Infrared thermography and its applications in civil engineering

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Infrared thermography is a powerful tool to investigate structural condition and equally useful for damage assessment. It is a non-contact and non-destructive method that enables rapid investigations. Highly efficient infrared cameras and versatile software have simplified thermography considerably over the years. While infrared thermography has wide applications in process industries, it is not yet extensively adopted in the investigation of buildings. The paper presents a brief historical account of infrared thermography, the phenomenon of electromagnetic radiation, thermal imaging and applications in civil engineering. Numerous other applications of thermal imaging are also discussed briefly along with the advantages and limitations.

Infrared thermography (IRT) can be defined as the science of acquisition and analysis of data from non-contact thermal imaging devices. The process of thermal imaging has simplified over the years with the availability of efficient, high resolution infrared cameras that convert the radiation sensed from the surfaces into thermal images[1]. Thermography literally means 'writing with heat', just as photography implies 'writing with light'. The invisible infrared radiation emitted by bodies is converted into temperature and displayed as thermal images (thermographs).

The recent developments in thermography and image processing has made the technique a valuable addition to the repertoire of non-destructive testing methods. Thermography is not only a non-contact technique but also totally non-destructive[1-6].

History of IRT

Infrared thermography was a chance discovery made around 1800 by Sir William Herschel, an astronomer (1738 – 1822), while searching for new optical filter materials to reduce the brightness of sun's image in telescopes during solar observations[1, 2]. He was surprised to find that some of the samples of coloured glass, inserted in the telescopes to reduce brightness of solar radiation, passed very little of sun's heat while some passed much heat. Herschel measured the temperatures along the spectrum of light from red to violet with the help of a conventional mercury thermometer with blackened bulb. The temperatures were found to increase from violet to red colours of the spectrum, and increased to a maximum value in the dark region well beyond the red end of the light spectrum. He christened the phenomenon 'dark heat' and 'invisible rays', and called that segment of the electromagnetic spectrum as 'thermometrical spectrum'. The term infrared (beyond red) was coined much later.

However, conventional glass has limited transparency to infrared radiation, and is not well suited for thermal imaging. Thermography developed further only after 1830 with the discovery by Macedonio Melloni (1798 – 1854) that naturally occurring rock salt (NaCl) crystals are transparent to infrared radiation. Rock crystals were extensively used in IRT before the advent of synthetic crystals in the 1930s. Melloni developed a sensitive device to detect heat (thermopile) by connecting several thermocouples in series. The first 'heat picture', as it was then called, was obtained in 1840 by Sir John Herschel, the illustrious son of the discoverer of infrared radiation. The light reflected from the differential evaporation of a thin oil film exposed to a heat pattern forms an image visible to naked eye. The thermal image obtained on paper was called 'thermograph' by John Herschel[1].

The sensitivity of the device improved further after the breakthrough invention of the bolometer in 1880 by Samuel P. Langley (1834 – 1906). Bolometer comprises a blackened strip of platinum connected in one arm of a Wheatstone bridge circuit, exposed to infrared radiation, to which a sensitive galvanometer responded. Several patented devices based on infrared radiation to detect personnel, artillery, airplanes, ships and even icebergs were developed during World War I. Some of these devices could detect airplanes 1.5 km away, and persons over 300 m away.

During the intervening period of the two world wars, rapid strides were made to develop infrared detectors capable of converting infrared radiation into visual photo image enabling to 'see in darkness'. While the military advantages of such devices in locating targets are obvious, the earlier devices were handicapped by the necessity to use infrared beams to heat up the targets for detection (active systems). Such search beams involved the risk of being detected by the targeted personnel, and were not considered to be of much tactical use. The World War II witnessed the development of 'passive systems' using photon detectors, that could provide thermal images without 'search beams' (passive systems).

It is only since the 1950s that the secrecy shrouding the wartime developments was lifted, and thermal imaging devices were made available for civilian applications. The earlier devices (infrared cameras, as they are now known) were cumbersome with oscilloscope and camera with weight exceeding 400 N besides a generator set to supply power. The present day devices weigh less than 10 N inclusive of battery, and are available with a wide range of options to suit various applications. The sensitivity of the devices is better than 0.05 ^oC with a temperature range of materials extending to 250 ^oC.

