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LASER VIBROMETRY FOR DAMAGE IDENTIFICATION IN HISTORICAL BUILDINGS

Mariella De Fino[1], Giambattista De Tommasi[2]
Polytechnic of Bari, Faculty of Engineering,
Department of Architecture and Town Planning,
Via Orabona,5, 70125, Bari, Italy
[1] m.defino@poliba.it
[2] g.detommasi@poliba.it

ABSTRACT

Vibration based methods offer effective tools to gather global information on the historical structures without interfering with their integrity and stability.

In fact, by analysing the dynamic response to suitable excitation sources, it is possible to define the mechanical properties of the structures, as well as to detect and localize some anomalies within their global behaviour.

Among the available technologies, laser vibrometry, which allows non contact measurements of vibration velocity of moving surfaces by a focused laser beam, is a very attractive method for qualitative dynamic characterization and damage identification. From the operating point of view, laser vibrometry shows different advantages. It is simple, speedy and non intrusive. It allows remote measures and it shows high sensibility and ample frequency response. Moreover, the system is completely computer controlled, so that data are easily stored, transmitted and elaborated for further analysis.

Beside the wide interest to this technology for applications in medicine, biology, acoustics and mechanical engineering, the attention to the historical buildings is more recent. Nevertheless, it is promising and challenging in that field.

In this study, some experimental validations of laser vibrometry in a wall model have been performed in order to assess the reliability and the effectiveness of this technology, by comparing the measures coming from undamaged and damaged configurations.

INTRODUCTION

Dynamic characterization of a structure is based on the vibration response analysis, in terms of frequencies, modal shapes and dumping, to a defined impulse. As the vibration response depends on geometry, physical and mechanical properties, as well as boundary conditions, dynamic characterization can be addressed to structural monitoring and damage identification.

Specifically, structural monitoring should start up from a preliminary dynamic test that can be used to calibrate the computational models (Finite Elements Models, FEMs) in order to assess their reliability [1]. In fact, as the analytic methods require actual input information, in terms of moment of inertia, density, Young's modulus and constraints, a semi empiric approach is proposed, in order to get a modelling that is as close as possible to the real structural behaviour: an analytic model is elaborated with the information coming from the in situ investigation; a comparison is addressed between the vibrations, measured in the structure and calculated in the model, due to the same impulse; input parameters of the model are iteratively changed, until the theoretical response is consistent with the experimental one [2].

This approach is particularly useful for historical structures, whose computational modelling is characterized by many assessment critical issues, related to properties of materials and components, as well to boundary conditions, that can significantly change over the time.

An accurate model, according with the preliminary vibration measurements, will be used as a reference to analyze a different dynamic response, subsequently occurring within a long term monitoring, in terms of structural alterations, due to global and/or local damage. Specifically, the model will generally assume that that damage is directly related to global and/or local decrease of stiffness, namely the Young's modulus.

Vibrations based methods for damage identification refer to a specific taxonomy [3].

Specifically, as far as the damage is concerned, a common classification is referred to:
- Fault occurring when the structure cannot longer operate satisfactorily, due to an unacceptable reduction in the performance requirements;
- Damage taking place when the structure is not operating in its ideal condition anymore, but it can still perform satisfactorily;
- Defect concerning the materials that inherently have some discontinuities that don't affect the structure from operating in its ideal condition by the way.

The definition above allows a hierarchical relationship: defects can lead to damage and damage to fault. According to that, vibrations based structural control concerns the detection of a critical state before it can develop into a fault configuration.

Then, as far as the identification is concerned, it is supposed to be composed of five subsequent levels:
- Detection (Level 1): qualitative indication that damage might be present in the structure;
- Localization (Level 2): information about the probable position of the damage;
- Classification (Level 3): information about the type of damage;
- Assessment (Level 4): estimate of the extent of the damage;
- Prediction (Level 5): the method offers information about the safety of the structure, estimating the residual operating life.

