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Structural identification through dynamic tests on historic buildings: some experiences

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Abstract – **In the last decades, professionals and researchers have made a strong effort to understand resisting and collapse mechanisms in masonry buildings, trying to evaluate the safety factor, especially in presence of horizontal seismic loads.**
Therefore, innovative techniques based on dynamic response have been developed, to calibrate structural Finite Element Models. The present paper contains some study cases were dynamic test were performed to calibrate numerical models in the seismic analysis of historic masonry buildings.

I. A NEW STRUCTURAL STAIR FOR THE CONSOLIDATION OF TORRE GORANI - MILAN

The insertion of new stairs in existing buildings, with particular reference to masonry towers, appears a quite complex design topic. The re-use is strongly influenced by the peculiarity of the space, developed mainly in vertical direction. The theme of the paths assumes a primary role and characterizes the project that has to deal with functional requirements, regulations and aesthetic.
The use of steel, suitably adapted to the specific cases, offers to the designer the freedom of expression, mechanical strength, compatibility with existing structures and reversibility.
In the case of Gorani Tower in Milan the new stair plays a decisive structural role, becoming the backbone of the tower. Along a convoluted vertical path, the stair is intertwined with five inclined steel tube, that support the stair and (by means of 16 vertical cables hanged to the top deck and parallel to the walls) "take over" a portion of the self-weight of the masonry walls, removing a percentage of the vertical loads.
The top deck and the masonry walls are strictly connected with hinged struts.
Along with traditional on-site and laboratory tests, designed to determine the residual mechanical properties of the masonry, dynamic tests were conducted on the tower to investigate its seismic response.
These tests were based on seismic microtremors, generated on the structure by the white noise always present on the earth's crust, with low oscillation amplitudes. Microtremors are mainly derived from oceanic, atmospheric, seismic and anthropic movements.
The surveys were conducted to verify the variation of the frequencies and the amplitude of the oscillations in the various stages of the construction work, until the final configuration, that corresponds to the "consolidated state".
Thus, the aim was to investigate the structural effectiveness of the intervention, both experimentally and numerically, evaluating static and seismic improvement.

Fig. 1. Gorani Tower in Milan, after the restoration works.

To evaluate the dynamic response of Gorani Tower three dynamic pads were made at different stages of the construction site:

1st Temporary security stage, where a structural scaffold was connected to the tower and the masonry was not consolidated.
2nd Intermediate construction stage, where the metal staircase was inserted in the tower, but not yet connected to the walls; in this stage the masonry was already consolidated by mortar injections, partial reconstructions, and the scaffolding was temporarily disconnected from the tower. This situation represented the tower empty internally and completely free.
3rd Final structural consolidation works stage, where scaffolding was removed and the staircase was connected to the masonry. This is the condition in which the structure is structurally improved, to resist to vertical load and to earthquake.
The experimental results of the 3 surveys were compared in terms of ground H / V response spectra, obtained using the Nakamura method, which returns the dynamic response of the structures in terms of vibration modes by filtering the signal from any non-seismic noise.
Measurements corresponding to the first modal shape were examined to verify the improvement of the overall structural seismic response.
The results of the surveys conducted were graphically returned in the two main north-south and east-west directions.

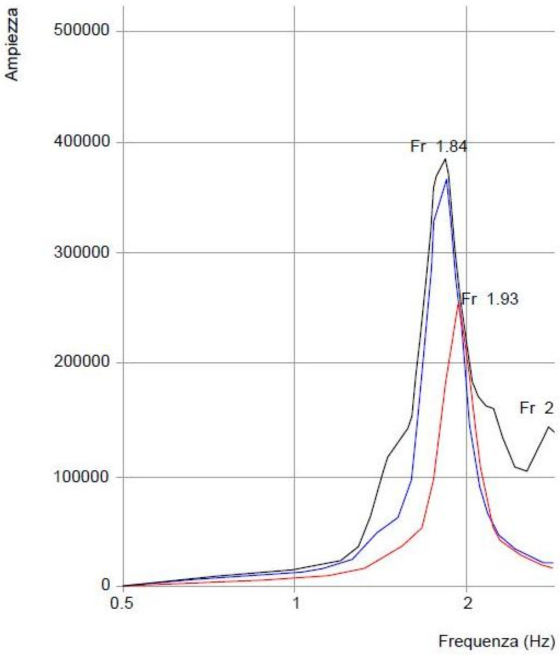

Fig. 2. Increase in frequencies and reduction in amplitudes experimentally recorded. Situation pre-intervention (blue and black lines) and consolidated situation (red line)

Analyzing the outcome of the tests, improvements were recorded both in terms of frequency and amplitude.

