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ANOMALY DIAGNOSIS IN CERAMIC CLADDINGS BY THERMOGRAPHY A REVIEW

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Abstract

With the increasing importance given to building rehabilitation comes the need to create simple, fast and non-destructive testing methods (NDT) to identify problems and for anomaly diagnosis. Ceramic tiles are one of the most typical kinds of exterior wall cladding in several countries; the earliest known examples are Egyptian dating from 4000 BC. This type of building facade coating, though being quite often used in due to its aesthetic and architectural characteristics, is one of the most complex that can be applied given the several parts from which it is composed; hence, it is also one of the most difficult to correctly diagnose with expeditious methods.

The detachment of ceramic wall tiles is probably the most common and difficult to identify anomaly associated with this kind of cladding and it is also definitely the one that can compromise security the most. Thus, it is necessary to study a process of inspection more efficient and economic than the currently used which often consist in semi-destructive methods (the most common is the pull off test), that can only be used in a small part of the building at a time, allowing some assumptions of what can the rest of the cladding be like.

Infrared thermography (IRT) is a NDT with a wide variety of applications in building inspection that is becoming commonly used to identify anomalies related with thermal variations in the inspected surfaces. Few authors have studied the application of IRT in anomalies associated with ceramic claddings claiming that the presence of air or water beneath the superficial layer will influence the heat transfer in a way that can be detected in both a qualitative and a quantitative way by the thermal camera, providing information about the state of the wall in a much broad area per trial than other methods commonly used nowadays.

This article intends to present a review of the state of art of this NDT and its potentiality in becoming a more efficient way to diagnose anomalies in ceramic wall claddings.

Introduction

Ceramic tiles systems coating building facades are one of the most complex kind of cladding that are still in use since long ago. Its complexity relates to the fact that it is a system in direct contact with a support (the wall) and composed by three different components with specific characteristics and technical requirements: the adhesive mortar, the ceramic tile and the joint filling mortar. Each one of these materials is of course liable to problems either due to deficient application or to its durability.

Among all the anomalies that can surge on this type of claddings there is one that requires special attention, not only due to the functional losses it implies but overall because of the risk to safety it can rise. The detachment of tiles is one of the most common anomalies in this kind of cladding representing more than 50% of the totality of anomalies cases verified [1,2]. In Brasilia, it reaches 71% of the anomalies on facades (fig. 1.) [3,4]. This anomaly consists on the loss of adhesion between two or more of the system's layers, the ceramic tile, the adhesive mortar and the support. The lack of adhesion can in turn give place to a detachment and creation of voids that will be filled by air or water. The main causes of detachment in ceramic claddings are [1]:

- faulty preparation of the support (all dust must be clean before application);
- wrong choice of materials;
- deficient attaching of the tiles (for example using a single layer when double layer is required);
- awry sizing of the joints;
- excessive deformation of the support;
- humidity presence.

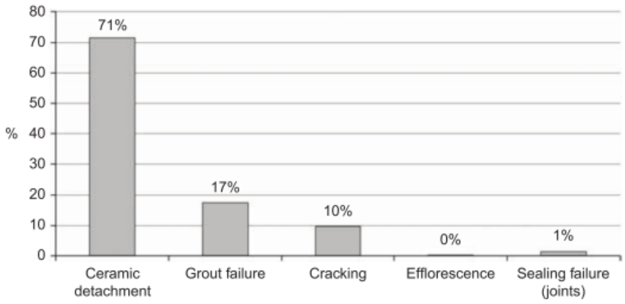

Fig. 1 - Incidence of anomalies in facade [3,4].

Nowadays there are some methods used to identify this anomaly, as maintained by [5]:

- sphere crash (for pavements);
- ultra sounds;
- tapping test;
- pull-off test.

Despite not having greater problems in identifying ceramic tiles detachment, what these testing methods have in common is that they are not practical when applied to a building scale. Using these methods, only small areas at a time can be assessed making assumptions on what the rest of the building's cladding may be like. Therefore, it is needed to identify and study expeditious methods of diagnosis to overcome the limitations of the currently used.

