup was designed, paying close attention to favoring modal decoupling. The configuration was designed to obtain information in the three spatial directions.

Fig. 1 depicts a view of the Hall B structure, whereas Fig. 2 summarizes the information of the experimental setup installed on the structure.

Fig. 1. View of the Hall B structure (https://www.google.it/maps/@45.0467459,7.6839451,144a,35y,318.98h,56.88t/data=!3m1!1e3).

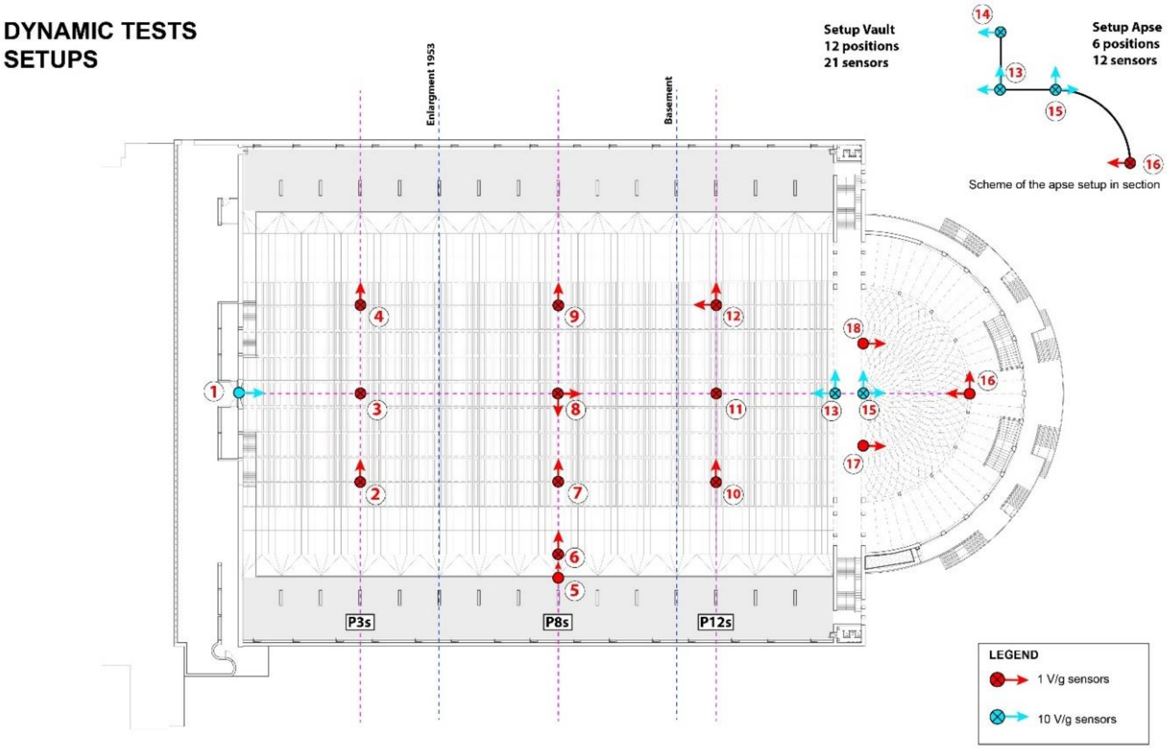


Fig. 2. Experimental setup installed on the structure; the figure indicates the position of the sensors with red circles, whereas the direction of acquisition is shown by red arrows. The "x" inside a red circle indicates a vertical acquisition with the positive direction facing upwards. X is the transverse direction, Y the longitudinal direction and Z the vertical direction.

3.2 System Identification

For the identification, all 34 signals were checked first to avoid the use of records with anomalous behavior. In the case of Hall B, all the channels that recorded the structural accelerations passed the manual check and thus, no anomalies were identified.

Later, the selected signals were first rotated in a global reference system to avoid errors in the eigenvector sign estimate, and then they were processed in order to remove trend and unwanted frequency components. More specifically, a constant detrend was applied and a band pass filter (Butterworth filter with order four) with cut-off frequencies of 1 and 15 [Hz] was used, as the sampling frequency of the records was 256 [Hz] (decimated by a factor of two from 512 [Hz], to reduce noise and speed up the analysis). Lastly, both the Fourier and Welch spectrum were carefully analyzed with the peak picking method, in order to select potential candidates in the frequency domain for authentic vibration modes. The analysed signals, *s*(*t*), lasted 1 hour, which provided a particularly good frequency resolution of 5.2394e-04 [Hz]. Fig. 3 depicts the time history and the Welch Power Spectral Density (PSD) of the recorded time-histories.

