Thermal Performance Assessment of Curtain Walls of Fully Operational Buildings Using Infrared Thermography and Unmanned Aerial Vehicles

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Abstract

Architecture's race skyward has brought with it a variety of functional innovations, one such being glass curtain wall systems. During such building's operating life, failures of insulation systems create areas of reduced resistance to heat transfer, or thermal bridges. These failures enable energy flows that trigger unanticipated temperature changes and increased energy consumption and ultimately, damage the façade structure and cause problems to occupants. Discussion includes design and test method for rapidly identifying thermal bridges in façade systems, with minimum or no-disturbance of occupants. Research focus is set in determining if the damages are just local failures or if they are related to a poor systematic construction assembly. A non-traditional approach is adopted to survey an entire fully operational building using infrared thermography and an Unmanned Aerial Vehicle (UAV). The system is comprised of a non-contact infrared camera mounted on and operated from the UAV. It enables the registration of the emissivity of the façade materials and calculation of the thermal radiation and equivalent factors to estimate localized temperatures. The registration process yields thermal imaging results of the actual state whose temperature will be analyzed quantitatively using graphs and compared with the ASHRAE standards, retrieving the perfect state using THERM software. After evaluation of the results a statistical analysis will be performed, to inform the Architecture, Engineering, and Construction (AEC) community about the areas of most common failures for existing structures. It is expected that the results will also identify improvements for construction methods by projecting better and more efficient processes.

Keywords

Curtain wall system • Building thermal performance • Thermal bridge • Infrared thermography
Unmanned Aerial Vehicle (UAV)

84.1 Introduction

The curtain wall system is an enclosure technique for buildings. It is comprised of several crystal panels assembled to bear its own weight and resist exterior loads such as wind or rain [24]. Most commonly, curtain wall panels are aluminum, span one floor, and support the main structure [18]. Thermal bridges are discontinuities in the curtain wall's thermal barrier, which is the building enclosure that provides an interior insulated environment for HVAC systems, control of vapor transfer, and thermal efficiency. Thermal negative effect is increased in the presence of a highly conductive material, like metal-exterior curtain walls [23]. The metal-exterior curtain wall is formed by vertical and horizontal exterior structures, crystal panels, and sealant finishing. Thermal bridges are most usually located on the interphase between the glass and metal panels or between different crystal panels where the sealant is placed [20]. A highly conductive material (e.g., aluminum) needs sealant as

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thermal breaks made from a non-conductive material (e.g., plastic or rubber) to prevent heat transfer and to provide resistance to condensation.

Several components of the curtain walls could perform poorly producing a thermal bridge. A common cause of problems is the failure of the gaskets and sealings [22]. Gaskets are strips of synthetic rubber or plastic, which also damper the glass when the structure suffers movement. Sealant is a flexible element but the glass is fragile and stiff so a small displacement is allowed by the structure. With age, gaskets dry out, shrink, and the elasticity degrades. Air spaces are created which admit air and moisture inside, leading to condensation, drafts, and leaks. This infiltration of condensation may point to failure, compromising thermal performance and visibility. As the gaskets further disintegrate, they may detach and pull away from the frame. Without the support, the glass loses stability and may shatter or blow out. As an extreme example, if the sealing requirements specified by the architect are not followed in the construction phase, the thermal isolation systemically fails, which means that apart from water leakage, there is air leakage, comprising even more the building envelope. The corrective action includes repairing all the seals at the curtain wall [15].

84.2 Related Work

There are several types of frame and fastening for curtain wall glazing systems [13]. Composed of steel, aluminum, multi-laminate glass, or other resilient materials, the frame is the support grid that holds the glass in place and must be studied separately to determine the possible causes of failure [5, 11, 17, 19].

