# Combined use of non-destructive methods for the assessment of facades anomalies of heritage buildings with structural concrete elements

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## Abstract

Heritage buildings based on structural concrete elements associated to infill or resistant masonry walls often present facade anomalies such as cracking, disintegration, settlement, delamination, wear, deflection or leakage.
The selection of the most suitable test method is essential for the reliability and confidence of assessment and service life prediction of heritage buildings. Usually, only one non-destructive test method cannot give enough information about the facade anomalies to support a diagnosis, so a combined use of different methods could be of great convenience.
This article presents the experimental results of the combined use of ultrasound testing, thermography and photogrammetry for assessment of anomalies occurring in facades of a heritage building, these results are compared and discussed and recommendations are made to address the advantages of the combined use of these techniques to support the diagnosis of the causes of anomalies in facades.

**Key words**: heritage buildings, non-destructive inspection, walls.

## 1 INTRODUCTION

Heritage buildings as well as other buildings with relevant cultural/historical value or public utility (EVPba buildings, or just EVPba), with structural concrete elements associated to infill or resistant masonry walls, constructed since 1920, often present facade anomalies such as cracking, disintegration, settlement, delamination, wear, deflection or leakage. Those anomalies can have great relevance concerning the service life of the buildings and his appearance and sometimes, also, the comfort of people.

The solution for the rehabilitation of facades shall include a proper diagnosis of the causes of deterioration that must include three main steps: i) the environment, the original design approach and the conditions of use; ii) detailed visual inspection of the facade elements; and, ii) selection of tests for anomalies assessment. The selection of the most suitable test method is essential for the reliability and confidence of the obtained results. The identification of these anomalies, particularly of the hidden ones, can be obtained by using in situ testing techniques, preferably non-destructive ones (NDT). Usually, only one NDT cannot give enough information about the anomalies to support a full diagnosis, so a combined use of different methods can be of great value.

This article presents the experimental results of the combined use of ultrasound testing (US), infrared thermography (IRT) and photogrammetry for the assessment of facades anomalies in EVPba buildings. The obtained results are compared and discussed and recommendations are made to address the advantages of the combined use of different techniques to support the diagnosis of the causes of anomalies in facades.

# 2 NDT APPLIED TO MASONRY WALLS AND CONFINING STRUCTURAL ELEMENTS ANOMALIES DETECTION

## 2.1 GENERAL

The corrective solutions of repair concrete elements and masonry walls shall be supported by a proper diagnosis of their causes. So, it is important to carry out a detailed survey of the anomalies and is essential to have information about the original design approach, the history of the building, the environment, the conditions of use and requirements for the future use. A detailed survey includes, in general, the identification and characterization of the deficiencies, and shall consist of a building inspection, through NDTs, with focus in the areas of concrete elements and masonry walls affected by anomalies.

In the following paragraphs, the use of US, IRT and Photogrammetry for the assessment of buildings anomalies are presented, as well as their potential use in the preliminary inspection/detailed survey of anomalies related with masonry walls or to their structural confining elements (Miranda Dias *et al.*, 2016). These three techniques are most valuable in EVPba inspection when a simple visual observation is not possible: areas too far away from the observer (example, the higher floors of the building) or of limited accessibility.

## 2.2 ULTRASOUND TESTING (US)

The US method is based on the assumption that the cracking, the lack of cohesion and the detachment of the material (i.e., the state of preservation of the material) reduces the speed of the ultrasonic waves. This inspection technique aims the evaluation of the state of conservation of the construction elements based on estimation of mechanical resistance and deformability of constituent material and it allows the evaluation of the compactness and stiffness by determining the rate of spread of ultrasonic waves through the material. The device consists of two transducers (an emitter of pulses of ultrasonic longitudinal waves and a receiver) and a central module which emits waves, processes the reading and records of the transmission time.

## 2.3 INFRARED THERMOGRAFY (IRT)

The IRT method is based on the assumption that for temperatures above absolute zero all the objects emit energy from their surface in the form of thermal radiation. Thermography

equipment captures the IR radiation and converts it to a thermal image (thermogram), which represents the distribution of surface temperature (Ts) of the object.
The IRT is a method of auscultation which can be classified in two categories: i) passive methods, for which no additional artificial source of heat is used specially to carry out the auscultation; or, ii) active methods: for which the diffusion of heat is provoked by artificial means, set up to carry out the auscultation. The infrared camera´s position results of a compromise between spatial resolution and size of observed area.