In fact, a rise in frequency was detected, due to the mutual connection between masonry and steel (partly mitigated by the mass increase of approximately 11.5 tons of steel added to 340 tons of masonry).
The increase was about 10%, varying from 1.84 Hz to 1.93 Hz in the north-south direction and 1.47 Hz to 1.51 Hz in the east-west direction.
With regard to the amplitude, compared with the displacement of the mixed tower + scale system, a decrease of 31% in the north-south direction and 46% in the east-west direction was obtained. The contribution in the east-west direction was more consistent due to the dissymmetry of the new scale, which results in greater rigidity in the north-south direction as planned at the design stage.
In fact, the FEM model of the only stair, during the design phase, had shown that the first two own modes took place in different directions from the east-west axis, thus denoting a greater rigidity in this direction than in the north -sud orthogonal one (that was the direction of first mode).

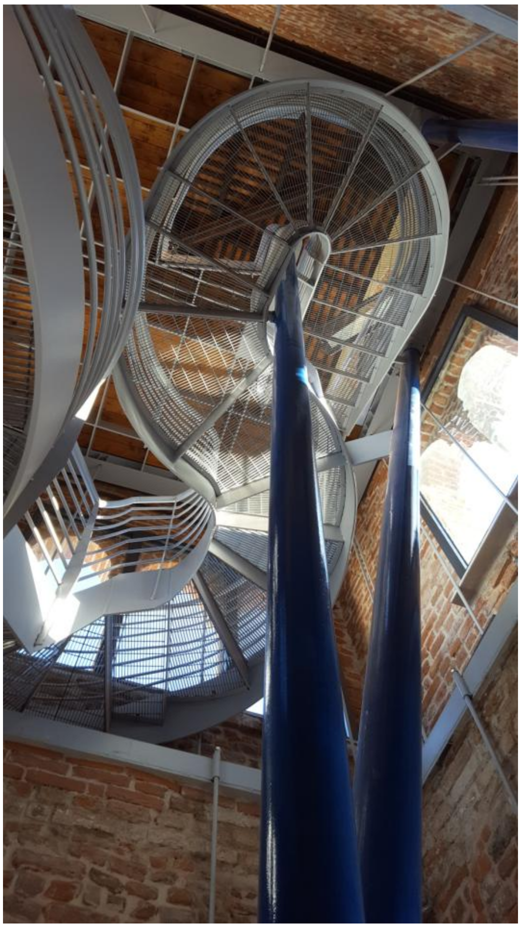

Fig. 3. The new steel stair in Gorani Tower

The experimental results, in terms of spectral frequencies, were compared with those obtained numerically, for calibrating the FEM model.

Dynamic numerical modeling, for which an hypothesis of linear elastic material was adopted, provided comparable results to those experimentally recorded.
Under horizontal load conditions, at the base of the masonry, the stress reduced from 0,48 N/mm^2 (in the non-consolidated situation) to 0.28 N/mm^2 (in the consolidated situation), bringing the masonry back to the limit of acceptable resistance, assumed equal to 0.30 N/mm^2.
The new steel ladder offered the tower a beneficial contribution also in terms of horizontal displacements at the top, which in the most severe situations were reduced by 48% in the event of wind and 30% in the seismic case, ensuring more than acceptable values, lower than H / 1000.