Mechanically fixed system. A mechanical fastening for the insulating glass is provided. The exterior mechanical restraint is thermally isolated from the interior frame. It may pose some issues, because when aging it is assumed to allow additional exterior air infiltration due to gasket shrinkage, especially if they are assembled onsite because the quality depends highly of the skills of the personnel. There are multiple arrangements described below:

Stick system. It is a structure of extruded horizontal and vertical metallic frame members (sticks) whose mullions are long elements generally made of aluminum or cold rolled steel with coating paint. The materials are cut in the factory and assembled onsite. Elastic gaskets are used under pressure plates. This method results in poor-quality control, given that it is built onsite, and depends heavily on the equipment and personnel involved in its construction.

Unitized. It is the most used type of curtain wall for high-quality finishing. Consisting of a bunch of preassembled glazing panels that are manufactured in controlled factory conditions, the metallic frame is directly attached to the different glass layers. The whole façade is sealed by means of elastic gaskets. It is more expensive than the stick system, but faster and easier to install, with fewer onsite operations. This process is more cost effective and provides a better performance and quality control.

Panelized. It is similar to the unitized system and consists of prefabricated panels. However, the panels are larger and generally have a store span height and a bay span width. This method seeks to avoid mid-span supports to avoid the problems of deflection.

Spandrel panel ribbon glazing. Long continuous glazed panels are fixed between spandrel panels connected to the building's floor slab. They are made of prefabricated metallic, composite panels, or precast concrete units. The glazed panels may be assembled onsite with horizontal transoms fixed to spandrel panels. Vertical mullions may be arranged for an easier construction method. The glazed parts may be of preassembled units that will be fixed on bottom and top to the spandrel panels and on the sides to one another. The level of prefabrication and repetitive assembly lets the performance be quite high and a demanding quality control.

Structural sealant glazing. Using silicone in sealings for a structure made essentially of crystal panels, it is possible to cover almost the total external façade with glazing panels. They can be preassembled, installed on the building's structure, and fastened together like the unitized system or a system of panels with a border frame bolted or fastened to an onsite assembled structure of mullions and transoms like the stick system.

Structural glazing. This system provides the most luminous space given that the glass area is practically the entire façade, being support systems minimized. It is achieved by means of assembling the panels with special brackets. Generally, the panels are fixed to the substructure at the corners with brackets providing support for four panels. The gaps between the panels are weather sealed onsite using wet-applied sealant. There are two types of assemblies: bolted and patched (suspended). However, the differences between the two are the fixtures of the panels to the attachment brackets.

To evaluate the existence of thermal bridges for all these structural systems, nondestructive analysis, in the form of infrared radiation measurement, is proposed. Infrared thermography (IRT) is a science dedicated to the acquisition and processing of thermal information from non-contact measurement devices [14]. The infrared radiation is an electromagnetic radiation with longer wavelengths than those of visible light [16]. Because the human eye is only capable of observing a quite tight range of radiation, the visible spectrum [3], the use of special cameras is required to measure such radiation. This radiation is mainly a function of their temperature and all objects that are not at absolute zero emit infrared radiation [21]. An x-ray test could be carried out. Though the test is usually effective, it costs more to conduct the test than the wall is worth. On the other hand, infrared thermography provides the solution for accurate, inexpensive, non-destructive, non-labor, and intensive results. It can cover a wide range, depending on the lens, and small areas can be tested by using the cameras which are fairly portable. Buildings are typically large constructions. Therefore a smarter way to perform thermal imaging inspections is the use of remotely operated Unmanned Aerial Vehicles (UAVs) equipped with IR cameras. Inspections can be easily carried out on roofs or tall constructions without an operator [12]. IR with UAV inspections of building can be used to detect heat losses, missing or damaged thermal insulation, and especially thermal bridges, air leakage, and moisture intrusions [2]. Advantages to these types of inspections are that repairs specific to the necessary areas will reduce costs while simultaneously saving on the heating and cooling costs that are cut when such defects are repaired.

84.3 Methodology

The framework of evaluation of a curtain wall is divided into different sections as described in the Fig. 84.1. It evaluates the elements conforming the frame and the structure to determine the existence of a thermal bridge and ultimately diagnose the structure and solve the possible defects.

