

The Application of Thermal Imaging as a Nondestructive Test in Historic Buildings

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ABSTRACT

Thermal imaging -or infrared thermography- is the use of infrared imaging camera to show and determine the surface temperature via measuring the thermal energy emitted from an object. Thermal imaging is a nondestructive test. The structures of historic buildings commonly exhibit performance problems that are basically appeared during different construction and maintenance phases in numerous years of their existence. These problems can impact comfort conditions, building energy performance and structural integrity.

Regardless of building type, thermal imaging can provide remarkable information about the historic buildings including;

- Validation of structural details,
- Location of thermal bridges and insulation failures,
- Location of air leakage,
- Location of moisture intrusion,
- Location of condensation in the building envelope,
- Identification of structural, mechanical and electrical degradation and aging infrastructure.

In this article, numerous useful applications of thermal imaging technology for inspection of the historic building envelopes have been studied. Also considerations, requirements and related inspection methods for historic buildings are being surveyed.

KEYWORDS

Thermal imaging, Infrared, Emissivity, Historic Buildings, Thermal Bridge, Moisture, Air leakage.

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1 INTRODUCTION

Building structures commonly exhibit quality and performance problems caused during construction and maintenance that can impact energy performance and, in some cases, render them dangerous. Regardless of the building type involved, infrared imaging has been shown to provide details in building performance.

The application of infrared thermography is to assess building envelope anomalies⁴ in historic buildings. However, infrared thermography alone will not identify the cause and source of any given anomaly nor does it quantify the depth and intensity of the cause or damage. In fact, proper interpretation based on a thorough assessment of the building is necessary for the inspectors to understand the nature of anomalies and suggest the sequence of resolving them. Normally, in historic buildings, the cause or source of the problem must be unwound first to result in resolved anomalies.

According to Sharon C. Park [1996], 'hidden construction problems that significantly reduce energy efficiency and the integrity and performance of the building envelope include condensation and mold growth inside building envelope elements, insulation damage, rot and corrosion in structure, frozen pipes in mechanical systems and failure of critical electrical components.'⁵

The scope of this study is to provide an increased level of knowledge to the historic building experts for an improved awareness of the benefits and limitations of using infrared thermography for inspecting serious anomalies of a historic building.

1.1 History of Thermal Imaging

According to Chris Linville [2002], 'Sir William Herschel discovered infrared radiation in 1800. His son, Sir John Herschel, more interested in photography, managed to record the heating rays on the infrared side of the spectrum. He termed this image a thermogram.'⁶ This laid the foundation for the sophisticated thermal imaging devices.

Today, heat sensed by an infrared camera can be very precisely quantified, or measured, allowing us to not only monitor thermal performance, but also identify and evaluate the relative severity of heat-related problems. Recent innovations, particularly detector technology, the incorporation of built-in visual imaging, automatic functionality and infrared software development deliver more cost-effective thermal analysis solutions than ever before.

1.2 Basics of Thermal Imaging

As a physics law, heat flows from a higher temperature zone (or body) to a lower temperature one. Such heat flow can take place in three forms of conduction, convection and radiation. According to S. V. Szokolay [2008], 'Radiation transpires from a body with a warmer surface to another, which is cooler. Thermal radiation is a wavelength band of electromagnetic radiation, normally taken as 700–10000 nm (10 μ m). 'Short infrared' is between 700–2300 nm (2.3 μ m) while 'Long infrared' represents the wavelength between 2.3–10 μ m (some suggest up to 70 μ m). The temperature of the emitting body determines the wavelength.'⁷ According to energy efficiency fact sheet, 'Emissivity is a material property, an efficiency factor that varies between 0-1.0, correction factor. For different materials, emissivity amount defines Blackbody ($\epsilon = 1.0$), Real body ($\epsilon < 0.1$) and Perfect reflector

⁴ John R. Kominsky et al., "A *thermal anomaly* is defined as a thermal pattern of a surface that varies from a uniform color or tone when viewed with an infrared imaging system."

⁵ Sharon C. Park, AIA, 'Controlling Unwanted Moisture in Historic Buildings', Washington, 1996.

⁶ Chris Linville, Thermography has become an invaluable asset for insulation energy audit, 2002.

⁷ S. V. Szokolay, 'Introduction to architectural science: the basis of sustainable design', 2008.