Spectrum of electromagnetic radiation

The electromagnetic spectrum of radiant energy is spread over a wide range of wavelengths, and is divided into various bands depending upon the wavelengths. The wavelength band less than 0.1 nm pertains to gamma rays, X-rays are of 0.1 - 10.0 nm bandwidth, ultraviolet radiation is of wavelength 0.01 – 0.1 μm, visible light has wavelengths between 0.4 – 0.7 μm, while the infrared waves lie in the bandwidth of about 1.0 – 14 μm; farther beyond are microwaves in the band 1.0 – 10.0 mm, and radio waves thereafter in the band extending from 10.0 mm to a few kilometres.

Infrared band comprises near infrared waves of about 1.0 μm, short waves of 2 – 5 μm and long waves of 8 – 14 μm. Not all waves are capable of transmitting thermal energy; the waves somewhere in the ultraviolet band extending to infrared wave bands through the visible band alone can transfer thermal energy. These waves travel at a very high velocity (at about 2,99,792.5 km / s, the speed of light in vacuum).

Energy of different wavelengths is perceived by human eyes as (visible) light of different colours. Radiant energy of 0.4 μm wavelength is perceived as violet light while that of 0.7 μm wavelength as red colour with the wavelengths in between showing up as other colours of a rainbow. While the colour of an object indicates its ability to reflect more of the specific radiation of the wavelength pertaining to that colour than any other energy, visible white light is a mixture of wavelengths.

The short and long wave bands are adopted in infrared thermography. The thermal energy transmitted by the atmosphere depends upon the wavelength of radiant energy. The transmissivity is high in the bands 0.7 - 5 μm and 8 – 14 μm; the band between 5 – 8 μm does not transmit thermal energy.

Thermography and infrared camera

Bodies emit thermal radiation as a consequence of their temperature. While thermal radiation is transmitted by most gases, including atmosphere, it is blocked by most liquids and solids. All the bodies emit and absorb thermal energy besides reflecting a part of the incident energy. The thermal radiation emitted by the bodies depends on their temperature basically, surface condition and thermal properties of the material.

A black body absorbs all the radiant energy (coefficient of thermal absorption = 1.0), and emits 100 percent of its energy. Such an ideal body does not exist in reality, but the concept is useful in comprehending the concepts of thermal radiation. The radiation on a body is partly absorbed, transmitted and reflected. Similarly, the exitant radiation from the surface of a body comprises components of energy emitted, that reflected from the surface and the energy transmitted through the body by a source behind it. The components of exitant energy depends on the emissivity and reflectivity of the surface, and thermal properties (specific heat and conductivity) of the body. Steel elements have uniform temperatures because of high conductivity, while temperatures on a concrete element are likely to vary over its surface.

The infrared camera senses the exitant (radiated, reflected and transmitted) thermal energy from the body, converts into temperature and displays thermal images. While thermal images provide useful data, the exitant energy should be considered in analysing and interpreting the thermal images. While the exact values of thermal properties (surface and body) are not always required to assess thermographs, the sources of radiation from the body (emitted, reflected and transmitted) help in correct assessment. A source of radiant thermal energy close to a body may lead to incorrect interpretation of the images.

It should also be appreciated that infrared camera senses only the radiant energy received from the surfaces, and not the visible light reflected from the surfaces. Thermal images are vastly different from visual images and do not require visible light. Thermal images can be obtained in total darkness. The thermal image of a light bulb appears to glow as brightly in total darkness after it is switched off.

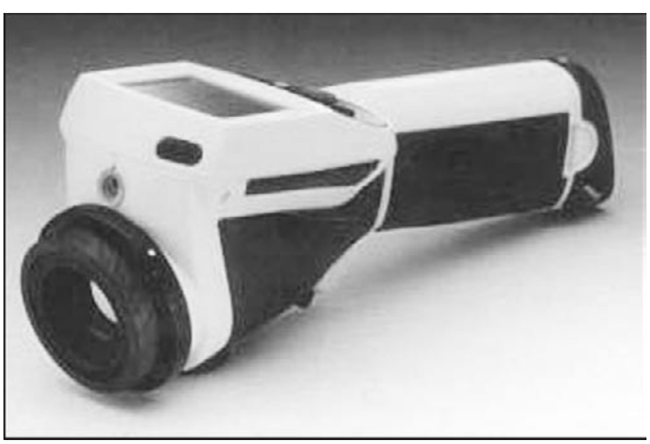


Figure 1. A typical infrared camera

Several types of infrared cameras suitable for various applications are available commercially. The focal length and lens opening govern the quality of image generally. Wide angle lenses (to cover large spaces) and telescopic lenses (to obtain images from a distance) are available for any model. Figure 1 shows a typical infrared camera for applications on buildings.