84.3.1 Formulation

To evaluate the thermal performance, the thermal flux must be measured [4]. The overall heat transfer coefficient ($U = [W/m^2\,^\circ C]$) represents the ability of an assembled curtain wall to resist heat transfer. It is a property inherent to the material or assembly [20]. Indeed, all the properties of the glazing materials and sealants must be known to calculate the net radiation of the window. Therefore, the materials and their disposition must be specified. Specifically, heat transfer is the movement of energy due to a temperature difference. It is formulated as a function if the heat transfer rate ($Q = [W]$), the area of the window ($A = [m^2]$), and the difference of temperature ($\Delta T = [^\circ C]$) [3]:

$$U = \frac{Q_{net}}{A(T_{out} - T_{in})} \tag{84.1}$$

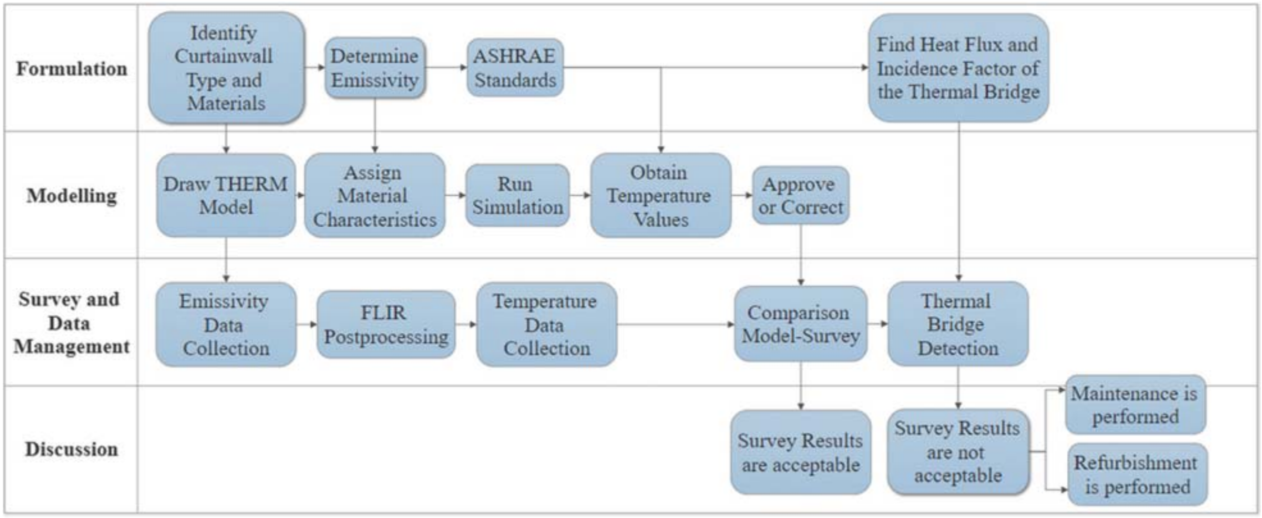

Fig. 84.1 Framework for the detection, diagnosis, and evaluation of thermal bridges

There are three physical mechanisms of heat transfer: conduction, convection, and radiation. To calculate the energy flux for crystal assemblies which have more than one layer, the following expression is used for the infrared energy flux leaving the kth surface as Q_k^r, where the superscript r stands for radiation. Then, it is defined for the nth layer whose boundaries are surfaces 2n and 2n–1 [7]:

$$\begin{aligned} Q_{2n}^r &= S_{2n}^r + R_{2n} Q_{2n+1}^r + T_n Q_{2n-2}^r \\ Q_{2n-1}^r &= S_{2n-1}^r + R_{2n-1} Q_{2n-1}^r + T_n Q_{2n+2}^r \end{aligned} \tag{84.2}$$

