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Original article

Historical plasters on light thin vaults: State of conservation assessment by a Hybrid ultrasonic method

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ABSTRACT

Historical plasters on light thin vaults, usually made by mats of reeds nailed to an upper wooden framework, were used in several historical and monumental Italian buildings and churches built between the 16th and the 19th century and almost all of the historical Italian theatres built between the 18th and the 19th century to cover the theatre-hall and to improve its acoustic properties. The non-destructive inspection of these structures is very important, but traditional inspection techniques are usually limited in resolution, which may be a problem for detection of defects at a very early stage. The paper presents the development and application of a high-resolution inspection technique based on a hybrid ultrasonic method, where a contact emitter probe and a non-contact air-coupled receiver probe are used. Results show the effectiveness of the method on laboratory samples and propose an inspection procedure for in-field application.

1. Introduction

In many historical and monumental Italian buildings and churches built between the 16th and the 19th century, light thin vaults carrying historical plasters can be found (Fig. 1), often decorated by stuccoes or sometimes enriched by frescoes. Furthermore, light thin vaults were used in almost all the historical Italian theatres built between the 18th and the 19th century so as to cover the theatre-hall, improving its acoustic properties [1–3].

These light thin vaults were usually made by mats of reeds nailed to an upper wooden framework. The mats were made by either small reeds, set side by side, or larger reeds broken and twisted in order to create an orthogonal grid. The wooden framework included a main structure of wooden arches, usually made by irregular boards joined together by nails, that was braced by a secondary structure of small section wooden beams. After these mats were implemented, they were coated by two or more layers of lime plaster. When the designed curvature of these light thin vaults was low, they could not stand by own shape and bending could occur. In these cases they were usually suspended to the wooden structure of the roof by wooden or metallic ties (Fig. 2) to minimize the wooden center sections and thus saving money.

Nowadays many of these constructions are frequently in a precarious state of conservation for intrinsic degradation factors due to the materials they are made by, for disarrangement events connected to particular static or dynamic events and for the greater thermal-hygrometric loads due to the adaptation of modern new air conditioning systems [4]. Furthermore, 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:

- detachments between the different plaster layers;
- detachments of the plaster from the mat of reeds;
- detachments of the reeds from their timber arches.

These kinds of defects are often very difficult to be evaluated, especially when they are at the initial phase and frequently reveal themselves only when it is too late. At present, in fact, the diagnostic process on this kind of vaults mainly relies on the expertise of the restorer/technician and typical investigations are mainly accomplished through manual and visual inspection of the structure by using a scaffolding. This task can be very difficult and expensive because this kind of vaults usually stands at significant heights, presents a wide (precious) lower surface and has an irregular upper surface that is very difficult to be inspected. The need to preserve these artworks, which characterize our historical, artistic and cultural heritage, and pass them on to future generations, as a testimony of our traditions, is thus of increasing interest. For that reason it is fundamental to improve applicability and reliability of

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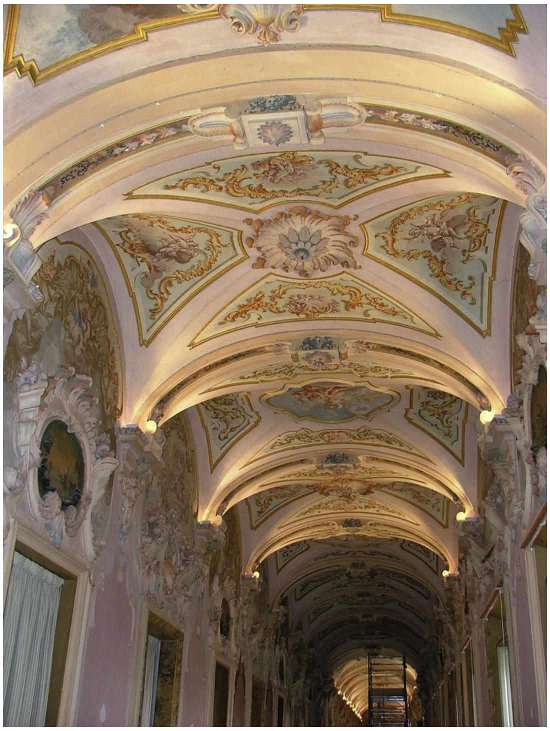

Fig. 1. Frescoes and stuccoes below a light vault.
Palazzo Pianetti, Jesi – AN, Italy.

non-destructive testing (NDT) methods for the accurate determination of their state of conservation, identifying 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 of these historical constructions: previous studies have, in fact, shown as 1 € spent in preliminary tests can allow a saving of 10 € during the execution of works [5].