These cameras and images are used extensively in chemical and manufacturing industry besides electrical engineering and in assessment of buildings and pavements, to mention a few. Infrared cameras are also useful for locating sources of fire in the case of fire ravaged buildings, fire potential of stored materials as well as surveillance. They are used in the food processing industry, wild life studies and diagnostics such as cancer detection.

The energy emitted by a surface is affected by the properties of the body. The changes in the quality of concrete due to local deficiencies such as poor compaction, seepage of water and deterioration, for instance, result in small changes in the surface temperature. Such images enable damage assessment of structures.

The cameras are often application specific. Cameras for applications on structures have lower range and precision than those for electrical equipment (motors and transformers).

Sources of radiation on the body should be shielded from the objects for valid results. It is advisable not to take thermal images in bright sun or when the body is exposed to radiation from any source of heat (glowing lights).

An infrared camera should be handled with considerable care. The lens should be protected from scratches and should never be wiped or touched by hand to protect its sensitivity.

Image processing

The infrared camera is a simple device and can be handled with usual precautions like an ordinary photographic camera. The images have to be focussed and composed the same way. The focus, composition and range of temperatures chosen cannot be altered later, though brightness and contrast can be adjusted in the image to highlight the required details. It is essential to focus the camera for sharp images, compose the significant details being monitored, and set the temperature range for useful results.

The images are processed by software to yield thermal images[2]. Various thermal patterns can be obtained by varying the palette (colour pattern), brightness and contrast of the image for locating details and correct interpretation of images. Various colour palettes can be selected, including grey palette. Thermal images appear as zones of different colours or shades depending upon the temperature range and mean temperature selected.

It should be mentioned here that the visual colours do not necessarily reflect the temperature patterns (thermal images). The bright regions in a thermal image indicate high temperatures, while the dark region indicates low temperatures and the intermediate regions are marked by colours ranging from white to black through yellow, orange, red and indigo. On a grey palette, various shades ranging from white (high temperature) to black (low temperature) distinguish the regions of reducing temperatures.

Figure 2 indicates a typical example; the visual image shows the seepage of water from a flower pot beneath a window of an apartment building. The water left a long streak all along the balcony wall (Figure 2 a). However, the thermal image (Figure 2 b) shows a much shorter streak, barely reaching the bottom of the flower pot. The presence of moisture lowered the temperature in the region, that showed up as a dark band, while the brown streak in the visual image is caused by the deposits due to water seepage.

These aspects should be considered while analysing thermal images. Similarly, some dark patches of low temperatures may be due to local effects (changes in emissivity or spray of water). The effects of surface features (curvature, colour and roughness) on exitant radiation should be assessed properly while interpreting thermal images.

Passive and active thermography

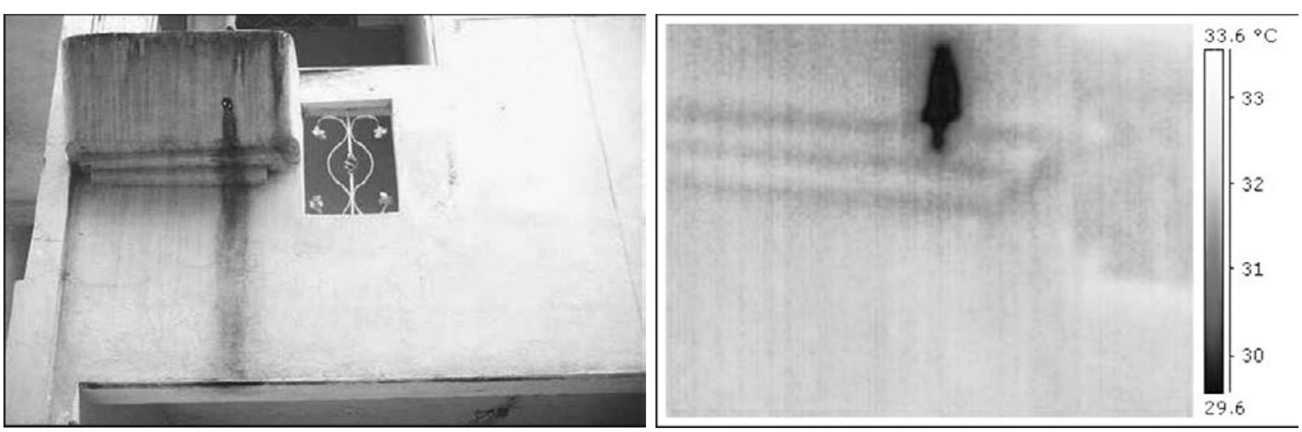
The exitant energy from the surface of a body depends primarily on its temperature. The quality of thermal image depends on the variation in surface temperatures; the greater the contrast in temperatures, the better will be the images.