($\varepsilon=0.0$).⁸ High emissivity include non-shiny surfaces, while low emissivity surfaces pertians to high thermal reflection in materials. Emissivity can change according to material, surface, wavelength and temperature while emittance changes with Angle of view.

2 THERMAL IMAGING

Thermography is the use of an infrared imaging and measurement camera to show and measure thermal energy emitted from an object. According to John R. Kominsky et all [1998]; 'In thermography, infrared imaging system (an infrared camera) converts the spatial variations in infrared radiance from a surface into a two-dimensional image, in which variations in radiance are displayed as a range of colors or tones. As a general rule, objects in the image that are lighter in color are warmer and darker objects are cooler. Pertaining to the thermal imagery of building envelopes, the atmosphere (in most cases) is considered transparent in the spectral bands of interest where absorption is limited to 3 to 5 μm (short waves) or in the 8 to 12 μm (long waves). The image is viewed through the eyepiece of a video scanner and can be recorded on videotape.'⁹

Maximizing the difference between the inside air temperature and the outside air temperature provides the greatest contrast between the hot and cold areas on the video image. Therefore, process equipment should be heated or cooled for testing if their normal operation does not provide an adequate temperature difference.

2.1 Infrared Thermal Imager

Infrared cameras for building applications are available in a wide variety of models and price ranges. Apart from using the proper camera and lens for a given application, the qualifications of the person operating the camera and performing the inspection is the most determining factor in obtaining an accurate assessment of the performance of the building envelope. Skilled interpretation can diagnose problems that affect the surface temperature. Most materials are opaque to infrared so items behind covers or doors are only detectable if they are so hot and so close as to transmit heat onto a clearly defined part of the cover. An excellent camera used with the wrong settings and under inappropriate environmental conditions will ultimately yield misleading and inaccurate results. Reporting results based on an inaccurate assessment will have an important impact on the subsequent decision making process. As a consequence, the wrong decision making may end in needless recommendations concerning building anomalies or it might result in important problems being overlooked.

2.2 Thermal Imaging Regulations and Conditions

In most cases, sample thermal images must be taken to demonstrate the majority of areas with anomalies or defects as well as the parts of the building with no anomalies, which demonstrate the correct functioning of building components.

Thermal images should be taken as close to perpendicular to the investigating surfaces as possible. Area and location of surfaces obscured by mirrors, metal, reflective tile or other low emissivity coverings might affect interpretation. Therefore, it is recommended that the images being taken in different angles.

Precipitation in the form of rain or snow will create an obstacle between the infrared camera and the exterior surfaces being inspected and this includes mist and fog. 'According to The minimum temperature criterion for satisfactory thermal conditions for an inside to outside temperature

⁸ Energy Efficiency Fact Sheet, 'Principles of Heat Transfer', Washington University, 2008.

⁹ John R. Kominsky et al., "A *thermal anomaly* is defined as a thermal pattern of a surface that varies from a uniform color or tone when viewed with an infrared imaging system."

difference of the wall surfaces is at least 10°C for a period of 24 hours. (Ref: ISO 6781, 5.1, a. recommends 10°C for a period of 24 hours.¹⁰

Investigation of any anomalies is done through physical examination of the building details, moisture meters, surface temperature devices, air exhaust devices and experience of the investigator. Exterior surfaces should be dry and surfaces should not be heated by direct solar radiation for a period of approximately 3 hours for frame construction and for approximately 8 hours for masonry veneer construction. Also exterior investigations should be planned for an appropriate time after sunset, before sunrise, or on an overcast day when the influence of solar radiation can be determined to be minimal. Standards suggest that wind speed should be less than 3.6 m/s.¹¹ It is necessary to mention that interior investigations can also be influenced by wind, sun, sky condition and moist exterior surfaces. These influences typically lag the more direct exterior influence depending on conditions and structure type.

As a case study, David house¹² has been chosen for structural and thermal investigations through infrared thermal imaging. The building envelope in David house consists of adobe structure and clay façade. In some parts, the clay façade has been replaced by brick. There are several openings in building envelope.

In thermography in David historic house the environmental conditions have been considered before thermal imaging. The best time for thermal imaging in order to detect airleakage, thermal bridges and insulation degradation is the coldest hours of the day and night that is before dusk. Thermography of David historic building was done on 10th december 2009. while the astronomical dusk was 5:18¹³, taking thermal images finished at 6:45 (Before sunrise). The wind speed on different hours of 10th december is presented in Figure 1.