Infrared thermography

IRT is a NDT with growing acknowledgement due to the variety of appliances not only in building inspection but also in many other applications areas. To understand this testing method it is needed to know some basic principles behind it, related with thermal radiation and heat transfer.

For temperature above absolute zero every object emits energy from its surface in the form of thermal radiation. Thermal radiation is a part of the electromagnetic spectrum which is divided in terms of wavelength and frequency. Thermal radiation, whose wavelength ranges between 0.4 μm and 10^2 μm, consists of a small proportion of UV, visible radiation (detectable by the human eye) and a large part of infrared radiation [7].

It was in 1973 that William Herschel through an accidental experiment discovered the infrared radiation, noticing that using a prism to separate the colours from blue to red, temperature was still rising beyond the red band where no radiation was visible and that the distance where the heating is greatest has a specific location, which in turn lead to the conclusion that it depends on the wavelength [8].

Spectral range of Infrared radiation is comprehended between 0.78 e 10^2 μm [9].

Infrared radiation can also be divided in three regions [8]:

- Near infrared (NIR), from 0.78μm to 1.5 μm;
- Medium infrared (MIR), from 1.5μm to 20 μm;
- Far infrared (FIR), from 20 μm to 10^2 μm.

When the electromagnetic radiation that surrounds us interacts with bodies, three processes can occur depending on the characteristics of the body: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected and a fraction τ may be transmitted [6].

There are three fundamental laws in which IRT is based on and to understand them it is needed to first know in what consists a blackbody, a physic abstraction characterized by absorbing the totality of the incident radiation, regardless off the wavelength and direction [10].

Planck's law describes the spectral distribution of the radiation from a blackbody. This law shows that, for a given wavelength, the emitted radiation increases with the temperature and that the higher the temperature, the shorter the wavelength at which the maximum occurs [6].

By integrating the Planck's formula from $\lambda=0$ to $\lambda=\infty$ comes the Sefman-Boltzman equation which states that the total emissive power of a blackbody (E) is proportional to the fourth power of its absolute temperature [6].

According to Kirchhoff's law of thermal radiation, for a specific temperature and wavelength, the spectral emissivity and spectral absorptance are equal at any given temperature and wavelength [6]. As a blackbody is a perfect absorber, from this law comes that it is also capable of emitting radiation at all wavelengths, and naturally, it has the maximum value of emissive power (E_0) correspondent to an absolute temperature. Thus, comes the concept of emissivity (ε) of a grey body ("common body"), which consists in the percentage of the emissive power in relation to the blackbody.

As stated above, all bodies at a given temperature emit some radiation depending on their emissivity. Hence, this diagnosis method consists in using an infrared camera that is able to detect infrared radiation and to create a thermal image by converting the different wavelengths of radiation detected in electrical signals that are displayed as a thermal image called thermogram, which shows the thermal variation of the surface that is being inspected. Of course that before all inspections characteristics like the emissivity of the surface must be set in the equipment so that a correct diagnosis can be done. For that purpose either this characteristic can be looked for in tables (most common building materials have emissivity values over 0.8 [11,12]), or a method based in the comparison with a standard tape used by Bauer et al. [13] and based on an ASTM standard [14].

Despite the thermogram showing only the superficial temperature, it is possible to make some assumptions on the condition of the inspected element if the principles of heat transfer and inspection conditions are understood. When a building has some heat related anomaly, although it can be behind the surface, it will affect the heat transfer through the element analysed and it will cause thermal variations in the surface that, depending on the thermal camera sensitivity, will be noticed in the thermogram. Based on these basic principles IRT has been used as a NDT to identify anomalies like air leakage, thermal bridges, lack of thermal insulation, presence of humidity [7,8] and anomalies in roof waterproofing systems [15] or claddings, especially when related with presence of air or water in the intermediate layers of the studied element [6].

Two kind of diagnosis techniques can be used: the passive (PIRT) and the active (AIRT).

PIRT consists in the interpretation of superficial temperatures without the appliance of any mean of thermal variation. Thereby, the thermal variations that can lead to a diagnosis are due especially to a heat flow through the inspected element.

