Applicability of infrared thermography to the study of the behaviour of stone panels as building envelopes

F. Cerdeira*, M.E. Vázquez, J. Collazo, E. Granada

E.T.S. Ingenieros Industriales, Universidad de Vigo, c/Maxwell, Campus Lagoas-Marcoende, 36310 Vigo, Pontevedra, Spain

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**ABSTRACT**

Thin stone wall cladding systems used on exterior building envelopes typically consist of stone panels made of granite. There is a risk of detachment if the cement used to stack the panels is defective. There is a wide range of destructive techniques to evaluate the state of the facades, but they are scarcely practical. Infrared thermography (IRT) offers a cost-effective alternative to traditional evaluation. The sizes and shapes of the defects detected by this methodology in the cement holding the panels are presented in order to evaluate the capacity of the aforementioned technique.

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**1. Introduction**

Building envelopes are designed to provide certain indoor conditions, protect the interior from the outside and give the building its external appearance. There is a wide range of finishes for constructing the building envelope using panels of diverse materials in many different shapes.

The attachment of cladding elements has been evolving and today three types of joints are widely employed, two of which are shown in Fig. 1.

1. **Anchor bolts**: Stainless steel screws that are inserted into a hole provided on the edge of the panel.
2. **Buried joints**: They fix the panel by introducing a tab in a groove made in the edge of the panel.
3. **Visible joints**: Plate that embraces the entire thickness of the panel.

The gaps between panels should be wide enough to absorb both the thermal expansion and the possible differential movements of the panels. 3/8 in. wide gaps are typically used. These joints are most commonly filled with a pliable sealant and they are the main line of protection against water penetrating into the wall cavity.

One of the more interesting recent developments in this industry has been the “ultra-thin” stone panels in commercial construction. Although this technology has been developed over the past 25 years, ultra-thin stone panel systems have become an increasingly popular alternative for facade applications on both residential and commercial buildings.

However, there are a large number of buildings that were built in times of mass development, when the facade panels were simply stuck to the walls of the building. These buildings require periodic inspections to evaluate existing conditions and discover deficiencies in order to arrange restoration to prevent catastrophic failure.

There are certain techniques, such as the visual inspection or destructive testing of some building elements, where results can be extrapolated to assess the risk of detachment of the panels. The whole surface of the facade should be accessible to examine it properly and this implies the installation of temporary structures, such as scaffolding, or the use of hazardous techniques, such as climbing. If the building is listed as having historic or artistic value, destructive techniques are not applicable because of the irreparable damage involved.

Accordingly, a new non-destructive technique based on infrared thermography (IRT) is employed to facilitate the inspection and reduce its costs. The thermal inspection of buildings is based on determining the temperature differences on surfaces that should present a regular profile. It is defined in ISO 18434–1 as a methodology that analyses patterns and thermal profiles to detect and...
Fig. 1. Types of joints. Anchor bolts are shown on the left and visible joints on the right.

Table 1
Properties of the materials employed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Thermal conductivity (W m⁻¹ K⁻¹)</th>
<th>Density (kg m⁻³)</th>
<th>Specific heat (J kg⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extruded polystyrene (XPS)</td>
<td>60</td>
<td>0.033</td>
<td>2000</td>
<td>1050</td>
</tr>
<tr>
<td>Brick</td>
<td>115</td>
<td>0.490</td>
<td>1200</td>
<td>840</td>
</tr>
<tr>
<td>Cement-mortar coating</td>
<td>20</td>
<td>1.400</td>
<td>33</td>
<td>1210</td>
</tr>
<tr>
<td>Granite</td>
<td>30 (20*)</td>
<td>3.500</td>
<td>2700</td>
<td>800</td>
</tr>
</tbody>
</table>

* Model #1.

Fig. 2. Scheme and images of the experimental models.

Fig. 3. Sketch of model #1 and image of the studied surface with the induced defects.
evaluate thermal anomalies. This technique has been successfully applied in a number of diverse areas as described in [1].

