IV Conferencia Panamericana de END
Buenos Aires – Octubre 2007

AAENDE
Asociación Argentina de Ensayos No Destructivos y Estructurales

Structural health monitoring techniques for historical buildings

Garziera R, Amabili M and Collini L
Department of Industrial Engineering, University of Parma
Viale G.P. Usberti 181/A, 43100 Parma, Italy
+39 0521 905701
+39 0521 905705
rinaldo.garziera@unipr.it

Abstract

Historical churches, masonry towers and bell towers are among the structures subjected to the higher risk, due to their age, elevation and low base area on height ratio. In this work a technique of monitoring the structural integrity of historical buildings by a non-contact and non-destructive analysis is presented and discussed. The damage of a structure, in terms of cracks and overall structural degradation, is detected throughout the measurement of its dynamic characteristics by a laser Doppler vibrometer (LDV). This technique can show the frequency spectrum of the structure with high accuracy and reliability. The results are computationally elaborated to identify the modal response of the structure and to detect the evolution of any damaged zone by calculating mass and stiffness changes in reverse based on changes in mode shapes. Since this technology is fairly new, the presented method needed to be validated on well know data, and this has been carried out comparing some results related to plates.

Keywords: Laser Doppler Vibrometer, structural integrity, modal analysis, vibration-based damage detection.

1. Introduction

The knowledge of the health conditions of historical buildings is a great concern for many towns in Italy, where is possible to find a large number of ancient churches and other monuments well known all around the world. The problem of the conservation of historical buildings and of the estimation of the residual life before maintenance is studied from some decades. For example in [1] a review of the studies on the Duomo (the main church) of Parma, Italy, is widely illustrated. The monitoring of the structural integrity of historical buildings is needed to preserve the precious cultural inheritance from the past. Churches, masonry towers and bell towers are among the structures subjected to the higher risk, due to their age, elevation and low base area on height ratio. This work focuses the attention on the town of Parma; here several are the buildings with evident structural problems. One of these is the San Sepolcro bell-tower showed in Figure 1.

Figure 1. The bell-tower of San Sepolcro in Parma, Italy; note the inclination.

Figure 2. The inside of the Duomo of Parma built from 1106. The roof vaults are visibly deformed. Paintings on the nave walls are by L. Gambara (1567-1571).

Its inclination on the ground is evidently extreme, and already in 1990 some dynamic measurements have been conducted. Another delicate situation is represented by the Duomo church, showed in Figure 2, where the vertical deformation of the vaults of the roof has reached critical values, [1]. A fundamental contribution to the stability of the structure is here represented by the presence of the reinforcing iron chains, visible in Figure 2.
Another problem for the stability of ancient buildings is the massive presence of car and heavy vehicles traffic, that causes random vibrations, [2]. A building in Parma which suffers this kind of degradation is the Steccata church, showed in Figure 5.
In this paper a relatively new non-destructive technique for the monitoring of the structural integrity of buildings is presented. The aim of this technique is the identification of the building's dynamic characteristics. Each body has its own shapes, frequencies of vibration and dumping properties (the modal parameters), that are a function of its mechanical characteristics: a damaged structure shows a frequency autospectrum which differs from that of the integral one, [3-5]. The detection of the dynamic characteristics of a buildings can then identify the presence of damaged zones, cracks and structural degradation during the time, as illustrated for example in [6, 7].
The methodology of measurement here proposed makes use of a laser Doppler vibrometer (LDV technique), a relatively new non-contact detection technique that provides measures of displacement with great accuracy and reliability, [8, 9]. The results of measures are elaborated via computational programs to identify the modal response of the structure and detect the evolution of any damaged zone by calculating mass and stiffness changes in reverse based on changes in mode shapes. The assessment procedure includes i) full-scale ambient vibration testing of the historical building, being ; ii) the modal identification from ambient vibration responses; iii) the finite element modelling and dynamic-based identification of the uncertain structural parameters of the model. The validity of the proposed method is firstly experimentally demonstrated through vibration measurement for a steel plate before and after damage, as shown in the next sections.