The temperatures inside and outside the building were 18°C and 7°C respectively. Figure 2 indicates the temperature of the outside of the building on 10th december 2009. also Meteorological reports indicate that the sky was partly cloudy on 10th december 2009. but no perticipation or mist was reported on the specific day.

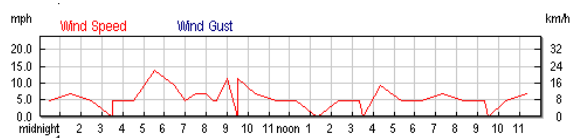


Figure 1. Wind direction and speed on December 10th 2009- Isfahan, Iran. (Source: Iran Meteorological Organization).

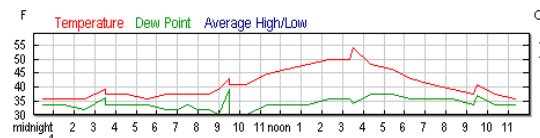


Figure 2. Hourly temperature on December 10th 2009- Isfahan, Iran. (Source: Iran Meteorological Organization)

3 THERMAL IMAGING IN BUILDINGS

Regardless of building type, thermal imaging can provide remarkable, nondestructive information about the historic buildings that facilitate the inspection and further maintenance phases.

3.1 Validation of Structural Details

In a well-insulated wall, the framing may not be as obvious; However, darker lines stemmed from thermal bridges may exist where two or more surfaces, such as wall-ceiling, wall-wall and at corners,

¹⁰ Resnet Interim Guidelines for Thermographic Inspections of Buildings [2010] state: "a minimum of 3/U degrees"; for example, 6 K for a U value of 0.5 W/m²K.

¹¹ Resnet Interim Guidelines for Thermographic Inspections of Buildings, 2010.

¹² David house is a historic residential building that is built in Isfahan, Iran more than 150 years ago. Today, this building is being used by Isfahan University of Art, Faculty of architectural conservation.

¹³ Iran Meteorological Organization, <http://www.irimo.ir/english/index.asp>.

meet. The success of a survey depends on understanding the construction under inspection. Also Construction drawings should be reviewed as part of the survey procedure. The construction details of specific areas can help to explain any identified weaknesses. Where no drawings are available, the operators must familiarize themselves with the building type and construction.

While construction drawings help in determining the nature of the problems highlighted by a survey, it is always best to undertake a visual inspection of the areas affected, as variation from design is not uncommon. Some examples of structural validation include grouted cells with re-bar in block walls, structural elements in poured wall, subsurface details in historic buildings.

3.2 Location of thermal bridges and insulation failures

Moisture in the insulation substantially reduces its R-value and increases heating and cooling costs. Wet insulation absorbs more solar gain during the day and it releases more stored solar heat during the night. Heat flux sensing equipment or calorimetry using a ‘hot box’ can be used to monitor heat flow across a building element over a period of time.

In David house, as case study, the building envelope has been checked for thermal bridges and insulation failure. By the date of David house development, thermal insulation was not conventional. Therefore, the building envelope does not consist thermal insulation. The thickness of adobe walls in David house vary from 60cm to 150cm and provide time lag in heat flow through building envelope. Figure 3 represents thermal time lag difference in concrete, clay brick and adobe walls. In Figure 4 attenuation of exterior/interior temperature variation, for different thickness of concrete, clay brick and adobe walls is represented. Considering these results, the thermal time lag becomes meaningless when the thickness is more than 50 cm, because temperature variation decreases more than 95 %.

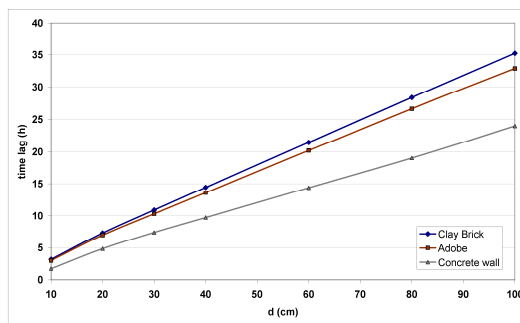


Figure 3. Time lag for clay brick, adobe and concrete walls.

