Extended summary

The combined use of innovative NDTs to assess the state of conservation of frescoes, stuccoes and plaster on light vaults

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Abstract. In recent years a growing interest by the public towards the Cultural Heritage was observed. In the field of building engineering, the research developed a series of completely non-invasive instruments that can assess the state of conservation of the architectural works, it is called NDT: Non Destructive Testing.
Two diagnostic techniques have been mainly tested: the Laser Doppler Vibrometer and the Ultrasound Technique; the aim was to develop strategies and innovative procedures in order to refine an effective and non-invasive method for the investigation of the state of conservation of reeds and gypsum vaults. The conservation of these vaults is closely linked to safeguard their precious intradoses, often decorated by frescoes and stuccoes of inestimable value. Some experimental samples were made, in each one or more defects were present. In particular it is defined a ultrasonic hybrid technique that uses both a contact probe from the side of the plaster and a probe coupled in air from the side of the reeds. The LDV was used primarily to verify the presence of structural gaps between the centers and the mat of reeds. Preliminary analyses were carried out through a numerical model.

Keywords. Frescoes, Laser Doppler Vibrometry, NDTs, Stuccoes, Ultrasound.

1 Introduction

During last years the growing importance of the correct determination of the state of conservation of artworks and monuments has been stated by all personalities in care of Cultural Heritage. Correct interventions on historical structures should have as their starting point an accurate diagnosis of the various elements, in order to minimize the interference of the intervention with the historical nature of the architectural work [1].

In many historical and monumental Italian buildings, churches and theatres built between the 16th and the 19th century, light thin vaults carrying historical plasters, often decorated by frescoes or stuccoes can be found [2, 3, 4].

Many of these ceilings are nowadays frequently in a precarious state of conservation as a result of a lack of maintenance over time. Many of them have begun to present cracks and vertical lowering on their lower surface, often due to: detachment between the different mortar layers of plaster, detachment between the mat of reeds and the mortar plaster or detachment of the reeds from their timber arches [5-7]. These defects are often very difficult to be evaluated, especially when they are at the beginning phase and frequently reveal themselves only when it is too late. At present, in fact, the diagnostic process mainly rely on the expertise of the restorer/technician and the typical investigation is accomplished mainly through manual and visual inspection of the structure. It is therefore crucial to improve the applicability and reliability of Non-Destructive Testing (NDT) methods to identify with accuracy their diseases, in order to achieve targeted and accurate interventions, minimizing the interference with the nature of the architectural work and optimizing the few resources often available. The economic effort required for the realization of diagnostic test will be repaid during the restoration: previous studies have, in fact, shown as 1 € spent in preliminary tests can allow a saving of 10 € during the execution of works [1].

In literature, few researches on non-destructive techniques are present for assessing the state of conservation of these vaults. Infrared Thermography (IRT, [8, 9]) and Laser Doppler Vibrometer (LDV, [10, 11]) were used in a case study [12]. LDV has been applied to different types of movable or decorative artworks, [13-15], with different degrees of success. The application to historical buildings is more recent [16-17] and still limited.

Ultrasonic inspection techniques can be essentially divided into two classes: the contact technique [18] and the most recent non-contact technique [19]. In the first case the transducer is placed directly on the work-piece; in the second case the probe is always maintained at a certain distance (coupled by air), this second solution is completely non-intrusive and more flexible. The main difficulty to use transducers coupled by air is the huge mismatch of the acoustic impedance between a solid and the air. However the sensitivity of air-coupled probes have significantly increased in last years making them suitable for different industrial applications [20-21]. No applications of ultrasonic investigation on these kind of vaults are known by the authors till now.

In particular this paper presents the first results of the use of LDV and of a hybrid ultrasonic technique (UT) for the assessment of the state of conservation of historical plasters carried by light thin vaults. The LDV focused its attention on macro-detachments between the wooden structure and the mat of reeds, while the UT focused on micro-detachments between different mortar layers of the plaster and on micro-detachment between the mat of reeds and the whole mortar plaster.

2 Phases and methods

To evaluate the effectiveness of the proposed techniques to identify the typical defects of camorcanna vaults it has been necessary to realize some experimental samples in which artificially reproduce typical defects. Three different types of specimen were, therefore, created (Figure 1):

- A camorcanna panel (50x60 cm^2) with detachment between plaster layers;
- A camorcanna panel (50x60 cm^2) with detachment between mat of reeds and plaster;
- A portion of vault (90x90 cm^2) with detachment between wooden structure and mat of reeds.

