Construction characterization through Thermography

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Dedication

I dedicate this work to my parents, and friends, whose unwavering support, encouragement, and constant motivation have been the driving force throughout my academic journey. Their belief in me has been my greatest source of strength, and it is with immense gratitude that I offer this work as a small token of my appreciation for their endless sacrifices and unconditional love.

Thanks

First and foremost, I would like to express my sincere gratitude to my professor Christina Calmeiro and supervisor for her invaluable guidance, continuous support, and constructive feedback throughout the completion of this Project II work. Her insights and encouragement have been instrumental in shaping the quality and direction of this research.

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Resumo

A termografia infravermelha (TRI) surgiu como um método crítico de ensaios não destrutivos (END) na engenharia civil, oferecendo a capacidade de detetar anomalias subsuperficiais sem danificar a estrutura. A técnica capitaliza a radiação infravermelha emitida naturalmente pelos materiais de construção, que varia com a temperatura da superfície e revela patologias ocultas como delaminação, infiltração de umidade, defeitos de isolamento e ponte térmica. Esta ferramenta de diagnóstico passiva e ativa é particularmente útil na fase de inspeção da reabilitação de edifícios, onde a identificação precoce de falhas pode orientar intervenções rentáveis e minimamente invasivas.

Os recentes avanços na tecnologia IRT, como sensores de alta resolução, imagens térmicas em tempo real e pesquisas baseadas em drones, expandiram sua gama de aplicações. Os pesquisadores implantaram com sucesso termografia passiva e ativa em estudos de caso envolvendo alvenaria histórica, concreto armado, camadas de gesso e estruturas de aço. A análise de sinais termográficos, apoiada por processamento digital de imagens e software especializado, tem permitido avaliações qualitativas e quantitativas da saúde estrutural. Essas ferramentas são fundamentais no mapeamento de distribuições de temperatura, identificação de áreas de perda de energia e localização de patologias não visíveis apenas por inspeção visual. (ThermoElite Inc., n.d.)

Além disso, a integração da TRI com tecnologias complementares, como testes de estanquidade ao ar de portas de ventilador, aprendizado de máquina para classificação de defeitos e BIM (Building Information Modeling), está redefinindo como a infraestrutura é monitorada e mantida. Neste cenário em evolução, a TRI é cada vez mais reconhecida como uma ferramenta fundamental na manutenção preditiva, diagnóstico de desempenho energético e reabilitação sustentável de edifícios. Apesar de limitações como sensibilidade às condições ambientais e pouca profundidade de penetração térmica, a literatura posiciona a termografia como um componente essencial do paradigma da inspeção digital e da infraestrutura inteligente.

Palavras chave

Termografia infravermelha, Ensaios não destrutivos, Monitoramento da integridade estrutural, Diagnóstico de edifícios, Engenharia civil.

Abstract

Infrared Thermography (IRT) has emerged as a critical non-destructive testing (NDT) method in civil engineering, offering the ability to detect subsurface anomalies without damaging the structure. The technique capitalizes on the infrared radiation naturally emitted by building materials, which varies with surface temperature and reveals hidden pathologies such as delamination, moisture infiltration, insulation defects, and thermal bridging. This passive and active diagnostic tool is particularly useful in the inspection phase of building rehabilitation, where early identification of failures can guide cost-effective and minimally invasive interventions. (Meola, 2013; Shrestha et al., 2025) (Wild, 2007; Martins, 2013) (Milovanović & Pečur, 2014)

Recent advances in IRT technology—such as higher-resolution sensors, real-time thermal imaging, and drone-based surveys—have expanded its range of applications. Researchers have successfully deployed both passive and active thermography in case studies involving historic masonry, reinforced concrete, plaster layers, and steel structures. Thermographic signal analysis, supported by digital image processing and specialized software, has enabled both qualitative and quantitative evaluations of structural health. These tools are instrumental in mapping temperature distributions, identifying areas of energy loss, and localizing pathologies not visible through visual inspection alone. (ThermoElite Inc., n.d.)

Moreover, the integration of IRT with complementary technologies—such as blower door tests for airtightness, machine learning for defect classification, and Building Information Modeling (BIM)—is redefining how infrastructure is monitored and maintained. In this evolving landscape, IRT is increasingly recognized as a foundational tool in predictive maintenance, energy performance diagnostics, and sustainable building rehabilitation. Despite limitations such as sensitivity to environmental conditions and shallow thermal penetration depth, the literature positions thermography as an essential component of the digital inspection and smart infrastructure paradigm. (Campbell Property Management, 2024)

Keywords

Infrared Thermography, Non-Destructive Testing, Structural Health Monitoring, Building Diagnostics, Civil Engineering. (Meola, 2013; Shrestha et al., 2025) (Wild, 2007; Martins, 2013)

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Symbol	Description
ε	Emissivity (dimensionless, 0–1)
ΔT	Temperature difference
λ	Thermal conductivity
α	Thermal diffusivity
ρ	Density
c	Specific heat capacity
Q	Heat flux
t	Time
h	Convection heat transfer coefficient
σ	Stefan–Boltzmann constant
T	Temperature (in °C or K depending on context)
Φ	Phase angle (used in phase thermography)
E	Elastic modulus (Young's modulus, for TSA analysis)
σ (lowercase)	Stress (in TSA context)
δ	Delamination depth

List of tables

List of abbreviations, acronyms

Abbreviation	Full Form
IRT	Infrared Thermography
NDT	Non-Destructive Testing
TSA	Thermoelastic Stress Analysis
UAV	Unmanned Aerial Vehicle
GPR	Ground Penetrating Radar
IR	Infrared
RC	Reinforced Concrete
FRP	Fiber Reinforced Polymer
TSR	Thermographic Signal Reconstruction
PCT	Principal Component Thermography
AI	Artificial Intelligence
ML	Machine Learning
R-CNN	Region-based Convolutional Neural Network
FEM	Finite Element Method
MWIR	Mid-Wave Infrared
LWIR	Long-Wave Infrared
ROI	Region of Interest

1. Introduction

1.1 Work Structure

In civil engineering, ensuring the quality, durability and comfort of buildings requires a close monitoring of their behavior over time. As buildings age, pathologies such as moisture infiltration or material degradation may arise, necessitating timely maintenance interventions. To support this, there is a growing need for efficient, real-time inspection methods that minimize disruption and avoid destructive testing.

This study explores the application of infrared thermography as a non-destructive technique to assess building conditions. Thermography allows for the detection of hidden anomalies by capturing surface temperature differences, providing valuable information without altering the structure. Although its origins lie in military use, thermography has gradually gained ground in building construction, especially with advances in camera technology, portability, and affordability. (Meola, 2013; Shrestha et al., 2025)

Initially developed in the 1960s, thermal cameras have evolved significantly, reaching construction diagnosis in the late 20th century. Today, thermography is used in various industries and its potential in building inspection is increasingly recognized. This work is positioned within this context, with the objective of understanding how thermography can support safer and more sustainable construction practices through early detection of defects and preventive maintenance planning.

1.2 Objectives of the work

The main objective of this work is to explore and analyze the application of infrared thermography as an effective tool to diagnose and monitor civil engineering structures. It aims to explain the fundamental principles that govern thermographic imaging and to present how this technique can be used to detect various types of structural and thermal anomalies in buildings and infrastructures. Specific objectives include identifying the advantages of IRT over traditional inspection methods, examining its potential for energy audits and defect detection, and reviewing real-world examples to illustrate practical implementation. A further objective is to evaluate the factors that influence the accuracy and reliability of thermal inspections, including surface conditions, environmental variables, and equipment specifications. Through this study, the work aims to contribute to the understanding and promotion of thermography as a valuable approach for the non-invasive evaluation of construction. (Meola, 2013; Shrestha et al., 2025)

1.3 Methodology

The methodology adopted in this work is based on a qualitative research approach, relying mainly on an extensive review of the technical and academic literature. The information was collected from reliable sources discussing the theoretical and practical aspects of infrared thermography in civil engineering applications. The study begins by examining the physical principles behind infrared radiation, blackbody behavior, and emissivity. It then investigates the classification of thermal imaging techniques, such as passive and active methods, and investigates the specifications and functions of thermal imaging equipment. Case-based examples have been revised to illustrate real-life applications in bridge inspections, building envelope diagnostics, and heritage conservation. By analyzing patterns of thermal behavior, diagnostic accuracy, and inspection results, the methodology aims to build a comprehensive picture of the role of thermography in structural evaluation and performance monitoring. (Meola, 2013; Shrestha et al., 2025)

1.4 Structure of the Work

This document is organized into five main chapters to provide a logical and comprehensive exploration of the topic.

- **Chapter 1** presents the theme, presenting the context, structure, objectives, methodology and structure of the work.
- **Chapter 2** focuses on the theoretical underpinnings of thermography, including the nature of infrared radiation, emissivity, blackbody radiation, relevant physical laws, and the types of thermographic inspections.
- **Chapter 3** discusses the main applications of thermography in civil engineering, such as detecting structural defects, evaluating thermal performance, and supporting the maintenance of historic buildings.
- **Chapter 4** presents practical insights through case studies that demonstrate the effectiveness and limitations of IRT in field applications.
- **Chapter 5** concludes the work with a summary of key findings, final reflections and suggestions for future developments and research in the use of thermography in the construction industry.

2. Introduction to Thermography

Infrared thermography (IRT) is a non-destructive technique that allows the detection, visualization, and interpretation of thermal energy emitted by objects. It operates based on two fundamental principles: the temperature of a surface and its ability to emit thermal radiation – known as emissivity. When a material emits infrared radiation, this energy can be captured by a thermal imaging camera and translated into visual data known as thermograms, which represent the distribution of the surface temperature of the object under analysis. Infrared cameras detect this radiation through specialized lenses and sensors that convert thermal energy into electrical signals, which are then processed and displayed as color or grayscale images corresponding to specific temperature ranges. (Meola, 2013; Shrestha et al., 2025)

In civil engineering, IRT has become an increasingly valuable tool for the inspection of buildings, bridges, and other structural elements. Its ability to identify thermal anomalies such as moisture intrusion, delaminations, thermal bridges, or insulation deficiencies makes it especially useful for diagnosing problems that are not detectable by conventional or visual inspection methods. Given the complexity of building materials and thermal interactions in structural systems, the collection and analysis of thermographic data must be carried out accurately. Accurate interpretation requires proper calibration, consideration of environmental influences, and a thorough understanding of the physical principles that govern infrared radiation and surface behavior. As such, thermography provides engineers with an efficient, real-time method to monitor building performance, inform maintenance decisions, and support preventative diagnostics without causing any damage to the structure. (Tomita & Chew, 2022) (Milovanović & Pečur, 2014)

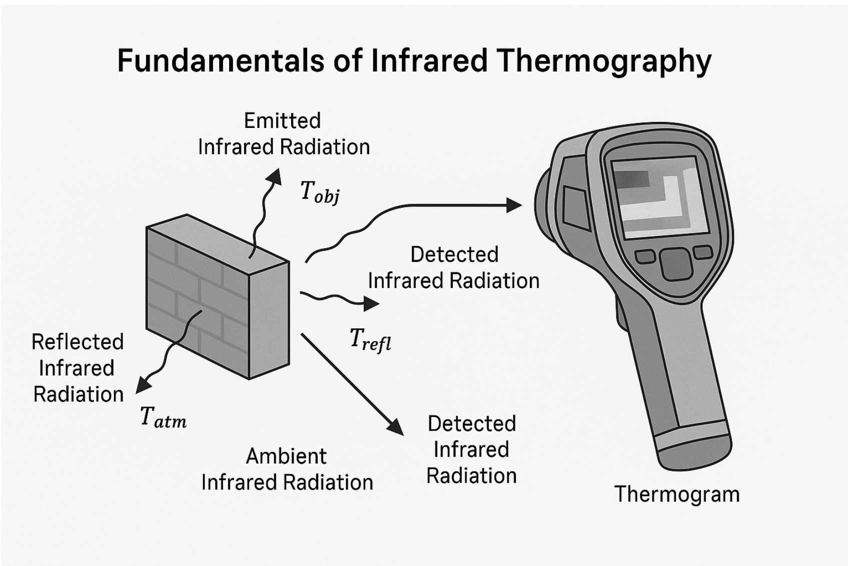


Figure 1 Fundamentals of Infrared Thermography

2.1 Infrared Radiation

Infrared thermography is based on the principle that all objects emit electromagnetic radiation as a function of their temperature. A significant part of this radiation is found in the infrared (IR) region of the electromagnetic spectrum, which extends from approximately 0.74 to 1000 in wavelength. This form of radiation is not visible to the human eye, but it can be detected using infrared cameras. In civil engineering, the most used range is the longwave infrared band (LWIR), between 7 and 14 , as it closely corresponds to the emission characteristics of building materials common at room temperature. (Meola, 2013; Shrestha et al., 2025)

The origins of the discovery of infrared radiation date back to the 1800s, when English astronomer Frederick William Herschel conducted experiments to understand how different colors of light affected temperature. It found that temperatures increased from violet to red in the visible spectrum, but the highest temperatures were recorded just beyond red light — beyond the visible range. This led to the discovery of infrared rays, which revolutionized thermal science (Barreira, 2004).

At the atomic level, all objects are composed of molecules and atoms that vibrate and exchange electrical charges, generating electromagnetic waves of various wavelengths. This molecular activity results in internal excitations that give rise to infrared radiation. The electromagnetic spectrum encompasses a wide range of wavelengths, including the region of visible light and, beyond it, the region of infrared. Infrared thermography captures this thermal radiation using specialized equipment capable of detecting it, even though it is invisible to the human eye. (Meola, 2013; Shrestha et al., 2025)

Infrared cameras assign artificial colors to different thermal intensities, transforming invisible radiation into visible images. These thermal images, called thermograms, represent the temperature distribution on the surface of an object, allowing engineers to assess structural conditions without physical contact or damage.