Each presented level is connected in a hierarchical way, as well.

Generally, Levels 1 and 2 are related to Global Methods, namely monitoring techniques, while Levels 3 and 4 are connected to Local Methods, namely destructive and non destructive diagnostic techniques and Level 5 concerns computational models.

Within this scheme, vibrations based methods for damage identification can be included into Global Methods, as they can alert the presence and detect the precise location of damage, but they do not give accurate information about the extent. As a result, they can assess the global residual performances of the structure and address local investigations in order to get a comprehensive diagnosis and to schedule suitable maintenance/repair measures. Nevertheless, they can be useful to assess the global effectiveness of maintenance/repair measures, as well, by controlling the dynamic configuration achieved by the structure after an intervention and then by monitoring its progression over the time.

LASER VIBROMETRY TECHNOLOGIES

Optical metrology techniques are effective tools to measure mechanical quantities, by non contact survey and detailed acquisition in the space, time and frequency domains. Within the structural control, laser vibrometry is a modern technology for measuring vibration velocities. Specifically, laser vibrometer allows at detecting the velocity of a moving point focused by a laser beam. The device measures the frequency shift of the laser beam, scattered back from the vibrating surface, according to the Doppler Effect.

Light beam from a laser source is split in two same power beams by a splitter. One of the two, called “measuring beam”, is focused on the vibrating surface. The other one, called “reference beam” is housed in the laser head. After being reflected, the measuring beam enters back the laser head. Here it is recombined with the reference beam. Surface displacement varies the optical path difference between the two laser beams. This results into a phase lag varying with vibration velocity v. As a consequence, a time varying phase difference corresponds to an instantaneous frequency component that follows v. This frequency shift is equal to the Doppler shift (f_D) that according with basic physics depends on v and source wavelength (λ):

$$f_{Doppler}\ \alpha\ 2v/\lambda$$

As a result, it is possible to extract the amplitude of velocity v, by demodulating the output signal.

Laser vibrometry devices are different, according to the operation modes and the performances.

A common classification is related to the measured velocity component:

- In-plane vibrometer, if it measures the velocity component that is parallel to the laser beam direction;
- Out-of-plane vibrometer, if it measures the velocity component that perpendicular to the laser beam direction;
- 3D vibrometer, if it measures all the three dimensions velocity components.

Another classification concerns the number of measures gathered simultaneously:

- Single point vibrometer allows at measuring the velocity only in one point;
- Differential vibrometer detects the relative velocity of two points;
- Rotational vibrometer provides with data referred to a rotating single point;
- Scanning vibrometer measures velocities for a complex set of points and gives a global mapping of the investigated surface.

Most diffused Laser Vibrometers have a maximum velocity range of 10 m/s, with a frequency upper limit of 200 kHz, a resolution of about 1μm/s and a base accuracy in the order of 1%-2%. Laser power is less than 1mW, so that no special safety measures are required. Nevertheless working distances of some tens of meters are possible with a spatial resolution of 1mm. All the systems are managed by a computer. Results are stored in digital formats as images, movies and text data files for further analysis.

From the operating point of view, laser vibrometry shows different advantages over conventional vibration measurement systems. It is simple to use, speedy and portable. It shows high sensibility and ample frequency response. It allows remote measurements that is particularly useful when contact devices are difficult to apply, due to high temperatures, low accessibility of the area, physical vulnerability and formal value of the surface. It leads to significant time and cost savings, especially if the survey concerns an extensive grid of measurement bases and/or an intensive periodicity. Nevertheless, this innovative technology can be even less intrusive if it uses non contact excitation systems, namely environmental sources (traffic vibrations for bridges, bells for towers, organs for churches) and artificial sources (loudspeakers).