AIRT on the other hand consists in applying a thermal variation on the specimen for example through the incidence of radiation from a lightbulb. This method studies the thermal variation caused by the imposed action that can either be from the side of the reading (reflexion method, used to find more superficial anomalies) or the opposite side (transmition method, used on more deep anomalies). This kind of IRT can further be divided in [8]:

- Pulsed IRT (PT) – Consists in applying a short thermal stimulation pulse and studying the temperature decay curve;
- Step Heating (SH) – Also known as long pulse IRT, it relies, as it is named of, in a long thermal stimulation pulse;
- Lock-in IRT (LT) – is a technique in witch thermal waves are imposed inside a specimen for example by periodic disposition of heat; this kind of AIRT is named after the need to precisely monitor the time between the input and the output signal;
- Vibrothermography (VT) – is based in the effect of mechanical vibrations induced on the specimen which result in heat creation that can be read by the thermal camera; this technique is especially effective in showing cracks or delamination zones where friction can cause a higher thermal variation.

Some crucial aspects must be kept in mind when leading an IRT survey as the thermogram obtained can be severely influenced by several factors such as:

- surface characteristics;
- camera characteristics and positioning;
- external factors influence like the weather or presence of neighbouring elements;
- atmospheric attenuation between the object studied and the camera.

As mentioned above, when detachment of ceramic tiles takes place, the voids created between the cladding layers are filled with air or water. The presence of one or both these elements in a wall will, even in an almost imperceptible way, cause variations on the overall thermal behaviour of the wall. These variations can occur in terms of thermal conductivity, λ, specific heat, c_p (amount of thermal energy necessary to raise a material´s temperature in 1ºC), thermal diffusivity, a (capacity of a material to transmit a thermal variation) and thermal effusivity, b (amount of thermal energy that a material is capable of absorbing or releasing). These characteristics are represented on table 1.

Table 1 – Some thermal characteristics of air and water [15].

	Water	Air
λ [W/(m.K)]	0.6	0.025
c_p [J/(kg.K)]	4187	1000
a [m^2/s]	0.14x10^{-6}	20x10^{-6}
b [m2/s]	1580	5

The thermal properties exchange will theoretically be related with the detached zones allowing the infrared camera to highlight these areas of anomaly. Therefore, for example according to Freitas et al. [11], upon the inspection of a building’s facade, “two phases can clearly be distinguished. In the heating phase, the thermal resistance caused by detachment inhibits the absorbed heat from reaching the interior, which means that the surface temperature is higher in the detachment. In contrast, at the end of the afternoon, when the environmental conditions change, the cooling phase of the facade starts. The heat absorbed by it is prevented from reaching the surface, which means that surface temperatures are lower in the detachment, due to the reduction in thermal capacity".

Research

Despite being a NDT that has been applied to building inspections as a valuable diagnostic tool [11], IRT has potential applications that have not yet been completely explored and valuated. One of these applications is the detection of delamination in facades that is not at the time covered by any standards like other construction related areas are [16].

Few efforts have been made in order to turn this diagnosis method a viable alternative to the other ones in use. However, there are some researchers that have given the first steps in order to make it possible: some have studied specifically the ceramic tiles delamination on facades [13,16] and other have studied closely related subjects [3,11,17,19,20].

For example Theodorekas et al. [17] have quantitatively analysed plastered mosaic detection by means of IRT. In this study, the researchers have quantitatively analysed five assorted panels in laboratory assuming that IRT would be "able to detect hidden mosaics, presented with temperature variations on the surface, due to the dissimilar diffusion that each layer renders". They used a method called Cooling Down Thermography (CDT) that allow to analyse the decay of temperatures as a function of time after heating. This technique has proven to be "very well suited" for the investigation of plastered mosaics demonstrating thermal contrast among "mosaic-consisted and mosaic-free areas" in all inspections. The research prove that numerical computation applied to the thermal images can be useful as it is not only able to provide information about the thermal response of the investigated structure (confirming or predicting results acquired through experimental testing) but also it makes possible to "acquire information regarding the influence of specific parameters variations to the produced detectability, as well as to estimate the detection limits under specific testing conditions" [17]. With this research the authors claim that IRT can be applied efficiently to detect plastered mosaics for example in cases of cultural heritage inspection. A similar survey was taken by Avdelidis [18] with analogous results.