II. THE CASE OF COLORNO CATHEDRAL

The case of Colorno Cathedral, in Italy, near Parma, is here presented.
The XVIII century masonry vaults of the cathedral widely suffered due to a seismic event occurred in 2012 and a relevant crack pattern appeared. A deep diagnosis was conducted before the interventions, aimed to evaluate the residual mechanical properties of the masonry and the dynamic response of vaults, facade and bell tower.
Nine measurement points were applied, 2 of which were placed at ground level, 2 at the level of the cleristor, 4at the level of the central nave, thus investigating vaults, the façade and the base of the bell tower. A last survey was located at the top of the bell tower.
Using the Nakamura method, the H/V spectral ratios (Horizontal / Vertical) were obtained. With the same purpose, directional spectra were also analyzed, for identifying the amplifications effects induced by the height of the structure, relative to the ground.
The results are showed a low frequency of the soil, equal to 0.8 Hz, and a frequency in the order of 2,5 - 3,0 Hz for the bell tower.
The first two ways to vibrate corresponded to the bell tower, according to translation in East / West direction and in direction North South.
The vibration modes of the façade and cracked vaults of the central nave were obtained for frequencies equal to 4.0 - 5.0 Hz, while for frequencies around 7.0 Hz activated the global modes of the entire the church.
Finally, the bell tower showed the lowest stiffness, compared with the other structural element investigated. the element that manifested itself as the least rigid is. Low frequencies were obtained even for the façade and the vaults of the nave, that corresponded to the elements most damaged by the earthquake.
The comparison between numerical results (obtained from FEM modeling) and the results of experimental measurements in terms of their own frequencies and modes have returned more than acceptable resemblances.
In a second time, some consolidation interventions were proposed and realized in order to restore the global resistance of the building, mainly focusing on the roofs and on the vaults, providing the so called "box-like behaviour", useful in presence of seismic loads.

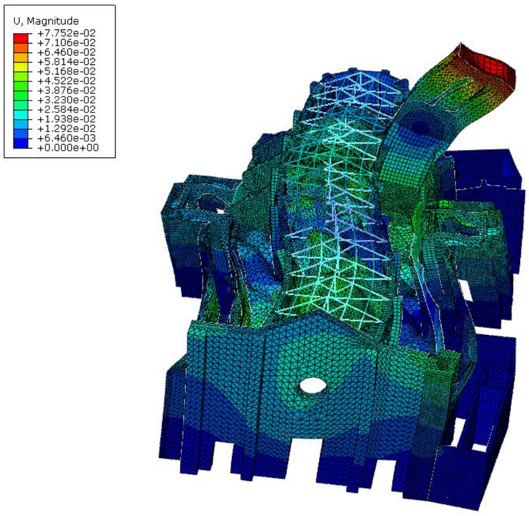

Fig. 4. The numerical FE model of the Cathedral

After the consolidation interventions, an "ex-post" dynamic diagnostic campaign was conducted to compare the new frequencies with the previously measured ones and with the numerical results. Concerning the vaults, repetition of measurements identified a shift of frequencies to higher values, in the consolidated situation, as shown in Fig. 5. Even the maintenance of the spectral form pre and post-intervention must be highlighted.

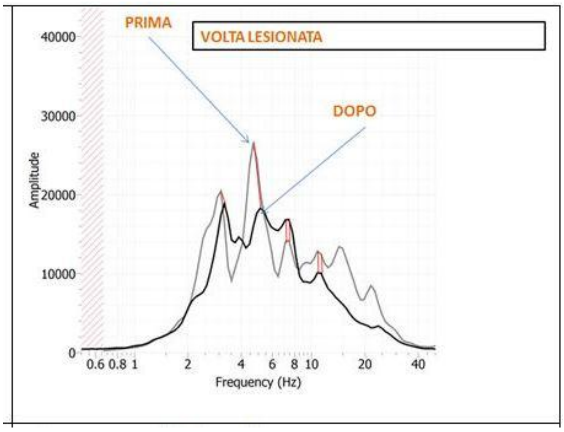

Fig. 5. Experimental frequencies pre and post consolidation intervention on the vaults

The shift recorded on the bell tower highlighted a variation of frequency not on the first mode, but on the ones characterized by higher values. It should be noted that the dynamic tests were carried out at a construction stage that did not yet include the full strengthening of the bell tower.

The promising aspect of this technique consists in the possibility to study the variations of frequencies pre and post intervention or pre and post damages. In practice, the positioning of sensors with the possibility of repeating measurements over time could highlight both the success of certain interventions, and report a decay of the structure (ad example using it for post-earthquake verification). The goal is to determine a kind of " microsismic imprint" of the building.

III. DYNAMIC TESTS FOR CALIBRATING THE NUMERICAL MODEL OF PALAZZO DELLA RAGIONE IN MILAN

Palazzo della Ragione, erected in 1228, represents one of the most ancient and relevant historic building of Milan. During the century, the Palace was subjected to many significant modifications, included the natural decay, so that the property (the Municipality of Milan) asked a new deep analysis (a first was conduced by one of the author in the early 1980s) to investigate the actual structural response in terms of vertical and horizontal loads.