IRT allows observing a field of temperature on a surface. The information is extracted from gradients observed at the surface at one time. Information may also be deduced from evolutions of the temperature field with time. Temperature gradients or variations can only be observed if the system is submitted to heat transfer.

In case of on-site applications, the influence of rain, fog and wind must be considered.
Passive thermography is used to the search of discontinuities (such as a delamination, cavity or crack), possible because they introduce a change of thermal properties that alters heat transfer. For instance, a hotter zone might appear or not at the surface depending on the thermal properties of the materials. Conversely, if there is heat loss (cooling), the signature will be a cold layer. Heat diffusion may also be modified by contrasting thermo-physical properties within the material.

Active infrared thermography methods are based on the active heating or cooling of the elements under test to provide an unsteady temperature gradient. These two active methods, impulse-thermography (IT) and pulse phase thermography (PPT), have been proven to be very useful for the investigation of structures close to the surface.

Experimental set-up and data acquisition are identical for IT and PPT: the surface of the structure is heated by using a radiation source. After switching off the heating source, the cooling down behaviour is recorded in real time with an infrared camera. The propagation of the heat depends on the material properties like thermal conductivity, heat capacity and density. While observing the temporal changes of the surface temperature distribution with the infrared camera, near surface inhomogeneities will be detected if they cause measurable temperature differences on the surface (Matias *et al.*, 2015).

The main approach of IT in analysing the thermal data is to interpret the function of surface temperature versus cooling time for selected areas with and without inhomogeneities.
PPT is based on the application of the Fast Fourier Transformation to all transient curves of each pixel. Thus, one obtains amplitude and phase images for all frequencies. Amplitudes images show the internal structure of a specimen up to a maximum available depth depending on the frequency. Phase images show the internal depth range depending on the frequency.

## 2.4 PHOTOGRAMETRY

Photogrammetry is used to produce orthomosaics (orthos) and/or point clouds of the surface of buildings or of details from photographs. Photogrammetric products (PP) – the orthos (more appropriate for flat surfaces) and point clouds (better suited for objects with a strong three-dimensional component) – are generated from photos using photogrammetric software (the processing steps of the generation of PP are described, for example, in Pierrot-Deseilligny et al., 2011). In the analysis of facades, both metric and interpretive photogrammetry should be used: the first because it enables measurements from PP (measuring the length and aperture of a crack is an example); the second because it allows, using image processing techniques, the recognition and identification of relevant features on the surfaces. Through the enhancement of some features (see Fig. 1 to 4) one can extract information such as the type of anomalies in concrete elements (cracking and delamination of concrete, and reinforcement corrosion) or in masonry walls (cracking, detachment of renders, degradation of the paintings, and presence of mould in the external surface of the facade).

