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Title: Time-lapse Thermography for Building Defect Detection.

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Abstract

Building thermography traditionally captures the thermal condition of building fabric at one single point in time, rather than changes in state over a sustained period. Buildings, materials and the environment are, however, rarely in a thermal equilibrium, which therefore risks the misinterpretation of building defects by employing this standard methodology. This paper tests the premise that time-lapse thermography can better capture building defects and dynamic thermal behaviour. Results investigating the temporal resolution required for time-lapse thermography over two case study houses found that under typical conditions small temperature differences (approximately 0.2K) between thermal areas could be expected for 30-minute image intervals. Results also demonstrate that thermal patterns vary significantly from day-to-day, with a 2.0K surface temperature difference experienced from one day to the next. Temporal resolutions needed adjusting for different types of construction. Time-lapse experiments raised practical limitations for the methodology that included problems with the distance to target and foreground obstructions. At the same time, these experiments show that time-lapse thermography could greatly improve our understanding of building transient behaviour and possible building defects. Time-lapse thermography also enables enhanced differentiation between environmental conditions (such as clear sky reflections), actual behaviour and construction defects, thereby mitigating the risk of misinterpretation.

Key Words

Time-lapse thermography, transient behaviour, defect detection.

1. Introduction

According to the United Nations Environment Programme, buildings account for over 40% of the world's energy use [1]. Within the European context, building energy use is rising, with EU dwellings responsible for approximately 70% of all energy use in buildings [2]. Of the 22.4 million dwellings in England, almost 90% were built prior to 1991 [3], a pattern which mirrors the housing trend throughout Europe [2]. Since new build construction in England for 2013 only totalled 109,370 units [4], the aim of the UK government to meet carbon reduction targets of 80% on 1990 levels by 2050 [5] appears unachievable unless widespread action is taken to thermally improve existing dwellings. In addition, increased energy costs are leading to increased levels of fuel poverty [6]. The risk of fuel poverty is typically larger amongst occupants of rural buildings [7] due to a lower uptake of gas central heating and less energy efficient construction. It is therefore important to improve existing dwellings that are energy inefficient thermally and to minimise the energy demand required for heating buildings.

The ability to identify thermally inefficient areas successfully, such as specific thermal defects, is fundamental to the subsequent success of thermally improving existing buildings [8]. Thermography is an analysis technique which is increasingly being used by construction professionals as a non-destructive tool suited for this task [9]. Thermography, also named thermal imaging, uses a special type of camera to detect infrared radiation, which is emitted from surfaces [10] such as the building fabric. Since the infrared radiation relates to temperature, this in turn depends on heat transfer through the building envelope. Providing there is sufficient temperature difference across a construction, thermography can be used as a tool to identify quickly potential building defects, such as moisture ingress, without the need to undertake costly and damaging physical exploratory investigations. However, image interpretation is a key limitation since thermographers need to be particularly mindful of the external conditions and parameters which can inhibit defect detection, such as emissivity, distance, level and span, etc. [11].

At present, building thermographers tend to capture a series of thermal images during a visit to a building but do not undertake any longitudinal studies [12]. Such images have the potential for misinterpretation due to transient effects, such as that provided by thermal mass dampening temperature change over time, which are not always recognised in images taken at a single point in time [13]. Furthermore, internal and external conditions have an impact on the temperature of a construction; the specific effects will vary depending on the ability of the particular fabric to store heat energy. For example, solid masonry walls have a greater capacity to store energy through thermal mass when compared with lighter-weight timber-frame walls. Depending on the internal room temperature and that of the inner wall surface, energy stored in thermal mass might reverse the heat flow direction [14] from that which might be initially expected. Alternatively, some constructions might contain insulation or cavities, which present less thermal conductivity when compared with solid wall constructions such as stone or cob. This will have an impact on heat flow through a wall. As such, low-conductive materials will present a barrier to the flow of heat in either direction and could have an impact on thermal image results.

However, some recent thermal cameras now have the ability to record sequences of images thus creating a time-lapse series and thereby presenting new opportunities for longitudinal building thermography [15] to observe the transient flow of heat through construction over a much longer period. To date, this approach has not been used for thermal studies of whole buildings.

This paper aims to develop and investigate the use of a time-lapse thermography methodology for the inspection of buildings. It seeks to better understand transient thermal changes of the fabric and how these interrelate with the identification of building defects through thermography.