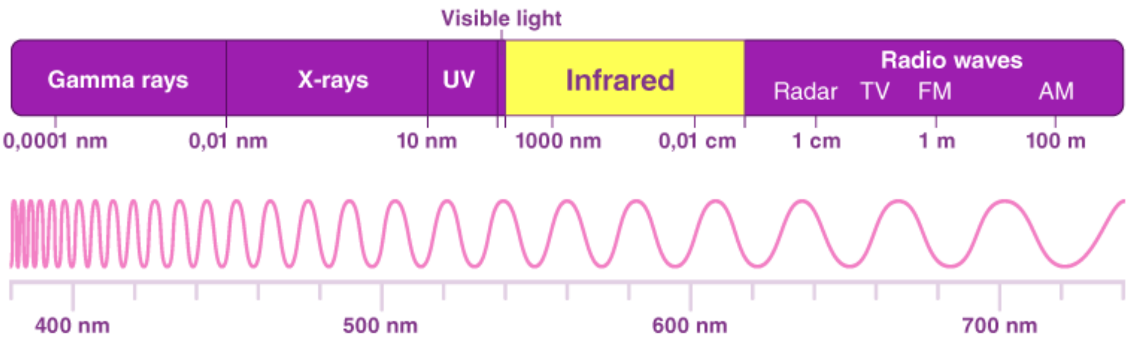


Figure 2 Range for infrared Radiation

2.2 Radiation Laws

2.2.1 Principles of Heat Transmission

Understanding the behavior of thermal radiation and the principles of heat transfer is essential for applying infrared thermography (IRT) in the field of civil construction and building diagnostics. The emission and detection of infrared radiation are governed by several fundamental physical laws. Planck's Law describes how the intensity of radiation emitted by a body varies with temperature and wavelength, providing insight into the spectral distribution of thermal emission. The Stefan–Boltzmann Law establishes that the total radiated energy from a surface is proportional to the fourth power of its absolute temperature, expressed as P=εσT4, where P is the radiated power per unit area, εεis emissivity, σ is the Stefan–Boltzmann constant, and T is the temperature in Kelvin. Wien's Displacement Law further connects an object's temperature with the peak wavelength of its emitted radiation, allowing the estimation of surface temperatures through the analysis of the infrared spectrum. (Meola, 2013; Shrestha et al., 2025)

Thermal energy is transferred through three primary modes: conduction, convection, and radiation, each playing a role in the thermal behavior of building elements. Conduction involves heat transfer through solid materials via direct molecular interaction, and its efficiency is characterized by a material's thermal conductivity. A low thermal conductivity indicates insulating properties, whereas a high conductivity denotes a good conductor. Convection refers to heat transfer in fluids (liquids or gases) and arises from temperature-induced density variations that cause circular convection currents. This mechanism is especially relevant in spaces between building elements and ambient air, where air movement affects surface temperatures. Radiation, on the other hand, does not require a medium to propagate and is the only mode of heat transfer detectable by thermal imaging cameras. Radiant energy emitted by an object can be absorbed, reflected, or transmitted by another object depending on its surface properties and environmental conditions.

In the context of thermographic inspection, these principles help explain how and why infrared cameras capture thermal differences on building façades or surfaces.. The thermal image captures not only the emitted energy from the façade but also portions of reflected solar radiation and, in some cases, transmitted energy through certain materials. The values detected by the camera are influenced by several factors, including the emissivity of the surface material, the angle and distance of measurement, atmospheric conditions, and the temperature differential between the object and its surroundings. For accurate analysis, it is crucial to understand these interrelated physical behaviors and the concept of the ideal black body, which serves as the reference standard in thermographic analysis due to its perfect emissive properties. (Janků et al., 2017)

2.2.2 Black body and Real Body

A blackbody is a theoretical object in physics that perfectly absorbs all incident electromagnetic radiation, with no reflection or transmission. It is also the most efficient emitter of thermal radiation across all wavelengths and directions, achieving thermal equilibrium with its environment as described by Kirchhoff's Law. A true blackbody has an emissivity ε=1, meaning it emits the maximum possible amount of radiation for a given temperature. While no real material behaves as a perfect blackbody, this model is essential for understanding thermal emission and serves as a reference standard in infrared thermography (IRT). (Meola, 2013; Shrestha et al., 2025)

The radiative behavior of a blackbody is governed by several fundamental laws of physics. One of the most significant is Planck's Law, which describes how the spectral radiance of a blackbody—defined as the power emitted per unit area, per unit wavelength, per unit solid angle—varies as a function of temperature T and wavelength λ. The spectral radiance is given by:

$$\frac{dR(\lambda, T)}{d\lambda} = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)}$$

Where:

h = Planck's constant (6.626 × 10^{-34} J·s)

c= speed of light in vacuum (2.998 × 10^{8} m/s)

k = Boltzmann's constant (1.381 × 10^{-23} J/K)

λ = wavelength in micrometers (μm)

T = absolute temperature in Kelvin (K)

This equation shows that the spectral radiance rises from zero at short wavelengths, peaks at a specific wavelength that depends on temperature, and then decreases again at longer wavelengths.

From Planck's Law, Wien's Displacement Law is derived, which relates the peak wavelength of emitted radiation (λmax) to the temperature T of the emitting body:

$$\lambda_{\max} = 2898\text{T}\ [\mu m]$$

This law confirms that higher temperatures result in radiation peaking at shorter wavelengths, which is key to understanding thermal imaging.

In real-world thermographic applications, most materials deviate from ideal blackbody behavior. Their thermal radiation emission capability is described by emissivity (ε), a material property ranging from 0 (perfect reflector) to 1 (ideal emitter). High-emissivity materials such as concrete, plaster, and wood are well-suited for thermographic inspection because they closely approximate blackbody emission, ensuring more accurate temperature readings. In contrast, low-emissivity materials such as polished metals or glass reflect significant ambient radiation, which can distort thermographic readings unless corrective calibration techniques are applied.

Understanding these principles is vital in interpreting thermograms accurately. The laws of blackbody radiation help explain how thermographic cameras detect infrared radiation and translate it into temperature values, while material emissivity must be accounted for to avoid diagnostic errors in building assessments, energy audits, and structural inspections.

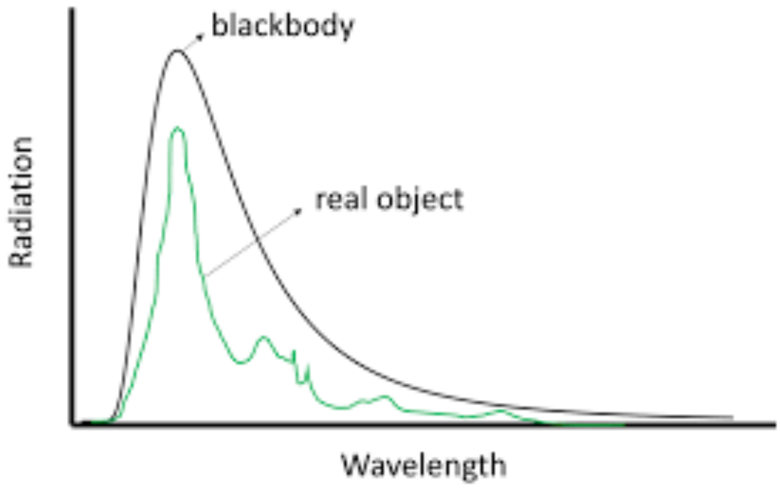


Figure 3 Graph for depicting Wavelength of Black body and Real body with respect to Radiation

2.3 Types of Thermography

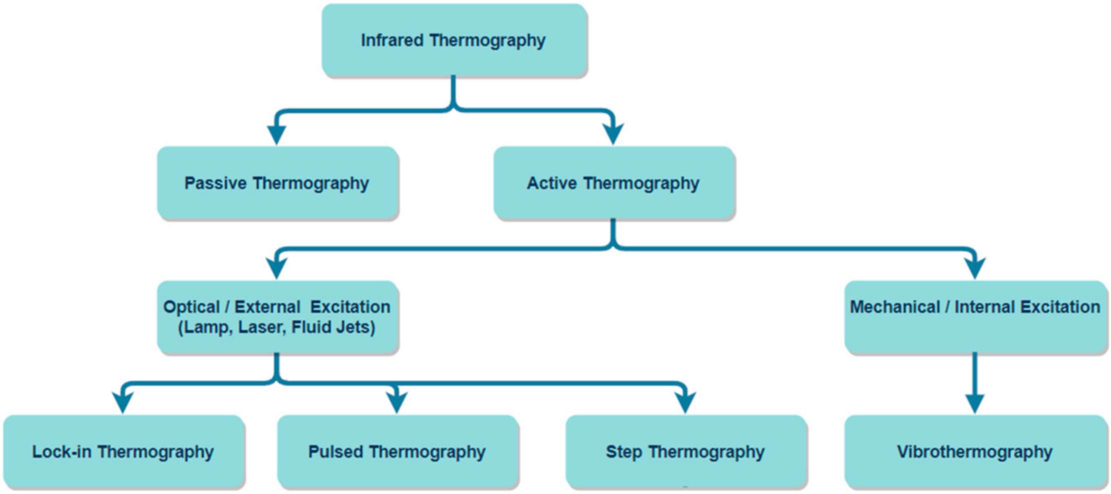


Figure 4 Flow Chart for Types of Thermography

2.3.1 Passive Thermography

Passive thermography is a non-intrusive imaging technique that utilizes naturally occurring thermal gradients to analyze the surface temperature distribution of building elements. These thermal gradients are typically generated by environmental factors such as solar radiation, external temperature fluctuations, or internal heating and cooling systems. Because it does not require external thermal stimulation, passive thermography is relatively simple, low-cost, and easy to implement, making it highly suitable for building envelope diagnostics, energy performance assessments, and moisture detection in walls and roofs. (Janků et al., 2017)

This method is particularly effective in scenarios where day-night cycles or indoor-outdoor temperature differences create sufficient thermal contrast to reveal thermal bridges, insulation defects, and areas of heat loss or air infiltration. However, passive thermography has limitations. Its accuracy and depth of detection are highly dependent on ambient conditions, such as wind, sunlight, and surface emissivity. Additionally, since it only captures surface-level anomalies, its capacity to detect subsurface defects is restricted compared to active methods. Therefore, while passive thermography is advantageous for initial surveys and quick diagnostics, it may not be sufficient for in-depth structural analysis or precise defect localization. (Tomita & Chew, 2022)

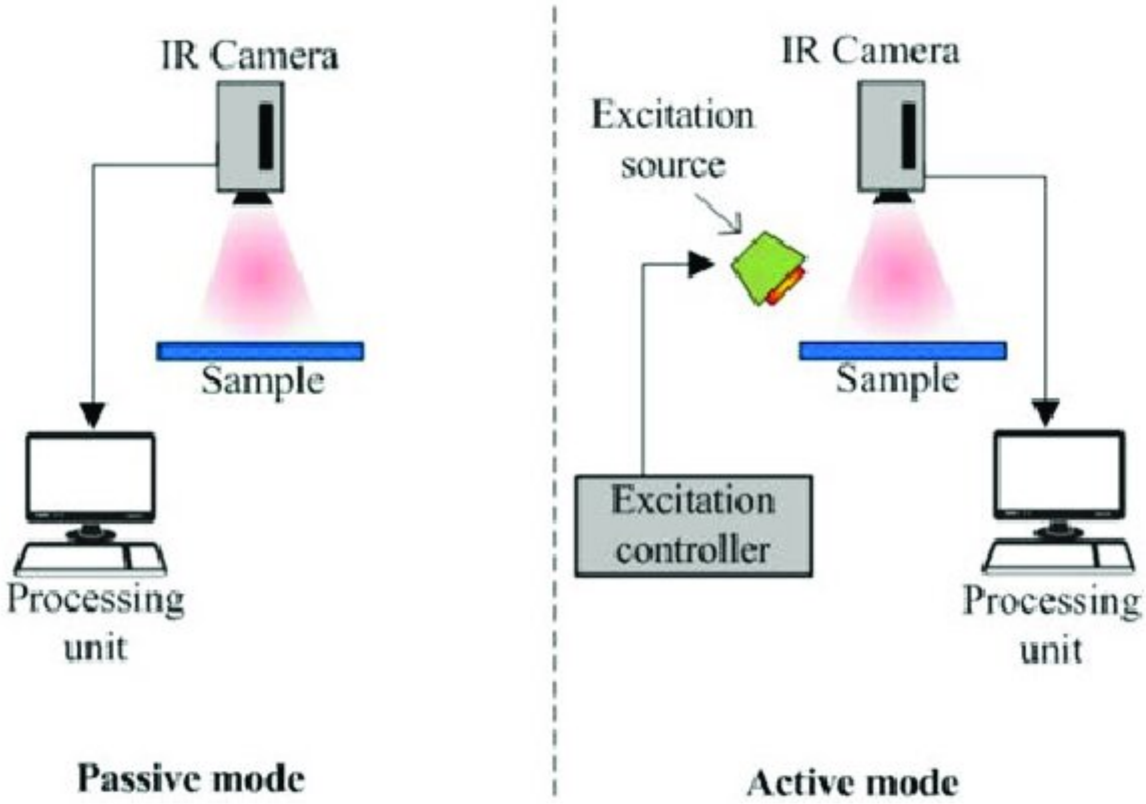


Figure 5 Difference between Passive and Active Thermography

2.3.2 Active Thermography

In contrast to passive methods, active thermography involves the application of an external heat source to induce a controlled thermal response in the structure under inspection. This artificially generated thermal gradient enhances the ability to detect subsurface anomalies and provides greater sensitivity for identifying hidden defects. Active thermography is especially useful when natural temperature differences are insufficient or inconsistent, as it allows for repeatable and targeted inspections regardless of environmental conditions.

Several advanced techniques fall under active thermography:

- Pulsed Thermography (PT): A short thermal pulse is applied (e.g., via flash lamps or halogen heaters), and the subsequent thermal decay is monitored. Variations in decay rates can reveal defects such as voids, delamination, or cracks. (Milovanović & Pečur, 2014)
- **Lock-in Thermography** (LIT): This technique uses periodic or modulated heating, often with sinusoidal thermal waves, and analyzes the phase shift between heating and thermal response. It is ideal for inspecting large areas with high resolution.

- **Vibro thermography**: Involves mechanical or ultrasonic excitation, causing internal friction at defect sites (e.g., cracks), which then heat up and become visible in the thermal image.
- **Induction Thermography**: Uses electromagnetic fields to induce eddy currents and localized heating in conductive materials like steel, making it suitable for reinforcement bars, metallic joints, or industrial components.

These active techniques enable the detection of deep-seated anomalies, such as debonding, delamination, voids, and fatigue cracks, making them essential tools in structural diagnostics, especially for bridges, tunnels, composite materials, and heritage buildings. (Milovanović & Pečur, 2014)

2.3.3 Thermography in Real time monitoring

Thermography is now a central component in real-time structural health monitoring (SHM) systems, especially with the advent of automation and smart infrastructure technologies. In this context, infrared sensors and thermal cameras are either permanently embedded in critical infrastructure or deployed periodically using drones, robotic crawlers, or handheld systems. This enables the continuous or periodic monitoring of thermal behavior across structural components, allowing engineers to track progressive deterioration, detect early signs of failure, and schedule predictive maintenance before catastrophic damage occurs. (ThermoElite Inc., n.d.)

Such real-time applications are particularly valuable in sensitive or high-risk infrastructures, including bridges, power plants, dams, industrial chimneys, and nuclear facilities, where thermal anomalies could signal corrosion, material fatigue, or system inefficiencies. These systems often incorporate AI and machine learning algorithms to analyze large volumes of thermographic data automatically, improving diagnostic accuracy and enabling remote monitoring with minimal human intervention.

As the integration of IoT (Internet of Things) and smart sensors progresses, thermography is expected to play an increasingly vital role in the digital twin modeling of infrastructure—creating dynamic virtual models that reflect the real-time physical state of a structure. This development supports more efficient asset management, safety assurance, and lifecycle optimization of built environments.

2.3.4 Qualitative and Quantitative Thermography

There are two different types of thermography analysis principles: qualitative and quantitative.

Qualitative analysis is fast, easy to interpret and is used whenever the objective is a superficial approach, thermograms are analyzed only by observation and without measurement details, it allows to technically evaluate the object under study.

In the quantitative analysis, surface temperatures are recorded using thermograms and some parameters. This method is slower because it requires more rigor and more detail, this analysis consists of a survey of thermograms, recording of parameter measurements with well-calibrated equipment to compare real temperature values for the object under study.