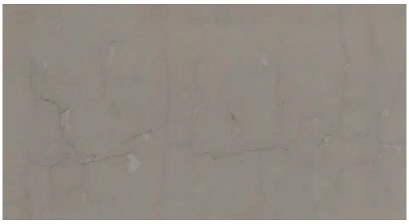


*Fig. 1 An ortho of a wall (pixel size: 3.5mm)*

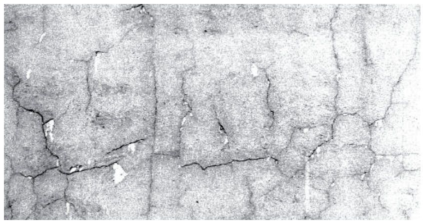


*Fig. 2 The same area, transformed in grayscale and enhanced*

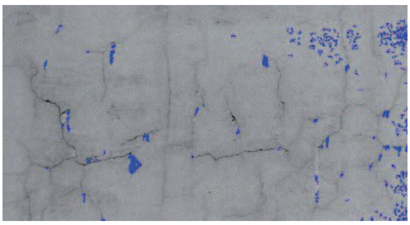


*Fig. 3 Brighter areas highlighted in blue*

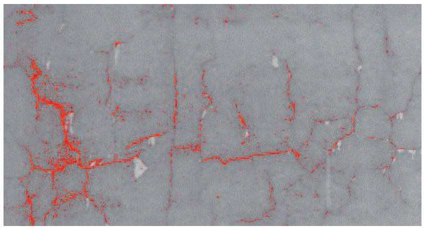


*Fig. 4 Darker areas highlighted in red*

The photo survey of facades can be terrestrial or aerial, this one using drones. In both cases the survey must be planed (the distance camera-wall and the maximum distance between consecutive photos are set) being that the quality of the camera (pixel size) and the accuracy of the final product contribute to establish the parameters of the survey. Concerning accuracy, there are different demands from the assessment of diverse types anomalies occurring in facades of a building. Some of the assessment requires, mainly, quantified type of analysis, and need to measure the aperture, length, orientation, evolution of the cracks, and, for these kind of assessments, accuracies of 1 mm are necessary; others requires, essentially, interpretative type of analysis, and need only to know if there are cracks and the distribution of these on the surfaces, being that simple image processing techniques like the ones used to create the image presented in Fig. 2 are sufficient.

## 2.5 USE OF NDT FOR INSPECTION OF ANOMALIES IN MASONRY WALLS

NDT can be helpful in finding hidden features (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests (Binda, 2009). In wall renderings, the technique of analysis by means of US is used for identification of possible degraded areas (such as cracks, loss of adhesion and cohesion) and, in combination with other NDT, allows adding valuable information with regard to the resistance of materials and to their condition (Magalhães *et al.*, 2008).

Between the NDT applied to the diagnosis of anomalies in renderings, the IRT may be used to evaluate the state of conservation of large areas of the rendering. Both photogrammetry and IRT, due to their quick use with small equipment and ability to reach places far from the observer or of difficult access to him, are particularly suited to help in the identification of anomalies and in the diagnosis of their causes. While IRT method allows evaluating the distribution of temperatures on the surface of the wall without direct physical contact, orthos are a valuable basis for measurements and features detection as presented before, in Fig. 2 to 4.

The IRT is useful, for example, when there is a detachment of the render that give rise to a formation of an air gap of air between the render and the support (masonry block or brick), which introduces an additional thermal resistance and leads to the existence of surface areas warmer or cooler, thus creating temperature differences that can be detected with infrared equipment. While IRT allows to relate observed situations of thermal inhomogeneity with an internal "picture" and state of the element, such as the characteristics of the materials as well as the occurrence in the wall renders of detachment, surface discontinuities and internal cracks and even the distribution of moisture on the wall, photogrammetry can explore in detail the apparent state of the surface of the facade element, namely superficial defects.

In respect to the use of NDT in detection of moisture presence and its evolution, it should be noted that several factors may, however, restrict the use of thermography. The method of detection depends on the wall surface temperature changes due to water evaporation rate or to the change of thermal characteristics of the constituent materials (Magalhães *et. al.*,2008).

## 2.6 USE OF NDT FOR INSPECTION OF ANOMALIES IN CONFINING STRUCTURAL ELEMENTS

NDT testing is widely used as a relevant tool for assessment of the condition of the structure and identification of the causes of deterioration, particularly to assess the uniformity of concrete *in-situ*, to delineate zones or areas of poor quality or deteriorated concrete in structures. The inspection methods that have been focused, are used with different objectives.

US testing when applied to concrete elements can be used for the determination of the uniformity of concrete, the presence of cracks and voids, changes in properties with time and in the determination of dynamic physical properties. It may also be used to estimate the strength of *in-situ* concrete elements or specimens. However, it is not intended as an alternative to the direct measurement of the compressive strength of concrete.

To provide a measurement of pulse velocity (measured according to EN 12504-4) which is reproducible and which depends essentially on the properties of the concrete under test, it is necessary to consider the various factors which can influence pulse velocity and its correlation with various physical properties of the concrete. The moisture content has two effects on the pulse velocity, one chemical, other physical. Variations of the concrete temperature between 10°C and 30°C have been found to cause no significant change without the occurrence of corresponding changes in strength or elastic properties. The path length over which the pulse velocity is measured should be long enough not to be significantly influenced by the heterogeneous nature of the concrete. The velocity of short pulses of vibrations is independent of the size and shape of specimen in which they travel, unless its least lateral dimension is less than a certain minimum value. Below this value, the pulse velocity may be reduced appreciably. Concerning the effect of reinforcing bars, one should avoid measurements near these when they are parallel to the direction pulse propagation.