The research has the following objectives, to:

a) Compare and contrast a time-lapse methodology with the more commonly used method of capturing images at one single point in time;
b) Develop a time-lapse thermography methodology, which explores the key limitations and practicalities involved with conducting on-site internal and external investigations;
c) Investigate different temporal resolutions required for undertaking time-lapse analysis, in order to better highlight defects and thermal behaviour.

This paper applies a qualitative time-lapse thermography methodology to three case-study buildings to explore the use of apparent surface temperature changes over prolonged periods of time in order to draw conclusions from transient changes. Although building thermography can also be used to observe the behaviour of and defects within HVAC systems, this work primarily focuses on observing the building fabric.

2. State-of-the-art in Building Thermography

2.1 Traditional building thermography

There are two schemes of analysis by which building thermography can be performed: *active* and *passive*. Active thermography utilises a forced heating or cooling stimulus, which creates an enhanced thermal contrast to locate specific defects such as subsurface cracks [16]. In contrast, passive thermography observes the natural temperature differences of objects which would normally be at a different temperature to each other [12]. Avdelidis *et al.* [17] reported that passive thermography is the most common analysis scheme for building inspections, typically combined with qualitative analysis, since the aim is to detect potential defects in buildings without artificial intervention. In this context, the use of heating systems is not considered to be an active/imposed stimulus since these are a regular part of the building.

Currently, the most common form of passive building thermography utilises a *walk-around* or *walk-through* methodology [18]. In this paper, these are collectively referred to as *traditional* passive building thermography. Given the higher speed and minimal disruption to occupants, authors such as Holst [19] advocate the sole use of a walk-around survey which only observes external building surfaces. Yet the presence of climatic conditions, such as precipitation or wind, during external thermography [11] can hinder external defect detection. Hence there may be the need for the addition of an internal walk-through, where the thermographer inspects internal surfaces [13]. Both approaches require the thermographer to scan each surface systematically with a thermal camera as he/she walks around, or through, the building [20], concentrating on any warmer or cooler spots (compared with the ambient temperature) that might suggest irregularities or defects. As stated, in traditional thermography thermal images are recorded at one moment in time, and not longitudinally. This is significant because the condition of the element being observed is only captured at the specific moment the image is taken. Traditional passive building thermography can be subject to a number of different sources of inaccuracy, such as camera thermal resolution [21], emissivity [22], problems with reflected apparent temperatures [19] and climatic weather conditions [13].

Climatic conditions pose particular problems for thermography. Firstly, climatic conditions dictate when thermography should or should not be undertaken; the recommendation [13] is for dry conditions with low wind levels, cloud covered sky and at least a 10.0K temperature difference between internal and external spaces. However, climatic conditions can also have an impact on the thermal condition of the building fabric. In particular, such changes could alter the apparent properties of materials on a transient basis, particularly when subject to environmental stimulus such as temperature, wind, moisture or solar gain. The impact of varying air movement, for example, is very complex [10] and can vary more quickly than other conditions owing to gusts, which could have an impact on single image results due to forced convection. This can be compounded when coupled with other climatic conditions such as moisture in the material [11].

2.2 Time-lapse building thermography

For the longitudinal application of thermography, the terms 'transient' and 'time-lapse' are important. ‘Transients’ are found when certain factors such as climatic conditions vary over time. ‘Time-lapse’ is the process of capturing spaced data sets (such as images), which can be presented in a sequence to speed up slow processes such as transient changes.

Accordingly, we define time-lapse thermography as a passive thermal imaging methodology, which aims to better understand transient heat flow within a building's fabric by recording a sequence of images. Time-lapse image capturing is commonly attributed to photography [23] where typically slow or fast events can be accelerated or slowed by saving image frames at different temporal intervals to that of traditional film speeds (25 frames per second). Given the slow nature of transient changes in building materials, time-lapse image recording appears well suited to thermographic investigations.

