Journal of Building Engineering 6 (2016) 93–104

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Analysis of building facade defects using infrared thermography: Laboratory studies

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ARTICLE INFO

Article history:
Received 27 August 2015
Received in revised form
5 February 2016
Accepted 25 February 2016
Available online 27 February 2016

Keywords:
Infrared thermography
Façade
Delta-*T*
Thermal contrast
Temperature gradient
Pathologies

ABSTRACT

One of the main problems facing the inspection of facades by means of passive infrared thermography, in order to identify and evaluate defects or pathologies, is the definition of the most appropriate moment to perform the inspection. Most studies focus on the Delta-*T* value as a criterion for the identification and evaluation of defects. Nevertheless, the identification of defects will primarily depend on the heat flux, since the way defects appear on the thermogram is determined by their type and by the direction of the flux. This study set out to analyse this problem by studying the behavior of the Delta-*T* and contrast functions in defects in ceramic tiles and mortar. Accordingly, test samples were made with induced defects during the manufacturing process, to simulate the detachment problems that occur with ceramic tiles of different thicknesses and cracks of different depths. The test samples were assessed during direct and inverse heating cycles. The results showed that it is possible to detect differences in behavior when varying the thickness of the ceramic tiles and the depth of the cracks by considering the Delta-*T* and contrast functions. In consequence, the inspection moment should be defined according to the behavior of the gradient temperature, the type of the defect and the direction of the heat flux.

1. Introduction

Infrared thermography, involving an analysis of surface temperatures, is able to identify internal anomalies since heat transportation is affected by the presence of faults, inclusions, moisture, and other occurrences. These anomalies change the heat flux pattern and thus affect the resulting surface temperature, relative to the surface temperature of a defect free surface [1]. Although internal defects can be detected, infrared thermography is considered to be applicable to surfaces since it more easily identifies anomalies close to the surface.

The possibility of identifying anomalies will not depend only on the characteristics and depth of the defects. Elements or components, in thermal or hygroscopic equilibrium are difficult to study with thermography [2]. The thermal flux in plan elements is obviously not one-dimensional. However, the thickness being smaller, it is observed that in this direction occur the fastest answers of the alteration of the temperatures. That way it is possible to study these heat flux in a simplified form which permits the identification of defects and anomalies.

The gradient temperature between the external and internal surfaces (facade), as well as the direction of the heat flux that passes through the wall, will determine when a defect will be visible and how it can be identified in a thermogram. It can be characterized as being either a cooler or warmer zone.

The heat flux in a building envelope obviously is neither static nor constant throughout the day, and is closely dependent on the ambient temperature, solar heating, and cooling of the facade. The performing of a thermographic inspection for delamination or detachment detection it is often recommended at the moment of the day when the values of the heat flux in the facade are greater, that is, when the greatest wall temperature gradient values appear (this study was conducted in stone panels) [3]. A study of the solar trajectory in order to identify the potential effects of sunlight and shade, which will define the heat flux and, consequently, the conditions for the detection of anomalies, is of great importance. The use of sun charts for this assessment is simple and effective but must be completed with priority to the inspection [4].

There are different conditions to consider when identifying anomalies that depend on orientation, making it necessary to study both schemes, direct and inverse heat flux, in order to define the analysis criteria for each inspection. In such cases, it is even more important to conduct a pre-analysis of the heat flux schemes. The aim is to understand the heat flux conditions in the

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http://dx.doi.org/10.1016/j.jobe.2016.02.012
2352-7102/

facade, and the behavior of defects in different directions of flux. Applying thermography, it is possible to identify and map the areas with defects. The forms in which have been analyzed the defects in facade elements (ceramic tiles and mortar) in laboratory studies are presented in the next items.

2. Theoretical background

Different forms of analysis are used to identify anomalies with infrared thermography. The considered to be the most important are the visual temperature differences in the thermogram (used in qualitative thermography) and the Delta-*T* (used in quantitative thermography). Qualitative thermography is based on a relatively simple analysis to identify hot spots and cold spots of the thermal image by color difference, that is, a visual analysis. The analysis is made by a comparison with standard situations, and the evaluation depends heavily on the expertize of the evaluator [5]. Quantitative thermography is used to classify the importance of an anomaly, being necessary to obtain as accurately as possible the temperature of the target object. It is necessary then measure and appropriately define the thermographic parameters (eg emissivity, reflected temperature). Graphical representations and contrast functions have also been used in other studies as complementary tools for the identification or quantification of defects [6,7].

The thermogram visual differences have been used to enable the identification of cold and hot areas in building facades, thermal bridges, presence of structural elements, like beams and pillars, different materials like mortar and brick, failures in the insulating materials [8], as well as common pathologies like cracks [9,10] and moisture [11,12].