Qualitative thermography relies on the analysis of thermal patterns to discover anomalies and their location, while quantitative thermography uses temperature measurement values to quantify the degree of severity of the anomaly.

Figure 6 Qualitative and quantitative method of thermography

In this work, an approach will initially be adopted at the level of qualitative thermography, to identify the patterns that define the constructive solutions existing in the captured thermograms.

Later, deeper analyses will be carried out in a single building to try to verify the existence of anomalies in the element and thermal parameters through a quantitative analysis.

2.4 Factors affecting Thermography

The accuracy and reliability of thermographic measurements are highly dependent on a variety of surface, environmental, and instrumental factors, all of which must be carefully considered and managed to ensure meaningful data interpretation. Infrared thermography, being a surface temperature measurement technique, is inherently sensitive to how the inspected surface emits, reflects, or absorbs thermal radiation. (Meola, 2013; Shrestha et al., 2025)

2.4.1 Surface Characteristics

One of the most critical parameters affecting thermographic results is the emissivity of the surface under observation. Emissivity is a material-specific property that describes how effectively a surface emits thermal radiation relative to an ideal blackbody. Surfaces with high emissivity (such as concrete, plaster, or painted wood) typically yield more accurate and stable thermal readings, as they emit most of their absorbed heat. Conversely, low-emissivity surfaces—such as polished metals, glass, or glossy tiles—reflect a significant portion of ambient radiation, potentially causing misleading results unless emissivity corrections or surface treatments (e.g., matte sprays or adhesive tapes) are applied.

Additionally, surface texture, moisture presence, contaminants, and cleanliness also influence thermal emission. A dirty or dusty surface may create localized anomalies in the thermal pattern, while moist or wet areas may alter emissivity and mimic false thermal gradients due to their evaporative cooling behavior. These effects must be visually inspected and accounted for during both field measurement and post-processing analysis.

2.4.2 Environmental Conditions

Environmental parameters play a substantial role in the quality of thermal imagery and the accuracy of temperature readings. External factors such as ambient air temperature, solar radiation, humidity, and particularly wind speed can distort thermal measurements if not properly managed. (Janků et al., 2017)

- Wind causes forced convection, which can rapidly cool surface temperatures and obscure thermal gradients indicative of defects such as delamination or insulation failure. (Milovanović & Pečur, 2014)
- Solar exposure (especially during midday) can result in non-uniform surface heating, introducing thermal noise that masks underlying issues or creates misleading artifacts.

- Humidity impacts infrared signal transmission, especially at longer wavelengths, due to the absorption and scattering of infrared radiation by water vapor molecules.
- Temperature fluctuations between day and night can provide natural thermal gradients beneficial to passive thermography, but if not carefully timed, may reduce contrast and mask defects.
- To ensure optimal conditions, thermographic inspections are typically conducted during early morning or late evening, when solar effects are minimized and thermal contrasts between building elements are naturally enhanced.

2.4.3 Geometric and Positional Factors

The angle of observation significantly affects the measured emissivity and therefore the apparent temperature. For most materials, emissivity remains stable at near-perpendicular viewing angles (0–30°) but begins to decline rapidly as the viewing angle exceeds 60 degrees. This phenomenon, known as angular emissivity degradation, can lead to underestimated surface temperatures if the camera is not correctly aligned. As a rule of thumb, thermographic cameras should be positioned as perpendicular as possible to the surface, or correction factors should be applied during post-processing for angled observations.

Moreover, observation distance influences image resolution and atmospheric transmission. For distances greater than 10 meters, atmospheric attenuation—caused by air particles, humidity, and dust—can degrade the infrared signal, reducing the accuracy of thermal readings. In such cases, it is essential to:

- Use high-resolution cameras,
- Apply distance corrections in the camera software,
- Or use infrared-transparent windows in enclosed environments.

2.4.4 Instrument Calibration and Configuration

The thermal camera itself must be properly calibrated to match the target material's emissivity, ambient reflected temperature, distance, and relative humidity. Most modern infrared cameras allow for manual input of these parameters, and some advanced models offer real-time atmospheric correction algorithms.

Routine calibration against known blackbody references or certified calibration plates ensures measurement traceability and accuracy. Additionally, ensuring uniform detector response, lens cleanliness, and stable internal temperature of the camera are vital steps for minimizing internal measurement noise and drift.

In conclusion, accurate thermographic assessment is not solely reliant on the equipment but also on the operator's understanding of physical principles, measurement environment, and surface behaviors. When these factors are meticulously managed and corrected for, thermography becomes a highly powerful and reliable tool for diagnosing thermal and structural anomalies in civil infrastructure.

2.5 Applications of Thermography in Civil Engineering

Infrared Thermography (IRT) has evolved from a military and industrial diagnostic tool into a vital technology within the field of civil engineering. Its non-contact and real-time diagnostic capabilities make it exceptionally suited for evaluating buildings and infrastructure, detecting hidden anomalies, and enhancing the safety, efficiency, and longevity of construction projects. This section outlines the key applications of IRT in civil engineering, supported by findings and case studies from peer-reviewed literature. (Meola, 2013; Shrestha et al., 2025)

2.5.1 Structural Defect Detection

One of the most critical applications of IRT is the detection of structural defects within buildings and bridges. Defects such as delamination, voids, cracks, rebar corrosion, and spalling in concrete can severely compromise structural safety and performance. In studies conducted by Michal Janků et al., IRT was successfully utilized to identify delamination and voids in concrete bridge decks. During daytime heating by sunlight, subsurface voids and defects exhibit different thermal behaviors compared to surrounding sound concrete, appearing as distinct anomalies in thermal images. (Milovanović & Pečur, 2014)

The analysis of thermal response to daily heating and cooling cycles further aids in defect detection. For instance, delamination tends to manifest as hot spots during the day due to retained heat and appear as cold spots during nighttime cooling phases. Moreover, the detection of steel rebar corrosion is possible through indirect thermal gradients and moisture mapping, as corrosion-induced expansion affects surface temperatures and moisture accumulation patterns, both of which are visible in thermograms. (Milovanović & Pečur, 2014)

2.5.2 Building Envelope Diagnostics

IRT plays a significant role in evaluating the thermal performance of building envelopes, particularly in energy auditing and diagnostics. It is highly effective in detecting thermal bridges, air leakages through doors, windows, and joints, and identifying areas of moisture intrusion in walls and roofs. In the dissertation work of Adriana Martins, thermography was combined with blower door tests to enhance the detection of air leakage pathways. Induced pressure differentials exposed by the blower door system made concealed leaks more pronounced and visible through thermal imaging. (Tomita & Chew, 2022) (Campbell Property Management, 2024)

Case studies conducted by Martins on various educational buildings constructed between the 1960s and 1990s revealed substantial differences in thermal behavior between rehabilitated and non-rehabilitated structures. These findings highlighted the importance and effectiveness of thermal retrofits in improving energy performance and reducing thermal anomalies.

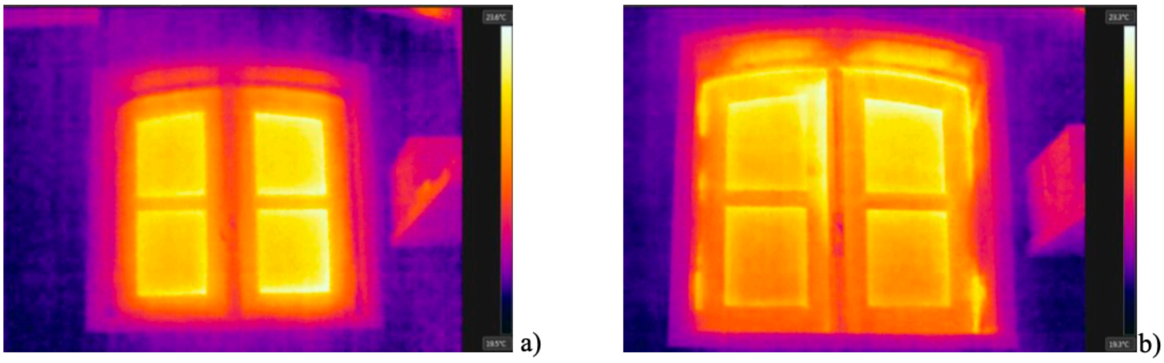


Figure 7 Detection of air leaks in the glazed opening: a) thermogram of a window without the aid of the mechanical equipment; b) thermogram of a window with the aid of mechanical equipment

2.5.3 Preservation of Historical and modern structure

IRT has proven indispensable in the preservation of both historic and modern structures. Walter Wild's research demonstrated the application of thermographic surveys on historic buildings in Germany, where town halls were evaluated for insulation performance, moisture ingress, and hidden construction irregularities. The ability to gather such critical information without invasive testing methods greatly aids in heritage conservation, ensuring minimal disturbance to delicate and culturally significant structures.

In modern construction, IRT supports post-installation quality control by verifying the correct placement of insulation materials, detecting concealed flaws, and ensuring the optimal operation of HVAC systems. By identifying problems early, IRT enhances both construction quality assurance and long-term operational efficiency.

2.5.4 Integration with other Non-Destructive Techniques

The integration of IRT with other Non-Destructive Testing (NDT) methods has expanded its diagnostic power. Ground Penetrating Radar (GPR), for instance, complements thermographic inspections by providing subsurface imaging that corroborates thermal anomaly findings. Ultrasound and acoustic methods further assist in validating the presence of cracks and voids initially detected via thermal contrast. (Wild, 2007; Martins, 2013)

Digital image processing advancements, including sophisticated software and artificial intelligence algorithms, have automated the interpretation of thermograms, reducing human error and enhancing the reliability of diagnostic outcomes. In their comprehensive review, Shrestha et al. emphasized the revolutionary impact of drone-mounted thermal cameras, which allow thermographic inspections of hard-to-reach locations such as bridge undersides and tall facades, thereby broadening the scope and accessibility of IRT in large-scale infrastructure assessments. (ThermoElite Inc., n.d.)

2.5.5 Construction Quality Control and Maintenance

In the construction sector, IRT is increasingly employed for quality control during the building phase and for routine maintenance inspections. It enables the verification of waterproof membrane installations, checks the integrity and continuity of insulation layers, and detects faulty electrical connections, which typically present as localized overheating in thermal imagery. Furthermore, through periodic thermal monitoring, the long-term performance of building components can be assessed, helping to identify early signs of deterioration or system failures.

By integrating IRT into routine maintenance schedules, asset managers can adopt predictive maintenance strategies, extending the lifespan of infrastructure while minimizing the risk of catastrophic failures.

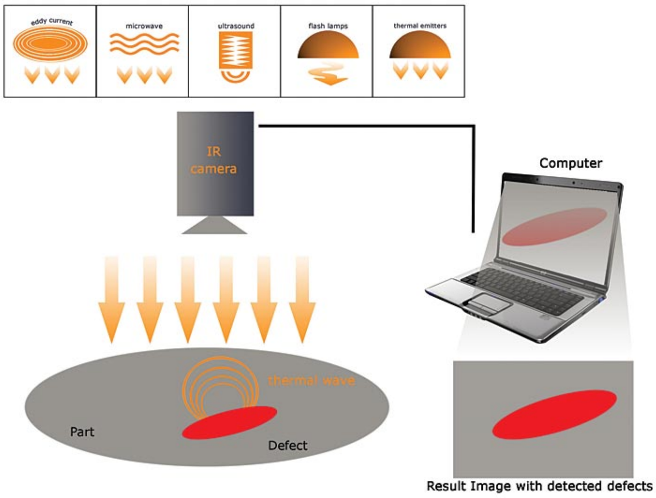


Figure 8 Process for Thermal Imaging for Quality Control

2.6 Thermographic Equipment & System Equipment

2.6.1 Infrared Cameras

Infrared cameras are the cornerstone of thermographic inspections and play a critical role in capturing thermal patterns from building elements. These cameras detect infrared radiation emitted by surfaces and convert it into thermal images (thermograms), which visually represent temperature distribution. Two major categories of infrared detectors are used:

Uncooled detectors, typically based on microbolometer arrays, operate without cryogenic cooling and are widely used due to their cost-effectiveness, portability, and mechanical simplicity. These are suitable for most building diagnostics and general-purpose inspections.

Cooled detectors, using sensors such as Indium Antimonide (InSb) or Mercury Cadmium Telluride (MCT), require cooling to cryogenic temperatures (usually via Stirling engines or liquid nitrogen) and offer superior thermal sensitivity and frame rates. They are more commonly used in advanced industrial applications, research, and precise scientific studies.

Infrared lenses, made of materials like germanium or chalcogenide glass, are optimized for the infrared spectrum, ensuring accurate focus and minimal dispersion of IR radiation. Most infrared cameras used in civil engineering offer resolutions ranging from 160×120 to 640×480 pixels, with higher resolutions available for detailed analysis. A crucial parameter for assessing camera performance is the Noise Equivalent Temperature Difference (NETD)—a measure of the camera's sensitivity to small temperature differences. Lower NETD values (e.g., $<0.05°C$) allow the detection of fine thermal gradients, making subtle defects like moisture intrusion or insulation gaps more identifiable.

Figure 9 Example of Equipments used Thermal Imaging

2.6.2 Image Processing & Analysis Software

After capturing thermal images, sophisticated image processing software is used for analysis and interpretation. Tools such as FLIR Tools, FLIR ResearchIR, Testo IRSoft, or ThermoViewer allow users to enhance thermograms, correct measurement errors, and extract precise data.

Key functionalities include:

- **Temperature profiling**: Measuring temperatures at specific points, along lines, or within selected areas.
- **Image fusion and overlay**: Combining thermal images with visible light photos for better spatial context.
- **Time-lapse thermal sequences**: Analyzing changes over time, helpful for evaluating thermal inertia or dynamic responses to heating and cooling.
- **Emissivity and environmental adjustments**: Correcting for different material emissivity's, ambient temperature, humidity, and reflective surfaces.
- **Statistical analysis and reporting**: Automatic generation of reports with thermal metrics and visual annotations for documentation and decision-making.
- **Pattern recognition and AI integration**: Some advanced platforms now integrate artificial intelligence to assist in automated detection of defects or anomalies.

These tools greatly enhance the diagnostic value of thermographic data, allowing engineers and inspectors to make accurate judgments about the condition of materials, structural integrity, and energy performance.

2.6.3 Complementary Diagnostic Tools

To increase the effectiveness of thermographic inspections, various complementary tools and techniques are integrated into the diagnostic workflow:

a. Blower door systems: These are used to depressurize or pressurize a building envelope, artificially enhancing air infiltration or exfiltration through leaks. When combined with thermal imaging, this technique makes air leakage paths (e.g., around windows, doors, or insulation gaps) highly visible and quantifiable. (Campbell Property Management, 2024)
b. **Active thermography setups**: External heating or cooling sources are used to induce thermal contrasts in building components. Examples include:
    - **Flash lamps or halogen lights** to heat surfaces quickly.
    - **Hot air blowers** to uniformly warm surfaces before imaging.