Thermal images can usually be obtained under ambient conditions. When the body is heated by ambient conditions (solar radiation), it implies passive thermography. Sometimes the body is heated by an external source to obtain temperature contrast. Such a process is known as active thermography. The former process is adopted while assessing large bodies, while active thermography is generally adopted in laboratory investigations.

Other procedures adopted are impulse thermography (local heating), lock in thermography (exposed to infrared radiation) and pulse phase thermography (repeated heating at short intervals of time).

Applications

The technique has numerous applications in condition assessment of structures, locating the source of distress, assessment of damage potential in concrete and masonry structures, identifying moisture ingress and flow through



(a) Visual image **(b) Thermal image**

Figure 2. Infrared camera senses only apparent temperatures and not colours

Figure 3. Moisture penetration in a canopy

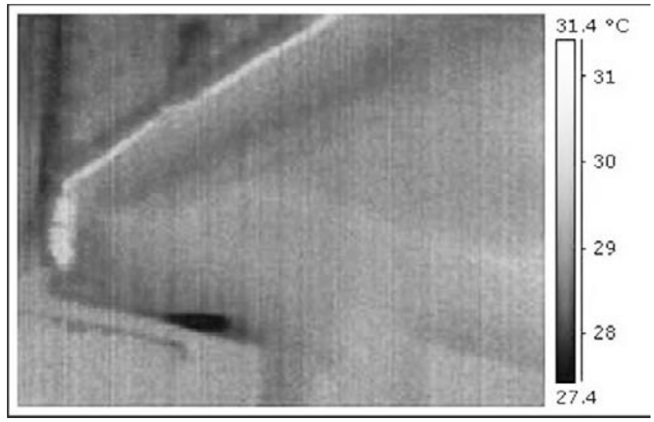


Figure 5. Flow through sewage pipes

pipes. Thermal images are widely used in all branches of engineering including computer systems where it is especially used to locate components of excessive heat generation. Some of the applications with typical images are discussed here briefly.

Moisture penetration

Presence of moisture causes lower temperatures due to ambient evaporation, and consequent cooling of surfaces. Thermal images indicate the regions of temperatures distinguished by various colours or shades, depending upon the palette selected.

Figure 3 indicates the thermal image of a canopy. The image was taken late in the evening on a hot summer day in May. Most of the structure is at a high temperature of about 47°C due to the absorption of solar radiation, but for two bands of about 43°C on the soffit. On closer examination, it was found that the structure has a brick lining on the three free sides and rainwater stagnated along the two bands. Subsequently, dust and muck got deposited along the bands, providing some degree of insulation leading to lower temperatures. Further, the soffit along the bands sounded hollow when struck by a small hammer indicating delamination of plaster and possibly of concrete. The temperature differences caused by the muck deposited and delamination manifested in the form of dark bands.