APPLICATION OF LV TECHNOLOGIES TO A WALL MODEL

Vibration response analysis by laser vibrometry techniques has been addressed in laboratory on a wall model, in order to assess their reliability for damage identification. Specifically, a comparison has been carried out for different damage scenarios, when the structure was undamaged (Damage 0), then naturally damaged after some compression tests (Damage 1) and, finally, artificially damaged by cutting some mortar joints (Damage 2). All the tests were carried out at the School of Construction, Management and Engineering, University of Reading, UK.

Experimental Set-up

Wall model was made out of low density concrete blocks (Thermalite Shield, by Hanson Aggregates) and cement/sand mortar (classified as mortar M2 by the Italian code DM 20 Novembre 1987 "*Norme tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento*").

Each block was 210mm x 105mm x 105mm. Wall model was 8 blocks high, 4 blocks long and 2 blocks wide. The global wall dimensions were 910mm x 930mm x 230mm (Fig1).

Fig1 Wall model

Physical and mechanical properties of blocks and mortar are listed below.

- Block

Density = 600 Kg/mc; Failure stress = 3,1 MPa; Young's modulus = 2,4 GPa

- Mortar

Density = 1800 Kg/mc; Failure stress = 5,6 MPa; Young's modulus = 4,2 GPa

Wall has been impacted by a pendulum on the back side with a force of about 6N. A grid of 16 measurement points has been marked on the front side (Fig2).

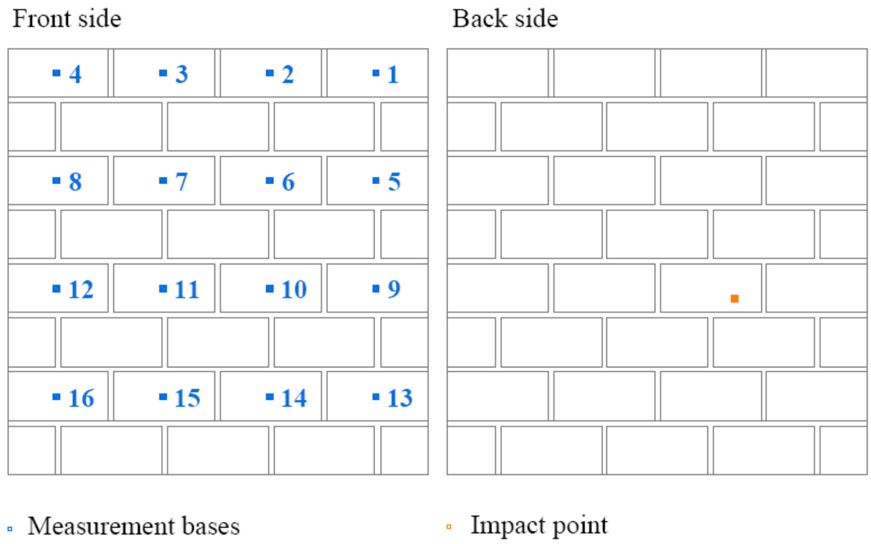

Fig2 Test set up

Measures have been acquired by a single point compact laser vibrometer, CLV 700 by Polytech C, (Fig3 and Fig4):

- Dimensions:174mm x 48mm x 38.8mm;
- Weight: 0.5 Kg;
- Operating temperatures: 0° C - 45°

Results were elaborated by LabView 8.2 (National Instruments), with a sampling frequency of 2000 Hz. Before starting, laser vibrometer has been checked by measuring the signal coming from a loudspeaker, set at 52Hz and 72Hz.


Fig4 and Fig5 Compact Laser Vibrometer, CLV 700, Polytech

Measurements Data

First, the undamaged wall has been tested. Six measures have been acquired for each measurement point. All the point showed a similar velocity signal (Fig.6), with decreasing peak amplitudes from the top to the bottom on the same column and from the centre to the edge on the same row (Tab1).