Edis et al. [16] have also done some research on this NDT using quantitative analysis to study detachment of adhered ceramic cladding by Time-dependent PIRT. With this purpose in mind the authors inspected two buildings in Lisbon not only with IRT but also recurring to other testing methods such as tapping control by hand and by hammer. They also used some other instruments to evaluate some of the climatic and the facade's conditions like the wind speed, the intensity of the sunlight beams and the moisture content in the facade. They improved the accuracy of the inspection results by using a method of time-dependent PIRT (td-PIRT) as well as three different quantitative analysis methods: simple image subtraction (SIS), nonnegative matrix factorization (NMF) and principal component analysis (PCA). The td-PIRT is a method to enhance themograms used in medium to high rise building where AIRT is not viable. The method consisted in taking thermograms with half an hour intervals gathering information on how the surfaces temperatures variate and relating it to the other data mentioned above. At the end they crossed the results obtained with the quantitative IRT and the tapping tests. It came to conclusion that td-PIRT is the most appropriate technique to detect detachments in adhered ceramic cladding, since new areas with detachments "were identified during supplementary tapping controls performed with indications in the thermograms and quantitative analysis results being taken into account" [16]. The PCA analysis technique was the one who proved to be the most efficient showing high consistency in different time periods and environmental conditions. They also claim that the greatest advantage of td-PIRT over PIRT is its consistent performance in showing defective areas when proper analysis methods are used. More general conclusions were taken such as the effectiveness of the IRT in detecting delamination before detachment occurs.

Freitas et al. [11] conducted a study to verify the viability of IRT in detection of facade plaster detachments. Despite not being the same type of cladding as ceramics, the principle is the same: detachment creates an air gap that increases thermal resistance to heat flow. To this purpose physical models were created in laboratory with artificially detachments. Specimens were formed by a concrete sample cladded with a layer of plastic with air bubbles (in the zone of the induced anomaly) simulating the air gap between the support and the fine polymeric plaster. The technique used for testing was a qualitative AIRT where "thermograms were obtained on a minute-by-minute basis in three phases: without a heat source; with the heat source switched on (for 30 min) and after the heat source was switched off (for 70 min)" [11]. From the laboratory tests the authors concluded that PIRT is not a viable method for laboratory testing because "without the action of the heat source, the detachment created in the sample is not visible" [11]. However, when the heat source is switched on, there is an increase in surface temperature throughout the sample, particularly in the area with the defect. Similarly, "when the heat source is switched off, the temperature drop is greater in the detached area" [11].

After the laboratorial survey in situ measurements were done on the southern facade of a residential building in Porto with occasional detachments. Similarly to the experimental campaign taken by Edis et al. [16], PIRT was used and then crossed with the results from a tapping control inspection. "Thermograms were obtained hourly in three phases: without sunlight falling on the facade, with sunlight falling directly on the facade and after the sun had been on it" [16]. Simultaneously, a numerical simulation was done using the program WUFI Pro 5.3 and the characteristics of the facade studied in situ. Comparing the results from the numerical simulation with the ones obtained in situ, it is claimed that "the temperature change in the numerical simulation is analogous to the change in surface temperature obtained by IRT, both in the area without detachment and in the area with detached plaster; that is, on a southward-facing facade, at the end of the morning, the temperature of the detachment zone is higher than that of the facade and, in early evening, the temperature in the detachment area is lower" [16]. Once more, IRT was proven to be a valuable tool to detect early detachment situations.

Bauer et al. [13] have likewise done some work on this field. Authors created a model for laboratorial testing composed by a slab cladded with three ceramic tiles with different thickness. The detachment was simulated by a middle flaw zone with a width of 20 mm in which adhesive mortar was lacking. Using a long pulse AIRT technique it was proven by a quantitative analysis that, as expected, the thicknesses of the cladding influences the thermal variations of the surface since a higher thermal variation between the normal zone and the faulty zone was noticed on the thinner tile. From the quantitative analysis another important conclusion was obtained; when the thermal variation considered is between the faulty zone and the whole tile, they noticed that the thickest tile verified the lower thermal variation. This observation lead the researchers to claim that thermal variation factor alone does not serve as a defining parameter of anomalies and that is necessary to consider also the facade´s temperature, the materials characteristics and the existing heat flows.