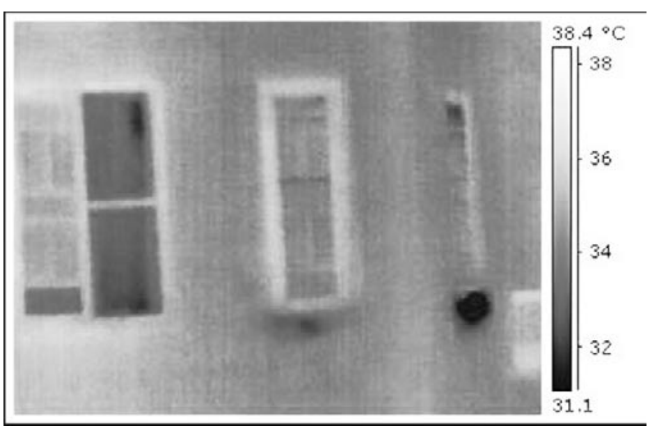


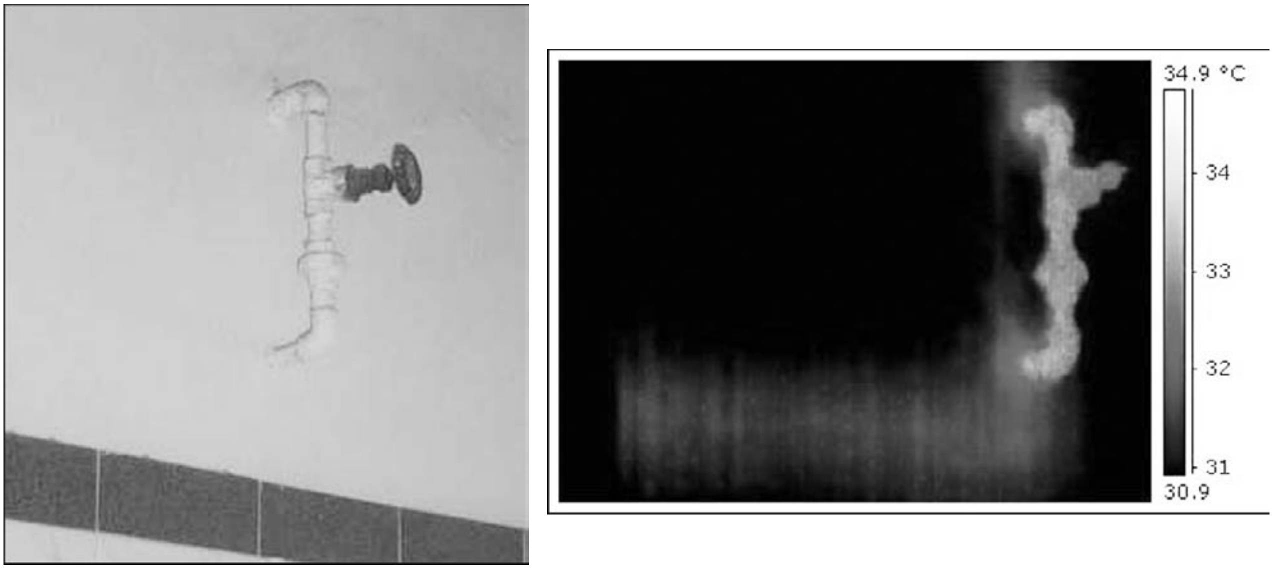
Figure 4. Moisture penetration under the windows of a masonry structure

The dark regions underneath the windows in Figure 4 indicate moisture penetration. The image was taken two days after brief showers in the summer month of May. The rest of the wall is more or less of the same temperature of about 34°C, while the dark regions are at temperatures lower than 31°C, indicating the presence of moisture.

Plumbing

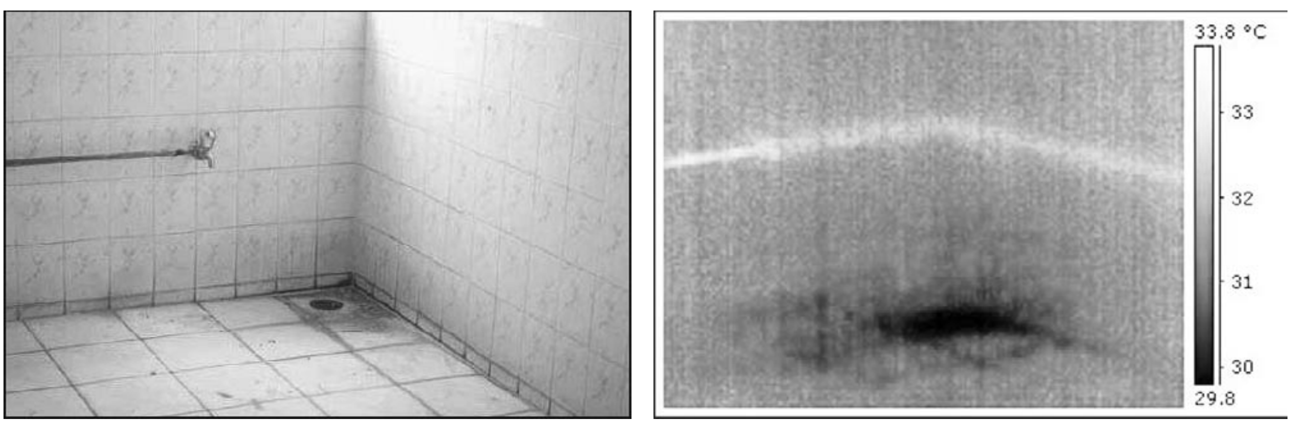
Infrared camera also helps assess plumbing and flow through pipes[7]. Figure 5 is the thermal image of sewage pipes in an apartment building. The flow of warm sewage flowing in the pipes is discernible in the thermal image taken in the morning at about 8.00 am before the pipes were exposed to sunlight. The bright band along the inclined pipe indicates that the pipe is not running full and is not choked and there is no sedimentation. It may also be noticed that the pipe is enclosed in a recess below the cantilever beam. The dark patch on the beam soffit indicates leakage from the pipe and accumulation of moisture. Repairs can be planned to seal the couplings in the regions of seepage suggested by thermal images.