Being R_k the infrared reflectance of the layer measured from the kth surface and T_n the transmittance for the nth layer. In addition, transmittance multiplied by the flux gives the transmissivity. The same happens for the reflexivity. The emitted energy flux from the kth surface, S_k is defined:

$$S_k = \varepsilon_k \sigma \theta_n^4 \tag{84.3}$$

where ε_k is the emissivity of the kth surface, θ_n is the temperature of the layer n. The emissivity is the ratio of the radiation emitted compared to that emitted by a black body which absorbs all radiation. Emissivity has a range of values between 0 and 1. The emissivity is the key value for the infrared measurement because it is the value detected by the IR camera. However, there must be a correction to avoid the interference of other radiation like conduction, convection, and solar radiation. At this stage, the intention is to formulate, quantitatively, the possible presence and how to evaluate thermal bridges. The thermograph (thermal image) yields information in every pixel about the radiation emitted by the object of study [1]. Using the methodology proposed, the thermal transmittance can be estimated with a confidence level of 95% given IR tests. It is possible via a reverse analysis of the linear thermal bridge equation [10]:

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j \tag{84.4}$$

Being $\Psi = [\mathrm{W/(m\,^\circ C)}]$ the linear thermal transmittance, L_{2D} is the thermal coupling coefficient for a 2D space, U_j is the linear perpendicular thermal transmittance for the element separating the two environments, and $l_j = [\mathrm{m}]$ is the length of the element, which leads to the determination of a parameter that notices the presence of a thermal bridge using only the thermograph itself. It is then defined, the incidence factor of the thermal bridge I_{tb} as the ratio between the actual heat flowing in and the theoretical heat flowing in [1]:

$$I_{tb} = \frac{Q_{tb}}{Q_0} = \frac{h_{tb} A_p \sum_{p=1}^{n} \left(T_{ext} - T_p\right)}{h_i A (T_{ext} - T_{1D})} = \frac{\sum_{p=1}^{n} \left(T_{ext} - T_p\right)}{N (T_{ext} - T_{1D})} = \frac{\mathrm{U_{tb}}}{\mathrm{U_{1D}}} \tag{84.5}$$

where Q_{tb} is the heat flux through a thermal bridge, Q_0 is the theoretical heat flow that there should be through this precise element, h_{tb} is the laminar coefficient of the thermal bridge, h_i is the internal laminar coefficient, the temperatures T_{ext} and T_p respectively represent the external air and the temperature of the thermograph pixel, and T1D is the unaltered temperature. A_p is the area of a pixel and A is N times A_p the total number of pixels. When considering that in the limited domain of the image area, the laminar coefficient is constant $h_{tb} = h_i$, and so it results the equation in Formula (84.5) being U is the thermal transmittance.

To set logical boundaries to the temperatures formulation, ASHRAE standards are followed, specifically the Energy Standard for Buildings manual guides. In ASHRAE/IESNA Standard 90.1-2007 a range is provided according to the purpose of the building and the type of frame.

84.3.2 Modelling

The purpose of modelling is to have a deeper understanding of the different layers' U-factor and obtain the temperatures in the perfect scenario, as well as to have some reference to compare the values obtained in the tests. Under ASHRAE standards, the boundary conditions for temperature and materials are defined as well as the drawing the geometry.

84.3.3 Survey and Data Management

Emissivity is to be measured under the test, however it is not the only existing radiation. The incident solar radiation, transmittance, and air leakage rating could influence the variation of the temperature increasing the effect of the thermal bridge, and not being registered in terms of emissivity [6]. However, the detection of the thermal bridge is just a matter of detecting an anomaly in the emissivity values.

On the other hand, there might be some elements that produce a radiant barrier [8]. Elements like some type of aluminum alloy could produce a low emissivity response in the infrared register. Emissivity stands for the grade up to which a material emits energy as thermal radiation. However, thermal radiation can be present in the form of conduction or convection. Therefore, special attention needs to be paid with such elements. For most non-metallic materials, the value is usually above 0.80. However, for metallic surfaces, especially when polished, the emissivity values drop down between 0.05 and 0.2. Therefore there is the need to adopt corrective measures to determine the exact temperature. For such metals, the values specified in emissivity tables must not strictly be considered because the surface conditions can influence the measurements more than materials themselves [9].