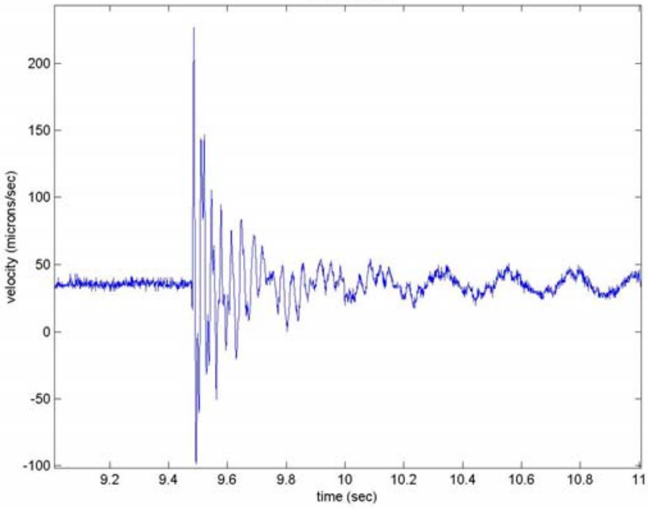

Fig6. Example of velocity signal from measurement point 1(Damage0)

Damage0_Average Peak Velocity (microns/sec)															
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
187	148	157	193	120	100	108	153	93	75	85	102	68	40	50	85

Tab1. Average peak velocities (Damage0)

As far as the frequencies are concerned, the power spectral analysis has showed the highest amplitudes at about 30Hz and 87Hz (Fig.7).

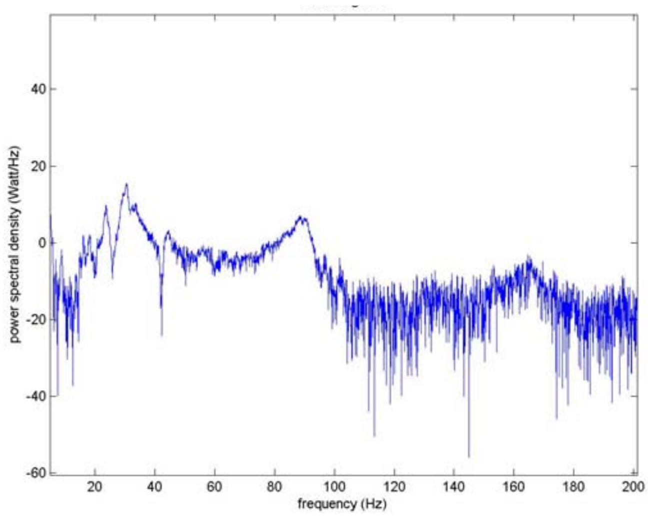

Fig7. Example of power spectrum from measurement point 1(Damage0)

An FEM has confirmed the experimental data, in terms of frequencies (Fig.8) and velocities.