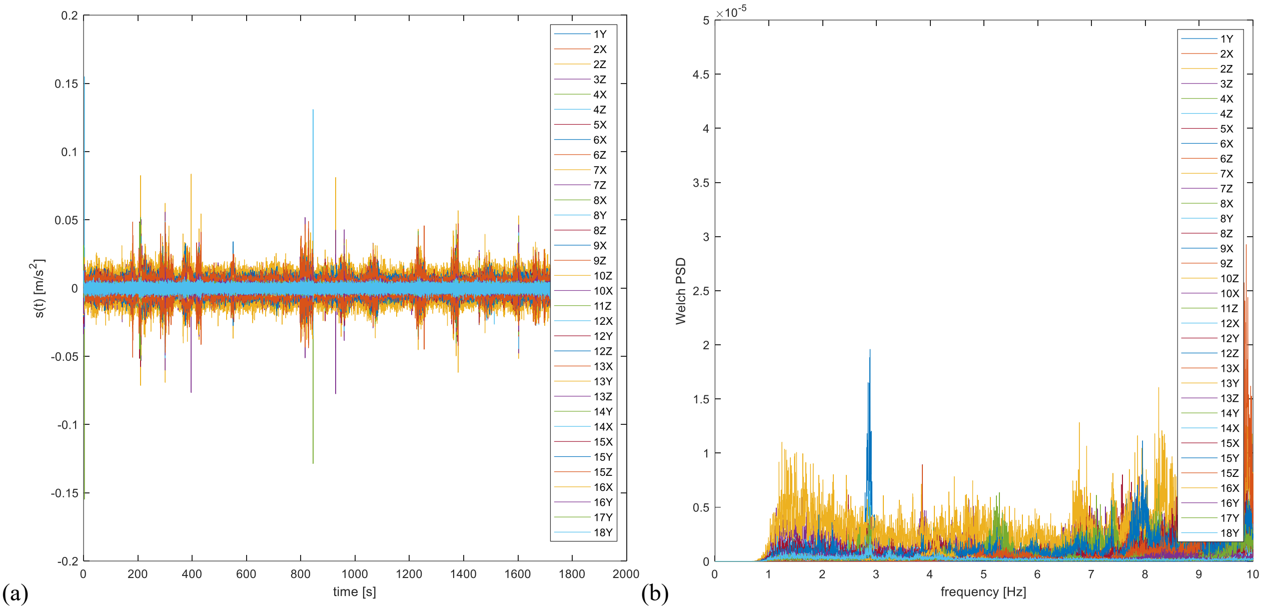
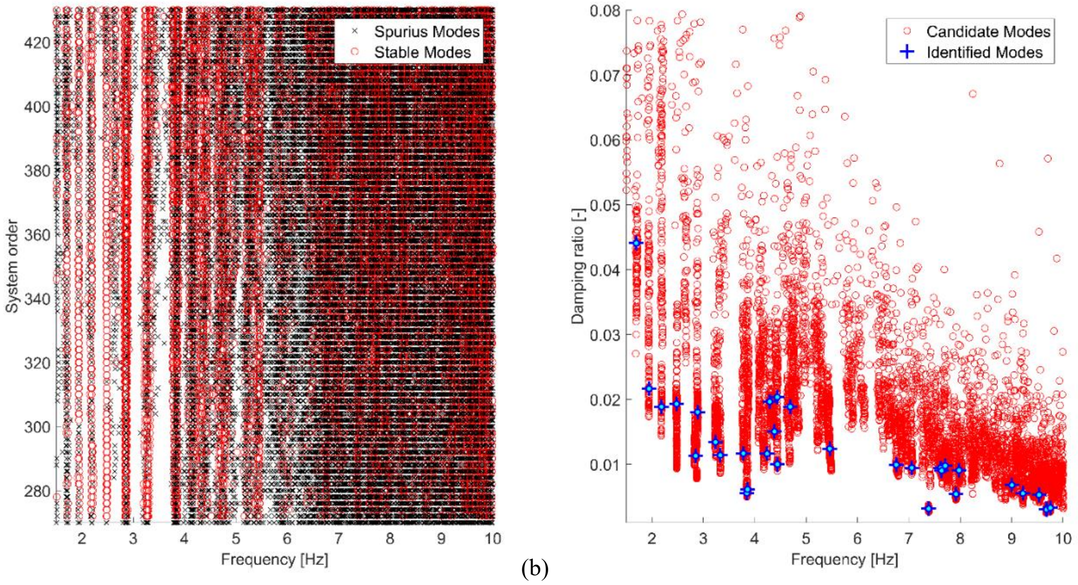