The most commonly used criterion in quantitative thermography is associated with the Delta-*T* between the area with defects and the defect free surrounding area [13]. However, the use of this criterion does not lead to a conclusive assessment when identifying anomalies in facades [6,14]. It is necessary to consider the gradient temperature and to determine the conditions under which anomalies in the thermograms can be better identified [15]. The study developed by Bauer et al. [1] proved that it is possible to quantify the defects created in a sample, thus exhibiting excellent reproducibility in the three cycles that were evaluated. Despite the differences in the temperatures recorded by the two different thermographic cameras in the study, the Delta-*T*, quantitative criterion used to evaluate the defect, showed very small differences between the two cameras, proving that it can be used for the evaluation of damage and defects in facades as long as the variations in the temperature gradient are considered in the analysis process.

Studies conducted during the day to evaluate defects in facades have been carried out considering the influence of the variation of exterior and interior air temperatures. De Freitas et al. [16] studied polymeric plaster detachment on a facade, obtaining different Delta-*T* values throughout the day. They concluded that the best period for the inspection was during the hours of the greatest exposure to sunlight (at noon). Edis et al. [17] detected moisture problems from the heat gain of the facade during the daytime and nighttime. These authors recommend carrying out the inspection during the night because the Delta-*T*, between the moist area (with defects) and dry area (without defects), is stable for a longer period. In this study, the magnitude of Delta-*T* was also higher around noon.

One of the main problems facing the thermographic inspections of facades is when to get the thermal imaging [18]. Thermographic inspections are normally based on finding the thermogram with the highest Delta-*T* (the defect will always be more visible when the value of the Delta-*T* is the highest). However, in these situations, the physical limits of the defects are not always well identified, hindering the precise delimitation of the anomalies. Delta-*T* not only depends on the temperature gradient, as the type of the defect, its size, and the depth at which it exists can modify the Delta-*T*'s behavior [13]. In studies of small thickness defects, located at a shallow depth relative to the surface, the value of Delta-*T* tends to be constant after the initial heating moments at the laboratory study, as occurred in the studies developed by Bauer et al. [1] and Freitas et al. [16].

The identification of the optimum time (moment) to perform a thermographic inspection to identify and evaluate defects is a problem which has been studied in cases of active and passive thermography, when a specific heat flux is induced in a sample. In addition to a visual and Delta-*T* analysis, in active thermography, contrast functions are used as an auxiliary tool for defect identification. In some specific material studies, the value of the contrast function can indicates the presence of the defect [19]. However, in studies of building elements in which the defects are larger, it is expected that this function can be used to determine the optimal time to identify the defects. The thermal events that occur within, an area incorporating defects, and a defect free normal area, change with time because the heat dissipation varies with time, among other variables. Thus, the selection of the most adequate thermogram, at a particular moment in time, is required in order to extract and define the boundaries of the local defects. The selection criteria for this thermogram is generally based on a thermogram with the highest thermal contrast. This contrast can corresponds to the differential temperature of the defects over the differential temperature from a free defect area [20].

Maldague [13] used the contrast function called '*Standard Contrast*' *(C^s)*, which is calculated according to Eq. (1). The contrast is the temperature variation in the area with defects, relative to the evolution of the temperature of the closest defect free area.

$$C^s(t)=\frac{T_i(t)-T_i(t_0)}{T_s(t)-T_s(t_0)} \quad (1)$$

where $C^s(t)$ is the *'Standard Contrast'*, $T_i(t)$ is the temperature of the defective area at time t, $T_i(t_0)$ *is* the temperature of the defective area at time t_0, $T_s(t)$ is the temperature of the defect free area at time t, $T_s(t_0)$ is the temperature of the defect free area at time t_0, and t_0 is the start time (beginning of the cycle).

A similar contrast function (standard temperature contrast) was used by Nowak and Kucypera [21] to study the presence of concealed materials inside the walls in laboratory. This function contrast is the temperature variation at any selected point on surface of the material under testing relative to the temperature variation at surface point over homogeneous area prior to thermal stimulation.

According to Nowak and Kucypera [21], the '*Standard Contrast*' *(C^s)* is independent of the type of material being tested; it is dimensionless and oscillates around a constant value close to one in the steady state, such that it is possible to compare the results of various experiments, as was done by Bauer et al. [14].

Vavilov [19] used a contrast function called *'Running Temperature Contrast' (C)* in the study of sensitivity and noise in thermographic measurements. Basically, this contrast function is obtained from Eq. (2), being determined during the periods of heating. These values are generated for each time and correspond to the evolution of the Delta-*T* (temperature of the region incorporating defects minus that of the defect free region), in relation to the evolution of the average temperature of the sample. With this evaluation, it should be possible to identify the optimum times at which to identify anomalies.

$$C(t)=\frac{T_d(t)-T_{nd}(t)}{T(t)} \quad (2)$$