When an ultrasonic pulse travelling through concrete meets a concrete-air interface, there is negligible transmission of energy across this interface. Thus, any air-filled crack or void lying immediately between two transducers will obstruct the direct ultrasonic beam when the projected length of the void is greater than the width of the transducers and the wavelength of sound used. When this happens, the first pulse to arrive at the receiving transducer will have been diffracted around the periphery of the defect and the transit time will be longer than in similar concrete with no defect. Depending on the distance separating the transducers it is possible to make use of this effect for locating flaws, voids or other defects greater than about 100 mm in diameter or depth.

# 3 ACESSING THE POTENTIAL COMBINED USE OF NDT ON MASONRY AND CONFINING STRUCTURAL ELEMENTS

## 3.1 LABORATORY TEST

To previously achieve a higher sensitivity of the use of the above referred NDT (US, IRT and Photogrammetry), and assess their advantages and limitations, some tests were made: masonry specimens were subjected to axial compression till they reached a state of significant cracking, without reaching a global collapse. During the loading phase a combined use of NDT were used to assess the presence of cracking. With this goal, it was tried to find out, during the process of applying increasing axial load, the degree of sensitivity of each of these techniques in the detection and evaluation of the evolution of cracking in masonry, which generally corresponded, during the test, to an increased opening of the cracks in the masonry with the increased load.

Specimen Test A1 (Fig. 5) was built with vertically perforated ceramic blocks, with average dimensions of approximately 296 mm (length) x 137 mm (thickness) x 193 mm (height), and cement mortar joints. The value of the compressive strength of blocks was near 21.4 N/mm$^2$. Specimen Test A2 (Fig. 5) was built with massive concrete blocks of expanded clay aggregates, with average dimensions of approximately 500 mm (length) x 150 mm (thickness) x 200 mm (height), and cement mortar joints. The value of the compressive strength of blocks was near 10.1 N/mm$^2$. Due to the different dimensions of Specimen A1 and A2, the tests were made in two different compression presses (Fig. 5).

The results of the measurement of deformations with alongameter in both specimens throughout the loading steps revealed that the horizontal deformations measured could capture the onset and progression of cracking along the charging of specimen.

*A1 - perforated ceramic blocks*

*A2 - massive concrete blocks*

*Fig. 5 General view of compression test of masonry specimens*

The ultrasound measurements, the acquisition of images of IRT and the photos were made during the tests breaks. As it was intended that the photo and the IRT surveys were the less disturbing, the equipment was mounted on fixed tripods during the tests.

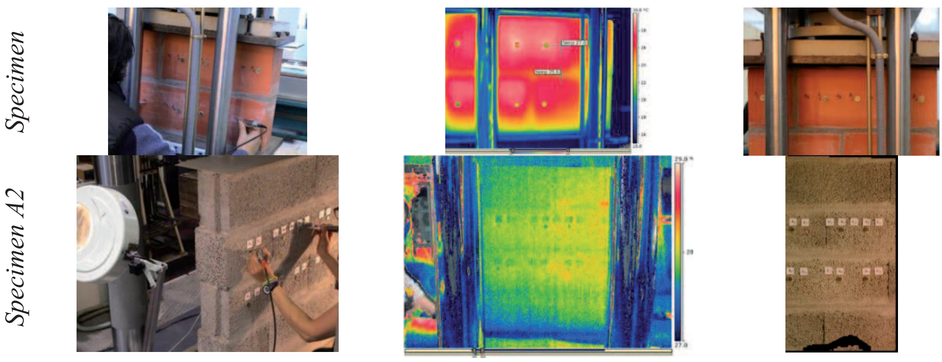
The US tests on Specimen A1 and A2 revealed that, with the direct measurement, it was possible the detection and evaluation of the progression of cracking occurring in the specimen; in contrast, in indirect measurement, there was not a clear indication of the evolution of cracking.

IRT applied to Specimen A1 revealed that the cracks could not be detected during the test. Following the previous heating of the specimen it was only possible to distinguish the different materials; in the Specimen A2, IRT also could not detect the cracks because the cracking occurred in an area outside of range view of infrared thermography equipment (Fig. 6).

In both specimens, each ortho was generated, using software Micmac, from two photographs taken by two digital cameras fixed on a horizontal bar (35 cm apart), attached to a tripod. Details of the surveys are found in Table 1. The existence of disturbing elements (metal parts belonging to the compression press) that occupied much of the photography and were near the specimen did not allow a good geometric correction of the ortho. This was more noticeable in Specimen A1 because the area free of obstacles was smaller. Specimen A2, although have better conditions to be photographed had a very rough surface: the few fissures that emerged were not highlighted. These would be more easily recognized if the wall had been smoothed and white painted.