To establish the current thinking regarding time-lapse thermography, a review of existing literature was conducted. From this, it was discovered that the most commonly reported use of time-lapse thermography involved active thermography. This is exemplified by Hamzah [26] whose work located structural defects hidden beneath material surfaces using forced heating phases prior to thermographic observation over periods no greater than 22 seconds. Avdelidis [17] asserts that time-lapse thermography is in the realm of active thermography. However, work which explored the evaporation process from moistened plaster samples under laboratory conditions by Grinzato, *et al* [27] is one example where a time-lapse methodology has been applied to passive thermography. Also, work by Lehmann *et al.* [28] applied a passive time-lapse methodology to determine the most influential environmental conditions to external thermographic analysis. This study identified solar gain in combination with differences in construction composition (insulated versus uninsulated brick wall construction) as presenting the greatest impact on thermography. Madding [29] and Kato [30] have explored the determination of thermal transmittance (U-value) using passive time-lapse thermography by measuring apparent surface temperatures over a prolonged period of time. Previous research by the authors of this paper [31] studied the warming and cooling phases of sample typical construction materials using time-lapse thermography; analysis compared measured results with simulated results using the *Voltra* transient heat transfer software [32]. Lehmann *et al.* [28], Madding [29] and Kato *et al.* [30] have captured thermographic images at intervals ranging from 5 to 20-minute. For quantitative analysis, Fox *et al. [31]* utilised 5 minute intervals, which served as a useful initial experiment to establish image intervals for measuring finite temperature differences in small samples. For qualitative analysis, Lehmann *et al.* [28] reported using an image interval of 5 minutes; however, when publishing the image data in their paper, images were reproduced at a 60 minute intervals only, which suggests that the images between 60 minutes did not show a discernible difference in the displayed patterns to enable qualitative analysis.

While this existing work utilised passive time-lapse thermography for the study of some transient aspects of thermal building behaviour, there is no evidence in literature on the use of time-lapse thermography to identify building defects. Currently, there is no evidence in the peer-reviewed literature of a practical methodology for time-lapse thermography as applied to the study of whole buildings. Indeed, recommendations regarding temporal resolution for such studies are non-existent.

3. Methodology for Time-lapse Thermography

3.1 Case study buildings

This research explores the application of time-lapse thermography on the study of transient building behaviour, with a view to identifying building defects. In order to compare in-situ time-lapse building thermography with traditional methodologies that only capture images at one point in time, and to explore the practicalities involved with conducting time-lapse thermography, action research [33] was employed on two domestic properties in the south west of England. Building 1 consisted of 18th and 19th century solid cob (natural building construction comprising organic material such as earth and straw) and stone walling respectively, while building 2 an 18th century cottage comprised of solid stone with a 21st century concrete block cavity wall extension. Both buildings offered large back yards, which enabled a thermal camera to be positioned so that entire elevations could be observed. Building selection was based on the need to find contrasting construction methods that reflected existing UK housing stock and contained the likelihood that defects would be present. By investigating a mix of construction types, a broader assessment of temporal resolutions for time-lapse thermography of different scenarios could be studied. Building selection was also based on convenience sampling, given the extended access required internally and externally for these experiments and their proximity to the research centre.

3.2 Hardware

A calibrated FLIR T620bx thermal camera was used for the experiments. Figure 1 provides its technical specifications. Environmental conditions were monitored using a WH1080 wireless weather station, which has an internal and external sensor that measures humidity, precipitation, wind speed and air temperature. Indicative surface temperatures were obtained using simple k-type thermocouples fixed to the wall at head height next to an openable window and readings were noted by hand; these served as a benchmark check for the thermographic results.

IR resolution	640 x 480 pixels	
Field of view (FOV)	25° x 19° / 0.25m (0.82ft)	
Spatial resolution (IFOV)	0.69 mrad	
Thermal sensitivity (NETD)	<40 mk @ +30°C (+86°F)	
Image frequency	30 Hz	
Temperature range	-40°C to +150°C (-40°F to +302°F) and +100°C to +650°C (+212°F to +1202°F)	
Accuracy	±2°C (±3.6°F) or ±2% of reading	
Image recording	Simultaneous storage of IR/Visual images Periodic image storage	

Figure 1. FLIR T620bx Thermal camera technical specifications (adapted from FLIR [34]) and photograph of the device by the authors.

To perform time-lapse thermography, the thermal camera was set on a tripod (approximately 1m from the ground level) facing the target building surface and positioned far enough away so that as much of that surface could be captured within the Field of View (FOV). The camera was tilted to capture the best view of the elevation within the FOV. The angle of tilt was between 0° and approximately 10° (from horizontal). Hart [10] argued that emissivity can vary with angle (depending on the material being observed), though not significantly until angles of more than 65° from perpendicular are exceeded. It is also important to recognise that when perpendicular to a target, the camera can act as a source of reflected radiation, which can impact results [35].