- **Microwave or ultrasonic pulse generators** for subsurface defect detection.
- **Moisture meters and hygrometers**: Used alongside thermography to confirm suspicions of water ingress or damp zones highlighted in thermograms.
- **Laser distance meters and GPS tagging**: Enable spatial referencing of detected anomalies for future intervention and documentation.

By integrating these complementary techniques, thermographic inspections gain a **multi-dimensional diagnostic capability**, improving reliability and depth of interpretation—especially in complex structural or energetic assessments.

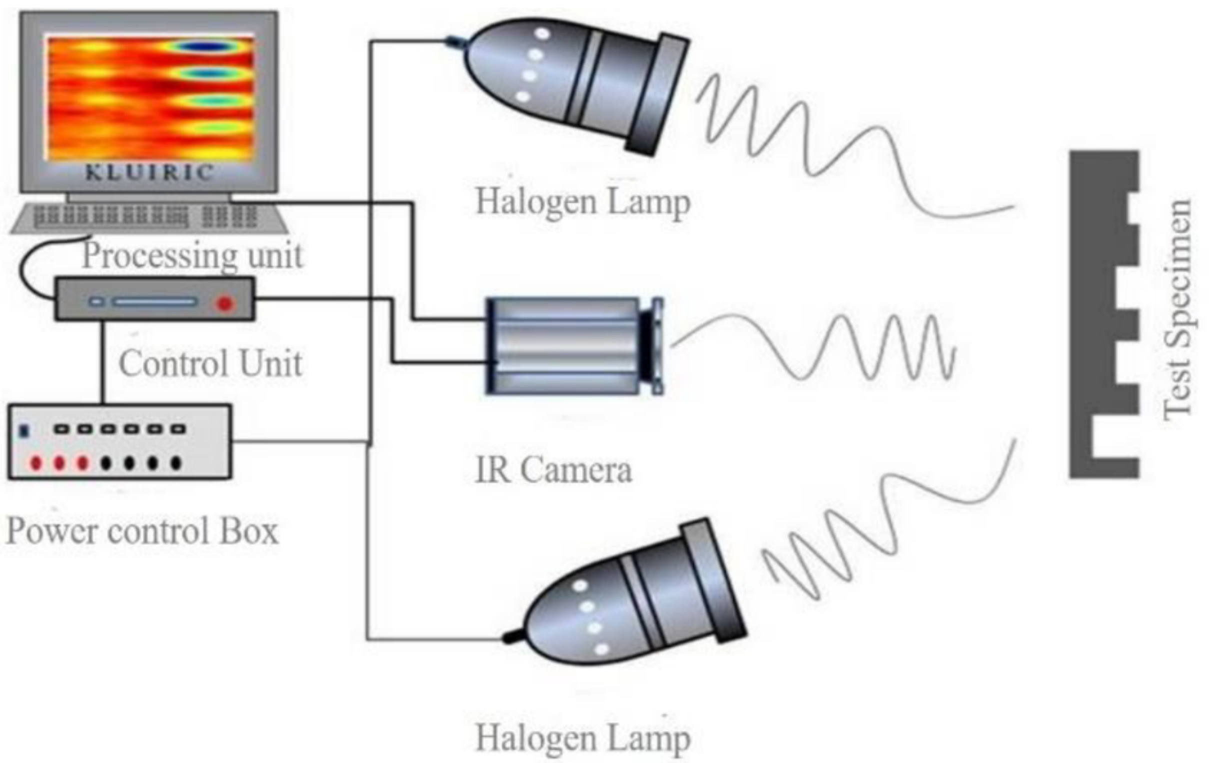


Figure 10 Active infrared thermography setup: dual halogen lamps heat the test specimen while an IR camera captures thermal responses, feeding data to the control and processing units for real-time defect mapping

3. Recent Research Works (Case Study)

To demonstrate the real-world utility and adaptability of infrared thermography (IRT) in civil engineering, a series of case studies were analyzed across various structural contexts. These examples span both contemporary infrastructure and heritage assets, showcasing thermography's value in detecting hidden anomalies, assessing material integrity, and guiding maintenance or conservation decisions. Each case illustrates a unique inspection scenario—ranging from delamination detection in concrete bridges to crack monitoring in steel structures and moisture mapping in historic façades—highlighting how both passive and active thermographic techniques can be tailored to specific diagnostic objectives. The following subsections summarize the methodology, key findings, and conclusions from each study, offering a grounded perspective on thermography's effectiveness in diverse engineering environments. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

3.1. Infrared Inspection of Concrete Bridge Deck Delaminations

3.1.1. Background

Reinforced concrete (RC) bridge decks are prone to subsurface delamination due to processes like freeze-thaw damage and rebar corrosion, which can lead to cracks, spalling, and potholes. Traditional inspection methods (visual surveys, chain dragging, hammer sounding) often rely on subjective judgment and only detect defects when they become surface visible. Identifying delaminations early – before spalling occurs – is critical for timely maintenance and public safety. Infrared Thermography (IRT) offers a non-contact, rapid screening tool to augment these inspections by revealing hidden deterioration zones. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

3.1.2. Methodology

The thermographic survey was conducted as a passive IRT inspection under natural solar heating and cooling cycles. A thermal camera was positioned to scan the concrete deck surface, typically during a sunny day and subsequent night, to capture thermal contrasts. As the sun heats the deck, areas over delaminations warm faster, and after sunset they cool more slowly than solid concrete, creating temperature differentials. Studies have found that for effective detection the daily temperature change should exceed ~10 °C, with the best imaging window around midday (peak heating) or early evening cooling. In practice, the camera setup (often mounted on a vehicle or tripod) records a series of thermograms of the deck; a typical arrangement is shown in published guidelines (e.g. a heat source like the sun and an IR camera positioned perpendicularly to the surface). Environmental conditions are carefully noted, since wind, clouds, or a wet surface can diminish the thermal contrast needed to spot subsurface flaws. (Milovanović & Pečur, 2014)

3.1.3. Findings

Thermographic images (thermal maps of the deck) successfully identified anomaly patterns corresponding to delaminations. In daytime thermograms, delaminated zones appeared as hot spots where the underlying air gap caused the surface to heat more quickly than intact areas. Conversely, during the night cooling cycle those same zones became cold spots (remaining warmer than the cooling intact concrete) and thus appeared darker in the IR image. Figure 7(here Figure 12) of the referenced study, for example, shows typical deck thermograms with clear thermal indications of potential delamination both in daytime and nighttime conditions. By comparing the IR results with ground truth (e.g. core samples or chain-drag surveys), the researchers confirmed that the hotspots and cold spots corresponded to delamination voids beneath the surface. Notably, areas of shallow delamination gave stronger contrast, while very deep or small delaminations were harder to discern unless a high thermal gradient was present. (Milovanović & Pečur, 2014)

3.1.4. Conclusion

This case study demonstrated that IRT can reliably detect subsurface delaminations in concrete bridge decks before visible deterioration (like spalls) occurs. Thermography provided a rapid full-field assessment, highlighting suspect zones that merit closer inspection or repair. The findings underscored the importance of favorable environmental conditions for successful IRT (adequate solar loading and diurnal temperature swings) and showed IRT to be a valuable supplement to routine bridge inspections. Agencies can integrate thermographic surveys to enhance condition assessments, enabling early intervention on decks with internal delamination damage and thereby improving maintenance decisions. The trade-off is that infrared inspection requires proper timing and equipment investment, but the ability to “see” hidden defects non-destructively offers significant benefits for infrastructure management. (Milovanović & Pečur, 2014)

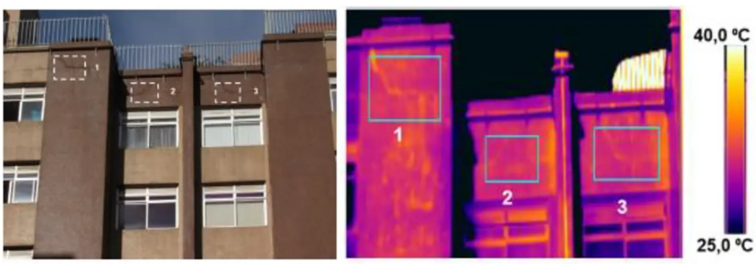
3.2. Thermographic Evaluation of Historic Building Facades

3.2.1. Background

Historic masonry buildings often face challenges in energy efficiency and material preservation. When centuries-old structures (e.g. heritage city halls or churches) are retrofitted, modern insulation standards must be balanced against preserving original materials. There is a need to assess where these buildings might be losing heat or suffering moisture ingress without invasive measures. In this context, infrared thermography provides a means to map thermal performance of building façades and identify "climate sinners" – spots of poor insulation or dampness – that could compromise both comfort and the building's fabric. For example, several historic town halls on the Baltic coast (with thick medieval walls and later restorations) were examined via IRT to verify the efficacy of their renovations in reducing heat loss. (Meola, 2013; Shrestha et al., 2025)

3.2.2. Methodology

Surveys were conducted on exterior and interior surfaces of the target buildings during winter conditions, when a high indoor-outdoor temperature gradient could be achieved. A minimum temperature difference of about 20 K (20 °C) between heated interiors and cold ambient air was maintained to ensure clear thermal contrasts, since smaller differentials (e.g. 10 K) are sometimes insufficient for reliable results. Infrared images of each façade were captured at night or early morning (to avoid direct sun) using a calibrated thermal camera. Prior to imaging, ambient parameters were recorded – including outside temperature, humidity, distance to the target – and an emissivity of ~0.95 was assumed for the masonry and plaster surfaces (as most building materials have high emissivity in the IR range). For each building, the thermographer took a corresponding daylight photograph to contextualize the thermal patterns. Notably, inside scans were also performed in some cases to locate cold bridges (areas where heat from the interior is escaping, appearing as cool zones on inside walls) which might not be evident from the exterior due to weather effects. The thermographic procedure adhered to standard protocols for building diagnostics: calm, dry weather was chosen (no wind or rain), and in the case of exterior surveys, late night imaging ensured that solar heating did not mask insulation deficiencies.



(a) (b)

Figure 11 Thermographic inspection of a building façade (historic masonry structure) revealing crack and delamination zones. Photo (a) marks several crack locations, and IR image (b) shows higher temperature at those areas (bright rectangles) due to solar heating and different thermal properties around the cracks.(Figure A2)

3.2.3. Findings

The thermal images revealed distinct patterns of heat distribution on each historic façade, reflecting the success of insulation and the presence of any defects. Key observations include:

- **Rostock City Hall (13th c., baroque façade):** The thermograms showed that the thick ancient brick walls retained heat effectively – most of the façade appeared uniformly cool – while the windows on the upper floors were conspicuously warmer, indicating they did not meet modern insulation standards and were major points of heat loss. Overall, the building's envelope performed well except for those window areas.
- **Wismar Town Hall (19th c., classical style):** This building's IR survey found generally good insulation, but a few "red white" window signatures stood out in the thermogram. These corresponded to specific rooms being heated more than others, highlighting uneven heating or insulation – the windows of warmer rooms leaked more heat. This identified where additional insulation, or sealing might be needed around certain windows.
- Greifswald City Hall (15th c. origin, rebuilt in baroque style): Infrared imaging identified this building as the worst insulated of the sample. The thermograms were mottled with warm patches along the façade, revealing many thermal bridges and areas of heat leakage left after a 2000 restoration. In other words, despite renovations, significant portions of the exterior were losing heat (likely at interfaces between old and new materials or around repaired sections), underscoring deficiencies in the retrofit. (Tomita & Chew, 2022)

Additionally, the thermographic survey occasionally detected moisture-related anomalies: for instance, parts of a masonry wall showing cool damp spots in the IR image, indicating water infiltration that could risk frost damage if not addressed. In all cases, the IR data provided a clear visualization of hidden problems – whether insulation gaps, construction voids, or moisture – that would be hard to pinpoint otherwise.

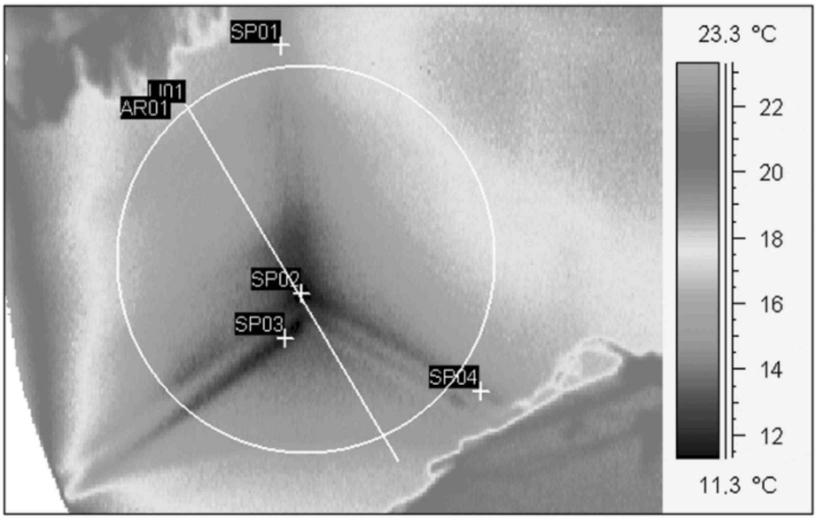


Figure 12 Complete report of the thermographic investigation a heat bridge with the growth of mold

IR-Daten	Wert
Erstellungsdatum	10.02.2005
Erstellungszeit	08:16:21
Kameratyp	THV 550
Objekt-Parameter	Wert
Emissionsgrad	0.95
Umgebungstemperatur	19.8 °C
Relative Luftfeuchtigkeit	61%
Bezeichnung	Wert
SP01	15.5 °C
SP02	11.2 °C
SP03	11.5 °C
SP04	14.4 °C
LI01: max	16.6 °C
LI01: min	10.9 °C
LI01 : max-min	5.7 °C
AR01: max	18.2 °C
AR01: min	10.8 °C
AR01: max-min	7.4 °C

3.2.4. Conclusion

Infrared thermography proved to be a powerful diagnostic tool for evaluating the building envelope of heritage structures. In these case studies, IRT non-invasively identified where historic façades were thermally deficient or compromised by moisture, guiding architects and engineers to specific trouble spots. The results confirm that even in thick-walled monuments, infrared scans can compile evidence of heat losses, water leaks, or structural voids that escape visual detection The implications for conservation are significant: thermography allows for targeted interventions (e.g. adding insulation to a specific wall zone or repairing seals on windows) while avoiding unnecessary alterations to intact areas. Overall, this study highlighted that construction thermography – when conducted with proper expertise – yields quantitative documentation to support energy efficiency improvements in historic buildings. It enables stakeholders to make informed decisions that enhance comfort and sustainability of heritage buildings, all while respecting their historical integrity. (Meola, 2013; Shrestha et al., 2025)

3.3. Detecting Internal Plaster Delamination in Heritage Structures

3.3.1. Background

Many heritage buildings and artworks (such as old, plastered walls, frescoes, and mosaics) suffer from internal delamination of plaster layers. This occurs when the plaster or render loses adhesion to its substrate (masonry or lath), often due to moisture penetration, thermal cycles, or material aging, and it creates air gaps or voids behind the surface. Such subsurface detachment can lead to bulging or flaking of decorative finishes and ultimately loss of historic material. Traditional detection (tapping for hollow sounds or peeling back sections) is labor-intensive and risks damaging the artwork. Infrared thermography offers a sensitive means to locate these hidden voids by exploiting temperature differences across the surface. In essence, areas of plaster that are delaminated will heat up and cool down at different rates than well-bonded areas, providing a diagnostic thermal signal. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