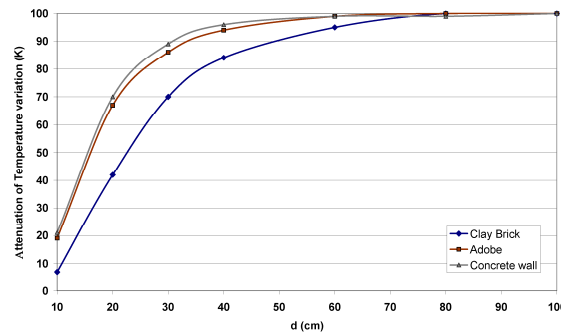


Figure 4. Relative temperature attenuation of clay brick, adobe and concrete walls.

3.3 Inspection of building insulation and envelope for thermal bridging

Anomalies in building envelope usually pertain to problems with insulation system or defects in envelope that cause thermal bypasses to occur. Incomplete or discontinuous insulation in walls cause large amounts of thermal loss in the buildings and decrease thermal comfort for the occupants. Thermography can assist building inspectors to identify insulation failures and thermal bypasses. Before any application regarding thermography, the insulation type and construction details of the buildings should be detected and documented. Also the best inspection is done from both inside and outside.

As mentioned before, thermal imaging for inspection of defects in insulation and building envelope is a qualitative method. Quantifying the results in technical reports, include thermal lag of the envelope that is measured through thermometers installed on the sides of the wall to quantify the thermal resistance, transmittance and inertia of the building envelope components.

In the case study, the building envelope in David house includes adobe walls with brick facades in some parts. Also there are several opening in the building envelope. These openings are mostly woodframed windows with a single glazed glass or wooden doors with loose conjunctions with the rest of the envelope.

Thermography of David house indicates that the most important thermal bridges of the envelope were single glazed windows. Figure 5 and Figure 6 Show thermal bridges in David house. The red parts in the windows represent thermal loss through single glazed windows, which are considered as thermal bridges. In order to resolve thermal defects through windows, their glasses should be double glazed or another frame should be added in front of the old window from inside or outside the envelope. The decision making on double glazing the existing window or adding another frame depends on the structure of window in terms of bearing the load of a new material and historic preservation theories.

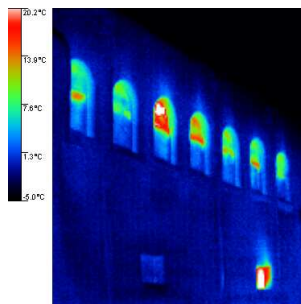


Figure 5. Thermal bridges in thermal images of David house, Isfahan, Iran.

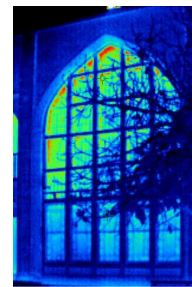


Figure 6. Thermal bridges in thermal images of David house, Isfahan, Iran.

3.4 Location of Air Leakage

Apart from thermal discomfort for occupants and thermal loss from the building, air leakage is usually rainwater ingress pathways too. Therefore, it is necessary to spot the thermal bypasses in the building envelope to stop rainwater ingress along with unwanted ventilation.

IR is an important tool for quickly finding the highest impact air leakage locations in existing buildings. Because air leakage sites may be difficult to locate under natural conditions, air must be artificially forced across the building enclosure by use of a fan such as a blower door or by using the mechanical and/or ventilation system(s) in the building. Building depressurization and inside inspection are preferred because of less interference of solar radiation and wind. The outside air is at a different temperature than the inside air and will therefore leave a thermal signature for the infrared imaging system to capture. The thermal image for air leakage will appear as “fingers” or “streaking” showing as dark when cold air is observed and lighter colors when warm air is viewed.

The thermal images will produce irregular shapes with uneven boundaries and large temperature variations. These air leakage sites are often at joints, junctions or penetrations in the enclosure. There is often a temperature gradient within a finger or streaking area. A scan of all interior surfaces may reveal indications of significant air leakage in locations not imagined as connected to the exterior. Discrimination between thermal bridging sites and thermal bypass or air leakage sites should be done by sufficient accuracy. Thermal bridging sites will not change size or shape during the inspection. Also the inspection should be done from both sides to make sure that all the points of infiltration and exfiltration have been detected. Infiltrating cold air itself cannot be seen; however, infiltration can be located because the materials and surfaces that are washed by the cold air flowing through or past them are cooler. Moving air patterns are normally not well defined and are irregular in shape. Fan shaped patterns or semicircular dark areas originating along seams or penetrations reveal the location of holes or linear cracks.