Infrared cameras transform the thermal energy radiated from objects in the infrared band of the electromagnetic spectrum into a visible image where each energy level is represented by a colour, or grey level. Objects emit energy proportional to their surface temperature, so the energy actually detected depends on the emissivity of the surface under measurement and on the environment. In fact, a fraction may be either absorbed by the atmosphere between the object and the camera, or added as reflected by the surface from the surroundings. Typically, the temperature distribution on the studied surface is recorded at the time of maximum contrast to maximize the detection of any defects [2].

Therefore, the key condition for a thermographic inspection of a building is the existence of a given thermal gradient [3]. The presence of internal defects affects the propagation of heat and causes thermal breakage, producing local temperature differences on the surface [4–6] which are captured on a thermal map by an infrared camera.

If applied to construction, certain building flaws, such as air leakages, thermal bridges, abnormally moist spots, heat loss through windows and other hidden irregularities [7–9], can be detected. Infrared thermography and other non-destructive techniques, such as Fibre Optics Microscopy or Digital Image Processing, have also been used by Moropoulou et al. [10] to assess and evaluate the weathering damage to the fortress in the medieval city of Rhodes. Meola et al. [11] presented a multidisciplinary and multi-methodological approach to evaluate architectural structures

Table 2
Average temperature and corrected emissivity of the reference zones.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Average temperature (°C)</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI2</td>
<td>46.9</td>
<td>0.95</td>
</tr>
<tr>
<td>CSD2</td>
<td>47.0</td>
<td>0.95</td>
</tr>
<tr>
<td>CID2</td>
<td>46.4</td>
<td>0.95</td>
</tr>
<tr>
<td>CG2</td>
<td>46.7 (46.4)</td>
<td>0.94 (0.95)</td>
</tr>
</tbody>
</table>
Fig. 7. Photo and thermogram to determine stone emissivity.

Fig. 8. Thermogram and profile of temperature in the line Li1.

Fig. 9. Model #1. Thermogram and temperature profiles with a thermal gradient of 23 °C.

Fig. 10. Model #2. Thermogram and temperature profile with a thermal gradient of 14.9 °C.
applying non-destructive tools such as infrared thermography, ultrasonic and electric-type micro-geophysical methods. Experimental tests were carried out in a laboratory, where several building materials were analysed with the aforementioned techniques. In addition, thermography was used for the inspection of the status of tiles covering the walls of a building.

This paper discusses the feasibility of using IRT to inspect facades. Two laboratory scale models reproducing a real building envelope were configured using stone panels of different thicknesses stacked directly on the wall with concrete. A number of defects of different shapes and sizes were applied to the concrete film. The experiments involved determining the type of defect that is detectable in the wall surface under certain thermal conditions.

2. Experimental

Two experimental models were set up to simulate facade behaviour under controlled conditions. These models served to evaluate the efficiency of the IRT as a non-destructive inspection technique applied to stone panels. Tests were performed in a laboratory using the FLIR thermography system with its software package.

The models are cubes with 1.2 m edge length. All the cube faces are closed with the exception of the rear one, which allows accessing the interior to carry out sundry maintenance and setup operations. The front face has a typical facade cladding configuration with a stone panel to simulate the desired thermal conditions in a dwelling. The other faces are made of extruded polystyrene. The stone panels are 20 mm and 30 mm thick, as is normally the case on buildings. The properties of the materials used are listed in Table 1.

There is a wide range of stone types and surface finishes depending on both the area and the supplier. In this work, standard granite from the Spanish region of Galicia was selected because it is one of the most widely used in building. To minimize edge effects, six rectangular panels of albero granite, with dimensions of 0.4 m width by 0.6 m height, were arranged vertically. The visible surface has a bush hammered finish.

A typical wall was built to hold the stone panels. The wall consists of double hollow bricks (thickness 115 mm) and a layer of mortar where a series of faults of diverse size and shape were introduced to simulate a lack of adherence. A scheme and images of the experimental configurations are shown in Fig. 2.

Stone panels of 30 mm thickness were used in model #1. The capacity of the studied method to detect defects of different sizes and shapes was tested. Standard E1213-92 [ASTM, 1213] served as reference to define the defects. The position of the imperfections and their main dimensions are shown in Fig. 3. The edges of the panels are depicted by continuous lines in the sketch view.