3.3 Experimental conditions

Weather conditions were monitored for two days prior to experimentation commencing, which was determined to be a logical step which stemmed from guidance that called for a steady temperature difference across the built fabric [36]. This period was also chosen to help monitor/minimise the effects of other weather conditions. For example, had there been heavy rain prior to the experiment, this would have been postponed. Experimentation periods were chosen to minimise the likely presence of clear skies, precipitation and wind, and which had an external temperature that remained at least 10.0K lower than internal air temperatures. To ensure that early images were not adversely effected by the camera sensor adjusting to the atmospheric temperature, the camera was turned on 30 minutes before commencing, as advocated by Vollmer and Möllmann [11]. Once acclimatised, the camera was programmed to record periodic images. Emissivity values were measured in situ [37] and selected in the camera settings for the predominant material being observed, which for these experiments was either painted render or plaster.

3.4 Data collection

Images were captured every 20 to 30 minutes. This interval was chosen as a mid point between the 5-minute image interval used in references [28, 31] and the 60 minute displayed image interval used in the work of Lehmann et al. [28]. Following the survey period, all images were uploaded and assessed using the FLIR Tools software [38]. This software enables image adjustment so that each had the same temperature span (between minimum and maximum temperatures). This allows creation of a time-lapse sequence of multiple images covering the same temperature range, which enables the evolution of transient heat losses to be viewed more clearly.

3.5 Practical methodology

There has been no previous research detailing a time-lapse methodology for passive building thermography. This work therefore sought to introduce and explore a practical methodology for this form of thermographic investigation.

Through conducting time-lapse experiments using passive building thermography, practical issues were identified. Limitations to a time-lapse methodology were encountered both internally and externally. External constraints encountered during studies 1 and 2 included:

- The safe and secure positioning of equipment;
- Challenges with monitoring environmental conditions (wind, rain, cloud cover);
- Maintaining power for equipment throughout the survey period;
- Balancing spatial resolution with FOV;
- Minimising unwanted foreground objects.

Pearson suggested [13] that there are fewer limitations to internal thermography than external thermography due to the presence of a more controllable environment. However, the following limitations were encountered during study 3:

- Capturing entire elevations within narrow FOVs;
- Avoiding occupant interference;
- Avoiding unwanted foreground objects.

Once the practical limitations had been considered, a robust practical methodology for time-lapse thermography was developed. Figure 2 demonstrates the equipment set-up for an external time-lapse investigation, and the following aspects detail the practical approach to the acknowledged methodology constraints.