3.3.2. Methodology

Researchers conducted controlled experiments to study plaster delamination detection via active infrared thermography. In the laboratory, simplified models of historic plaster were prepared: for example, a two-layer specimen consisting of a plaster top layer applied over either a marble or brick substrate was embedded with artificial defects. Defects were simulated by inserting small panels of different materials (e.g. air-filled plastic boxes and cork pieces) at known depths (shallow at 10 mm beneath the surface, and deeper at 20 mm) to mimic voids or inclusions in plaster. Using a high-resolution cooled infrared camera (such as a FLIR SC3000), the sample was thermographically inspected under a pulse heating regime: the surface was briefly heated (e.g. using lamps) and the camera recorded the cooling phase, or alternatively a periodic heating (lock-in thermography) was applied, and phase images were captured. Tests were repeated under different conditions – notably, the plaster specimens were imaged in a dry state and then in a partially wetted state – to observe how moisture content affects defect detectability. For field validation, the team also performed in-situ thermography on actual heritage elements: for instance, an IR lock-in survey was carried out on an ancient mosaic wall in Naples to identify detached mosaic tiles and plaster backing detachment without physically touching the artifact. All thermographic data were then post-processed to enhance contrast and analyze the thermal profiles over defect vs. sound areas. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

3.3.3. Findings

The thermographic experiments successfully revealed subsurface defects in plaster and yielded insights into the factors influencing detection. Key findings include:

- Defect visibility: All simulated delaminations were detectable as thermal anomalies in the plaster surface images when proper heating was applied. Notably, shallow defects (at ~10 mm depth) became visible earlier and with higher initial contrast during the cooling phase, but these spots tended to fade as time progressed and deeper defects (at ~20 mm depth) became apparent. This temporal evolution is consistent with heat diffusion theory: near-surface voids produce a quick thermal response that dissipates sooner, whereas deeper voids require more time to manifest but remain visible later as the surface cools. (Milovanović & Pečur, 2014)
- **Defect size and material:** Larger air-filled voids yielded a stronger thermal contrast than smaller or more thermally conductive inserts. For example, the air-filled plastic box defects showed up more prominently in the IR images than same-size cork inserts, since air acts as a better insulator creating a bigger temperature differential. Similarly, defects with greater lateral dimensions were easier to detect than very small ones, as the latter might not produce a resolvable temperature change at the camera's resolution.
- Moisture effect: The presence of moisture significantly influenced the thermographic contrast. In tests, plaster containing porous inclusions (like tuff or cork, which can absorb water) exhibited higher contrast when the material was partially wet, because the wet defect and surrounding moist plaster altered heat flow and accentuated differences. In contrast, non-porous inserts (like Plexiglas) showed roughly the same thermal signature in dry vs. wet conditions. This indicates that moisture can either help or hinder IRT detection depending on how it changes thermal properties – in practice, a slightly damp wall might make airgap delaminations more pronounced, but excessive moisture could also homogenize temperatures and mask defects. (Milovanović & Pečur, 2014)
- **Lock-in thermography on artwork:** The field application on the mosaic provided a proof-of-concept that active IRT can be safely used on heritage surfaces. By using low-intensity periodic heating, the phase thermography technique could differentiate materials of the mosaic (stones of varying composition) and successfully **located disbonded tiles and plaster detachments** behind the mosaic without any contact. The phase angle images clearly indicated spots where tiles were no longer firmly attached to the underlying plaster, guiding conservators to those specific areas of concern.

3.3.4. Conclusion

This case study confirms that infrared thermography, especially active approaches, is highly effective for detecting internal plaster delamination in heritage structures. The experiments functioned as a form of thermal modeling – validating how defect depth, size, and material properties affect the heat transfer and the resulting thermogram. The findings provide practical guidelines: shallow or large voids are easiest to find, deeper defects may require longer observation or higher thermal input, and environmental factors like moisture must be considered when planning a survey. Importantly, the ability to identify hidden detachments with IRT has significant implications for preservation: restorers can pinpoint unstable sections of plaster or frescoes and intervene before they collapse or cause surface damage. Moreover, the non-destructive nature of the technique means precious surfaces (e.g. centuries-old murals or mosaics) can be examined without risk. Overall, the study demonstrates IRT as a valuable diagnostic tool for heritage conservation, enabling proactive maintenance of historic finishes. As shown in the mosaic example, even delicate artworks can be investigated with thermography, which helps ensure that conservation efforts are focused and effective in sustaining our cultural heritage. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

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3.4. Thermal Imaging for Fatigue Crack Detection in Steel Bridges

3.4.1. Background

Steel bridges, especially long-span truss and girder bridges, are susceptible to fatigue cracking over decades of service. Repeated traffic loading can initiate microscopic cracks at welds, joints, or other stress concentrations; these cracks grow and can threaten the structural integrity if unchecked. Conventional crack inspection techniques (visual inspection, magnetic particle testing, ultrasonic testing) require close access to the steel components and can be time-consuming for large structures. In recent years, researchers have explored infrared thermography as a remote NDE technique to detect and monitor fatigue cracks in steel bridge members. The principle is that active cracks or stress concentrations in metal can produce localized thermal signals: either through external stimulation (heating) or through the material's own thermoelastic response to stress. If these thermal signatures can be captured, it opens the possibility of finding cracks at a distance (for instance, from a drone or a roadside scan) without direct contact. (Meola, 2013; Shrestha et al., 2025) (ThermoElite Inc., n.d.)

3.4.2. Methodology

Two main thermographic approaches have been applied for crack detection in steel. Thermoelastic Stress Analysis (TSA) is a passive loading method: the steel component is subjected to cyclic loading (e.g. vibration or normal traffic loads), and a sensitive IR camera measures the minute temperature changes on the surface caused by the thermoelastic effect (as metal stretches and contracts, it heats and cools slightly). Cracks disturb the stress field and yield a distinctive thermal pattern under cycling. In experiments, high-speed IR cameras were stationed at a standoff distance focusing on critical details (like a welded connection); as the bridge member was stressed, thermal images or videos were recorded to see the "hot spots" from stress concentrations at crack tips. The other approach is induction thermography, an active technique: an induction coil is used to rapidly heat the metal by inducing eddy currents, and any surface-breaking cracks generate local hot spots due to the interruption of current flow and elevated resistive heating at the crack edges. The IR camera captures these hot spots in real time. Induction heating can be applied via a robotic scanner or handheld device moving over the steel surface. Both techniques can be deployed in the field; for instance, TSA might be done on an in-service bridge by looking at members while vehicles pass (using their load as the stimulus), whereas induction requires bringing equipment to each area of interest but can pinpoint cracks in complex geometry. Recently, there is also a push to mount thermal cameras on UAVs (drones) or mobile rigs to survey large portions of bridges automatically. Coupled with machine learning algorithms (e.g. a Faster R-CNN for image analysis), such systems aim to automatically detect cracks from the IR imagery without manual interpretation. (ThermoElite Inc., n.d.)

3.4.3. Findings

Studies on steel bridges have demonstrated that thermography can reveal fatigue cracks that are not easily visible. Key results from various investigations include:

a. Thermoelastic stress method: Sakagami et al. found that under cyclic loading, even fine fatigue cracks in steel bridge welds produced a measurable thermal signal. In IR stress maps, cracks appeared as localized zones of temperature fluctuation (or as contour anomalies) corresponding to the high stress intensity at the crack tip. This allowed inspectors to not only detect the crack but also gauge its significance by the intensity of the thermoelastic response. In a follow-up study, the same team successfully verified crack repairs using this method – the IR images after retrofitting showed a reduction in stress-induced thermal concentration, confirming the effectiveness of the repair.

b. Induction thermography: Research involving induction heating reported that surface cracks as small as a few millimeters could be detected as bright hot lines on the thermogram when the induction coil passed over them. The technique was able to estimate crack depths as well: deeper or longer cracks tend to produce a larger and longer-lasting thermal signature, whereas shallow cracks cool quickly. Standardization efforts are underway to refine this method, given its promise for rapid scanning of welds and critical regions.

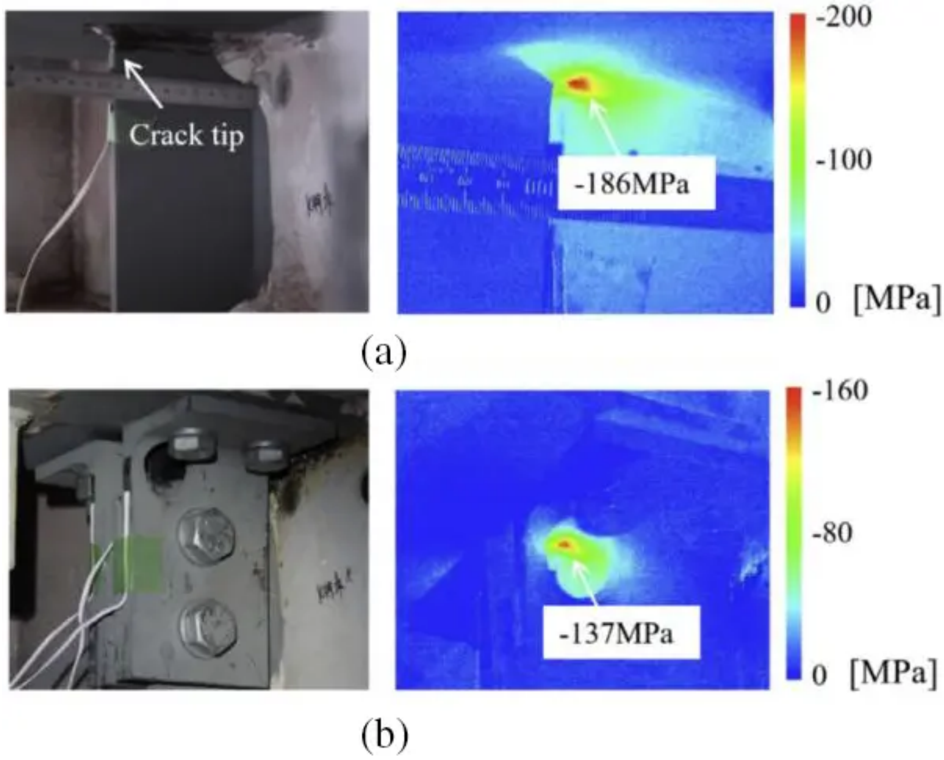

Figure 13 Thermographic stress analysis of a steel bridge component with a fatigue crack. Image (a) shows the stress distribution before repair, and (b) after crack repair, as measured by thermoelastic infrared thermography (temperature changes under loading are converted to stress contours (Figure A3)

c. Remote and automated detection: A 2022 study introduced a thermal imaging method to detect fatigue cracks under random traffic loads (passive heating) and successfully identified cracks in welded bridge components by analyzing thermal variance over time. Furthermore, prototype automated systems have been tested: one project used an infrared drone to collect thermal videos of a steel bridge girder and employed image recognition algorithms to flag crack-like hot spots. Early results show that such AI-assisted thermography can accurately locate cracks and even distinguish them from false indications due to reflectivity or noise. This points toward a future where routine bridge inspections might include periodic thermal scans by UAVs, dramatically improving coverage of hard-to-reach areas. (ThermoElite Inc., n.d.)

3.4.4. Conclusion

The application of infrared thermography for steel bridge crack detection is an exciting advancement in structural health monitoring. These case studies illustrate that IRT can detect fatigue cracks by highlighting their thermal footprints – either stress-induced or via external heating – providing a non-contact means to find damage that would otherwise require meticulous close-up inspection. The implications are significant: critical cracks could be discovered earlier and without extensive traffic disruptions (for example, scanning a bridge with a drone-mounted IR camera could identify a growing crack long before the next scheduled hands-on inspection). Thermography also offers a way to monitor crack growth or repair efficacy over time, as demonstrated by thermoelastic measurements confirming reduced stress after crack repair. There are still practical considerations (thermal methods require calibration, adequate stimulus, and interpretation expertise), but as equipment and algorithms improve, we can expect IRT to become a valuable complement to traditional steel bridge inspection techniques. In summary, this case confirms that with proper implementation, infrared thermography enhances our ability to ensure the safety of steel bridges by detecting fatigue cracks in a timely and cost-effective manner. (Meola, 2013; Shrestha et al., 2025) (ThermoElite Inc., n.d.)

3.5. Roof moisture Intrusion

3.5.1. Background

Flat roofs on commercial and residential buildings are prone to water leakage over time due to membrane failures, aging, or damage. Water can seep beneath the roofing membrane and saturate the insulation or decking. Such hidden moisture is a serious concern – it not only reduces the insulation's effectiveness (increasing energy costs) but can also lead to wood rot, mold growth, and eventually structural deterioration of the roof deck. Detecting these "invisible" roof leaks early is challenging with ordinary visual inspections, since the surface may look intact while layers below are wet. Infrared thermography has become a well-established technique for flat roof moisture surveys since the 1970s. It leverages the thermal behavior of wet roofing materials: during a sunny day, areas of wet insulation absorb and store more heat than dry areas, and then at night the wet spots release heat more slowly. This difference in cooling rate causes temperature contrasts on the roof surface that an IR camera can detect. Building owners often commission IR roof surveys when a leak is suspected or as part of preventive maintenance, to accurately locate any water-damaged sections of the roof for repair. (Meola, 2013; Shrestha et al., 2025)

3.5.2. Methodology

In this case, a thermographic inspection was conducted on a large flat roof of a commercial facility to pinpoint areas of moisture intrusion. The inspection was timed for the late evening, shortly after sunset, following a clear, sunny day – ideal conditions for a passive thermal survey of the roof. During the day, solar radiation heated the roof's surface and the underlying materials. As dusk fell, the roof began to cool. However, any portions of insulation that were wet retained heat longer into the evening than the dry areas. Certified thermographers accessed the roof and used a handheld infrared camera to scan the entire surface in a grid pattern. They waited until a sufficient temperature differential emerged between wet and dry spots. The weather conditions were carefully chosen and monitored: the day had been mostly sunny and warm, ensuring maximum solar heating of the roof, and the evening was clear with low wind (wind and clouds can disrupt the cooling pattern). The roof was also dry of any recent rain or surface moisture. As the survey progressed after sundown, the thermographers observed the live thermal image display to identify "hot spots." These hot spots are areas that appear warmer on the IR image than the surrounding roof, due to stored heat in wet insulation. For each such anomaly, the exact location was marked on the roof with washable paint or flags. The team also took high-resolution thermal images and visible-light reference photos of those locations. In some cases, a UAS (drone) equipped with a thermal camera was flown over the roof to capture an overall infrared image, complementing the on-roof handheld scanning. After the IR survey, follow-up verification was done: the inspectors returned during the day to physically core-sample or use a moisture meter on a few marked spots, confirming whether the insulation was indeed wet in those areas (this step ensures that the thermal anomalies correspond to actual moisture, not, for example, an area of heavier roofing material or shading effect). (Janků et al., 2017) (ThermoElite Inc., n.d.)