Model #2 is clad with 20 mm stone panels. In this case, more defects were created in the cement-mortar layer as shown in Fig. 4. The size of the circular faults has been increased because heat transfer by conduction in the panel was found to prevail over the temperature difference caused by the fault. The size of rectangular faults was increased for the same reason. The main dimensions of the faults and their situation are shown in Fig. 4. Two square defects were added in these zones in order to study possible edge effects in the proximity of the panel joints. One side of the defect coincides with an edge on the panel.

Once the models had been built, temperature sensors were inserted in different parts of each model, placing four on the outer wall of the stone panels, four on the inner wall of bricks and two more to measure ambient temperature in the laboratory and tem-
were conducted with thermal gradients defined in reference to the mer, although this was of no relevance because the experiments inspection.

and a minimum difference of 10 K is required for a reliable thermal inspections on buildings. To analyse the problem under steady-
ation was controlled by a thermostat that regulated the desired tested by controlling the thermal gradient.

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infrared camera and body[12].

surface and the infrared emission of the atmosphere layer between emitted, the surrounding infrared radiation reflected on the body surface is always composed of three fractions: the body radi-

ation close to the blackbody. The apparent surface temperature will depend directly on its emissivity. Most common building materials, except can range between 0 (perfect reflector – mirror) and 1 (perfect emitter – blackbody). The apparent surface temperature will depend directly on its emissivity. Most common building materials, except metals, have high emissivity values (usually higher than 0.8), allowing the direct measurement of temperature by the infrared camera.

Reliable results from thermography can be obtained only if the emissivity of the inspected object is known. The emissivity of different materials under various circumstances has been published [12]; however, emissivity is not a constant, since it depends on temperature [13], amongst other factors, as well as on the inclination angle between the object and the infrared camera.

Infrared radiation received by an infrared sensor from a heated body surface is always composed of three fractions: the body radiation emitted, the surrounding infrared radiation reflected on the surface and the infrared emission of the atmosphere layer between infrared camera and body [12].

Thus, various tests were conducted in the laboratory using granite stones with exactly the same specifications, which is remarkable as surface composition varies widely depending on the content of quartz, mica and feldspar and a rough surface finish. The emissivity of the stone is determined according to data on a body of known emissivity close to the blackbody.

The procedure consisted in placing contrast tape in various areas on the granite stone, marked with small boxes on the study area, Fig. 7, proceeding then to the heating of the piece in an oven for different periods of time to temperatures of more than 20 °C above room temperature, so that the stone acquired uniform thermal characteristics. Based on the average temperature of the box, above the centre of the piece to avoid edge effects, we determined the emissivity of the stone by equalizing the temperature of that area with temperatures in the areas of known emissivity (small boxes).

As the piece cooled, sequences of infrared images were obtained, which adjusted the emissivity of the largest stone in the box so that its temperature had a value equal to areas of known emissivity. The last row in Table 2 shows both the value corrected for temperature and the emissivity sought, and in brackets the uncorrected baseline. By analysing the results recorded in different cases, it was established that the emissivity of the stone is 0.94, consistent with the values obtained by other authors [13–16].

3. Determination of emissivity

The radiated energy registered by the infrared camera not only depends on the object temperature but also on emissivity. The optical properties of a body are characterized by the emissivity that compares the amount of energy emitted with the energy emitted by an ideal blackbody at the same temperature. Values for emissivity can range between 0 (perfect reflector – mirror) and 1 (perfect emitter – blackbody). The apparent surface temperature will depend directly on its emissivity. Most common building materials, except metals, have high emissivity values (usually higher than 0.8), allowing the direct measurement of temperature by the infrared camera.

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4. Thermographic analysis (results)

The thermographic analysis of the two models consisted in tuning the thermal adjustment of the thermograms and the variation in the colour palettes or employing various tools, such as temperature profiles or isotherms, to detect the defects created under the panel. In addition, the influence of other aspects, such as the apparent temperature reflected in the laboratory, although admittedly a scarcely significant parameter, has been analysed.