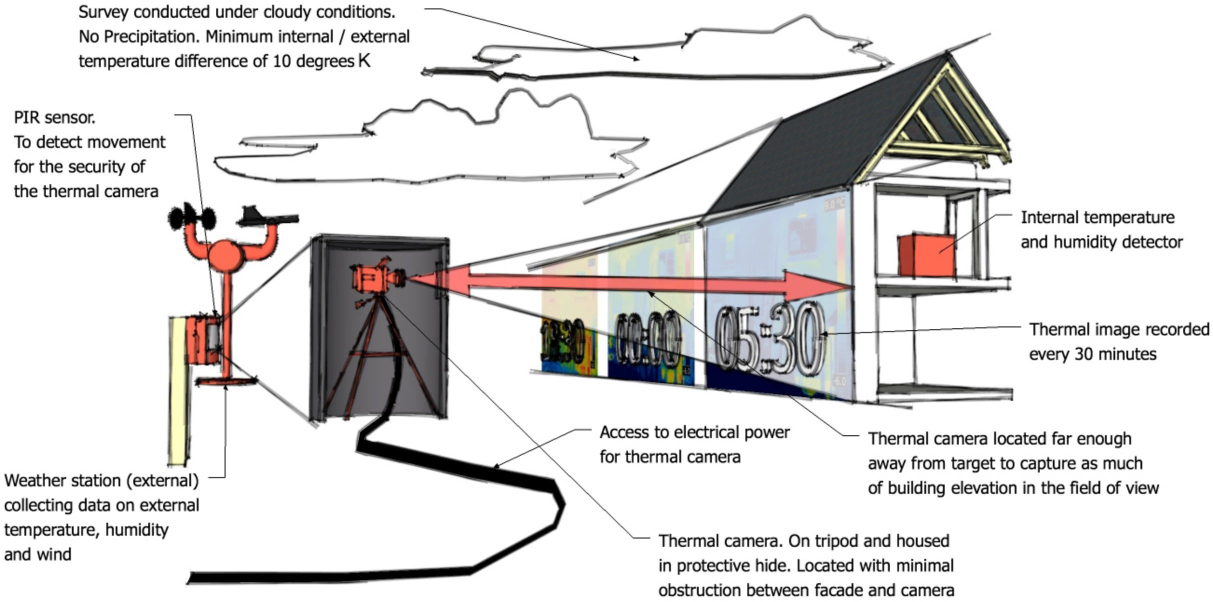

Figure 2. Experimental set-up for external time-lapse thermography showing designed solutions to the methodological constraints.

Safety and security

Although less of an issue during internal investigations, when left outside unattended for prolonged periods of time, the safety and security of the thermal camera (valued at approximately GBP £12,000) was a key concern. Despite positioning the camera in back yard locations, away from public view, the security risk was not completely eliminated. To further aid security, a remote passive infrared (PIR) security alarm device was used to observe the vicinity of the thermal camera during the experiments (figure 2). Weather protection was also paramount. While nights with a cold and dry weather forecast were chosen, care needed to be taken that the thermal camera did not get wet when left outside. To guard the camera against precipitation and frost damage, a simple shelter with a viewing hole was placed over the camera (figure 2), this proved invaluable during the unexpected snowfall experienced during study 2.

Monitoring environmental conditions

Environmental conditions such as temperature, precipitation and wind were easily monitored using a weather station; however, monitoring the presence of cloud cover (which might reflect off the target surface) was very difficult due to the large expanse of sky and the possibility of fast moving and irregular density of cloud cover. Although forecasted cloudy nights were chosen, the actual presence and density of cloud was not observed and might have had an impact on the results of the external experiments. It is therefore important to note such factors and their potential for impacting time-lapse results, which might vary from image to image in a continuous sequence.

Prior to a thermal image being recorded, ITC [37] recommend pointing the thermal camera away from the observed object to identify surrounding sources of infrared radiation (sky, other buildings, appliances etc.), which might reflect off the target surface and could impair measured results. This methodology might work for images captures at a single point in time, however, for automated periodic image recording, a second thermal camera would be required, which if automated would only give data for a comparatively small (compared with the entire background scene) area of sky/background, which might miss many possible areas of potential reflected radiation sources. Internally, an aluminium foil methodology was used to measure reflected apparent temperature [39]. Because of the distances involved externally, the aluminium foil methodology could not be used since a very large sheet of foil would be required and might obscure parts of the observed object.

Maintaining power for equipment

The battery operational time for the T620bx thermal camera is listed as being 2.5 hours long [34]. To avoid reliance on battery power, it is essential to maintain a mains electricity supply throughout the experiment. Alternatively, an additional battery is required; for instance a typical 60Ah automobile battery (using a Buck-boost converter giving 97% conversion efficiency) would power a 3amp rated thermal camera for about 19 hours. Whist it is easy to address internal thermography with mains electricity, it is more problematic for external thermography, which requires long extension leads that place restrictions on camera location and distance from target surface. A source of external mains electricity was available for all studies in this paper, but future studies might not have this luxury. Furthermore, relying upon mains electricity might limit the positioning of the thermal camera (to the yard), as it could be impractical to establish a power supply some distance from the property due to features such as roads. For studies 1 and 2, mains electricity was supplied via a 20m-extension cable. Fortunately in these cases, this distance also corresponded to a suitable camera location to capture as much of the elevation within the FOV as possible. Had either property been larger, it would have been more difficult to locate the thermal camera further from the building surface and reliance on a car battery would have been necessary.

Balancing spatial resolution with FOV

Traditional walk-by / walk-through [18] methodology permits thermographers to scan entire surfaces at relatively close proximities. Multiple views of the surface can then be captured and merged into higher spatial resolution single images of the elevation [40]. Unattended automated time-lapse thermography, however, requires the thermal camera to be fixed on a tripod, resulting in only one view being captured. In order to capture as much of the surface within the FOV as possible, the camera must often be placed at a large distance from the target. This is significant because increased distance equates to reduced spatial resolution. Distance relates to instantaneous field of view (IFOV) [37], which stipulates the smallest discernible target. Yet the smallest target that can be accurately measured is known as the measuring IFOV (MIFOV) and is often three times the IFOV [19]. With greater distance, the smallest discernible target size becomes larger making small details harder to discern [41]. The camera used in these studies held an IFOV of 0.69mrad, which at a 20m distance with a pixel size of 640 x 480, meant that defects smaller than 41.6 x 41.6mm could not be accurately measured due to their falling below the MIFOV. For comparison, had the camera been 5m from the surface, defects as small as 10.4 x 10.4mm might have been detected.