Fig. 6. Palazzo della Ragione in Milan

Numerical analysis conducted with the FEM model were developed on the basis of some experimental tests.
In particular, the diagnostic campaign performed in 1979, in which flat jacks and dynamic tests were applied, allowed us to obtain useful information on the mechanical characterization of the masonry.
In addition, the execution of dynamic identification tests in 2017 has returned the own frequencies of the building 40 years later.
These recent surveys, alongside an accurate geometric relief by laser scanner, led to a more refined and updated FEM analysis model than the one developed in the 1980s.
Before conducting the structural verifications, the consistency between the structural response of the numerical model and the one of the real building, obtained by dynamic tests, was carried out.
Through these results, modal frequencies and the presence of "phase" or "out of phase" movements were determined at various points in the building, comparing the numerical data with the experimental one.
It was an iterative process of refining the numerical model, based on the reduction in the difference between the FEM and the experimental result, recorded in situ, in terms of the first period of vibration.
The calibration process was expected to operate parametrically on the type of constraints and the elastic modulus value.
Concerning the constraints at the base of the masonry walls, two alternative conditions were modeled, assuming hinged or clamped perfect joints.
From the modal model analysis, the following first frequencies of the structure have been obtained:
- Hinged constraints: First mode of vibration f1=1.358 Hz
- Clamp constraints: First mode of vibration f1=1.534 Hz

Through on-site measurements the first frequencies of the building were detected:
- Frequency measured and relative to the first mode of vibration in the north-south flexural component of 1.34 Hz Frequency measured and relative to the second mode of vibration in the north-south torsional component of 2.43 Hz

The difference with the average of the in situ measured frequencies was equal to 1.34% for hinged constraints and 14.5% for clamped constraints.
Due to the minor difference obtained in the first case, the model with hinge constraints was used.
To "calibrate" the first frequency (or first period) of the FEM model so as to make it as close as possible to the measured frequency in situ, some variations on the elastic modulus E of the masonry were applied.
Using an iterative procedure and calculating the M/R ratio (Mass/stiffness) for various values of the elastic modulus, a "calibrated" elastic modulus of E = 1373 N/mm^2 was obtained, with a difference from the module detected by flat in the order of 8.47%, that is an acceptable value.
By inserting this "calibrated" elastic modulus into the FEM model, a first frequency f1 = 1.35 Hz was obtained, which is a value not far from the experimental data.
With this "calibrated" elastic module, the stresses and deformations of the global model were subsequently calculated.
In addition, the modal deformations obtained from the FEM model respect the phases and counter phases highlighted by on-site dynamic surveys, conducted to obtain the own frequencies of the building by measuring environmental microtremors.

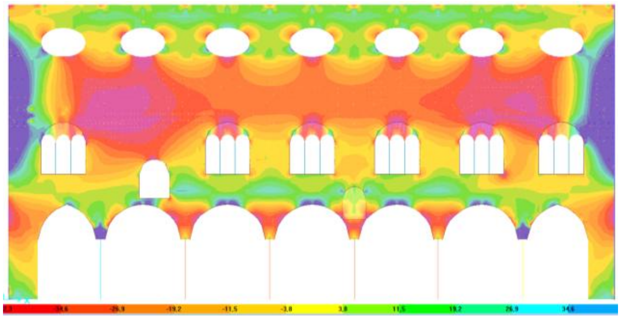

Fig. 7. Numerical state of stress of the Palace, obtained through the calibrated model.

IV. DYNAMIC RESPONSE ANALYSIS OF A MARBLE STAIR

The knowledge and characterization of materials is needed in the world of consolidation, in order to find the best reinforcing solution, according to the principles of conservation and minimum intervention . It follows the importance of knowing how to choose the most appropriate structural hypothesis, depending on the case study.

Results of the diagnostic campaign conducted on a staircase in stone blocks in Milan, carried out with the support of static and dynamic measurements are hereafter presented.