Quantifying the results of thermography need de/pressurization of the building that is done by Blower door fans, Household exhaust fans and HVAC systems. The extent or a gradation in the contrast typically indicates the direction of flow to the thermographer. Endoscopes (or borescopes) allow visual inspection, through a small hole, of gaps in insulation and air leakage pathways.

In David house, locations of air leakage in building envelope are mostly loos conjunctions between openings and the rest fo envelope. Figure 7 shows the heat loss from top of the wooden doors through their conjunction. In most cases, in historic buildings, the loos conjunction occurs when the framing materials have lost their initial shape. In most cases, airleakage problems are solved through repairing the framing parts for giving them their initial shape and injection of some materials such as polystyrene foams in their gaps.

3.5 Location of Moisture

Moisture in building materials can destroy structural integrity and nurture mold. The first step in moisture problem remediation is to locate and remove all sources of moisture quickly and accurately. On the other hand, as liquids evaporate, they draw heat energy from their surroundings. Therefore, damp surfaces will typically be cooler. Thermography can identify surface temperature variations of the building envelope, which can indicate problems in a building's moisture content.

Water leakage is the number one cause of damaged insulation and substrate, corrosion and weakening of metal decks and building structure, even structural collapse and the growth of mold. Infrared thermography locates moisture anomalies in building envelopes by exploiting the thermal properties of water. The greater the specific heat¹⁴, the more energy is required to heat or cool a particular material. Consequently, water looses or gains heat much slower than wood or brick under similar conditions¹⁵. Because the heat capacity of a water-damaged material is greater than that of a dry material and air, areas of high-moisture content appear either warmer or colder than the surrounding infrastructure. The difference in temperature can be imaged and measured using an infrared camera.

In David house the ditected moisture problems mostly stemed from rain water ingress inside the material of the building envelope near the roof. The moisture intrusion was because of defect in draiange system on the roof. Figure 8 Represents the moisture problems in David house.

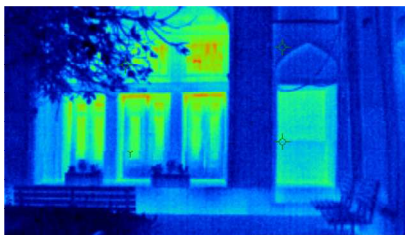


Figure 7. Heat loss from wooden doors through their conjunction, David house, Isfahan, Iran.

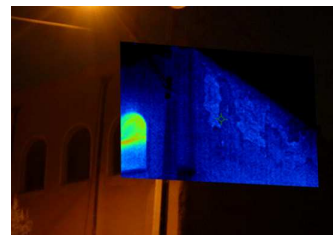


Figure 8. Moisture problems in David house, Isfahan, Iran.

A hand-held moisture meter can be very useful in diagnosing thermal anomalies. Masonry walls are often found to have variable moisture contents leading to thermal patterns not directly related to insulation placement. According to Resnet Interim Guidelines for Thermographic Inspections of Buildings [2010] 'Wet thermal insulation will also give thermal anomalies and can be confirmed with a moisture meter. It is worthy to remind that prior to the moisture inspection in structures, no precipitation should be occurred for at least 24 hours'.¹⁶ The location of condensation in the building envelope appears to be the same method for moisture inspection.

¹⁴ Specific heat is the amount of heat required to raise the unit mass of material one unit of temperature

¹⁵ For example, water has a higher specific heat ($4,180 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$) than pine ($2,800 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$) used as framing lumber or common building brick ($840 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$).

¹⁶ Resnet Interim Guidelines for Thermographic Inspections of Buildings, 2010.

3.6 Identification of Structural, Electrical and Mechanical Degradation

Structural degradation

Aging in buildings may cause the occurrence of wood rot, metal corrosion, staining of bricks and concrete. Any of the mentioned anomalies are traceable through thermal imaging. The rotten parts of wooden structure may seem lost or partly absent in thermal imaging. Also the biological activities of bacteria and fungus cause the rotten parts of wood to present different thermal patterns in structure. Corroded metal have different surface properties, such as emittance and reflectance, comparing to normal parts of the structure. Chemically stained concrete parts and bricks also exhibit different behavior in thermal imaging that stems from the change in their surface properties. Consequently, their patterns differ in thermal imaging. Detection of cracks in concrete structures is possible through thermal imaging since the cracks appear as thermal bypasses in structure and stand out.