3.5.3. Results

The infrared roof survey successfully identified several **moisture intrusions** that were previously unknown. On the thermal images, most of the roof area cooled uniformly after sunset, appearing as a consistent background temperature. Against this background, the survey noted multiple warmer patches (some large, some small) scattered across the roof surface, each indicating a zone of moisture-laden insulation. These warm anomalies were precisely the areas where the roof was leaking. For instance, one sizable warm area was found near a rooftop HVAC unit – upon investigation, the flashing around the unit had a gap that allowed water in, soaking the insulation over an area of several square meters. Another elongated warm strip was detected along a parapet wall, consistent with a faulty seam in the roofing membrane by the wall. In total, the thermographic images pinpointed all significant wet spots in the roof system. The contrast was clear: wet sections remained on the order of a few degrees warmer than dry roof sections well into the evening, standing out brightly in the false color thermograms. These IR findings were later confirmed by direct inspection – core samples taken at the marked hot spots revealed damp insulation, while cores in the "cool" background areas were dry. Notably, some wet areas had not yet manifested any visible damage on the surface; they were early-stage leaks discovered only through the thermal pattern. By mapping these hidden pockets of moisture, the survey provided a clear plan for targeted repairs.

3.5.4. Conclusions

The thermographic roof inspection proved to be a cost-effective and proactive approach to managing roof maintenance. Instead of replacing the entire roof or waiting until leaks became obvious (and damage severe), the building owner was able to focus repairs on the specific sections where water had infiltrated. Based on the IR survey, roofing contractors cut open and replaced only the saturated insulation and membrane in those localized areas, restoring the integrity of the roof. This surgical repair strategy minimized cost and downtime compared to a full re-roofing. Moreover, by catching the leaks early, the infrared survey likely prevented further problems like mold growth in the roof or water dripping into the building's interior. This case highlights how IRT contributes to facility management: an infrared moisture survey can quickly and accurately detect roof leaks by showing the thermal signature of wet insulation. As a result, owners can make informed decisions – for example, whether a roof can be economically repaired or if a widespread replacement is needed, which aligns with the use of IR since the 1970s for guiding roof asset decisions. In summary, the roof case study demonstrates that infrared thermography is an invaluable tool for maintaining building envelopes, providing early detection of water intrusion that protects the structure and saves money over the long term. (Meola, 2013; Shrestha et al., 2025)

3.6. UAV Based Thermography Applications

3.6.1. Background

Unmanned Aerial Vehicles (UAVs), or drones, have emerged as a revolutionary platform for conducting thermographic inspections in civil engineering. They address a key limitation of ground-based surveys – the ability to quickly cover large or difficult-to-reach areas without the need for scaffolding or lane closures. UAV-based infrared thermography has been tested on structures such as long-span bridges, high-rise building façades, and expansive heritage sites. By mounting a thermal camera on a drone, engineers can capture heat maps of infrastructure from vantage points that were previously impractical. For example, a drone can fly under a bridge or hover alongside a tall building to image areas that inspectors cannot physically access easily. The promise of UAV-IRT is faster data collection and improved safety (keeping inspectors on the ground), but it also introduces new challenges. Flight instability, environmental factors, and data processing complexity can affect results. In this context, a real-world demonstration was undertaken to evaluate the feasibility of UAV-mounted thermography for structural inspections. The application was twofold: (1) a concrete bridge deck survey using a drone instead of a truck, and (2) a survey of a historic masonry structure's walls using a drone to cover upper sections. The aim was to assess if the UAV approach could detect the same kind of defects (delaminations, moisture zones, cracks) identified by traditional IRT, and to understand the practical considerations (flight conditions, image quality, etc.) in the field. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014) (ThermoElite Inc., n.d.)

Figure 14 Thermal Imaging using a Drone

3.6.2. Methodology

The UAV-based thermographic inspection required careful planning and adaptation of standard IRT procedures to the aerial platform. First, the team selected a drone with sufficient payload capacity to carry a thermal imaging camera with high resolution and refresh rate. A gimbal-stabilized FLIR thermal camera was used to compensate for drone movements and ensure steady, blur-free thermograms. Flight tests were scheduled under favorable weather conditions, since wind, temperature extremes, and precipitation can all interfere with both the drone's stability and the thermal contrast on the target structure. The operators chose to fly during times that maximize thermal defect detectability: for the concrete bridge deck, this was in the late afternoon into evening (after solar heating of the deck, similar to the earlier case study), and for the masonry walls of the heritage building, flights were done in early morning when the walls were releasing heat from the previous day. Wind speed was kept below about 10 mph during flights, as higher winds caused the drone to sway and introduced noise in the thermal images. The drone's flight path was pre-programmed to ensure complete coverage: it flew back-and-forth transects over the bridge deck at a fixed altitude, and performed slow, vertical sweeps alongside the building façade to image the walls. Dozens of thermal images were recorded. Because UAV imagery can suffer from slight misalignments and "drift" between frames, the dataset was post-processed with digital video stabilization techniques. Stabilization algorithms corrected for any minor camera jitters, resulting in cleaner thermal maps. The images of the bridge deck were stitched into an Ortho mosaic thermogram (georeferenced to the bridge layout), and the images of the building were mapped onto a 3D model of the structure using photogrammetry. This integration of thermal data with 3D photogrammetric models allowed the team to accurately locate each thermal anomaly on the structure. Standard analysis was then applied: on the bridge thermogram, the team looked for hot spots indicative of delaminations; on the building model, they looked for temperature anomalies suggesting moisture or material variation. The entire UAV operation was completed with a two-person crew (a drone pilot and a thermographer) in a matter of a few hours, demonstrating a rapid deployment compared to traditional methods. (Milovanović & Pečur, 2014) (ThermoElite Inc., n.d.)

3.6.3. Results

The UAV-based thermography trials yielded encouraging results, effectively uncovering defects on both test subjects. For the concrete bridge deck, the drone's thermal survey identified several hotspot patterns on the deck surface, very similar to those that ground-based IRT would detect. These hotspots were flagged as likely delaminations or voids. Despite the drone's motion, the stabilized and mosaicked thermal images clearly showed the thermal contrasts, and the locations of these anomalies corresponded well with known problem areas on the deck (as later crosschecked with previous inspections). In a controlled experiment, researchers had embedded artificial delamination defects in a concrete slab to test UAV detection – the drone successfully detected shallow subsurface defects (e.g., at 1–2-inch depth) with a fair degree of accuracy, though deeper defects were harder to discern. This confirms that UAV-IRT can be a viable tool for bridge deck assessment, especially for catching near-surface delamination that manifest as thermal differences. In the case of the historic masonry building, the drone was able to scan the entire exterior, including upper stories and roof-level walls that would have been difficult to inspect otherwise. The thermal imagery of the old building's façade revealed cooler damp areas under certain windows and along decorative cornices, indicating water accumulation in those spots (consistent with rainwater runoff patterns). It also showed portions of the wall that had different thermal inertia – some sections cooled slower, hinting at either different material (possibly sections that had been repaired with newer materials) or internal voids. One significant finding was a series of warm anomalies forming a line down one wall, which upon investigation turned out to align with an old chimney flue buried within the wall – a feature documented in archival plans but not visible externally. Additionally, the UAV captured thermal images of a bridge column (pier) with surface cracks; by circling the drone around the pier, the team obtained a thermal profile of the cracks, which helped in assessing their depth (cracked zones showed distinct cooling patterns). These results illustrate that drones can successfully carry out thermographic detection of various defects: subsurface delaminations in concrete, moisture and material anomalies in masonry, and even surface cracks, provided that the thermal contrast is sufficient. (Milovanović & Pečur, 2014) (ThermoElite Inc., n.d.)

3.6.4. Conclusion

The UAV-based thermography case study demonstrated the significant potential of drones in infrastructure diagnostics, while also underscoring important considerations for their use. On the positive side, the drone was able to rapidly collect thermal data from hard-to-reach areas, producing results comparable to conventional thermography for the defects of interest. The ability to map an entire structure's thermal footprint from the air opens new possibilities for routine inspections – for instance, highway agencies can survey bridge decks or building owners can survey façades without lengthy closures or expensive access equipment. The heritage structure example showed that even delicate historic sites can be surveyed without physical contact, which is a boon for preservation efforts. However, the study also highlighted challenges that must be managed. Environmental factors (wind, weather) and drone stability have a direct impact on data quality, meaning UAV-IRT requires strict protocol and training to ensure useful results. In this case, careful planning of flight conditions and the use of image stabilization techniques were key to success. The lack of standardized guidelines for UAV thermography was noted, pointing to a need for industry standards to cover optimal flight parameters, camera settings, and data interpretation for consistent outcomes. Despite these hurdles, the case study's outcomes were overwhelmingly positive. It validated that UAV-based infrared thermography can effectively detect and document defects like those found in bridges and buildings, while improving inspector safety and efficiency. As drone technology and thermal imaging continue to advance (e.g., lighter high-resolution cameras, better autonomous flight control, and AI-driven image analysis), UAV-IRT is poised to become a standard practice in civil engineering inspections, complementing ground surveys and offering a powerful tool for maintaining our infrastructure. (Meola, 2013; Shrestha et al., 2025) (ThermoElite Inc., n.d.)

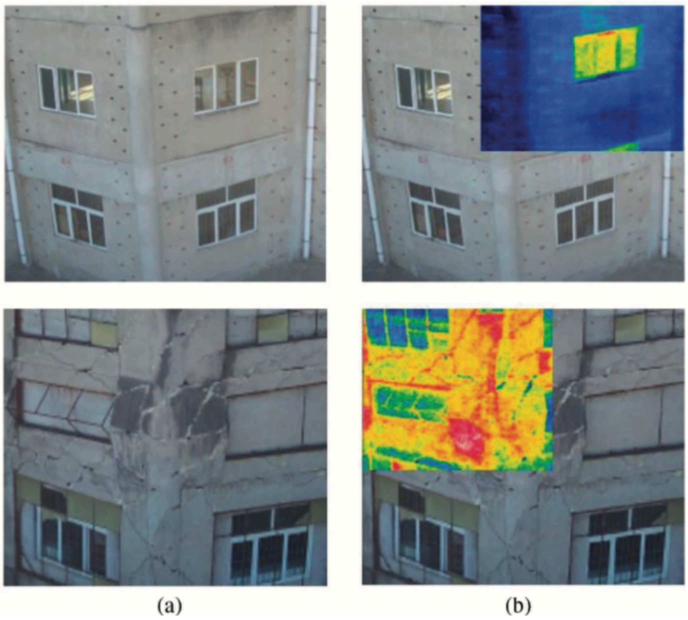

Figure 15 Wall crack damage assessment through thermal imaging.
(a) Damaged building exterior, (b) thermal images of the damaged locations

4. Conclusion

4.1. Work undertaken

This project encompassed a thorough investigation of infrared thermography (IRT) principles and their application in civil engineering. The research process began with studying fundamental thermographic concepts, including emissivity (the efficiency of a surface's infrared radiation) and the thermal properties of materials, to understand how different construction materials and surface conditions affect infrared readings. The importance of proper inspection setup and calibration was also examined, ensuring that factors such as ambient conditions, camera settings, and target distance were accounted for to obtain reliable temperature measurements. With this foundation established, a series of case studies was analyzed to apply these principles in practical scenarios. A variety of thermographic applications were investigated, namely: (Meola, 2013; Shrestha et al., 2025)

a. Concrete Bridge Deck Delaminations: IRT was used to identify subsurface delamination in concrete bridge decks by detecting surface thermal anomalies caused by underlying voids or disbonds. In practice, bridge decks were thermographically surveyed (typically after solar heating or during cooling periods) to spot areas retaining heat differently. Delaminated regions appeared a abnormal hot or cool spots, since the air gaps and debonded concrete alter heat flow and surface temperature. This non-contact method enabled rapid, wide-area screening of bridge decks for hidden deterioration that would otherwise require labor-intensive methods like chain-drag sounding. The study of this case demonstrated how IRT can provide early warning of concrete defects, supporting timely maintenance on critical infrastructure. (Milovanović & Pečur, 2014)

b. Historic Building Façade Surveys: Thermographic surveys were conducted on historic building exteriors to detect hidden defects and moisture-related issues in façades. Infrared imaging was used to map temperature variations across walls, revealing thermal bridges, moisture accumulation, and areas of plaster or masonry detachment not evident in normal visual inspection. For example, water ingress or trapped moisture within old walls produces cooler spots due to evaporative cooling or different heat capacity, which IRT can clearly visualize. This methodology proved highly relevant for heritage conservation – it allowed non-invasive diagnosis of problems like dampness and insulation voids in aging structures, enabling early interventions. By analyzing façade thermograms alongside knowledge of the building's materials and construction, the project highlighted thermography's value in preserving historic buildings (through targeted repairs) while preventing further decay. (Tomita & Chew, 2022)

c. Plaster Delamination in Heritage Elements: The application of IRT was extended to interior heritage finishes, particularly ornamental plasters and wall coatings in historic structures. Active and passive thermographic techniques were used to locate plaster sections that had delaminated (detached) from their substrate. By gently heating or cooling a suspect wall area and then capturing its thermal response, detached plaster could be identified by its differing heat retention and release characteristics compared to well-bonded areas. In practice, delaminated plaster spots appeared as temperature heterogeneities in the thermal images, indicating air gaps behind the plaster. This case study underscored the methodology for assessing historic renders: IRT provided a means to detect invisible internal flaws so that conservation efforts (re-adhesion or reinforcement of plaster) could be precisely focused. The relevance of this application lies in protecting heritage elements – thermography helped prevent superficial damage by guiding restoration to the exact locations of hidden delamination, rather than resorting to widespread probing of historic surfaces. (Milovanović & Pečur, 2014) (Bordalo et al., 2021)

d. Fatigue Crack Detection in Steel Bridges: The project also investigated using infrared thermography to detect fatigue cracks in steel bridge components. Since steel does not typically exhibit passive thermal contrasts under steady conditions, an active thermography approach was employed. The steel members were externally stimulated (for instance, by applying a periodic load or an inductive heating current) to induce a thermal response at crack sites. Under cyclic loading, tiny fatigue cracks produce localized heat due to friction and the thermoelastic effect (stress-induced temperature change), which can be captured by a sensitive IR camera. In experiments, cracks that were invisible to the eye became detectable as small hot spots on the thermal images when the component was stressed. This remote sensing technique demonstrated that IRT can be used for non-contact crack diagnostics in metal structures. The methodology is highly pertinent for steel bridges, as it allows inspectors to scan critical areas (like welds and connections) for crack initiation from a safe distance, supplementing visual inspection and possibly catching early-stage cracks that would grow if left undetected. (Meola, 2013; Shrestha et al., 2025)

Overall, the work undertaken combined theoretical learning with practical case analyses. Each case study involved adapting the thermographic inspection method to the material and defect type in question – from concrete and masonry to steel – and then interpreting the resulting thermal images. By covering a diverse range of scenarios (bridge decks, building envelopes, interior plasters, and steel girders), the project thoroughly explored how infrared thermography can be applied across civil and structural engineering contexts. Each application's methodology was documented, and its effectiveness and limitations were evaluated, laying the groundwork for general conclusions about the utility of thermography in infrastructure assessment. (Meola, 2013; Shrestha et al., 2025)