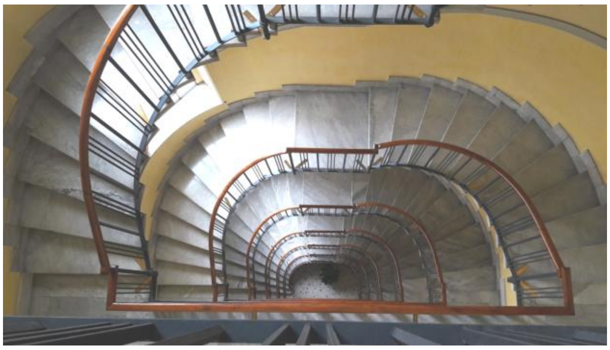

Fig. 8. View of the investigated marble stair

Following the appearance of some worrying cracks on the stone staircases of a seven-storeys building, dated back to the first half of the last century, a detailed analysis was conducted to find out its actual state of health.

The staircase of the building was constructed with monolithic stone elements (in the case of white marble with gray grain type “Arabescato”) inserted directly into the perimeter masonry, with a static shelf scheme. The thickness of the planks was only 6 cm.

During the first inspections, three different degradations were observed. The first consisted in a cracking pattern on a staircase wall. The cracks were wider and more frequent at the top of the compartment and were inclined by about 45 °, a trend which suggests the differential lowering of a masonry portion.

The other two structural degrades observed directly affected the slabs of the stairs and consisted in a misalignment of certain elements (manifested by the presence of detachments between the lifting and pedestrian elements) and the presence of cracks affecting several lifting plates in the ramps, in the higher floors.

The absence of a link between lifting and treading or, as in the present case, the detachment of such elements caused a reduction of safety against the applied loads. Thus, every single step worked in isolation.

For these reasons, some diagnostic investigation was performed on 158 steps.

First, in-situ observation of the scale allowed to highlight a perceptible response variability. Simply following the stairs, one realized a different vibration of each single tread, when subject to the load of a person in transit.

In order to quantify these differences, it was proposed to conduct a diagnostic campaign to identify and characterize all individual treads, with particular attention to the identification of the material and technological peculiarities of the constructive elements, and above all to define the degradation of the elements themselves, to obtain a valid reference to the state of health of individual steps.

In particular, local dynamic surveys was performed, by measuring the own frequencies of vibration of all treads, recording with some triaxial accelerometers positioned on the individual elements.

Fig. 9. Instruments adopted for dynamic tests

Furthermore, some static load tests on selected sample elements was applied to characterize the specific deformation response. Finally, inspection tests were carried out to verify the depth of support of the slabs.

Accelerometric measurements applied to individual marble shelves, excited with an instrumented hammer, allowed to catalog all the elements according to the first recorded vibration frequency, thus distinguishing three subgroups:

- 74 elements characterized by a high frequency (> 80 Hz);
- 75 elements characterized by a mean frequency (50 <Hz <80);
- 9 elements characterized by a low frequency (<50 Hz).

In principle, at equal mass, geometry and stress, it can be

stated that at a low frequency corresponds to a wider vibration, which in the specific case may be due to the presence of defects or cracks that reduce the stiffness of the plate or to a more tolerable bond condition, or a less confined situation.
The conditions of the elements on which a low frequency is recorded are therefore critical.
It is noted that most of the emerging critical features of low-frequency elements are located at the top of the staircase, where faults and breaks can also be visually observed.
Subsequent to the measurements of the frequencies on the 158 treads, seven load tests were conducted to determine the deformation of some of them. A distributed load was applied on the tread and the sag of the shelves was measured.
Three load tests were conducted on low frequency steps, two load tests on mid frequency and two on high-frequency treads.

Fig. 10. Instruments adopted for load tests

The results of the load tests clearly showed a direct correlation between the measured frequency and the deformation obtained from the test. In fact, the elements characterized by a high frequency (i.e. the most stiff and less damaged) have undergone a limited deformation, with a sag at about 0.05 mm, while the other loaded elements showed greater deformation, with displacements ranging from 0.11 to 0.26 mm, or from 2 to 5 times the previous one.
Thanks to these results, a detailed consolidation intervention was designed and it is now under realization.

V. CONCLUSIONS

The study cases here presented have shown how dynamic tests can be adopted, in order to get information about the structural behavior of a building, either in non consolidated condition or in the consolidated one. Furthermore, dynamic results can be useful to calibrate or verify a useful model of seismic analysis, in fact experimental data representing a real measurement comparable to a virtual modeling, so it can be validated.

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