Similarly, by attempting to capture an entire internal wall surface within the FOV, the thermal camera needed to be placed as far from the observed surface as possible. Given the small domestic room size for study 3 (4.5m x 2.5m), the thermal camera had to be located on the farthest opposite side of the room to the target (approximately 4m from the surface). Based on the camera FOV (25^{o} x 19^{o}), this gave an observable area of 2m x 1.5m, which proved insufficient to capture the entire external wall surface of 2.5m wide x 2.8m high. Therefore, only a portion of the wall could be observed at any one time using this camera/lens, as illustrated by the red box in figure 5, which shows the approximate FOV for the thermal camera in context with the surrounding wall area. To help provide a larger FOV, a wider angle lens could be used, though these are costly.

Minimising unwanted foreground objects

During each experiment, unwanted objects such as bushes and pictures obscured surface detail. Internally, every effort was made to remove such items. FLIR [35] recommend that obscuring items are removed at least 6 hours prior to the survey starting; however, in practice this was not always possible, particularly when dealing with large pieces of furniture or immovable planting. Externally, it was important to angle/situate the camera to avoid foliage or garden furniture concealing the building surface. Furthermore, during study 3, all occupants were instructed to avoid entering/using the room whilst the experiment was being conducted as they might have an adverse impact on results.

To mitigate practical issues such as camera security, FOV and power supply, it became routine to locate the camera in back yards. This, however, constrained the studies to the observation of rear elevations only. Therefore, had defects been present on other façades, these might have been missed.

3.6 Case study information

Building 1, study 1

Study 1 observed a Devon vernacular cottage that was formed of two construction types (figure 3). The original 18th century cottage had cob construction with a 19th century, solid, stonewall extension. Both constructions were covered with a cement-based render. Observing the rear (west) elevation, the camera was situated approximately 20m from the dwelling in the back yard.

Survey parameters.

Survey duration: Start: 17:00 on 28th November 2012

End: 08:00 on 29th November 2012

Duration: 15 hours

Image intervals: Every 30 minutes

Weather two days prior to survey: Dry with periods of cloud cover and direct solar exposure on the target (west) elevation. External temperature range: 273.45K to 281.25K

Weather during the survey: Whilst mostly cloudy, there were times when pockets of clear night sky could have been reflecting off the surface. At no point was there precipitation or wind speeds over 1m/s.