2. Organization of the study and civil importance

The knowledge of the health state of ancient buildings has a big importance for the maintenance and tutelage of historical structures. The work here presented has the double aim: i) to acquire the spectrum and the mode shape of the analyzed buildings and ii) to measure the strain and stress in the inner chains of the vaults of churches, that are directly responsible of the structure stability. Both these aspects, conducted via non-destructive techniques, are of great importance from the point of view of the extendibility to other structures and engineering fields.
Each detected frequency spectrum, relative to the portion of one single building, is integrated in a data base which will be the history of that building. The program comprehends a five years test plan for each building; in these five years the evolution of the frequency response of the building will be monitored and elaborated, to obtain the trend of behaviour of the structure in a mean period. The detection of anomalous dynamic responses will be the basis of a preventive intervention to consolidate the foundations or to apply bearing structures to the building.
The same dynamic investigations are able to state the stress in the chains applied to the concave part (i.e. inside the buildings) of the roof vaults of many churches. The problem

of the vaults stability, i.e. of the flattening of the roof with consequent deformation due to the roof weight, is actually spread especially for the churches with a wide central nave, which is a common architectural solution for the Romanic churches, [10]. The determination of the stress state in the support chain, usually made of iron and low-carbon steel, is of interest to estimate the residual strength of the chains themselves. Extreme traction states in these supports are a really dangerous condition, especially if overloads, as seismic waves or particular thermal loads, occur in the life of the structures. The rupture of a support chain can be a catastrophic event for the building. The novelty of the present study is the methodology of investigation and measurement by a non-destructive and non-invasive technique, which demonstrates its indisputable advantages when applied to buildings of high historical, civil and artistic value; the experience obtained from the application of this technique to the prevention of some of the numerous historical buildings of the city of Parma, can be easily extended to a wide scenario of ancient and newer structures.

3. The damage detection methodology

3.1 Damage model in state-space equation of motion

The equation of motion for a multi-degree-of-freedom structural system can be written in a state-space form as, [6, 11, 12]:

$$\mathbf{A}\dot{\mathbf{y}} + \mathbf{B}\mathbf{y} = \mathbf{f}\,'(t) \qquad (1)$$

where:

$$\mathbf{A} = \begin{pmatrix} \mathbf{C} & \mathbf{M} \\ \mathbf{M} & 0 \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} \mathbf{K} & 0 \\ 0 & \mathbf{-M} \end{pmatrix} \qquad (2)$$

and $\mathbf{y} = \{\mathbf{x}(t) \quad \dot{\mathbf{x}}(t)\}^T$, $\mathbf{f}\,'(t) = \{\mathbf{f}(t) \quad \mathbf{0}\}^T$. The vector $\mathbf{x}(t)$, $\dot{\mathbf{x}}(t)$ and $\mathbf{f}(t)$ denote the displacement, velocity and applied force respectively. The matrix **A** and **B** are the system block matrix, which consist of mass [**M**], stiffness [**K**] and damping matrix [**C**]. The homogeneous solution of Eq. (1) is obtained by solving the eigenvalue problem:

$$\mathbf{B}\boldsymbol{\Phi}_\mathbf{u} = -\mathbf{A}\boldsymbol{\Phi}_\mathbf{u}\boldsymbol{\Lambda}_\mathbf{u} \qquad (3)$$

where $\boldsymbol{\Phi}_\mathbf{u}$ and $\boldsymbol{\Lambda}\mathbf{u}$ are eigenvector and eigenvalue matrix respectively. Here, the subscript **u** denotes the undamaged state of the system. Structural damages are modelled as deviations or changes of mass, stiffness and damping coefficient. The changes will be defined as $\delta\mathbf{M}$, $\delta\mathbf{K}$, and $\delta\mathbf{C} \in \mathbb{R}^{N\times N}$, respectively. In these matrices, system connectivity should be maintained so that the solution is physically meaningful. Following the definition in Eq. (2), the system matrices after damage become $\mathbf{A} + \delta\mathbf{A}$ and $\mathbf{B} + \delta\mathbf{B}$, where $\delta\mathbf{A}$ and $\delta\mathbf{B}$ denote the deviations of matrix **A** and **B** respectively, and are defined as:

$$\mathbf{A} = \begin{pmatrix} \delta\mathbf{C} & \delta\mathbf{M} \\ \delta\mathbf{M} & 0 \end{pmatrix} \quad \mathbf{B} = \begin{pmatrix} \delta\mathbf{K} & 0 \\ 0 & -\delta\mathbf{M} \end{pmatrix} \quad \text{...(4).}$$