In the vault portion, over the time can be observed further damage, in particular:

- A casting resumption;
- A longitudinal crack near the nail involving the entire thickness of the plaster;
- Two superficial crack of the plaster;
- The detachment between mat of reeds and plaster.

The first two kinds of sample were scanned with Hybrid Ultrasound Technique, while the portion of vault has been scanned with Laser Doppler Vibrometer.

A numerical model has been implemented in order to preliminary evaluate the vibrational behaviour of the vault portion; this has been very useful to understand the natural frequencies of the structure and to choose the most effective method of excitation. The numerical results were, then, compared with the experimental ones.

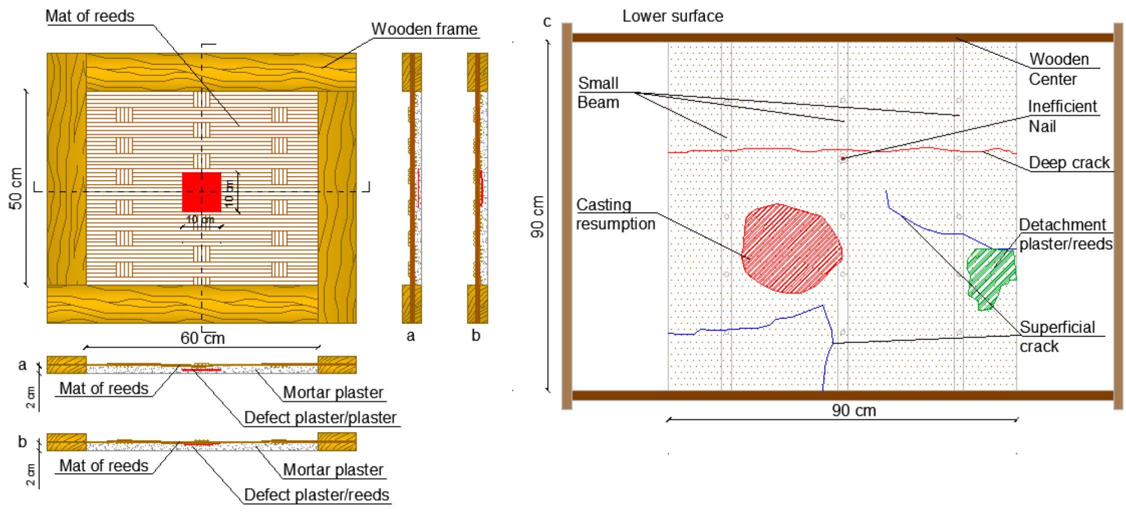

Figure 1. a) camorcanna panel with central detachment between plaster layers; b) camorcanna panel with central detachment between mat of reeds and plaster; c) portion of vault with a inefficient nail (detachment between small beam and mat of reeds).

2.1 The ultrasonic test

Ultrasonic tests were carried out in transmission mode; two transducers placed at two opposite sides of the specimen were used.

In order to exploit the high penetration of a contact method and the inspection flexibility of a non-contact approach necessary in particular on the reed side, a combination between contact and non-contact probes (hybrid configuration) was exploited [22].

The contact probe was coupled with a thin layer of water that enhanced the amplitude of the signal output from the non-contact probe in reception. On the reeds side, because of the irregular surface, the air-coupled probe was positioned 2 cm far from the mat of reeds. The inspected panels were placed on an automated workbench with a 2 axes scanning system for probe motion. The two ultrasonic probes were vertically aligned and they were moved by the scanning motors in the two orthogonal directions. A grid of 71 rows and 12 columns was realized; in this way an area of 35x12 cm^2 was inspected.

2.2 The Laser Doppler Vibrometer test

In order to identify the most efficient technique of investigation on camorcanna vaults, numerous techniques for exciting have been proposed and tested; for brevity in this paper only the results obtained with impact hammer were mentioned.

The vault portion has been forced into vibration by means of an automatic impact hammer connected to the moving platform of an electro-dynamic shaker driven by a pulse signal (with period of 0.93 s and duty cycle of 20%) conditioned by a RC filter in order to produce a short impulse at the frequency of 1.07 Hz. The impact hammer was supplied with a force cell measuring the input force transmitted to the structure.

The LDV scanning was performed at the intrados with two different methods:

- a frequency scanning;
- a scanning over time.

In the first one, input and output signals are processed in the frequency domain (FFT); in the second one, for each point of the specimen, the vibration speed at successive instants was acquired.