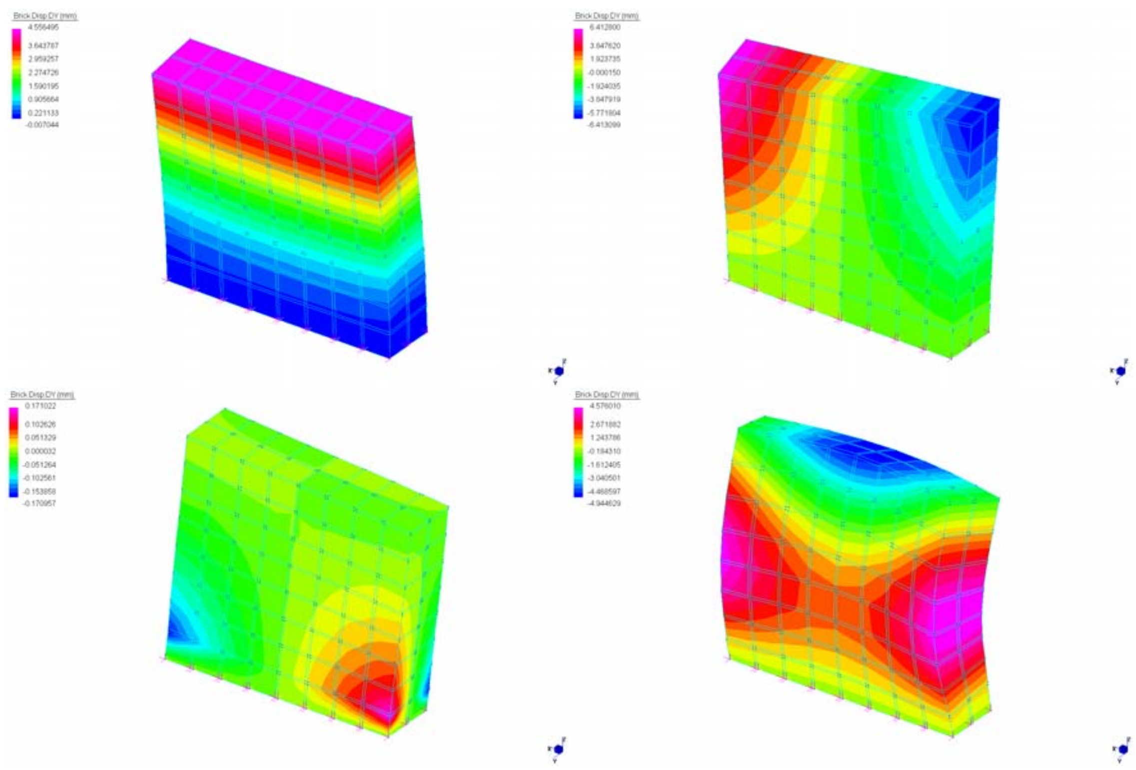

Fig8. First four modes (40Hz, 88 Hz, 114Hz and 206Hz)

In order to naturally damage the wall, four compression tests have been carried out. During the first two tests a centred load has been applied up to 25 tons, namely $12 Kg/cm^2$, that is about half the failure stress. Nevertheless, during the third and fourth tests, load was 50mm offset. As a result, some blocks, equipped by strain gauges, have undergone a deformation of about 1300 micro strains, calculated as the failure strain of the wall.

After loading, wall showed some cracks, especially at the top. Moreover, some strain gauges on the wall recorded higher strain values on the right side of the wall, probably due to a not perfectly distributed load transmission. Then, a new survey by laser vibrometer has been carried out. Six measures have been acquired for each measurement point, as well. Detected velocity signals showed similar patterns (Fig7), compared to the undamaged scenario ones.

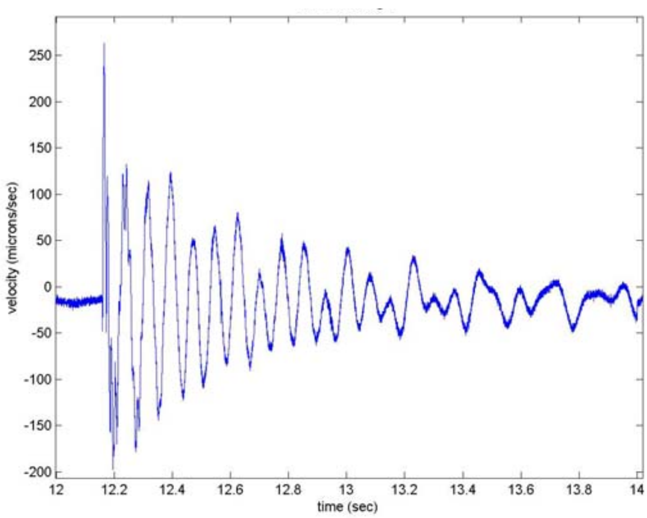

Fig9. Example of velocity signal from measurement point 1(Damage1)

Nevertheless, the amplitudes were generally higher (Tab.2).