For this test, the practice under ASTM E1933 – 14 is followed under the Contact Thermometer Method conditions to correct the emissivity to perform the tests. Although they may not be applicable for IR measurements under UAV conditions, the adjustments have been followed under these conditions. Therefore, the test is carried out for the IR camera, model Flir Vue Pro R, on the UAV on the adequate location pointing at the targeted element whose emissivity is to be corrected, in this case to correct the emissivity of the surface of polished metals. For that purpose, the function to measure and compensate is used for the high reflected temperature upon the specimen. Therefore, the contact thermometer is used to measure and correct the actual temperature. Focusing the imager on the same spot, adjust its emissivity control until the it indicates the same temperature recorded by the contact thermometer. The indicated emissivity value is the measured emissivity of the specimen at this temperature and spectral waveband. This procedure is repeated a minimum of three times and the emissivity values averaged to obtain an approximate actual emissivity.

On the other hand, there may be other environmental factors that may generate some error or noise in the measurement [2], such as large particles present in the atmosphere, like water vapor or gas molecules. Those interferences will alter the measurement, as well as the ambient air temperature and the distance or angle of incidence from the sample. For that reason, the recommendation is to take measurements as close as possible to be accurate and to let the camera get warm to acclimatize. The sample should be at a temperature that is at least 10 °C warmer or cooler than the ambient temperature so the measurement yields little error on the emissivity results.

Winds may also disturb the results. Therefore, for winds exceeding 5 m/s it is recommended to perform an accurate correction because there may be a difference in temperature of 3 °C or more depending on the humidity or atmospheric conditions [1].

At night, heat energy is dissipated from the external surface. If the façade is being investigated it is possible to observe different behaviors during winter, for example. Then, the external surface will have a lower surface temperature. To avoid the confusion of temperature, increased for the solar radiation, IR measurements should be performed at night or on a cloudy day, with low wind speeds to minimize convective heat losses. Moisture may induce some measurement problems because a wet mass retains the absorbed heat more time than a dry mass. That is how moisture problems are identified.

Going into detail, the emissivity of a specimen is strictly related to a determined combination of temperature and the spectral waveband of the radiometer used to make the measurement. The emissivity is inversely proportional to the reflectivity. For that reason, measurements should be taken from different angles to avoid the reflection from other objects which may interfere in the measurements [21]. When measuring, special attention must be paid when determining the reflected temperature. For materials with emissivity less than 0.5, radiometric temperature measurements and emissivity measurements may have higher errors.

84.3.4 Discussion

Based on the ASHRAE guidelines for interior temperatures, a quantitative analysis will be provided in terms of the materials' quality and desired insulation. Therefore, a desired U-factor is obtained so the actual works aim to emulate that performance and perspective. Throughout time, the assembly should not degrade as much and have a worse performance.

84.4 Case Example

Because the tests are performed from the exterior, only the exterior façade surface is surveyed. For reference, a chart is drawn according to the actual temperatures to detect thermal bridges in specific layers. If the most problematic area is the interphase, a line throughout the exterior surface is plotted following the line between the support, considering the interphase as the origin and ending in the crystal as shown in Fig. 84.2. The intention is to cover from the problematic area until areas where temperatures are not altered by the effect of the thermal bridge, or the undisturbed zone.

THERM results are observed. Focusing on the interphase, there are little hints of an energy flux through the sealant and in the interphase. To quantify these measurements, a graph is plotted that records the variation of temperature along the length of the window so the simulation can be observed and compared with the test results in Fig. 84.3a.

The thermal image is filtered using the Flir software, assuming a straight line from the interphase until the undisturbed zone, to obtain a plot as shown in Fig. 84.3b.