These two matrices are sparse matrices where the non-zero elements appear only at degrees-of-freedom that are associated with damage. Following Eq. (3), the homogeneous solution at after-damage becomes:

$$(\mathbf{B} + \delta\mathbf{B})\mathbf{\Phi_d} = -(\mathbf{A} + \delta\mathbf{A})\mathbf{\Phi_d}\mathbf{\Lambda_d} \text{ ....(5)}$$

where the subscript **d** denotes the after damage state. Equations (3) and (5) are both exact regardless of the number of measured modes, even when the number of measured modes (N_e) is less than the total number of DOFs, (N). Transposing Eq. (3) and post-multiplying the result by $\mathbf{\Phi_d}$ afterwards yields:

$$\mathbf{\Phi_u}^{\mathbf{T}}\mathbf{B}\ \mathbf{\Phi_d} = \mathbf{\Lambda_u}\mathbf{\Phi_u}^{\mathbf{T}}(\text{-}\mathbf{A})\mathbf{\Phi_d} \text{ ....(6)}$$

Now, pre-multiplying Eq. (5) by $\mathbf{\Phi_u}^{\mathbf{T}}$ and subtracting from Eq. (6) leads to:

$$\mathbf{\Phi_u}^{\mathbf{T}}\delta\mathbf{A}\mathbf{\Phi_d}\mathbf{\Lambda_d} + \mathbf{\Phi_u}^{\mathbf{T}}\delta\mathbf{B}\mathbf{\Phi_d} = \mathbf{\Lambda_u}\mathbf{\Phi_u}^{\mathbf{T}}\mathbf{A}\mathbf{\Phi_d} - \mathbf{\Phi_u}^{\mathbf{T}}\mathbf{A}\mathbf{\Phi_d}\mathbf{\Lambda_d} \text{ ....(7)}$$

One can see from Eq. (7), that there are two unknown matrices on the left hand side of the equation, $\delta\mathbf{A}$ and $\delta\mathbf{B}$. Owing to its complicated format, Eq. (7) is usually solved iteratively. However, it can also be solved non-iteratively by employing some matrix algebra manipulations in such a way that the unknown matrix is transformed into a vector space so that the vector addition can be performed. Moreover, the mode shapes matrices $\mathbf{\Phi_u}$ and $\mathbf{\Phi_d}$ can take the form of rectangular matrices and therefore allows the technique to be applied to data from measurement with incomplete modal information.

3.2 Laser Doppler Vibrometry (LDV) at the University of Parma

The measurement of the frequency response of a building (i.e. the frequency spectrum, the modal shapes and the damping parameters of its main structural parts) can be nowadays made by one of the most modern instruments available in the field of vibration measure and control, the Laser Doppler Vibrometer (LDV). The LDV technique significantly extends measurement capabilities with respect to traditional vibration sensors (such as accelerometers, strain gauges, etc.), as it allows remote non-intrusive, high spatial resolution measurements with reduced testing time and increased performances (high frequency up to 20MHz, velocity range of 730m/s, resolution of about 8nm in displacement and 0.5mm/s in velocity), [13].
During the 1980s, the first LDV models were introduced, but their limited sensitivity and low signal-to-noise ratio (SNR) allowed measurements only on very diffusive surfaces or by applying a retro-diffusive tape on the measurand. Only in the early 1990s,