External temperature range: 270.05K to 277.65K

Internal temperature range: 280.95K to 293.45K

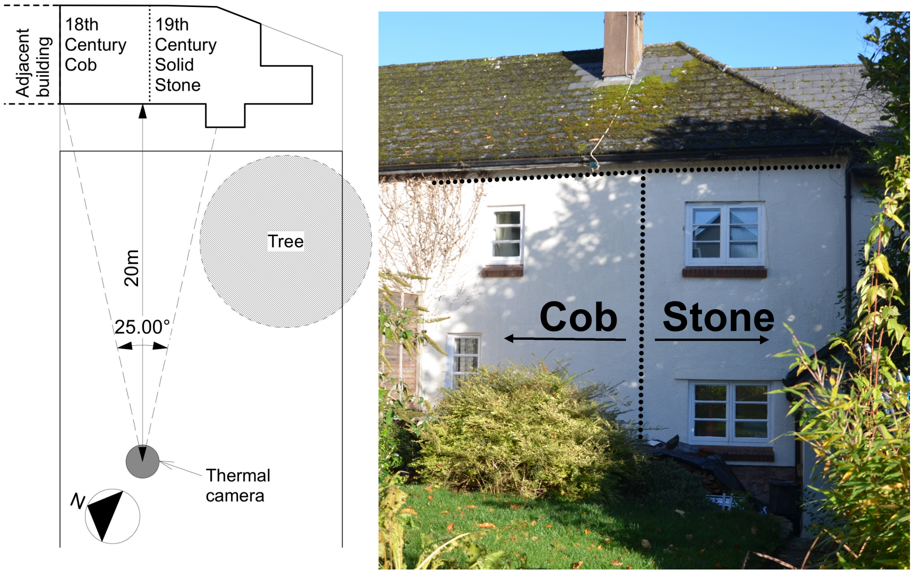

Figure 3. Plan and photo of building study 1

Building 2, study 2

The original cottage was formed of solid stone construction with a 20th century rendered concrete block extension towards the rear of the dwelling. Combining modern with traditional construction, this portion of the dwelling formed the focus of this study. Located in the back yard, 20m from the dwelling, the thermal camera was angled to observe the northwest elevation (see figure 4).

Survey parameters.

Survey duration:

Start: 17:00 on 15th January 2013

End: 08:00 on 18th January 2013

Duration: 63 hours

Image intervals: Every 20 minutes

Weather two days prior to survey: Dry, with periods of changeable cloud cover.

External temperature range: 274.45K and 281.75K

Weather during the survey: The sky consisted of fluctuating cloud cover, with periods of clear and cloudy sky, while other times there was unpredicted snowfall. There was at least a 10.0K temperature difference between inside and outside throughout the survey.

External temperature range: 272.35K to 276.65K

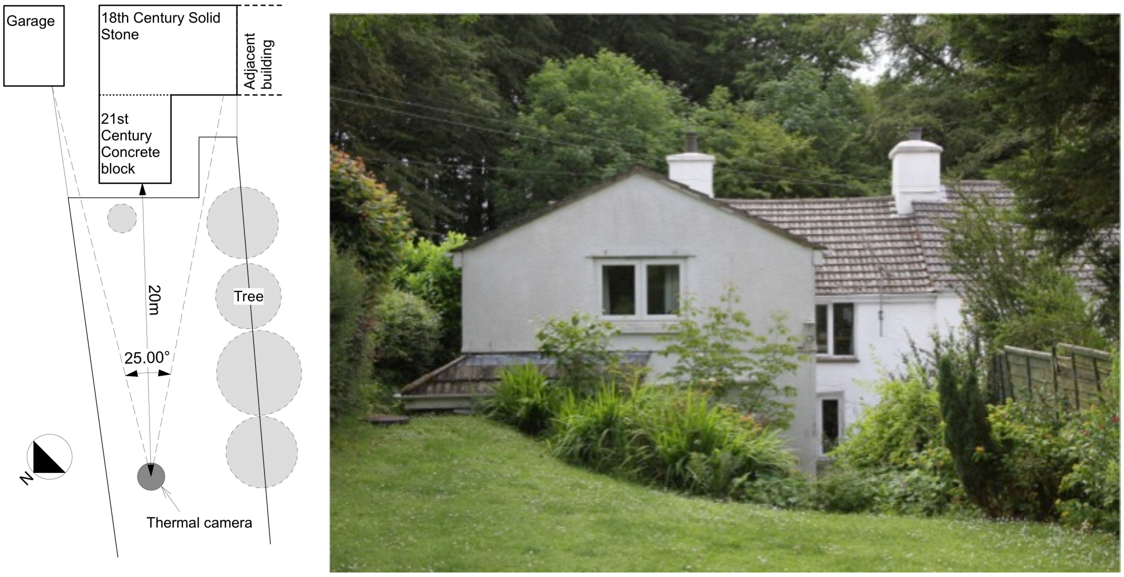

Figure 4. Plan and photo of building study 2

Building 1, study 3

Using the same building as used in study 1, this experiment explored internal time-lapse thermography. Located in a bedroom to observe an east facing external wall (figure 5), the construction observed was predominantly solid cob with a thinner section of brick infill above a window.

Survey parameters.

Survey duration: Start: 17:00 on 13th March 2014.

Finish: 07:00 on 14th March 2014

Duration: 14 hours

Image intervals: Every 30 minutes

Weather two days prior to survey: Dry with small patches of cloud cover, though long periods of clear sky during the day and night periods.

External temperature range: 284.25K to 276.95K

Weather during the survey: Dry with predominantly clear skies.

External temperature range: 280.35K to 277.05K

Internal temperature range: 291.15K to 286.95K

Internal temperatures were largely dictated by the heating system coming on at 17:30 and stopping at 22:00 on the 13th March 2014.