The year after, Bauer et al. [3] continued the study of detachment detection by means of IRT, this time using the specimen mentioned by Freitas et al. [11]. The same specimen was studied this time using two different infrared cameras aiming "to assess the effect of the specific adjustments and acquisition characteristics of the equipment" [3]. After once more confirming this method's capacity to detect detachments, the authors claim that "when the quantitative criterion ΔT between regions was being assessed, the differences between the two cameras were very small. Thus, quantitative IRT can be used for the assessment of damage and anomalies in facades" [3]. They also state that "in field inspections, when PIRT is being used, different thermal flow regimes need to be implemented. Thus, assessing the facade under different temperature conditions (under the action of sun, at night, amongst others) it is possible to identify damages and anomalies comparatively by applying quantitative criteria" [3].

Melrinho et al. [19] studied a method for the detection and mapping of anomalies in flat roofs, more specifically waterproof related problems, with IRT. The efficacy of the NDT was proven again. One interesting conclusion from the survey is that one of the factors that can influence the image obtained is the angle of observation. However, through the experimental campaign it was verified that though some error may occur from the angle variation, it is not significant, hence, together with the use of a special support during the campaigns, turns this type of inspection extremely viable for application on real cases.

Another interesting survey taken by Freitas et al. [20] aims to verify the possibility of using IRT to detect cracks on facades of render in situ. Here authors claim that, despite not being able to identify all the failure zones with IRT alone, when using a computional program to overlap the thermogram and the digital image, as well as inputing the surface temperature in points of interest, it is possible to claim that IRT is a highly capable technique to evaluate and diagnose problems in facades' claddings.

Critical analysis

Without many weak points to appoint on the research done so far, it is necessary to say that some of the results obtained may lack of the supposedly necessary number of specimen to test, often being only one specimen tested. Despite this, all the surveys studied in this paper revealed similar conclusions regarding the applicability of the diagnosis method in question.

The crossing between traditional testing methods such as the tapping method and IRT proved to be valuable not only to verify the accuracy of the "new" method but also to compare efficiency of both methods. As well as testing techniques as the one mentioned above, numerical simulation before the actual survey may help to foresee the results, eliminating possible errors. Despite its complexity, a quantitative analysis taking into account as many aspects as possible proves to be a useful tool to ensure the credibility of the data obtained.

In the case of ceramic claddings there is an additional problem for the use of IRT to assess detachments due to the high reflectance characteristic of the tiles and the height that the facades can have.

Conclusions

With the review of several articles regarding the use of IRT applied as a diagnosis technique to building facades it is possible to take conclusions such as:

- Several aspects should be taken into account when leading an IRT survey; thus, it is necessary to characterize the surface of the inspection element with some care, as well as evaluate the climacteric conditions.
- The accuracy of the camera used in surveys can take a substantial impact in the thermogram quality.
- Inspections achieve the best results when taken in the morning with the increasing of the heat or in the afternoon with its decrease.
- Anomalies detection requires some kind of thermal action applied, either by active methods destined specially to laboratory analysis or passively using the sun as heater, a more practical way to inspect the "real cases" of building facades.
- The repetitive results in the surveys studied so far ensure the viability of IRT as a valuable diagnostic technique for detachments, not only in the case of ceramic claddings but also in some other coating systems.
- As the early detection of detachment has been shown possible using this NDT, the creation of a specific report / document dedicated to facade anomalies inspection by IRT may help this technique to gain a better recognition.

References

[1] J. A. C. Lucas. Anomalies in ceramic coatings (in Portuguese). 2001. ITCM 28. LNEC. ISBN: 972-49-1886-6.

[2] J. Dufour, G. Della Giustina. Pathologie of tiles (in French). Paris, ITBP. Annales de I'ITBP No 426, Julliet-Août 1948, Série Questiones Générales 162.