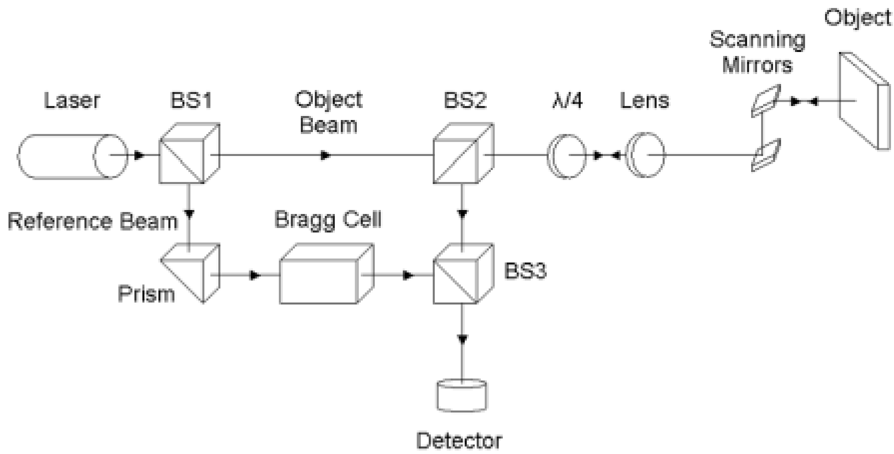
the hardware and software developments increased instrumentation performances and applicability and therefore many researchers started to use LDV. In several cases, it has proved to offer significant advantages over traditional accelerometers, allowing one to obtain results which were not foreseeable only 10 years ago, [14].

Using a laser vibrometer simply as a single point transducer it is possible to perform accurate and flexible non-intrusive measurements. Results will not be affected by errors due to accelerometer mass loading, which seem to be relevant for modal parameter estimation, especially when testing light or small structures or highly damped non-linear materials (as rubber). Furthermore, LDV is a remote measurement technique, because it can measure also if positioned far from the measurand, with sufficient accuracy (1-2.5% RMS of reading) at a distance larger than 30m. This feature is not common to all the non-contact sensors (as triangulation ones or fibre optic proximities) and seems to be very useful to extend the boundary of vibration analysis to several applications, as the testing of large civil structures, [6, 8].

This kind of advances offer effective solutions for many problems in several fields of application, as in the study of mechanism under operational conditions, in damage detection, in material characterisation and also in some biomedical branches, [13].

The LDV at the University of Parma, laboratory of vibrations measurement, is a Polytec PSV300 single point axial laser vibrometer, since it measures only the component of the velocity along the laser line-of-sight. It is showed in Figure 3(a). The principle of functioning is based on the Doppler effect that occurs when the laser light (usually He-Ne, of wavelength of 632.8 nm) is scattered from a moving surface and on the interference between the measuring and a reference beam, it allowing to convert the instantaneous velocity v into the Doppler frequency shift, [14]. Optical interference is observed when two coherent beams of light coincide. The resulting intensity varies with the phase difference between the two beams. This phase difference is a function of the different path lengths of the two beams. If one of the two beams is reflected back from a moving object, then the path difference becomes a function of time. The interference fringe pattern moves, and the displacement of an object can be calculated by directionally counting the passing fringe pattern.

(a)



(b)

Figure 3. (a) Schematic view of scanning laser vibrometry; (b) the Polytec laser Doppler vibrometer at the laboratory of the University of Parma.

In the Polytec PSV300 Scanning Laser Vibrometer adopted in this work the velocity and displacement measurements are carried out using a modified Mach-Zehnder interferometer. The optical configuration of the scanning head is shown in Figure 3(b). A helium-neon laser provides a linearly polarised beam of light. A polarising beam splitter (BS1) splits the beam into object and reference beams. The object beam passes through a second polarising beam splitter (BS2) and a quarter wave plate before being focussed by a lens and directed to a specific point on the object by the scanning mirrors. The beam is then reflected back from the object, via the scan mirrors and lens again passing through the quarter wave plate. As the beam has twice passed through the quarter wave plate the polarising beam splitter (BS2) directs the beam to the third beam splitter (BS3). The Bragg cell adds a frequency offset to the reference beam in order to determine the sign of the velocity signal. The resultant interference signal of the object and reference beams is converted into an electronic signal by the optical detector to be decoded by the instrument's control system.
The excitation of a civil structure can be obtained by two main methods, [8, 15]:

1. the "natural" conditions present on the structure (as action of wind or traffic, or a seismic event);
2. the use of one or more input or swap load generators (as shakers) applied to the structure in critical points.

The experimental in-situ acquired data are stored and then elaborated to identify the modal parameters of the building. A comparison with data from literature about analogue buildings is interesting to evaluate peculiar dynamic behaviours that understate the presence of damaged structures. The dynamic characterization of an ancient building is also of great concern to estimate its behaviour in case of a seismic event. The most dangerous areas and sub-structures of the buildings can be identified in order to preserve any catastrophic evolution.