Fig. 3. Filtered signal: (a) Time history of the recorded signals *s*(t); (b) Welch Power Spectral Density (PSD) of the recorded signals. In the legend, the position and direction of acquisition is reported.

After the signal processing phase, system identification was conducted. Given the long duration of the signals, they were fragmented into four parts and the SSI-CVA algorithm was applied on each sub-part. The outcomes of the four sub-parts were then clustered and averaged to obtain unique estimates of each modal parameter. To ensure reliable and robust results, the order of the system was varied between 270 and 430, and a stabilization analysis was performed to allow modes with estimated damping ratio between 0.1% and 8%.

In addition to the stabilization study, a cluster analysis was implemented. The reference value of the frequency and damping used as the outcome of the overall identification procedure was assumed to be the average value of the frequency-damping cluster. To strengthen the results, the cluster analysis focused only on modes with a natural frequency in the range of 1.5-10 [Hz], after previously checking with preliminary identification for the absence of modes for frequencies below 1.5 [Hz], and the absence of relevant modes for the dynamic of the hall for frequencies over 10 [Hz]. Fig. 4 depicts the stabilization and clustering diagram, whereas Table 1 and Fig. 5 report the results of the identification in terms of natural frequency, damping ratio, and main mode shapes of the first four identified modes.



(a) (b)

Fig. 4. Results of the stabilization and cluster analysis; (a) Stabilization diagram; (b) Clustering diagram. The identified modes are highlighted by a blue “+” on the clustering diagram.

Table 1. Results of the identification in terms of natural frequency, damping ratio, and mode shapes of the first four identified modes. **The interpretation of description is based on the mode shapes of a simply supported beam with edge hinges.*

Mode	Freq. [Hz]	Damp. [%]	Description*
1	1.70	4.41	Mode of the vault: 1st flex. mode in Y and 2nd flex. mode in X
2	1.94	2.16	Mode of the vault: 2nd flex. mode in Y and 2nd flex. mode in X
3	2.19	1.89	Mode of the vault: 3rd flex. mode in Y and 2nd flex. mode in X
4	2.48	1.93	Mode of the vault: 1st flex. mode in Y and 3rd flex. mode in X