In the first case it is possible to observe a vibration speed at each point on the grid for each frequency; in the second case a vibration speed at each point on the grid for each instant of time is observed, regardless of the frequency.

3 Analysis and discussion of main results

In Figure 2 the C-scan maps obtained on two different kinds of samples, taken as representative, inspected with the hybrid ultrasonic configuration are compared. The maps report the RMS (Root Mean Square) signal amplitude, which is thus proportional to attenuation.

In this configuration, where the signal amplitude at the receiver is attenuated in correspondence to the defects, both the types of simulated defects (defect located between the two layers of mortar plaster and defect located between the mat of reeds and the mortar plaster) was found with a flexible scan. The contours are not perfectly defined: when the probe is located on the edge of the defect, the signal is only partially attenuated because the diameter of the probe is 38 mm. The total signal attenuation is in fact detected only when the entire active surface of the probe is completely covered by the defect. For that reason the detected defect is smaller in size than the actual defect. The map shows with good approximation the shape of the defect. The maps shows also some areas with lower attenuation (in the order of 5-10 dB), indicating local non-homogeneities visible thanks to the high resolution of the method. These areas could be highlighted as zones to be further monitored after a certain time period.

The results obtained with the LDV have been encouraging. The numerical observations were confirmed by experimental results. The effectiveness of the technique depends primarily on the frequency of excitation of the structure. The camorcanna behaves like a plate, alternating mode shapes typical of a main homogeneous plate and defective mode shapes. In these second, the defect appears as an area with higher mobility, as if the defect showed its own vibration mode.

By observing the Figure 3-4 it is possible to notice the similarities between the experimental results and the numerical model: at the frequency of 85.00 Hz in the experimental sample and at the frequency of 58.51 Hz in the numerical model, which can be defined as own of the defect, greater mobility in correspondence of the not efficient nail can be observed.

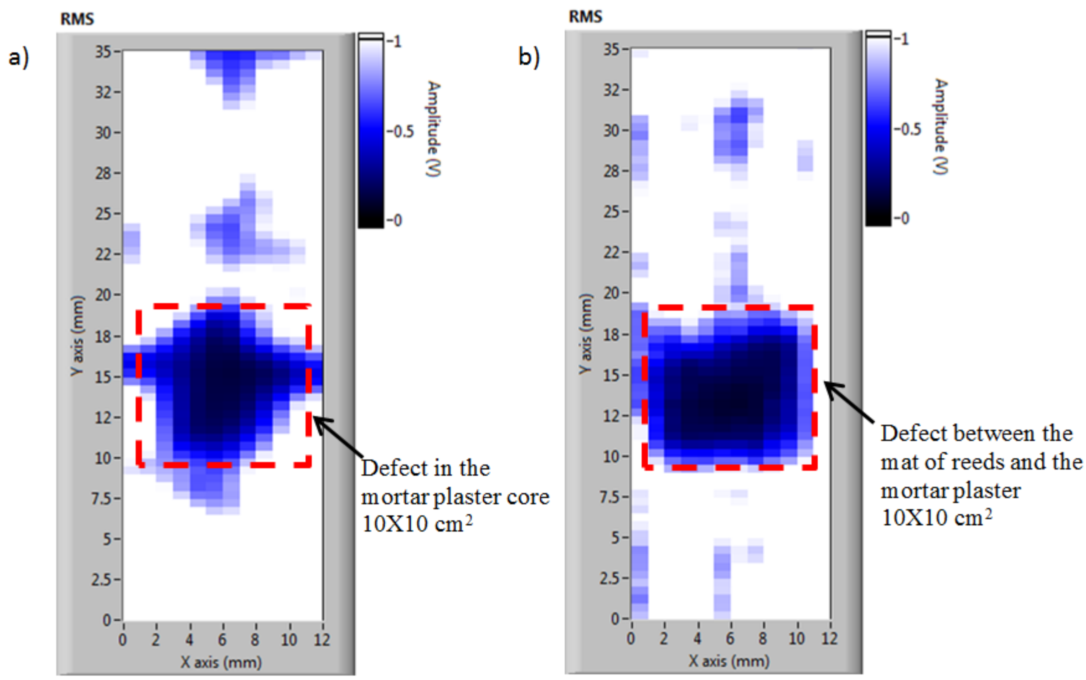

Figure 2. C-Scan map, through transmission mode 100 kHz probes; a) sample n.1 with detachment between plaster layers, b) sample n.2 with detachment between reeds and plaster.