3.2 A strain measurement technique for the vaults chains

As told before, the churches analyzed in this work present a system of inner steel chains or tie rod for the stability of the roof vaults, as shown in Figure 5. Here the internal roof

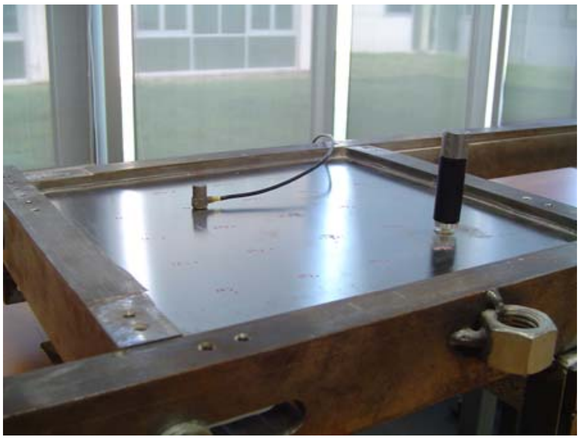
of an ancient church in Parma is shown; in the case of failure of one only of these structural supports, the overall stability of the church would be compromised with the possibility of serious injuries. It is then essential to know the stress state of the tie rods to quantify the possibility to them to support overloads (thermal shocks or seismic events) or simply to estimate their residual life.
The knowledge of the strain state of these particulars is also important to valuate the overall equilibrium of the building. Therefore the monitoring of the stress state of the chains has to be performed periodically.

Figure 5. Paintings by Parmigianino (1503-1540) in the "Madonna della Steccata" church (Parma); in evidence a chain that acts as a support of the vault.

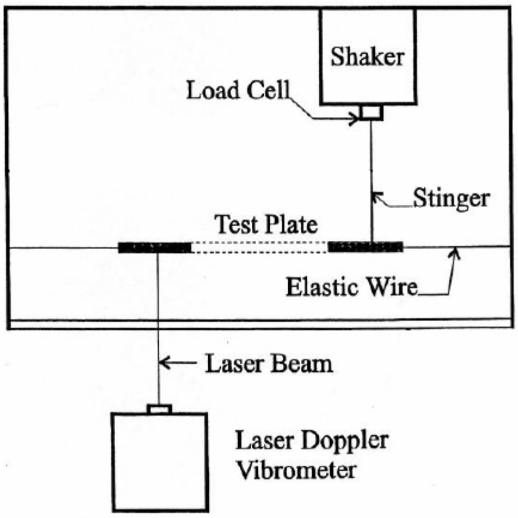
Nowadays, the measure of the stress in the tie rods is an opened question. Naturally a direct measure is not possible; an indirect appropriate measure could be i) the quantification of the bending inflection of the rod under a determined static load and ii) the measure of the first natural frequency of the rod. The second measure is of crucial importance because of the uncertainty around the pliability of the anchorage system of the chain on the church walls. However this double measure is not sufficient to determine the stress in the steel chain; a numerical model of the system is necessary to simulate its dynamic behaviour and calculate the stress state in the vault chains.
In this work an innovative methodology of non destructive measure is introduced identifying an higher number of natural shapes or modes of vibrating of the tie rod. An experimental modal analysis is conducted with the help of the CADA-X measure system by LMS at the laboratory of the University of Parma, with the creation of a dynamic model of the structure based on the Rayleigh-Ritz method which takes into account the behaviour of the anchorages, the real behaviour of the steel and any change in the cross-section of the rod, [16]. This model calculates several shapes of vibrating of the chain, that can be compared with the experimental results to determine the stress state of the chain.

4. Experimental test validation

To validate the measurement method by the LDV technique, some experiments in laboratory have been conducted on the square stainless steel plate of Figure 6(a), which has the following dimensions and material properties: a =0.210m, b = 0.2085m, h = 0.0003m, $E = 198\times10^9$Pa, $\rho = 7850$kg/m^3 and $\nu = 0.3$, [17]. The plate was inserted into a heavy rectangular steel frame made of a few thick parts, see Figure 6(a), having grooves designed to hold the plate. Silicon was placed into the grooves to hold better the edges of the plate and then avoid out-of-plane displacements at the edges. The in-plane displacements at the edges, in direction orthogonal to the edge itself, were allowed because the constraint given by silicon on this displacement was small. The in-plane displacements parallel to the edges were restrained by friction between the panel and the grooves and by silicon. Therefore the experimental boundary conditions are close to those of a simply supported plate with movable edges in the *x*-*y* plane.