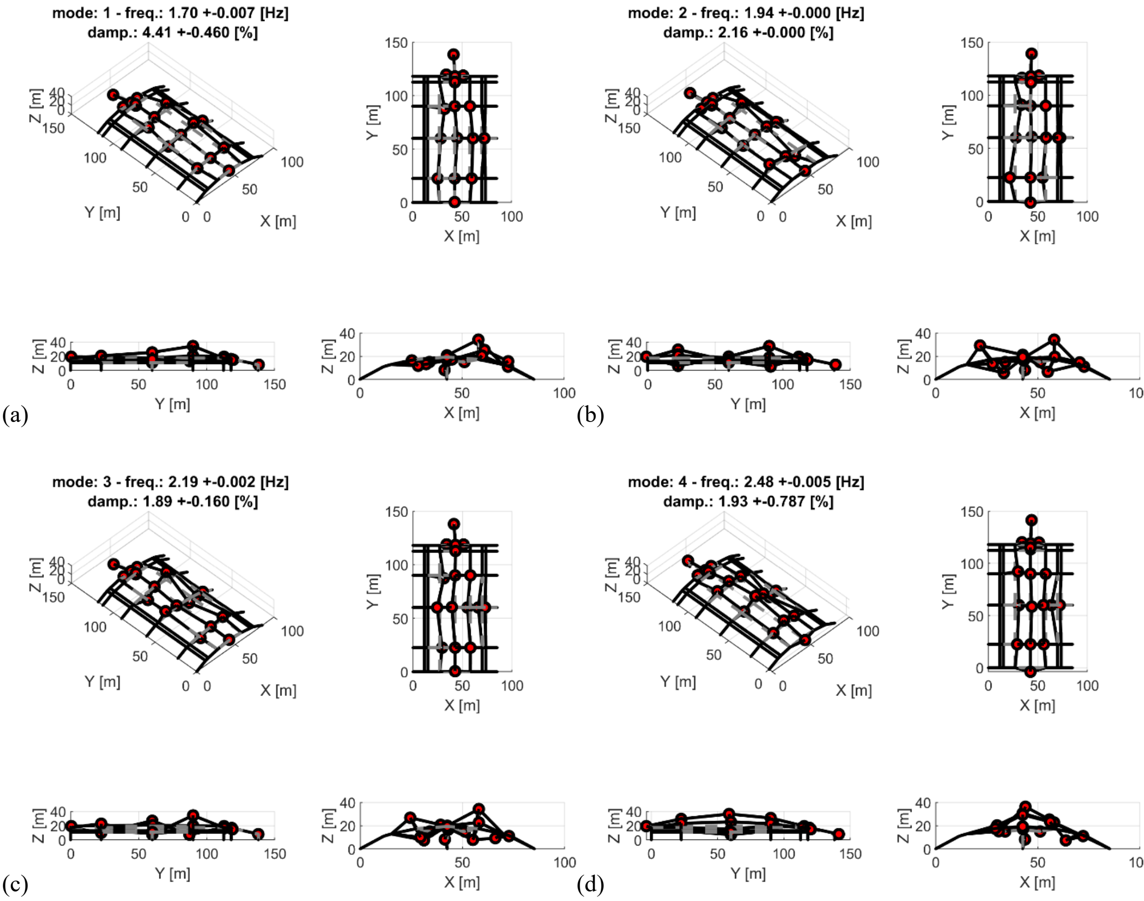


Fig. 5. Identified modes; (a) 1st mode; (b) 2nd mode; (c) 3rd mode; (d) 4th mode. The red spheres indicate the position of the sensors installed on the structure.

4 Discussion of the Results

In order to validate a pre-existing (not calibrated) numerical model of the Hall B, the identified modes were compared with the raw numerical predictions. It is worth stressing that not all the identified modes can match a numerical correspondent, due to: (i) the possible presence (albeit very low) of spurious modes that have escaped the identification algorithm; (ii) the inability of the numerical model to replicate the real modal behavior of the structure. This is especially true for high frequency modes, for which a very low-step size mesh of the FE model is required (however difficult to reach, as it would unreasonably increase the computational effort to obtain the numerical predictions).

Table 2 reports the tentative data assumed in the FE model to carry out the preliminary eigen-analyses. In this initial stage, material properties were estimated from a literature review [19]. The model is fixed at the base, and any soil-structure interaction were not considered.

Table 2. Estimated materials and properties of the preliminary FE model.

Material	**Elastic Modulus E [GPa]**	**Poisson's ratio**	**ρ [kg/m^3]**
Ferrocement	26	0.2	2,500
Masonry (infill walls)	2.0	0.2	1,100
Reinforced concrete	30	0.2	2,500
Reinforced concrete slabs	21	0.2	1,250
SAP hollow block slab	25	0.2	1,250

As can be perceived by Fig. 6 , the comparison of the first two identified mode shapes with the first two predicted by the FE model is quite in agreement. However, the same cannot be said for the natural frequencies, for which a rather marked underestimation of the model is observed (0.87 [Hz] and 0.93 [Hz] for the first and second numerical modes, respectively, compared to 1.70 [Hz] and 1.94 [Hz] of the identified ones). This result indicates the need to implement a calibration process on (eventually) both mass and stiffness parameters, however this is beyond the scope of this work.