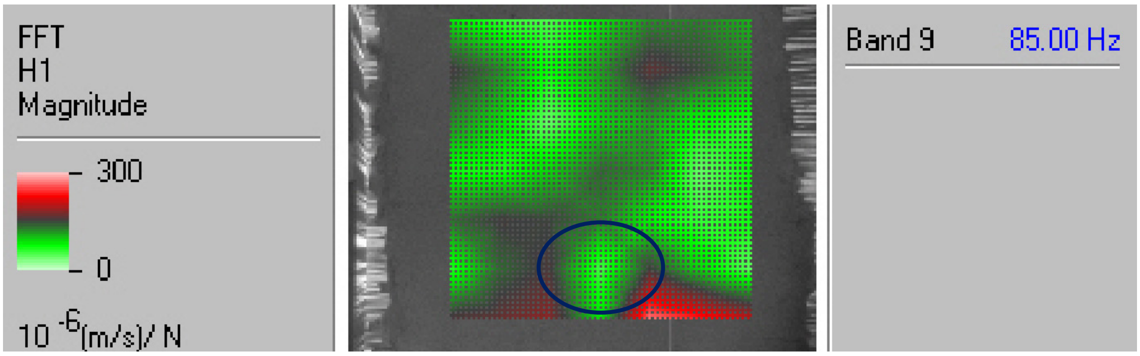

Figure 3. FFT at frequency of 85.00 Hz. Near the defective nail the blue circle highlights a discontinuity of the vibration mode, with different mobility.

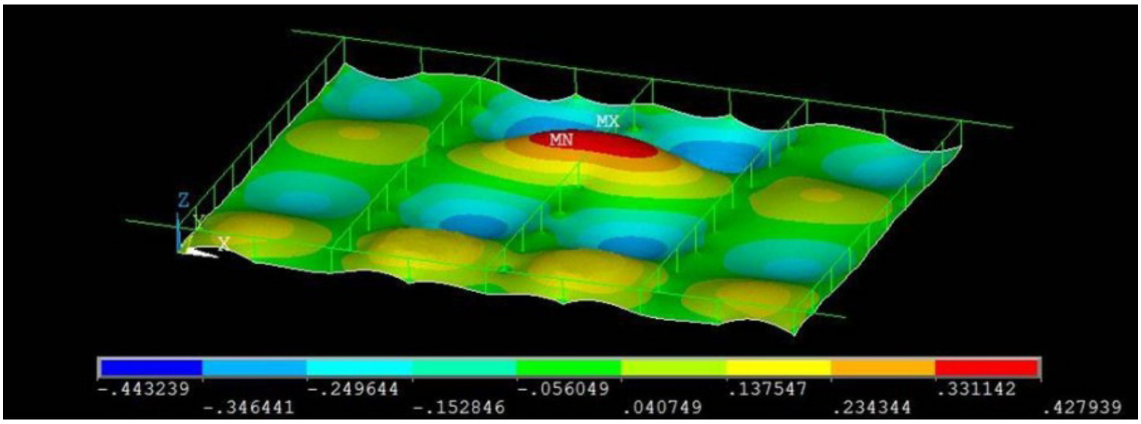

Figure 4. Vibration mode of the numerical structure, at a frequency of 58.51 Hz.

4 Conclusions

In conclusion, it is possible to say that the hybrid ultrasonic technique is perfectly able to detect discontinuities between the materials that make up the camorcanna vaults.

This technique requires access from both sides of the vault, this is possible in most cases, especially in churches and theaters, thanks to the attic, which for reason of ventilation and safety, is often accessible. The proposed set-up seems to be suitable for practical applications in real structures, provided that access on both sides is available. In Figure 5 a possible design of a real installation is sketched, showing potentials for in field application, which will represent the next step of this research.

The efficiency of LDV to identify detachment between wooden arches and mat of reeds has been widely demonstrated both numerically and experimentally.

The experimentally frequencies do not correspond exactly with those numerical, although they differ slightly; this phenomenon is mainly due to the fact that the experimental sample, unlike the numerical model, presents a greater number of discontinuities and defects that inevitably affect the vibrational behaviour.

The fact, however, that, despite the substantial differences, it is possible to identify clearly a general common behaviour, confirms that, the LDV is able to detect one of the most common and more difficult to identify defects in camorcanna vaults: the detachment between wooden structure and mat of reeds.

The complete non-invasive method guarantees perfect preservation of the frescoes and stuccoes that are present on the lower surface of these vaults.