(a)



(b)

Figure 6. (a) The 4-side constrained steel plate for the validation of the laser Doppler measurement method; (b) Diagram of the experimental set-up.

The plate has been subjected to a shaker excitation in order to identify the natural frequencies and modes shapes by experimental modal analysis, as illustrated in the scheme of Figure 6(b).

The panel response has been measured on a grid of 50 points, the excitation has been provided by a miniature instrumented hammer *B&K* 8203. The plate response has been measured by using the Polytec laser Doppler vibrometer (sensor head OFV-505 and controller OFV-5000). The time responses have been measured by using the Difa Scadas II front-end connected to a HP c3000 workstation and the software CADA-X of LMS for signal processing and data analysis. Frequency Response Functions (FRFs) have been estimated by using averages of 8 measurements and H_V algorithm.

In Figure 8 and 9 the comparison among experimental and theoretical natural frequencies of the plate (first 9 modes, identified by using number of half-waves in x and y directions) is shown. In the numerical simulations both (i) rotational stiffness k = 0 and (ii) k = 4.5 N/rad have been used to simulate the effect of silicon; the introduction of these springs change only a little the frequencies, making them closer to experimental results. However, these differences for $k = 0$ with respect to experimental results can also be attributed to geometric imperfections of the plate.

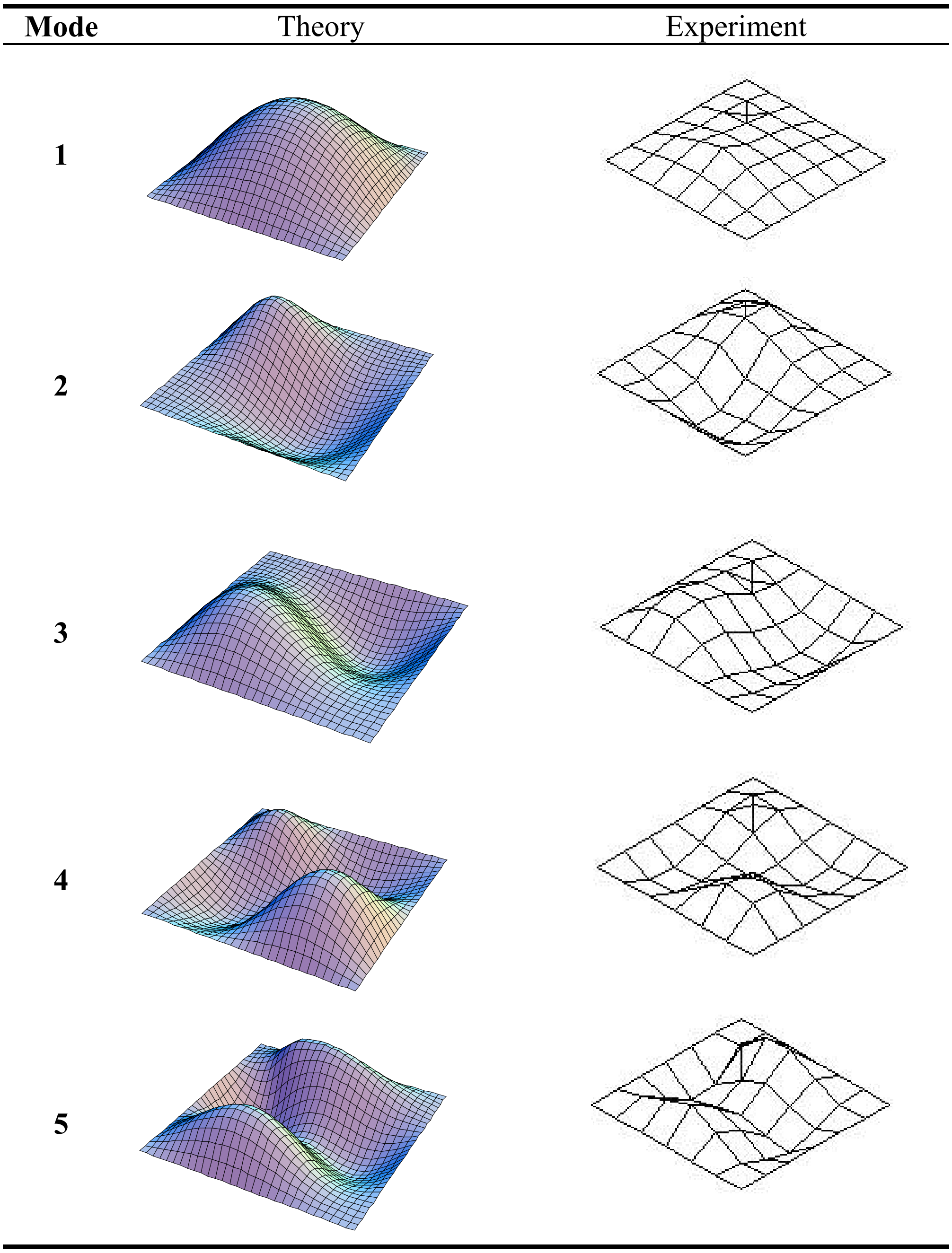


Figure 8. Theoretical and experimentally LDV-detected first 5 mode shapes of a 4-side constrained steel plate.

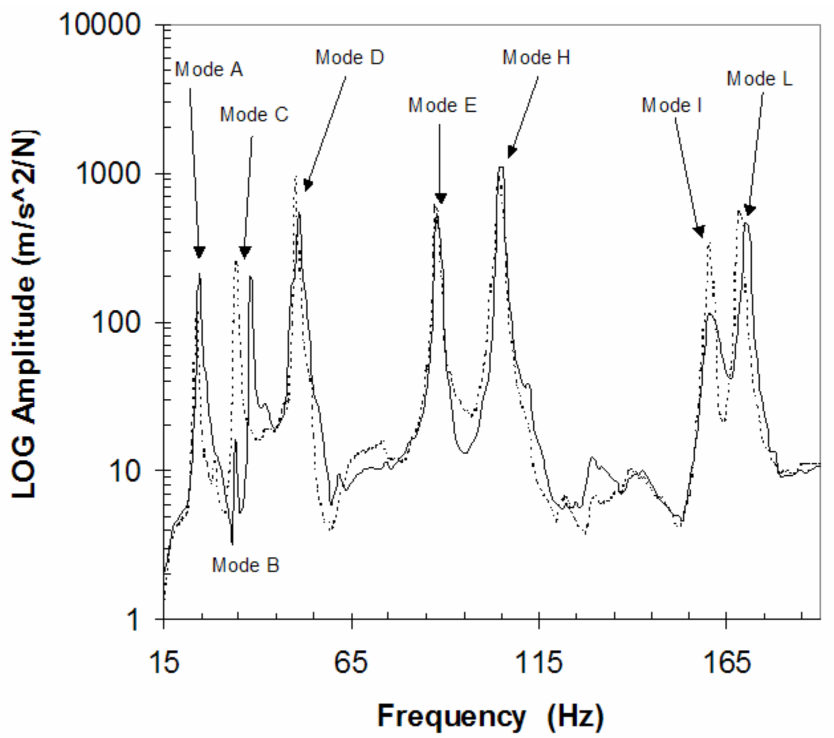


Figure 9. Comparison between the theoretical (dot line) and the experimental (solid line) dynamic response of a square plate.

5. Conclusions

The present paper illustrates the start of a research activity on structural dynamic. This activity is aimed to the monitoring of the health state of ancient and historical buildings. It is based on the possibility of determining all the significant dynamic characteristics of a building or a monument via non destructive and non invasive sensors (as the Laser Doppler Vibrometry).
Although the research is at its early stage, significant data have already been collected. The authors believe that this kind of work should produce huge impact over the monument conservation branches.

Acknowledgements

This study makes part of the research project "Monitoraggio dell'integrità strutturale di edifici storici attraverso prove dinamiche: creazione di una banca dati dell'area parmense" in collaboration with CARIPARMA Foundation, Parma.

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