Concealed pipes are difficult locate in a structure and require removal of plaster and masonry to expose them. Figure 6 (a) and (b) indicate the visual and thermal images of a control valve, respectively. The images were taken on a hot day in the month of May, when the



(a) Visual image (b) Thermal image

Figure 6. Images of a sub-surface pipe



(a) Visual image (b) Thermal image

Figure 7. Images of a pipe in a masonry wall

water flowing in the pipe system was heated by the sun as the tank is located on the terrace of the building. The trace of the concealed pipe inside the wall can be noticed by the light band of temperature higher than the wall. The wall is at a temperature less than 31^{o}C, while the concealed pipe is at about 32^{o}C and the exposed pipe is at about 33^{o}C. The small differences in temperatures help locate the concealed pipes.

Similarly, figure 7 (a) and (b) indicate the visual and infrared images of a concealed pipe taken on a hot day in May. The hot water flowing through the concealed pipe locates its position. This technique is useful in locating the quality of grout in prestressing tendons as well[8].

Concrete structures

Thermal images help determine the state of fresh as well as hardened concrete[4]. Figure 8 is the thermal image of a ready mix concrete truck delivering at a site on a hot summer afternoon. The tyres of the truck are at about 46^{o}C, and the pump at a temperature over 50^{o}C, while the drum is at about 38^{o}C. The uniform colour of the drum, with no patches of variation, indicates good mixing and concrete of uniform quality. Figure 9 shows

Figure 8. Ready mix concrete delivery truck

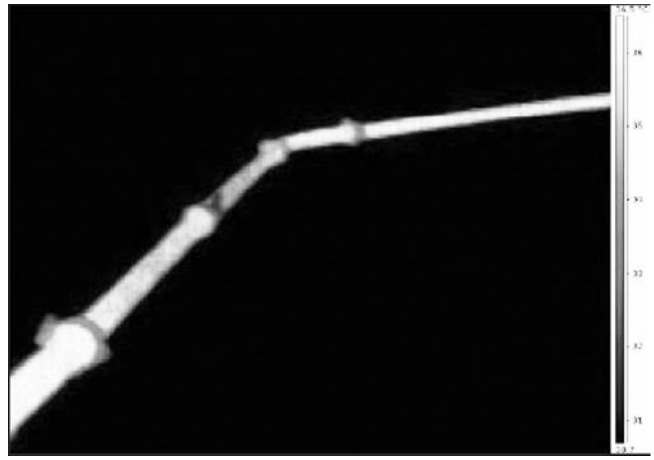


Figure 9. Flow of concrete through a delivery pipe

Figure 10. Hot weather concreting

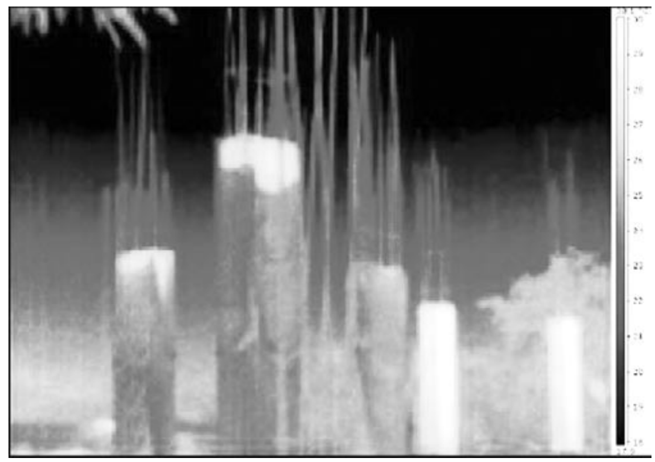


Figure 11. Inadequate curing of columns

a segment of pipe delivering concrete; the leakage of slurry at the joints is discernible in the image.