Damage1_Average Peak Velocity (microns/sec)															
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
193	*191*	*222*	*272*	*187*	*123*	*163*	*183*	*127*	*90*	*112*	*140*	*90*	*60*	*48*	*75*

Tab2. Average peak velocities (Damage1)

As far as the frequencies are concerned, the power spectral analysis has showed the highest amplitudes at lower values, namely about 13Hz and 78Hz (Fig.10).

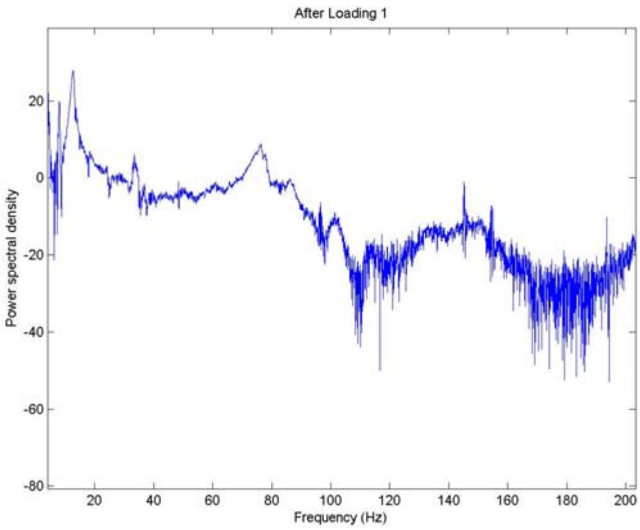

Fig10. Example of power spectrum from measurement point 1(Damage1)

All the experimental data were consistent with the model according to a Young's modulus reduction of 40%.

Finally, the wall has been artificially damaged by cutting some mortar joints for half the thickness of the wall from the back side (Fig11).

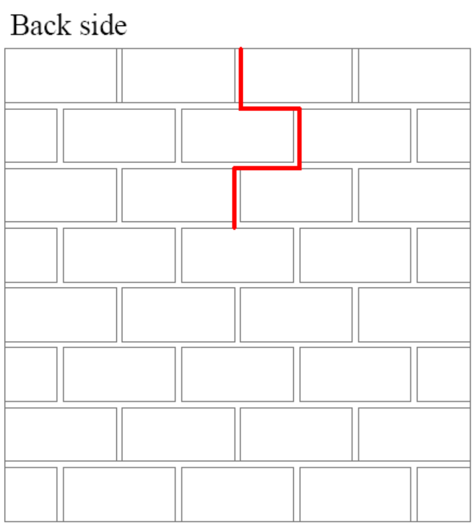

Fig11. Artificial damage (Damage2)

In this case, less significant changes have been detected compared with Damage1 values. Velocities are slightly higher and frequencies are slightly lower. Fig12 and Fig13 show the values of velocity and highest amplitude frequency for each point and each damage scenario.