*Table 1 – Characteristics of the photo surveys of two specimens*

| Specimen | Camera Cannon | Size of the pixel in the sensor | Size of the image | Distance to specimen | Size of the pixel in the specimen |
|---|---|---|---|---|---|
| A1 | 600D | 6.4 µm | 8 Mpx | 1.8 m | 0.35 mm |
| A2 | 350D | 8.9 µm | 4 Mpx | 2.4 m | 0.57 mm |




b) ultrasound testing c) infrared thermography d) photogrammetry

*Fig. 6 Use of NDTT in the compression test of Specimen A1 and Specimen A2*

### 3.2 CASE STUDY - FACADES OF A BUILDING

The three NDT - US, IRT and Photogrammetry - were used in the analysis of facades anomalies of a EVPba for detection of cracking and detachment in the wall renders and in concrete elements. Three walls (East, West and North) around a yard were selected.

### 3.2.1 Ultrasound testing (US)

US was used in the analysis of anomalies of the East façade (Fig. 7). The results show that, with the indirect measurement, it was possible the detection of cracking and local detachment of the facade renders.

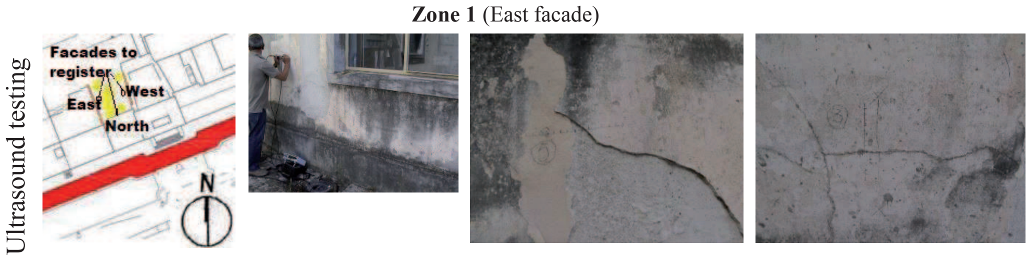


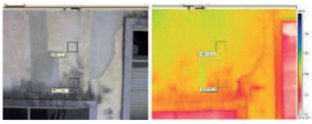

*Fig. 7 Use of ultrasound testing (indirect measurements) for the detection and evaluation of anomalies occurring on East facade*

### 3.2.2 Thermography (IRT)

IRT was used for detection of cracking and local detachment in the wall renders and in concrete elements, and detection of transition zone between concrete elements and masonry walls (Fig. 8).

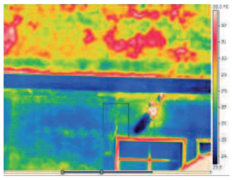
East wall of the building (Fig 8a) was analysed without solar incidence that not help for a good use of IRT. Nevertheless, it was possible to notice cracks and detached area, also visible in real picture. In opposite facade (Fig 8b), with the imposition of a heat flux (solar radiation) IRT easily detects a crack difficult to spot when seen at ground level. Fig 8c shows the last analysed facade (exposed to North), with structural concrete elements visible with IRT. The area under the window on the left side is more noticeable (warmer) probably due to the presence of a heater inside the room. The white area between the windows identifies detachments of coatings. It was possible to show local detachment of concrete in the column of East corner zone of the facade.

**Zone 1** (East facade)



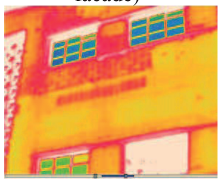
a) East Facade – Photography and thermography showing detachments and cracks


**Zone 2** (West facade)



b) West Facade showing rendering fissure

**Zone 3** (Top of North facade)



**Zone 4** (East corner of North facade)


c) North facade showing structural concrete elements (in particular the column of East corner zone of the facade)

*Fig. 8 Use of infrared thermography for the detection and evaluation of anomalies*

### 3.2.3 Photogrammetry

Photogrammetry was used to get orthos of each facade (Fig. 9) and a point cloud of the set. There were made a terrestrial survey (lower facades: the East and West) and an independent aerial survey, with a drone DJI Inspire 1V2 (Fig. 10 and 11). Characteristics of the surveys are displayed in Table 2. It was applied image processing techniques in the analysis of anomalies (Fig. 12), for detection of cracking and detachment in the wall renders, and of cracks and repair zones in concrete elements.