[3] E. Bauer, V. de Freitas, N. Mustelier, E. Barreira, S. de Freitas (2014) - Infrared thermography – evaluation of the results reproducibility. Structural survey, Vol. 33, No 1 (2015), pp. 20-35 (doi: 10.1108/SS-05-2014-0021).

[4] E. Bauer, E. K. Castro, F. E. Leal, G. R. Antunes (2011) - Identification and quantification of failure modes of new buildings façades in Brasília, Proceedings of XII International Conference on Durability of Building Materials and Components, FEUP Edições, Vol. 3, pp. 1089-1096.

[5] J. Silvestre, J. Brito. (2008) – Inspection and diagnosis of adhered ceramic claddings (in Portuguese). Revista Eng. Civil - U. Minho, No 30 (2008), pp. 67-82.

[6] J. M. Hart. A practical guide to infra-red thermography for building surveys. 1991. Building Research Establishment Report. ISBN: 0 85125 448 9.

[7] L. Matias. Testing Techniques for Structures Inspection. DURATINET project. Lisbon, LNEC, 29th and 30th May 2012.

[8] X. Maladague . Theory and practice of infrared technology for nondestructive testing. 2001. Editors: K. Chang. Wiley-Interscience. ISBN 0-471-18190-0.

[9] X. Maladague. Infrared methodology and technology. Nondestructive testing monographs and tracts. Vol. 7. 1994. Editor-in-Chief: W. J. McGonnagle. Gordon and Breach Science Publishers. ISBN: 2-88124-590-0.

[10] F. M. A. Henriques. Higrothermal behaviour of buildings (in Portuguese). Version 11.5. 2011. Universidade Nova de Lisboa. ISBN: 978-989-20-3993-0.

[11] S. S. de Freitas, V. P. de Freitas, E. Barreira (2014) - Detection of facade plaster detachments using infrared thermography - A nondestructive technique. Construction and Building Materials , Vol. 70 (2014), pp. 80-87. (doi: 10.1016/j.conbuildmat.2014.07.094).

[12] G. Gaussorgues (1984) – Infrared thermography: principles – technologie – aplications (in French). 1999. Edition TEC & DOC.

[13] E. Bauer, E. K. Castro, A. H. Oliveira Filho, E. Pavón (2014) – Criteria for application of passive infrared thermography as an auxiliary technique in the diagnosis of pathologies on the facades of buildings. Iº Encontro Luso-Brasileiro de Degradação de Estruturas em Betão Armado, Salvador, Bahia, Brasil, (2014), pp. 266-277.

[14] ASTM E1862 – 97 Standard Test Methods for Measuring and Compensating for Reflected Temperature Using Infrared Imaging Radiometers (Reapproved 2010).

[15] A. Melrinho. Anomalies in roof waterproofing systems: Detection by infrared thermography (in Portuguese). MSc dissertation, Universidade Nova de Lisboa. 2014.

[16] E. Edis, I. Flores-Colen, J. de Brito (2014) - Time-dependent passive building thermography for detecting delamination of adhered ceramic cladding. J. Nondestructive Evaluation, Vol. 34, Issue 2 (2015), article 24 (doi: 10.1007/s10921-015-0297-5).

[17] P. Theodorakeas, N. P. Avedelidis, E. Cheilakou, M. Koui (2014) - Quantitative analysis of plastered mosaics by means of active infrared thermography. Construction and Building Materials, Vol. 73, (2014), pp. 417-425 (doi: 10.1016/j.conbuildmat.2014.09.089).

[18] N.P. Avdelidis, M. Koui, C. Ibarra-Castanedo , X. Maldague (2006) - Thermographic studies of plastered mosaics. Infrared Physics & Technology Vol. 49 (2007), pp. 254–256 (doi: 10.1016/j.infrared.2006.06.027).

[19] A. Melrinho, L. Matias, P. Faria (2015) – Detection of anomalies in roof waterproofing systems using infrared thermography (in Portuguese). TECH ITT, Vol.13, No 37 (2015), pp. 29-38.

[20] J. Freitas, H. Carasek, O. Cascudo (2013) – Utilization of infrared thermography for evaluation of cracks in plastered and painted facades (in Portuguese). Ambiente Construído, Porto Alegre, Vol. 14, No 1 (2014), pp. 57-73.