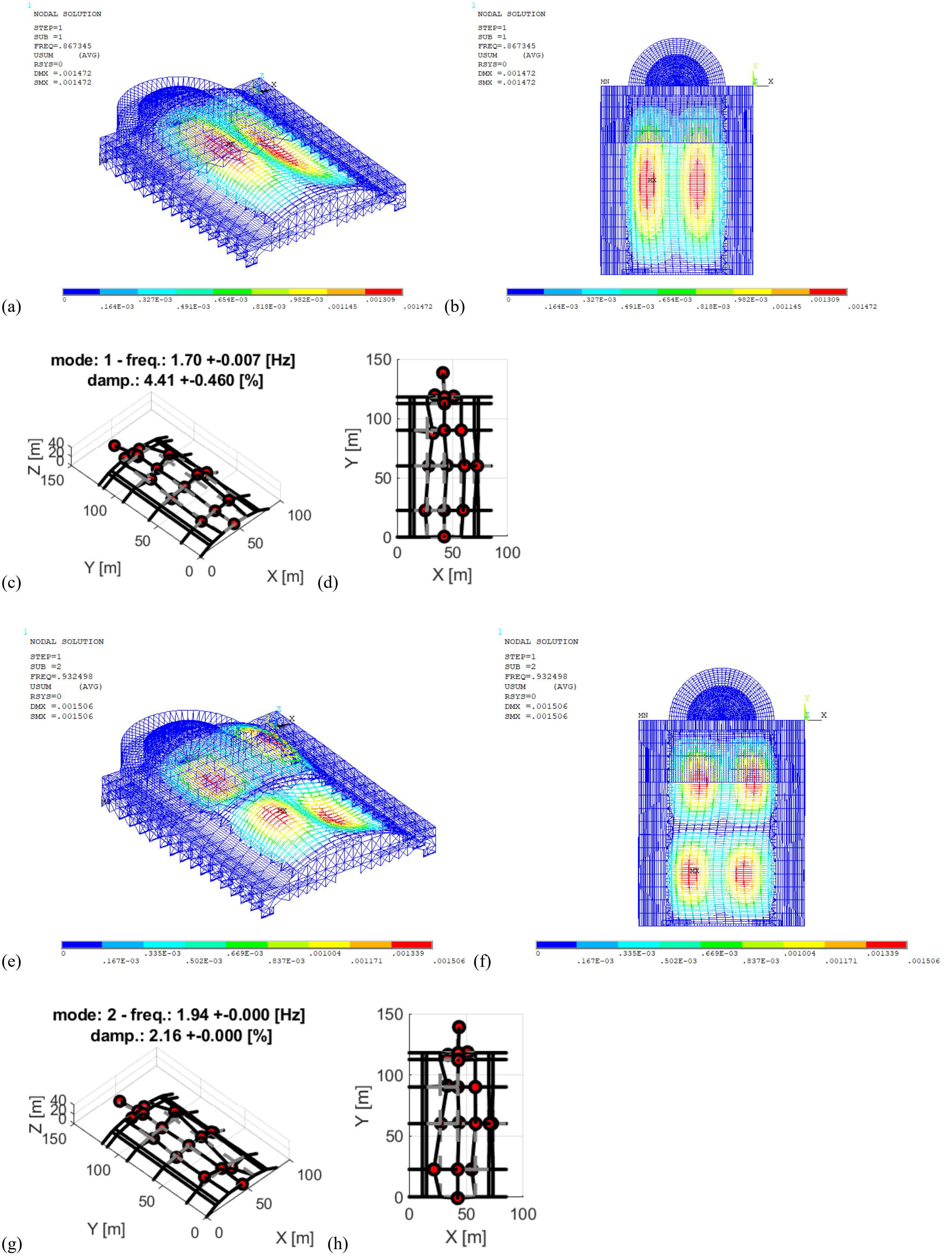


Fig. 6. Comparison between the predicted modes by the FE model and the experimental evidence; (a) First predicted mode, the contour plot refers to the vectorial sum of the components; (b) Plan view of the first predicted mode; (c) First identified mode shape; (d) Plan view of the first identified mode shape; (e) Second predicted mode, the contour plot refers to the vectorial sum of the components; (f) Plan view of the second predicted mode; (g) Second identified mode shape; (h) Plan view of the second identified mode shape.

5 Conclusions

As stated in the methodological section, the data from investigations and monitoring can be incorporated continuously in the model, so it becomes a tool for the Conservation Management Plan and for its implementation over time. The application sections show how experimental data can be useful to understand the true structural condition of the structure, in order to make changes to the numerical models to make them more compliant with reality.

In the specific case of the Torino Esposizioni, discrepancies were observed in the model of Hall B, presumably in terms of unmodeled stiffnesses and possibly also of masses. This entailed the need to conduct further investigations and in situ surveys, which brought to light some modelling discrepancies that had not been considered in the first phase. Furthermore, identification led to a joint modelling of the Turin Exhibition complex, in order to verify the interaction effect between the various halls, and thus reduce the discrepancy of the geometric/topological parameters (variables input) before updating the mechanical parameters (calibration inputs), as required by procedures currently used to update numerical models.

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