Comparing objectively the results, the shape of the curve is similar which means that the simulation matches the actual performance in terms of general capture. Apparently, both graphs help notice that there is a leak in the interphase which must be quantified obtaining the incidence factor of the hypothetical thermal bridge. In this example, it is $I_{tb} = 0.992$, which is not enough to consider it a thermal bridge. Indeed, it yields some conclusions, as it is a recently assembled façade, the degradation is low and it has been properly assembled to ensure thermal insulation. On the other hand, there is a slight difference in the increment of temperature registered on both plots, for the simulation $\Delta T = 0.5\,^{\circ}C$, meanwhile it has been measured a temperature with $\Delta T = 0.06\,^{\circ}C$. The reason is the simulation gets the most accurate results and a perfect estimation of the temperature. Meanwhile, the thermal imaging camera is not that accurate and levels the temperature to an average, possibly by means of the reflected radiation of the exterior or coming from the particles beside. However, this is not a concern because the aim of the project is thermal bridge detection in a macro scale.

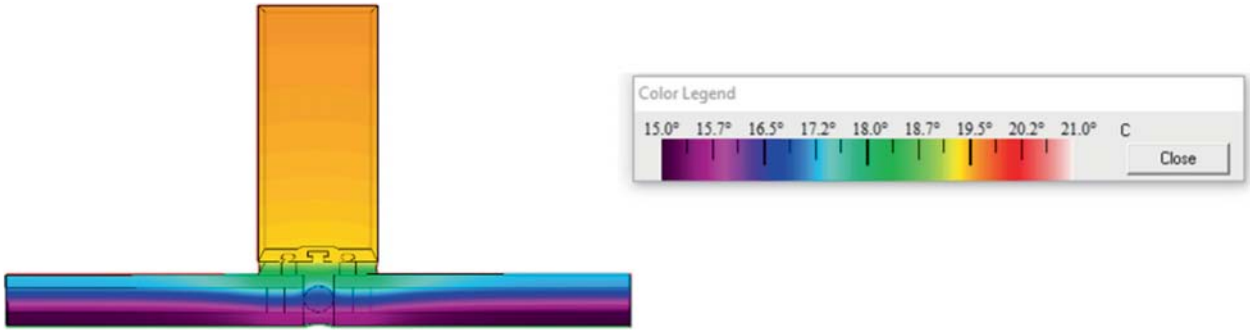

Fig. 84.2 Temperature distribution along the Façade surface of the mullion and the shadow box of the curtain wall

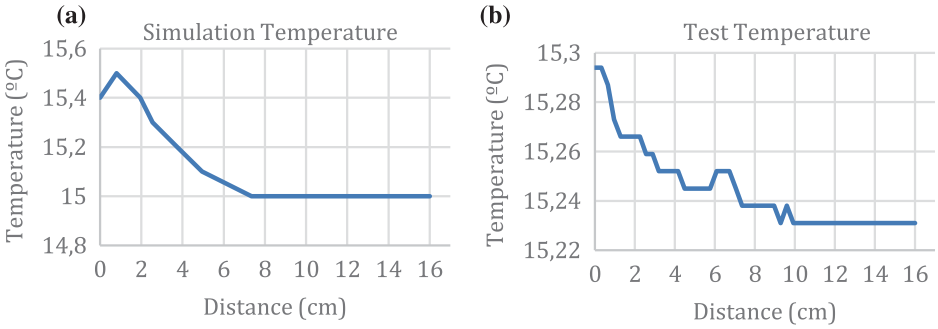

Fig. 84.3 **a** and **b** Temperature measurements of the Façade simulation and thermal imaging

84.5 Conclusion

The objective is to identify, according to the incidence factor, the existence of a thermal bridge and quantify the magnitude of it. According to the regulations for the tolerable temperatures in interior spaces, thresholds will be provided for the incidence factor to diagnose the actual building. An evaluation can be performed from a single window to the general performance of the building to tell the actual state of deterioration, obsolescence, energy consumption, and functionality. Based on these premises, different retrofitting actions will be adopted and the corresponding costs to make the best use of the existing structure will be determined. As an ultimate conclusion, determine the possible scenarios:

- The current state of the building or curtain wall is acceptable.
- The current state is not acceptable and maintenance is to be performed.
- The current state is not acceptable and refurbishment is to be performed.

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