Electrical degradation

IR inspections of electrical installations can be used to locate both loose and corroded connections before they cause a catastrophic failure or serious damage, with a possible serious impact on the connected equipment or even become a fire hazard and endanger the life of occupants and technical personnel.

Mechanical inspection

IR inspections of mechanical equipment can be used to identify sediment in boilers and tanks. In other cases boilers with missing and damaged insulation resulting to increased heat losses and energy costs may be inspected in building mechanical system. Overhanging motors have a shorter life span and a lower efficiency since it takes a lot of extra energy to produce that much heat. Thermography can also be used on mechanical plant such as pumps, compressors, fans, motors and coils.

Difficult to access HVAC installations can be inspected. For example, IR imaging can be used to distinguish air supply and exhaust outlets from hard to reach ceiling diffusers and determine their operational status. It is also possible to locate and trace hot and cold pipes inside building elements (i.e. floor piping in water heating systems), to identify the loops and minimize the guesswork when there is a need to replace them, to check for heat losses as a result of poorly insulated pipes and ducts, etc.

Finding boiler refractory or insulation breakdown, blocked cast iron sections, scale buildup, hot gas leaks and furnace tube blockages also can pay dividends in energy conservation, save countless maintenance hours and prevent boiler failure. Accurately detecting refrigeration and air conditioning air leaks, energy loss, heat exchanger, refrigerator and air conditioning efficiency and clogged condenser/heat exchanger tubes, will prevent inefficient operation and wasted energy.

4 THERMOGRAPHY RESULTS

The results of the scan can be subtle and customarily require the interpretation of the experienced thermographer. After reviewing the scan, a visual site inspection of problem areas, and a review of photos and detail drawings may be necessary to understand how the building envelope is constructed and to completely understand the causes of its problems. In some cases, other types of testing will be used to corroborate or pinpoint air leakage sites in remote locations. This may include the necessity of opening critical parts of the building envelope so that they can be visually inspected.

5 INFRARED MEASUREMENT PROBLEMS

Infrared thermography alone will not identify the cause and source of any given anomaly, nor does it quantify the depth and intensity of the cause or damage. Also thermal images can be difficult to interpret accurately when based upon certain objects, specifically objects with erratic temperatures; However, this problem is reduced in active thermal imaging. Accurate temperature measurements are

hindered by differing emissivities and reflections from other surfaces. Most of thermal imaging cameras are not as accurate as contact methods also they are only able to directly detect surface temperatures.

6 CONCLUSION

Thermography of David house indicates anomalies in building envelope that are mostly because of the age of building and lack of maintenance during recent years. The most intense problems are considered as heat loss through thermal bridges and thermal bypasses. Since building anomalies may show up in a building from time to time, it is better to check the building by thermal imaging more frequently. Therefore, building anomalies are detected while it is not too late for further actions.

Thermography of David house revealed thermal and moisture problems, however; building investigation could be more accurate if it could be accompanied by quantitative methods such as heat flux sensing, moisture meter and blower door. Furthermore, more resolution of thermal imager could yield in sharper images and consequently more accurate inspection and interpretation.

The investigation about the existing condition of David house has put into evidence few problems related to thermal bridges and moisture infiltration. It is obvious that in any rehabilitation action, the existing problems of the envelope must be taken into consideration, and the monitoring of the building after rehabilitation must be performed, for documentation and controlling the effectiveness of improvement actions.

The investigations demonstrate that qualitative infrared thermography coupled with an informed visual inspection and quantitative substantiation is an effective protocol to detect building anomalies. Infrared thermography provides a means of seeing the invisible thermal signatures that are related to many building enclosure problems and conditions.

Infrared thermography is a useful and effective tool for the detection of thermal and moisture anomalies in building envelope systems. Also structural, electrical and mechanical degradation are detected through this method in buildings. Although different complexities of building during construction and performance can be detected by thermal imaging, considerable care must be exercised in both collection and interpretation of thermographic data.

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