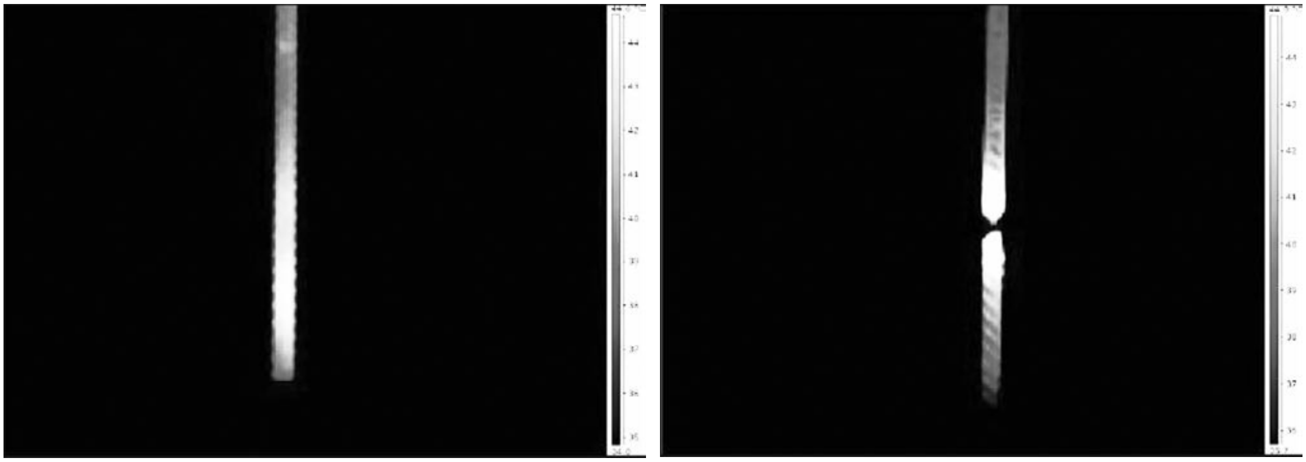
Any obstruction to flow can be observed from the temperature patterns of the thermal image. However, the dark patch on the pipe after the second joint from the left corner is not an obstruction in the flow, but, water spilled on the pipe, Figure 9.

The thermal image of concreting of a slab is shown in Figure 10. The concrete was cast on a hot day with temperature of about 40°C. The concrete poured is cooler than the forms as can be seen from the colour pattern. The forms are at temperatures of about 40 – 44°C due to exposure to direct sun, while the concrete is cooler at 32 – 34°C due to evaporation. The reinforcement bars of the column in the image are at about 38°C. A person with a needle vibrator can also be seen in the image.

The effectiveness of curing procedure adopted can be assessed by the camera. Figure 11 shows the concrete columns of a structure being cured. The image was taken at about 6.00 am (before sunrise) in summer. The bright columns at the right are at temperatures of 29 – 30°C with little curing, while the columns with gunny bags wrapped around are cured better with surface temperatures at about 25°C. However, the upper parts of the columns are not wrapped properly, and appear to have dried out with a surface temperature of about 28°C.

Tension tests on reinforcement bars

Reinforcement bars tested for their tensile strength fail at a section after necking. However, tensile tests do not reveal the yield point precisely, or the critical section until after failure.



(a) Before failure (b) After failure

Figure 12. A deformed bar under tension test

Figure 12 indicates the thermal patterns in a deformed bar during tensile tests. The temperature of the bar increases with load and generally the temperature rise is uniform along the bar length in the elastic region. During the post-elastic loading, the temperatures start increasing locally, in the region of failure, Figure 12(a). The temperature in the critical (brightest) region is about 45^{o}C, while in the vicinity of the critical section the temperature is about 43^{o}C, and the temperature away from the critical section is about 40^{o}C. Figure 12(b) shows the bar after failure, with the tips of the failed section at a higher temperature than the rest of the bar. Thermal image can be useful in determining the yield point more accurately than by conventional strain measurements.

Figure 13 shows a set of tested bars after failure. The bar in the foreground, tested last, is at the highest temperature, while the other bars at lower temperatures can be seen in the background.

The temperature pattern in a bar under bend test is shown in Figure 14. The rise in temperature of the bar at the bent section is discernible. It can also be seen that the bar is at a higher temperature along the outer radius than on the inside. The formation of plastic hinge at the bent section can also be noted in the figure.

Discussion

Infrared thermography is a non-destructive and non-contact testing method. All other NDT methods require access to the test element, and surface treatment (Schmidt rebound hammer and ultrasonic pulse velocity tests). Some of them may at the best be termed as semi-destructive (pull out and push off methods) rather than

Figure 13. A set of tested bars

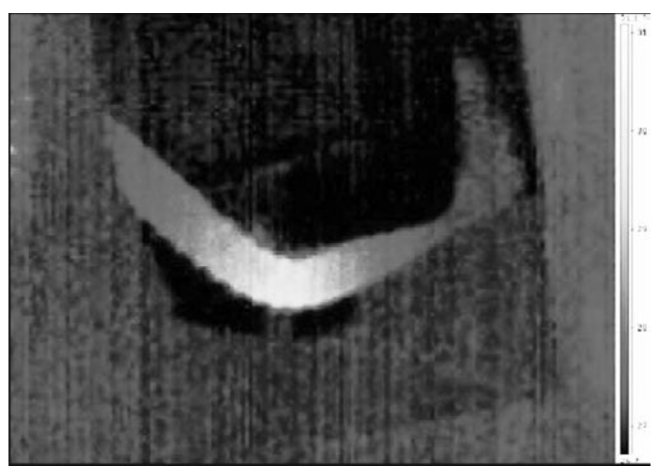


Figure 14. A deformed bar under bend test

non-destructive. In any case, all the methods, including the advanced techniques, such as ground penetrating radar and impulse echo, require direct access and contact with the structural element.