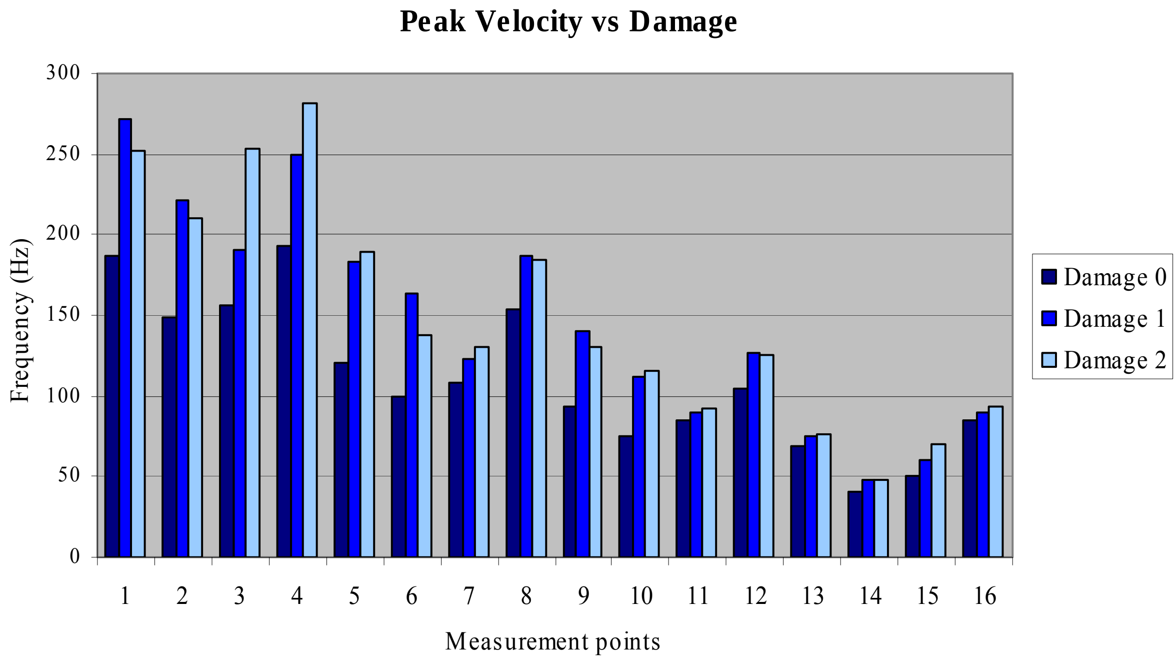

Fig12. Highest amplitude frequency vs Damage scenarios

Results and Discussions

Results show that dynamic response of the wall clearly change from the undamaged to the damaged configuration. Specifically, highest amplitude frequencies decrease and velocity peak amplitudes increase as a consequence of an increasing damage, according to the values calculated by the finite elements model.

By analysing the differences between Damage 0 and Damage 1, it is clear that the points (13, 14, 15, 16) on the bottom of the wall were less affected by the damage, as the velocities increased at a lower rate. As well, points on the right side of the wall detected a higher velocity decrease. These results can be correlated with the actual damage configuration, if we considering that the load was applied from the top and the strain gauges recorded an unbalanced load distribution towards the right side.

Frequencies decreased almost proportionally for each point. Nevertheless, the most significant drop was recorded for point 3 (first frequency from 29Hz to 8Hz), where there were some micro cracks after loading.

Results from Damage 2 show that an artificial material discontinuity doesn't affect the stiffness of the wall as a natural damage does. Further tests will be carried out by a scanner laser vibrometer in order to detect the presence of a crack, by measuring simultaneously the vibration motion of a wider set of points in the area surrounding the crack.

CONCLUSIONS

Testing, carried out in the present work, can be considered as a starting study within a more comprehensive research to assess the reliability of laser vibrometry to detect vibrations in building structures. Ongoing experimentations on different building materials aim at validating this technology, with reference not only to the damage identification, but also to the structural reinforcement assessment.

Nevertheless, some first remarks can be underlined.

From the operating point of view, laser vibrometer is easy and speedy. Measures can be detected by subsequently pointing the laser beam at several bases without interfering with the structural integrity. According to the distance, laser can be set in order to optimize the sensitivity. As a result, a non intrusive control can be achieved that is definitely attractive, especially if compared with the logistic complexity of commonly used accelerometers.

From the conceptual point of view, comparison of experimental results by laser vibrometer with finite elements models allows global structural health monitoring and damage detection and localization. Nevertheless, as damage progression is simply related to a stiffness decrease, the technology provides with qualitative information that should be related to further destructive and non destructive diagnostics techniques, in order to get an accurate damage identification. By the way, dynamic responses, corresponding to different damage configurations, can be used as qualitative reference to assess the global reliability of a maintenance/repair operation, by checking the vibration motion after an intervention and then by monitoring its mid and long term evolution.

ENDNOTES

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