Fig. 8 shows a thermogram of model #1 and the temperature profile of the line L1 that crosses the higher defect with a tempera-
ture difference of 16.3 °C between the inside and outside of the panel. The profile shows three sharp falls that represent the temperature of the wires that connect the temperature sensors used to set the temperature difference and compare the results. A slight drop in temperature of approximately 0.7 °C is found on the surface of the wall where the higher circular defect was created. IRT is able to identify a defect under a 30 mm stone panel.

Experiments with internal heating revealed that areas with defects in the concrete layer have a lower temperature than the surrounding areas, which shows that heat transfer by conduction through the wall is different depending on whether an area is defective or not. In defective zones, air acts as an insulating layer and hinders heat transfer through the wall.

The circular defect in model #1 is detected in Fig. 9. The thermal gradient between the inner and outer surface was set at 23 °C. Two profiles are shown in detail B in the figure; they plot the tempera-
ture profile in a line that crosses the defect (L1) and the profile with no defects (L2). Both profiles have a similar behaviour, with small oscillations due to the heterogeneous composition of the granite panel. The temperature difference of about 1 °C is a result of the defect created. Under these thermal conditions, IRT detects a difference of temperature that is slightly higher than that found with a lower thermal gradient. However, there is no presence of the smaller circular defect. This gives an idea of the minimum size of the defects detectable by IRT.

The thermogram for a thermal gradient of 14.9 °C is presented in Fig. 10. Model #2 has a thinner stone panel and defects are detected more clearly. The chart in Fig. 10 presents two steep valleys caused by the probe wires. A broad valley caused by the square defect is marked on the left, where the temperature variation is 0.6 °C. The smallest circular defect is detected (marked on the right), but the temperature variation is smaller. If the thermal gradient is reduced to 10.1 °C (Fig. 11), the defects created in the mortar with stone panels of 20 mm are detected with a difference in the vicinity of 0.4 °C.

The effect of solar radiation on a facade should be studied when conducting a thermographic inspection of a building [17]. Fig. 12 shows a thermogram when the hot air generator was disconnected to evaluate the effect of solar radiation separately. In the thermo-
gram, colours are inverted if compared to previous images because the heat flux now passes from the outer to the inner surface of the wall. Defective zones have higher temperatures than others because they offer resistance to the heat flux that crosses the wall.

The temperature profile shown in Fig. 12 indicates that solar radiation has a thermal gradient of 0.3 °C, implying that the effect of solar radiation is perceptible and must be taken into account during the analysis. This finding confirms that solar radiation should be avoided when inspecting a facade, which is consistent with the recommendations contained in European Standard EN13187.

5. Conclusions

This paper used infrared thermography to identify defects in the concrete used to stack the stone panels. Albero granite was chosen
as it is a common building material in numerous parts of Spain because of its aesthetic and thermal properties.

Infrared thermography has proven to be a suitable non-destructive technique for identifying defects in the cement wash on a wall. This allows using it as a working tool to inspect defects in a wall, such as the lack of adherence of the stone panels forming the envelope on a building.

IRT has been found to have its limitations for identifying wall defects. When dealing with panels of 20 mm thickness and with a difference of 10 °C between the inside and outside surfaces, the methodology employed can locate defects of 90 mm in diameter. The thinner the panels are, the more efficient this technique is at identifying attachment defects. This procedure provides reliable results when the panels are thinner than 30 mm.

Standards for accepting or rejecting the inspected panels can be established thanks to the new methodology presented. Conditions are also established for creating databases with the temporal evolution of the building's thermographic analysis.

Preventive maintenance with IRT should avoid uncontrolled panels falling from facades due to the poor application of the cement wash or a loss of its stacking properties in the cases studied in this work. Facade inspections can be conducted without mounting auxiliary structures to access the entire surface of the inspected building.

Inverted temperature maps are obtained if the facade is exposed to direct solar radiation because heat transfer occurs from the outside to the inside. Temperature differences from indoors to outdoors are required to be as high as possible to obtain consistent results from the IRT analyses. Early in the morning or late at night, when the temperature outdoors is lower, are the preferred periods of the day and when there is little chance of direct solar radiation on the facade during the inspections.

References