Thermography does not need any access and generally no surface treatment and it does not obstruct construction or restrict the use of the structure during investigations. The device is simple to handle (barely 10 N weight), and can monitor large areas in a short time. The images can be obtained instantly as in a digital camera and can be stored, retrieved and processed further for details later. The process is easy to comprehend, and not highly complex, despite the sophistication of the camera and software.

The cost of the cameras is a deterrent presently, though the prices have reduced significantly in the last five years. Nevertheless, interpretation of the images requires considerable experience, intuition and judgement. Good care is required in handling the camera, in composing and focussing the images.

It should also be emphasised that the images represent the surface temperatures influenced by external factors (ambient conditions and distance from camera) as well as surface conditions (emissivity and coatings). The ambient conditions such as temperature, radiation from surroundings and the time of the day affect the apparent surface temperatures significantly. Thermal images do not always represent the surface temperatures but the values of the apparent temperatures processed from the radiation received by the camera. Further, surface paintings and clutter may camouflage the actual temperatures and lead to incorrect conclusions. However, thermal images can be processed to obtain actual temperatures.

Within these parameters and limitations, infrared thermography provides an excellent tool for rapid assessment of the conditions of large concrete and masonry structures, such as chimneys, towers, bridges and buildings. The method helps in locating moisture penetration in concrete and masonry structures, loss of thermal energy from enclosed spaces to control the costs of airconditioning or heating, flow through pipes (obstructions), apart from identifying the nature of cracks (surface or deep) and delamination. The images provide data about the regions for further investigations and the investigations required.

Thermography is particularly useful in assessing the condition of historical structures, which have limited access and should not even be scratched during the investigations[9].

Other uses of the technique include rapid assessment of quality of bitumen pavements during laying and under service conditions. Uniform temperatures of the bitumen surface being laid indicate good quality control and compaction, while colder regions of the thermal images indicate inadequate compaction and possible early deterioration of pavements[3]. Similarly, regions of lower temperatures on bitumen pavement surface (dark patches in thermal images) indicate ingress of moisture and deterioration[5, 6].

Thermal images of chimneys and cooling towers provide a rapid method of determining surface temperatures for condition surveys. Deterioration due to corrosion of reinforcement, and damage due to fire can also assessed by thermal images.

The camera has numerous uses in locating the sources of problems in electrical (transformers, conductors, motors, fuses and cables), mechanical (pressure vessels, gears and pipes), production (temperatures and sedimentation in pipes and storage tanks), automobile (battery, coolant, pumps and motors), and electronics and IT (sources of overheating and component failures) systems. Thermography is also useful in medical diagnostics as in detecting cancer and other maladies that lead to localised minute changes in body temperatures. Thermography also helps the food processing industry in maintaining suitable temperature conditions. It is also used in wild life studies (census), and in security, surveillance and defence systems.

Firemen would find the images valuable in locating the source of fire in the buildings engulfed by smoke. Often smoke deters firemen from entering the premises on fire and in such cases thermal imaging could help in directing the efforts to put out the fire. In many a case, the firemen spray water into the smoke rather than at the fire because of impaired visibility. Thermal images can be used to locate the regions of heat so as to direct the extinguishing jet effectively.

Summary

Thermal images provide an excellent tool for rapid assessment of structures. Being a non-contact and non-destructive method, it is useful in rapid condition survey of structures without requiring any access. The method has immense potential in quality control during construction as well as investigations on deteriorated structures without interrupting construction or utility of the structure.

The basic concepts of thermography, historical developments and current trends are discussed in this brief paper. The technique and the equipment, besides the software for image processing are also explained. Various processes of thermography, and the applications in investigating concrete and masonry structures are presented. The applications include assessment of pavements, historical structures, plumbing, sewage lines, cracks, delamination and moisture ingress.

Other uses of infrared camera include a wide range of fields – electrical, mechanical, production, automobile, electronics and computer systems. It is also useful in fire fighting, food processing industry, wild life studies, and security, surveillance and defence systems.

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