*Table 2 – Characteristics of the photo surveys of facades*

| | Camera | Size of the pixel in the sensor | Size of the image | Distance to facades | Size of the pixel in the facade |
|---|---|---|---|---|---|
| Terrestrial | Nikon D200 | 6.1 µm | 10 MPx | 2.5 m: East<br>8 m: West | 0.5 mm: East<br>2 mm: West |
| Aerial | Zenmuse X3 | 1.5 µm | 12 MPx | from 8 m to 14 m | 3.5 mm |

***Zone 1** (East facade)*

***Zone 2** (West facade)*

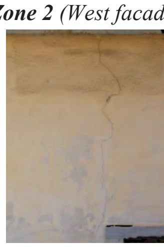


*Fig 9 Ortos. Zone 1: most deteriorated area in East facade; Zone 2: a detail of the West facade*

***Zone 3** (North facade, detail)*

*Fig 10 Photo*

*Fig. 11 Photos taken by the drone*

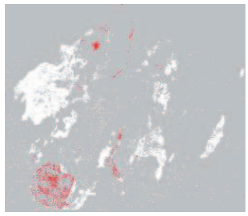


*Fig. 12 Classification*

### 3.2.4 Reflections about the results of the combined use of the NDT to access facade anomalies and their causes

The main results of the combined use of the NDT thorough the confront of individual results of the application of each of the three techniques to access the anomalies and their causes, particularly in four locations of North, East and West facades, are presented in Table 3.

*Table 3 – Analysis of the NDT used to access anomalies in EVPba facades*

<table>
<tr><th></th><th colspan="2">Anomalies</th><th>Analysis of the NDT used</th></tr>
<tr><td rowspan="2">Zone 1</td><td colspan="2">Cracking and render detachment of the facade masonry wall</td><td rowspan="2">Due to easy access of the observer to the inspection local, ultrasounds together with thermography can be useful to analyse the inside state of the façade, namely the respective cracking and render detachment.</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">Zone 2</td><td colspan="2">Near vertical cracking of the facade masonry wall</td><td rowspan="2">Photogrammetry together with thermography can be useful to capture the vertical cracking of the façade</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">Zone 3</td><td colspan="2">Render detachment and degradation of the painting of the facade masonry wall</td><td rowspan="2">In this zone the results of the applied NDTT reveals that, due to far distance of the observer to the inspection local, aerial photogrammetry together with thermography can be useful to capture render detachment and degradation of the painting of the façade</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">Zone 4</td><td colspan="2">Local detachment of reinforced concrete column concrete in the East corner zone and evidence of previous repair</td><td rowspan="2">In this zone the results of the applied NDT reveals that, due to far distance of the observer to the inspection area, ultrasounds cannot be applied. Photogrammetry together with thermography can be useful to capture local detachment of reinforced concrete column concrete and evidence of previous repair of that zone.</td></tr>
<tr><td></td><td></td></tr>
</table>

## 4 FINAL CONSIDERATIONS

The combined use of ultrasounds, thermography and photogrammetry for assessment of anomalies occurring in facades of a heritage building were here performed. To previously achieve a higher sensitivity of the use of the above referred NDT, and assess their advantages and limitations, tests on masonry specimens subjected to axial compression were made. In this study, the only method that gave good response was that of the ultrasound. The others presented limitations arising from special features which cannot be eliminated in such type of conditions: in case of photogrammetry, immovable structures involving the specimens (small field of view) and unsuitable surface of specimen for the adequate photo contrast; in case of thermography lack of thermal contrast. Outside, in the analysis of building facades anomalies (case study), all the techniques shown to be valid.

The use of just one of the NDT, in some cases, may not provide enough information for a proper diagnosis of facade anomalies of buildings, notably the cracking and local detachment in the wall renders and in concrete elements in the building elements. So, it is recommended the combined use of two or more test techniques. However, it is important to know the limitations and benefits of each technique to explore the combined use of these techniques to achieve suitable diagnosis of the causes of the anomalies.

The combined use of different techniques can eventually permit to obtain information enabling the identification of anomalies patterns, guiding the phase of detailed characterization of anomalies, including using in situ tests, laboratory tests or analytical studies.

### ACKNOWLEDGEMENT

LNEC Planned Research Programme (P2I) for the period 2013-2020 (P2I Project “COREAP” – Service life, conservation and rehabilitation of walls of buildings with relevant patrimonial value”) has funded the present study.

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