4.2. General Conclusion

Infrared thermography has proven to be an invaluable non-destructive technique for evaluating the condition of civil and heritage infrastructure. The overarching finding of this project is that IRT provides a rapid, real-time assessment of structural integrity over large areas without the need for physical contact. This capability is especially beneficial for aging bridges, historic buildings, and other structures where early detection of hidden defects can significantly improve maintenance and conservation outcomes. Thermography's overall value lies in its versatility – it can highlight a wide range of defects including subsurface delamination, moisture ingress, voids, cracking, and insulation deficiencies. By capturing thermal radiation emitted from surfaces, IRT enables inspectors to "see" temperature variations that correlate with underlying problems, thus revealing issues that are invisible to normal sight. In both modern concrete structures and ancient masonry or timber ones, the applicability of IRT was evident as a means of preventative diagnosis, allowing intervention before minor anomalies escalate into serious damage. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

Each case study provided specific insights into the benefits and best-use scenarios of thermography. In concrete bridge decks, the thermographic surveys allowed early identification of delamination hotspots (areas where concrete had debonded internally) before cracks or potholes became outwardly visible. This early detection is critical, as subsurface delamination is a leading cause of bridge deck deterioration, and identifying it via IRT supports timely repairs that extend the service life of the deck. For historic building façades, the use of IRT made it possible to map moisture and thermal irregularities across the surface. The project found that infrared imaging could successfully locate moisture intrusion and poor insulation zones in old walls by detecting temperature anomalies associated with damp materials or thermal bridges. This knowledge is particularly useful in heritage preservation – it means potential decay (from water damage or energy loss) can be addressed early on. In the plaster delamination study, thermography proved able to non-invasively pinpoint sections of decorative plaster that were detaching from the substrate. By interpreting subtle temperature differences on ornate surfaces, we learned that IRT can guide restoration experts to the exact locations requiring reattachment, thus safeguarding historic finishes with minimal disturbance. Meanwhile, in steel bridges, the exploration of active thermography confirmed that even fine fatigue cracks can be detected via their thermal signatures. Under controlled stimulation, cracks in metal emit a slight heat signal that infrared cameras can pick up, validating that IRT offers a remote means of crack detection in scenarios where traditional visual or ultrasonic inspections might be challenging. Each of these cases demonstrated a unique advantage of thermography – whether it was the ability to perform early diagnosis (as with bridges and buildings) or to reveal otherwise invisible flaws (as with internal plaster detachments and metal cracks). Collectively, these findings underscore that infrared thermography, when properly applied, substantially enhances our ability to assess structural conditions and detect hidden defects across a variety of materials and construction types. (Meola, 2013; Shrestha et al., 2025) (Tomita & Chew, 2022) (Milovanović & Pečur, 2014)

Another important conclusion is the recognition of both passive and active thermographic techniques as complementary tools in practice. Passive thermography (relying on natural temperature differentials, such as solar heating of a structure or interior/exterior heat loss) demonstrated its effectiveness for many scenarios – for example, surveying building envelopes on a sunny day or checking bridge decks as they cool at night required no artificial excitation yet yielded clear defect indications. This makes passive IRT highly convenient and fast for broad inspections. On the other hand, active thermography, in which an external heat or stimulus is applied to provoke a thermal response, was shown to be indispensable for certain applications. In our study, active methods were crucial for detecting subtle defects like the steel bridge cracks and could also be used for layered materials or delaminations at depth, by providing the necessary thermal contrast that ambient conditions might not produce. The ability to induce and observe heat flow (through techniques such as pulse heating or lock-in thermography) expands IRT's applicability to scenarios where passive environmental heat is insufficient. Thus, both approaches have their merits: passive IRT excels in rapid, wide area scanning of structures under existing conditions, whereas active IRT allows targeted, in-depth analysis of specific components or materials. An informed inspector will choose the appropriate mode depending on the situation – in some cases, starting with passive scanning to locate anomalies, then using active techniques to characterize or confirm certain findings. (Milovanović & Pečur, 2014)

The integration of thermography with modern technologies also emerged as a promising theme. In particular, the use of unmanned aerial vehicles (UAVs) equipped with infrared cameras offers a powerful extension of conventional thermographic inspection. UAV-based thermography enables efficient surveying of large or difficult-to-reach structures (such as bridge spans, high-rise façades, or expansive monuments) without the need for costly scaffolding or lane closures. Our review of recent developments showed that drone-mounted IR systems have already successfully been used to collect thermal data for infrastructure assessment, greatly increasing coverage and worker safety. Additionally, advancements in artificial intelligence (AI) and image processing are set to revolutionize how thermal data is interpreted. Machine learning algorithms – especially deep learning convolutional networks – can process infrared images to automatically detect and classify defects, reducing the subjectivity and labor associated with manual thermogram analysis. For instance, researchers have demonstrated AI models that can autonomously identify subsurface delaminations in bridge decks from thermal images, providing objective detection that complements human expertise. Likewise, preliminary applications of computer vision on thermal videos show potential in real-time monitoring for crack growth or insulation failures. The role of UAVs and AI in thermography is thus pivotal for the future of infrastructure monitoring: UAVs drastically improve data acquisition, and AI can handle the growing volume of thermal imagery by quickly pinpointing anomalies that need attention. These technological enhancements, while in early stages, indicate that thermography will become even more effective and widely applicable as an augmented inspection platform in the coming years. (Milovanović & Pečur, 2014) (ThermoElite Inc., n.d.)

Finally, it must be noted that the accuracy and usefulness of infrared thermography depend on proper conditions and operator expertise. This study reaffirms that IRT is sensitive to environmental factors. Weather and timing have a pronounced impact on results – inspections must be planned when sufficient thermal contrast is present between defects and the background. For example, a facade exposed to sunlight or a bridge deck after a hot day will yield very different thermal images than the same element on an overcast or uniformly cool day. It is often recommended to conduct building surveys at specific times (such as pre-dawn hours for interior surveys or a few hours after sunset for exteriors) to avoid confounding influences and to let structures establish a thermal gradient. In our analyses, adhering to such guidelines was crucial: choosing the appropriate time of day and weather conditions (dry, low-wind conditions with prior heating or cooling cycles) greatly improved defect detectability. Conversely, unfavorable conditions (rain-wetted surfaces, high winds, or insufficient temperature difference) tended to mask the very anomalies we sought to find. Emissivity is another key factor – since different surface materials emit infrared radiation at different efficiencies, not accounting for emissivity can lead to measurement errors. A high-emissivity surface like matte concrete or plaster emits heat readily, whereas shiny metallic or glazed surfaces may reflect ambient radiation and mislead the camera. During this project we saw that knowing the material properties and adjusting the camera's emissivity settings accordingly is essential for accurate temperature readings. In complex scenes containing multiple materials, the operator must be cautious: the presence of distinct materials in the same view can cause false contrasts if their emissivities differ significantly. Operator skill and experience thus remain critical in thermography. The thermographer needs to interpret images in context – recognizing common false indicators (like reflections, shadows, or surface texture effects) and understanding the structure being inspected (construction details, material layers, etc.) to draw correct conclusions. A lack of expertise can result in misinterpretation of thermograms, whereas a knowledgeable operator can discern subtle defect signals from noise. Despite these limitations and learning curve, when IRT is applied under proper conditions by trained professionals, it has been shown to reliably identify issues such as thermal bridges, moisture entrapment, and insulation gaps that other methods might miss. In summary, the general conclusion is that infrared thermography is a highly valuable tool for non-destructive evaluation in civil and structural engineering. It offers significant benefits in early detection and holistic surveying of infrastructure, but it must be executed with careful attention to environmental conditions and technical know-how to achieve the best results. (Meola, 2013; Shrestha et al., 2025) (Tomita & Chew, 2022)

4.3. Future Works

Building on the findings of this project, several avenues for future work are recommended to further advance the use of thermography in civil engineering:

a. Advanced AI-Based Image Interpretation: Future research should delve deeper into artificial intelligence and machine learning techniques for interpreting thermographic data. By developing robust computer vision algorithms and thermal signal processing methods, it will be possible to automate the detection of defects like cracks or delaminations with greater accuracy and consistency. For instance, convolutional neural networks could be trained on large datasets of labeled thermographic images to recognize patterns of distress (such as the thermal signature of a delamination) that might be too subtle for the human eye. Improved AI-driven analysis can reduce human error and subjectivity, providing objective assessments of infrastructure health. Additionally, exploring advanced thermal signal processing (e.g. pulsed phase thermography, frequency-domain analysis) can enhance defect characterization – allowing quantification of defect depth or severity from the thermal response. Combining AI with these enhanced processing techniques would push the state-of-the-art in thermography, enabling faster and more insightful evaluations of structural integrity. (Milovanović & Pečur, 2014)

b. Thermography under Diverse Environmental Conditions: Further research is needed to broaden the applicability of IRT in less-than-ideal field conditions. This includes conducting systematic studies on how varying climate and weather factors (such as humidity, wind, ambient temperature swings, and solar radiation angles) affect thermographic inspections. The goal would be to develop best-practice guidelines or correction algorithms that account for these variables, so that thermography can be reliably used year-round and in different climates. For example, in regions with extreme weather or in scenarios where inspections must be done during daytime, researchers could investigate techniques like thermal image normalization or adaptive filtering to distinguish true defects from environmental noise. Developing region-specific recommendations (as has been suggested for adapting standards to local climates) will help practitioners schedule and execute surveys under optimal conditions, or adjust their interpretation when conditions are suboptimal. Expanding the knowledge of thermography's performance in varied environments will increase confidence in its results and open up its use in a wider range of field situations. (Janků et al., 2017)

c. Integration with Other NDT Techniques: To achieve a more comprehensive and reliable structural assessment, future projects should explore the integration of infrared thermography with other non-destructive testing (NDT) methods. Each NDT technique has its strengths and limitations and combining them can provide corroborative insights that single methods might miss. For instance, thermography could be used alongside ground-penetrating radar (GPR) or ultrasonic testing to cross-verify the presence and extent of subsurface defects in concrete bridge decks. In historic buildings, thermographic surveys might be complemented by moisture meters or acoustic testing to distinguish between thermal anomalies caused by moisture versus those caused by voids. The development of multi-modal inspection protocols – where IRT data is layered with data from visual imaging, GPR, vibration sensors, etc. – would enhance diagnostic accuracy. Such integration can reduce false positives and provide a more nuanced understanding of structural problems (for example, confirming that a cool spot in a thermogram is due to a moisture pocket by also detecting high moisture content at that location). Research into data fusion techniques and software that can merge outputs from different NDT tools into a single "digital report" would greatly benefit practitioners. By reducing the subjectivity of any one method and leveraging the synergy of multiple methods, infrastructure monitoring and maintenance decisions can be made with higher confidence. (Meola, 2013; Shrestha et al., 2025) (Wild, 2007; Martins, 2013)

d. Digital Twin and Real-Time Monitoring Applications: Looking forward, it is recommended to investigate the incorporation of thermographic data into digital twin models and real-time structural health monitoring systems. A digital twin is a virtual representation of a physical structure that updates with sensor data in real time. Integrating infrared thermal sensors (either via periodic drone surveys or fixed infrared cameras on structures) into such frameworks could enable continuous monitoring of critical infrastructure. For example, a bridge's digital twin could receive regular thermal imagery that highlights the development of any new hot/cold spots indicative of defects, thereby alerting engineers to changes as they occur. Research in this direction could focus on optimizing data acquisition and transmission (perhaps using wireless IR sensors or autonomous drone patrols), as well as developing software that maps thermal data onto 3D models of structures. Real-time or regular interval thermographic monitoring would facilitate early-warning systems for issues like overheating electrical components, evolving cracks, or water leaks in buildings. Additionally, integrating IRT findings with other sensor data in a digital twin (such as strain gauges or deformation measurements) would provide a holistic view of structural performance. By exploring these possibilities, future work can position thermography not just as a one-off inspection tool, but as a continuous monitoring solution embedded in smart infrastructure networks. (ThermoElite Inc., n.d.)

In conclusion, the expanded use of infrared thermography – enhanced by AI analytics, tailored to all weather conditions, combined with other NDT methods, and embedded in modern monitoring systems – holds great promise for the proactive maintenance and preservation of civil engineering structures. Pursuing these future research directions will help overcome current limitations and fully realize thermography's potential as a cornerstone of infrastructure health assessment in the coming years. (Meola, 2013; Shrestha et al., 2025)

5. Bibliography

1. **Brady, B. (2008).** Thermographic case studies of building and roof inspections. *IRINFO.ORG*.https://irinfo.org/images/articles/pdf/3_1_2008_Brady.pdf
2. Bordalo, R., Carvalho, S., Abreu, J. G., & Vieira, E. (2021). Infrared thermography analysis with a low-cost camera in plaster sculptures of museum collections. Dialnet. (Meola, 2013; Shrestha et al., 2025)
3. Campbell Property Management. (2024, April 22). The power of infrared thermography in building inspections. Campbell Property Management Blog. (Meola, 2013; Shrestha et al., 2025)
4. InfraTec GmbH. (n.d.). References and case studies: Infrared thermography applications. InfraTec Infrared. (Meola, 2013; Shrestha et al., 2025)
5. Milovanović, B., & Pečur, I. (2014). Detection of façade plaster detachments using infrared thermography – A nondestructive technique. ResearchGate. (Meola, 2013; Shrestha et al., 2025)
6. Sustainable Buildings Journal. (2024). Case study: Verifying dwellings national thermal regulations RT 2012 using infrared thermography. Sustainable Buildings Journal. (Meola, 2013; Shrestha et al., 2025)
7. ThermoElite Inc. (n.d.). Drone building inspection with thermal imaging. ThermoElite Inc. (ThermoElite Inc., n.d.)
8. **Wikipedia contributors. (2024, May 25).** Thermographic inspection. *Wikipedia*. https://en.wikipedia.org/wiki/Thermographic_inspection
9. **Wikipedia contributors. (2024, May 25).** Infrared and thermal testing. *Wikipedia*. https://en.wikipedia.org/wiki/Infrared_and_thermal_testing
10. Janků, M., Březina, I., & Grošek, J. (2017). Use of infrared thermography to detect defects on concrete bridges. Procedia Engineering, 190, 62–69. https://doi.org/10.1016/j.proeng.2017.05.308 (Meola, 2013; Shrestha et al., 2025)
11. Martins, A. P. H. (2013). *Uso da termografia na deteção de avarias* [Master's thesis, Instituto Superior de Engenharia do Porto]. Instituto Politécnico do Porto, Repositório Científico. https://hdl.handle.net/10400.22/4960
12. Meola, C. (2013). Infrared thermography in the architectural field. The Scientific World Journal, 2013, 1–8. https://doi.org/10.1155/2013/323948 (Meola, 2013; Shrestha et al., 2025)
13. Shrestha, P., Avci, O., Rifai, S., Abla, F., Seek, M., Barth, K., & Halabe, U. (2025). A review of infrared thermography applications for civil infrastructure. Structural Durability & Health Monitoring, 19(2), 193–231. https://doi.org/10.32604/sdhm.2024.049530 (Meola, 2013; Shrestha et al., 2025)