In literature, few researches on non-destructive techniques are present for assessing the state of conservation of these vaults. Infrared thermography (IRT [6,7]) and laser Doppler vibrometry (LDV [8,9]) were used in a case study [10]. The results of this research have demonstrated that IRT and LDV can support effective analysis on light thin vaults as it concerns the detection of detached areas among different plaster layers (IRT) and of detached areas among the mat of reeds and the nailed connection with the wooden bearing elements (LDV). However, the effectiveness of these non-intrusive techniques may be limited when detachments have to be detected at a very early stage (e.g. for maintenance). In this case, voids or delaminations of a few tenths of millimeter of thickness have to be detected.

Fig. 2. Wooden and metallic hangings of a light vault.
Filarmonici Theater, Ascoli Piceno–AP, Italy.

This paper presents the first results of the use of ultrasonic technique for the assessment of the state of conservation of historical plasters carried by light thin vaults, focusing the attention on microdetachments between different plaster layers and on microdetachment between the mat of reeds and the whole plaster.

Ultrasonic inspection techniques can be essentially divided into two classes: the contact technique [11] and the most recent non-contact technique [12]. In the first case, the transducer is directly placed on the work-piece. A coupling mean (i.e. water, gel or oil) is often used, which increases system efficiency by reducing the energy losses due to impedance mismatch at the surfaces. In the second case, the probe is always maintained at a certain distance from the work-piece using non-contact ultrasonic sensors, this solution is completely non-intrusive and more flexible. The main difficulty in using air-coupled transducers is the huge mismatch of the acoustic impedance between a solid and the air. Due to the great difference of elastic properties and the several interfaces, the energy transferred from the transducer is very low with an attenuation of the transmitted signal often above 99.9%.

However, the sensitivity of air-coupled probes have significantly increased in last years (e.g. thanks to innovative sensor configurations and coupling materials), making them suitable for different industrial applications (e.g. on-line material characterization [13], inspection of aeronautic composite panels [14], etc.). Air-coupled ultrasonic techniques have also been used in the field of cultural heritage to inspect wooden panel paintings [15–17].

The contact ultrasonic technique, potentially able to inspect components with high thickness, presented no satisfactory results in preliminary tests performed by the authors, mainly due to:

- the difficulty of having information in pulse echo mode. In this configuration the best measurement accuracy is obtained when both front and back surfaces of the test piece are smooth and parallel. The upper irregular surface of the test piece (and also in the real structure) entails that the returning echo may be distorted due to the multiplicity of slightly different sound paths seen by the transducer. Due to the large variation of the thickness and irregular surface of the reeds it becomes difficult to distinguish between real anomalies and variations in thickness in particular when the defect is near the background (reeds support);
- problems in transmission mode due to the upper irregular surface of the reeds where a contact probe cannot be successfully applied.

Therefore the air-coupled technique was initially tested for the present study. However, due to the thickness and material non-homogeneities, the generated ultrasound waves had not enough energy to propagate through reed and mortar plaster panels.

Thus in this work the use of a hybrid configuration is proposed by coupling a contact emitting probe with a non-contact air-coupled receiver. This configuration has been already tested on thick FRP sandwich components for civil applications [18] with good results and it is here chosen to have a potential investigation set-up to be applied in actual cases, where the receiving probe can be exploited with no contact over the irregular upper surface of the vault.

No applications of this hybrid ultrasonic investigation on these kind of vaults are known to the best of the authors' knowledge.