It is important to underline that the LDV was not only effective to identify the separation points between the wooden structure and mat of reeds, but was perfectly able to identify all the many defect of the experimental sample. It was even able to identify those defects that were not present initially and that were not created artificially.

The most encouraging result was the fact that, despite the number of defects present in the sample was high, every one of them has been identified individually, as if the defects would not influence each other.

It is easy to understand how this fact is of great importance in the context of a diagnostic campaign, during which, probably, numerous defects of different nature, often close to each other could be present.

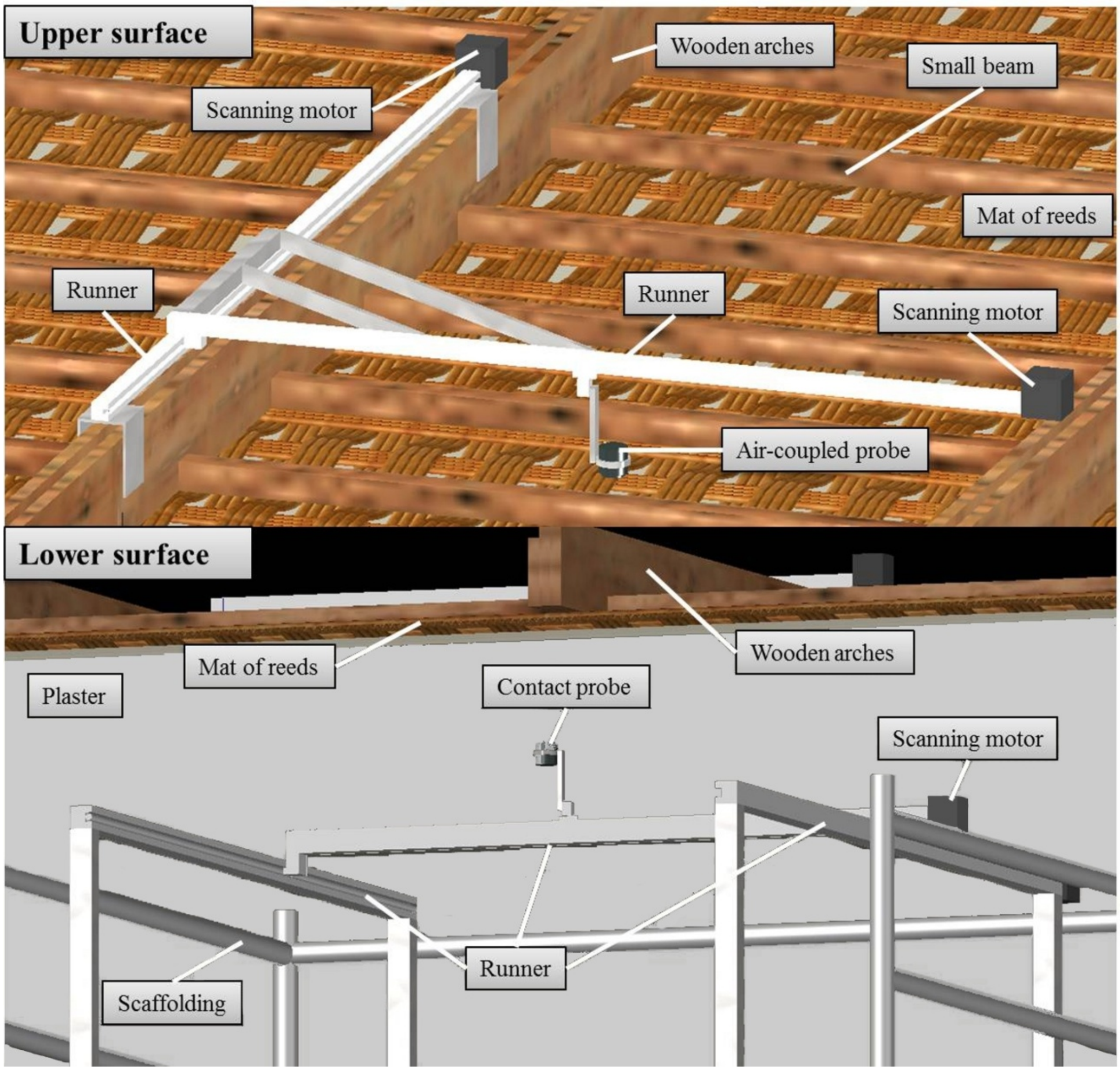

Figure 5. Sketch of potential in-field application.

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