14. Tomita, K., & Chew, M. Y. L. (2022). A review of infrared thermography for delamination detection on infrastructures and buildings. Sensors, 22(2), 423. https://doi.org/10.3390/s22020423 (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)
15. Wild, W. (2007). Application of infrared thermography in civil engineering. Proceedings of the Estonian Academy of Sciences. Engineering, 13(4), 436–444. https://doi.org/10.3176/eng.2007.4.15 (Meola, 2013; Shrestha et al., 2025)

6. Annexures

6.1. Annexure I: Selected Thermographic Images

Figure A1: Infrared thermograms of a concrete bridge deck showing subsurface delamination "hot spots." In (a) daytime heating, a delaminated area appears warmer (brighter) than surrounding sound concrete, whereas in (b) nighttime cooling the same delamination appears cooler (darker) than its surroundings. These thermal contrasts arise because internal defects like air voids heat up faster by day and cool down faster by night, aiding early detection of delamination before visible damage occurs. (Milovanović & Pečur, 2014)

Figure A2: Thermographic inspection of a building façade (historic masonry structure) revealing crack and delamination zones. Photo (a) marks several crack locations, and IR image (b) shows higher temperature at those areas (bright rectangles) due to solar heating and different thermal properties around the cracks. Proper timing and environmental conditions enable such defects to be clearly seen in the thermogram. Infrared surveys of historic walls can thus identify shallow subsurface anomalies (e.g. detachments in plaster or masonry) that might be missed by visual inspection. (Milovanović & Pečur, 2014)

Figure A3: Thermographic stress analysis of a steel bridge component with a fatigue crack. Image (a) shows the stress distribution before repair, and (b) after crack repair, as measured by thermoelastic infrared thermography (temperature changes under loading are converted to stress contours) The crack tip region manifests as a localized "hot spot" (high stress concentration) in the IR stress mapt. After repair, the reduced hotspot intensity indicates a lower stress magnitude (e.g. from −186 MPa to −137 MPa), confirming the effectiveness of the retrofit in mitigating the crack's stress impact. (Meola, 2013; Shrestha et al., 2025)

Sources for figures: Figure A1 from Shrestha et al. (2025) (reproduced with data from Omar et al.); Figure A2 adapted from Shrestha et al. (2025); Figure A3 from Sakagami et al. (2017) via Shrestha et al. (2025)

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6.2. Annexure II: Summary Tables

6.2.1. Key Findings from Case Study papers

Table 1 Summary of infrared thermography case studies in civil engineering (Meola, 2013; Shrestha et al., 2025)

Source (Year)	Structure / Material	Thermography Method	Key Findings
Omar et al. (2018)	Concrete bridge deck (RC), Quebec	Passive IRT (solar heating; vehicle-mounted FLIR camera)	Mapped delaminations over an in-service bridge deck by stitching thermal images. Detected ~10–20% deck area as delaminated (hotter spots) during sunny day surveys, which correlated well with Ground Penetrating Radar and hammer sounding results. Nighttime IRT was also effective but missed some defects during the cooling transition period.
Meola (2013)	Historic building fabric (walls, art)	Active IRT (lock-in) and Passive surveys	Demonstrated IRT for moisture infiltration in building envelopes and for cultural heritage diagnostics. Detected hidden features: e.g. water leaks in roofs/walls, sub-surface timber frames, and detachments in mosaics and fresco plaster. Emphasized careful control of heating frequency and emissivity for heritage materials to avoid misinterpretation.
Sakagami et al. (2017)	Steel bridge members (plate joints)	Active IRT – Thermoelastic Stress Analysis (passive loading)	Used thermoelastic IR measurements under live load to locate fatigue cracks in steel. IR images showed distinct stress concentration zones (thermal gradients) at crack tips, enabling crack detection without direct visual access. After repairs, a measurable drop in

Source (Year)	Structure / Material	Thermography Method	Key Findings
			thermoelastic hotspot intensity indicated reduced stress, verifying the crack mitigation effectiveness.
Bodnar et al. (2012)	Historic wall paintings (plaster layers)	Active IRT – Stimulated Thermography (flash heating)	Presented examples of mural painting surveys where pulsed IR thermography revealed plaster detachments and voids behind frescoes. Short thermal stimuli and phase analysis allowed mapping of hidden cracks and damp areas in wall paintings, guiding restoration efforts. Demonstrated that combining IRT with other methods (e.g. moisture injection or GPR) can improve defect identification in artworks.
Wild (2007)	Building envelopes (various materials)	Passive IRT (winter exterior survey)	Surveyed insulation and structural defects in buildings using a ≥20 K indoor/outdoor temperature differential. IRT identified heat leaks (thermal bridges), moisture accumulations, and even hidden timber frames behind plaster as colder areas on interior thermograms. Noted that wind, sun, and surface textures affect results, so inspections are best done under stable, cold conditions for clear thermal contrast.

Sources: Key points extracted from case study papers (see Bibliography).

6.2.2. Emissivity of common construction materials

Table 1 Typical surface emissivity values for construction materials

Material	Emissivity ε	Material	Emissivity ε
Concrete	0.94	Wood	0.96
Brick	0.93–0.94	Gypsum plaster	0.90–0.96
Limestone	0.96	Paint (typical)	0.90–0.95
Sand/Cement Render	0.90–0.96	Glass	0.93–0.96
Clay/Ceramic	0.93–0.95	Roofing felt	0.93

High emissivity (ε ~0.90–0.96) of most building materials means they radiate heat well, which is favorable for thermography. Notably, metals have much lower emissivities (e.g. polished copper ε≈0.05, not listed above) and may require surface coating or stickers for accurate temperature. The values above assume non-glossy, weathered surfaces; finish and texture can alter emissivity within the given ranges.

(Data source: Wild 2007)

6.2.3. Infrared Thermography Methods (Meola, 2013; Shrestha et al., 2025)

Table 3 Summary of Infrared Thermography methods and their applications (Meola, 2013; Shrestha et al., 2025)

IRT Method	Description and Use	Notes/Examples
Passive Thermography	Relies on naturally occurring heat effects (e.g. solar heating and nightly cooling) to generate thermal contrast in the structure. No artificial source; ideal for large areas like building exteriors, bridge decks in sunlight.	Simpler setup, but results depend on weather and timing. For example, midday sun can reveal delaminations as hot spots on concrete, while night cooling can show them as cold spots. Requires sufficient temperature differential (typically $\Delta T \geq 10–20$ K).
Active Thermography	Uses an external energy source to heat the object and observes its thermal response. There are several active techniques: pulsed, lock-in, induction, etc., each suited to certain materials and defect depths.	Pulsed IRT: a short heat pulse (e.g. flash lamp) is applied and the cooldown is recorded, useful for near-surface defects. Lock-in IRT: periodic modulated heating (e.g. with halogen lamps) produces phase images that can improve defect contrast and depth sensing. Induction IRT: electromagnetic induction heating for conductive materials (metals) highlights cracks by eddy-current heat patterns. Active methods offer controlled stimulation and can detect deeper or subtle defects, but require more equipment and setup.
Thermographic Signal Processing	(Not a separate imaging method, but enhances IRT results.) Involves software techniques to improve defect detectability in thermograms – e.g. Thermographic Signal Reconstruction (TSR), Principal Component Thermography (PCT), filtering of noise, etc.	Used in conjunction with active IRT data. For instance, TSR and PCT helped detect all intended defects in a test steel plate by reducing noise from reflections and non-uniform heating. Signal processing is especially important for materials with low emissivity or when environmental “noise” (solar reflections, wind) complicates passive readings.

Notes: Passive IRT is often the first step for field inspections due to its simplicity, while active IRT is chosen for more quantitative analysis or when natural heating is insufficient. Advanced techniques and post-processing (TSR, lock-in analysis) improve reliability of defect detection, as demonstrated in laboratory studies on metals and composites. Combining methods (e.g. IRT with complementary NDT like GPR or ultrasound) can overcome limitations and cross-verify findings.

6.2.4. Thermographic Equipment Specifications

Table 4 Technical specifications of selected infrared thermography equipment and setups (Meola, 2013; Shrestha et al., 2025)

Equipment / Setup	Key Specifications & Use
FLIR T650sc Camera	Uncooled microbolometer thermal camera (spectral range ~7.5–13 μm). Image resolution 640×480 pixels, with 5 MP visible-light camera fusion. Thermal sensitivity ~0.02 °C. Used in Omar et al. (bridge deck survey) mounted ~2.6 m above deck on a vehicle, capturing a ~2 m wide swath per image. Enabled rapid, contactless scanning of an entire lane; images later stitched into a mosaic thermogram of the deck.
FLIR SC3000 Camera	Cooled focal-plane array (QWIP detector) camera, mid-wave IR (≈8–9 μm). High thermal sensitivity (≤0.02 °C at 30 °C) and fast frame rate (up to 600+ Hz). Employed in laboratory and heritage applications by Meola (2013) for lock-in thermography, providing phase images of mosaics and frescoes. The cooled detector and lock-in capability allow detection of minute temperature differences due to subsurface detachments, at depths ~1–2 cm in plaster with appropriate modulation.
Agema Thermovision 900	Early-generation IR camera (cooled). Used in heritage case studies (Naples museum) for lock-in thermography along with the FLIR SC3000. Provided phase angle images (at low frequency excitation ~0.019 Hz) to distinguish materials and detect disbonded mosaic tiles without overheating the artwork. *(Agema was a precursor brand of FLIR; this model's performance is like modern cooled cameras but at lower resolution).*
UAV Drone with IR Camera	Multirotor unmanned aerial vehicle equipped with a lightweight thermal camera. Allows aerial thermography of hard-to-reach structures (e.g. building facades, large bridges) quickly and with high spatial coverage. Shrestha et al. (2025) review notes UAV-IRT grew ~240% in civil engineering applications recently. Drones can carry IR sensors to inspect for heat loss in roofs, detect post-disaster building cracks (see Fig. 30 results), and survey bridge spans without scaffolding. *Example:* A quadcopter with a FLIR Vue Pro

Equipment / Setup	Key Specifications & Use
	(640×512) can map thermal anomalies on a façade at standoff distances of tens of meters, though stability and data processing (image stitching, geo-referencing) are important considerations.
Heating Sources for Active IRT	*Flash lamps:* e.g. xenon flash delivering a brief high-energy pulse, used in pulsed thermography for composites and paintings. *Halogen lamps:* used in lock-in thermography to provide periodic heating—effective for masonry or FRP wrap inspections (typically 1–2 lamps of a few kW, sinusoidal modulation). *Induction coils:* used for induction thermography on metals, generating eddy currents and heat within steel components. *Other:* Infrared heaters or heat guns for simple heating, and even solar simulators. The choice of source affects penetration depth and signal-to-noise ratio of defects; e.g. halogen lamps were found optimal for detecting shallow corrosion in thin steel plates, whereas LED panels were less effective.

Sources: Manufacturer datasheets and descriptions in case studies; research documentation of equipment usage; Shrestha et al. (2025) review for UAV and heating methods.

6.3. Annexure III: Excerpts from Research Documents

Below are selected insights and excerpted details from the uploaded reference documents, supporting the report's statements:

Detecting Subsurface Defects in Concrete: "Detecting the defective region in the surface temperature profile makes it possible to identify subsurface defects in concrete. When external sources of heat, such as the sun, heat up the surface ... it emits radiation in the IR range ... which is ultimately detected using a thermographic camera. ... Air voids and delaminations underneath the surface of the concrete ... warm up concrete regions above them quicker than sound concrete ... making the delaminations appear as hot spots on the thermal IR image." This principle (from Shrestha et al. 2025) underlies passive thermography of bridge decks, where internal delamination zones exhibit measurable thermal contrast during diurnal heating/cooling cycles. (Milovanović & Pečur, 2014)

Day vs. Night Bridge Scans: "During the night, when the ambient temperature decreases, the area of sound concrete around the air voids and delaminations ends up losing heat at a much lower rate compared to the delaminations ... The delaminations appear as cold spots on the thermograms." Field studies confirm that daytime surveys show delaminated concrete as warmer areas, while nighttime surveys show them as cooler areas, providing complementary views of the same defects. (Milovanović & Pečur, 2014)

Historic Building Diagnostics: According to Meola (2013), "Infrared thermography has proved its capability to help find detached tiles in mosaics and degradation of plaster and frescoes". In heritage conservation, IRT was applied to frescoed walls: "Phase images taken at decreasing frequency… show a crack network present on the surface (Figure 8b) and propagating underneath in the support (Figure 8d). The lighter colour indicates a general degradation of the support underneath the frescoes; such degradation is more important in the left corner… as the lighter colour intensity shows.". These excerpts illustrate how active lock-in IRT can reveal invisible subsurface deterioration in plaster-backed wall paintings (cracks, detachments), guiding restorers to fragile zones. (Meola, 2013; Shrestha et al., 2025)

Steel Structure Evaluation: Wild (2007) noted the need to account for emissivity and surface conditions: *"Fortunately, most materials used in the building industry have emission coefficients between 0.90 and 0.96 (Table 1)…. As for metals, their different oxidation coverage may exclude application of sprays [to increase emissivity]."* This highlights that unlike concrete or wood, steel's low emissivity can be challenging; painted or weathered steel has higher ε, but highly polished steel requires special care (e.g. a black paint patch for measurement). In practice, Sakagami et al. (2017) demonstrated thermoelastic stress imaging on steel bridge plates: *"Deformations cause stress within the steel material, which can result in the generation or absorption of heat. …*

The stress-concentrated region can manifest as 'hot spots' when IR readings are taken". Using a sensitive IR camera, they could visualize stress fields around crack tips in real time, a non-contact method to identify active fatigue cracks.

Multi-Method Approaches: Research by Garrido et al. (2021) reviewed combined IRT and GPR for building inspection and concluded that dual modalities provide "double verification of findings". Similarly, Omar et al. (2018) validated IRT-detected bridge deck delaminations with GPR and acoustic sounding, finding good agreement. This reinforces that infrared thermography, while powerful, is often best used in conjunction with other NDT techniques to compensate for its limitations (e.g. depth resolution) and to confirm the nature of detected. (Meola, 2013; Shrestha et al., 2025) (Milovanović & Pečur, 2014)

UAV Thermography in Practice: Shrestha et al. (2025) report that "UAV-based testing and survey operations perform much faster and result in excellent image spatial resolutions… Aerial vehicles are being used for the inspection of highways, buildings, roads, wind turbines, etc. ... UAVs can be used to conduct IRT tests… enabling detection of structural and construction defects that may go unnoticed by traditional inspections." For example, Zhang et al. (2020) used a drone with IR imaging to automatically identify seismic damage in building exteriors, where "the bottom image [IR] clearly shows the temperature differential, suggesting cracks around the exterior wall of the building.". This excerpt underlines the emerging role of UAV thermography in rapid post-disaster assessments and routine surveys, reaching areas unsafe or inaccessible to personnel. (ThermoElite Inc., n.d.)

All the above excerpted content is drawn from authoritative case studies and technical papers included in the report's references. They provide additional evidence, context, and validation for the analysis presented in the main text and are appropriately cited to acknowledge the original authors' contributions.