Figure 5. Plan and photo of building 1, study 3. Red box shows limit of thermal camera FOV.

4. Results

4.1 Building 1, Study 1: External time-lapse study

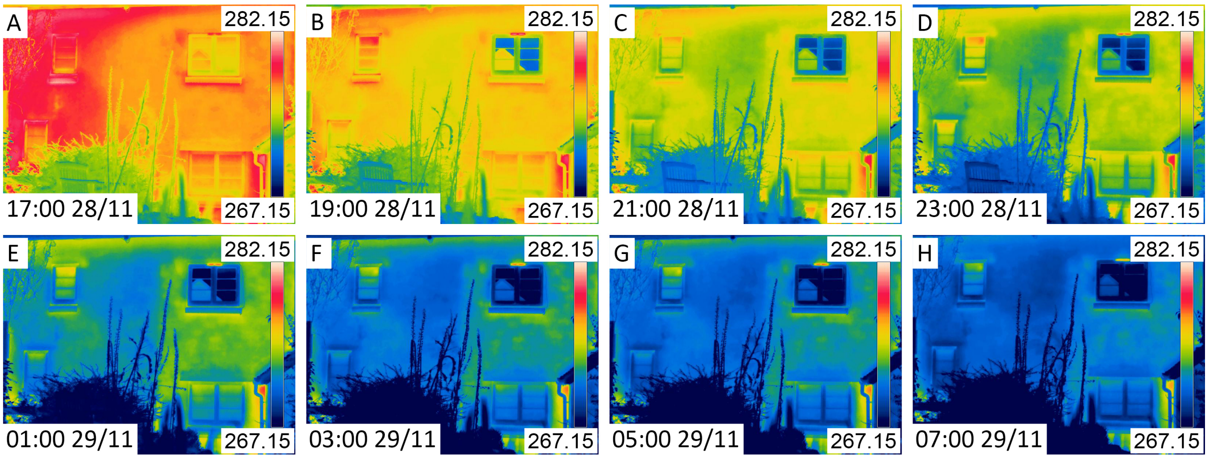

Figure 6. Top left to bottom right (A-H). Study 1. Displayed every 120-minute interval image only (every 4th image).

Differences in image colour patterns were qualitatively analysed (Figure 6A-H) as time-lapse sequences, leading to the following observations:

a) The cob and stone portions of the dwelling showed different thermal behaviour. Figure 6A shows the initial effects of solar exposure during the day, with higher surface temperatures for the cob walling (278.35K) noticed at the start of the survey that progressively cool down throughout the study into the morning, which ended at 269.65K. It can be noted (figure 6H) that the render over the cob had a lower surface temperature overall (269.65K) to that of the render over the stone (271.45K).

b) An approximately 1m diameter warmer patch became increasingly notable over time below a window in the cob walling (figure 7). Although the specific detail of this patch could not be distinguished by thermography alone, quantitative analysis of the thermal images was undertaken over the potential defect and normal cob areas, which has been illustrated in figure 8. At the start of the experiment, the temperature differential between the suspected cob defect and surrounding 'normal' cob was approximately 0.1K; this differential increased throughout the experiment to 1.0K by the end, and suggests that the patch represents a defect rather than an image anomaly due to emissivity or climate.

c) Adjacent to this patch, a hairline crack (figure 7) was observed as being cooler than the surrounding area and could be a related issue.

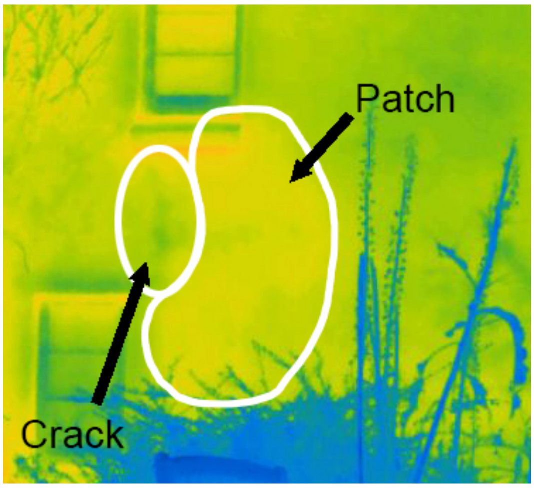

Figure 7. Locations of identified crack and patch

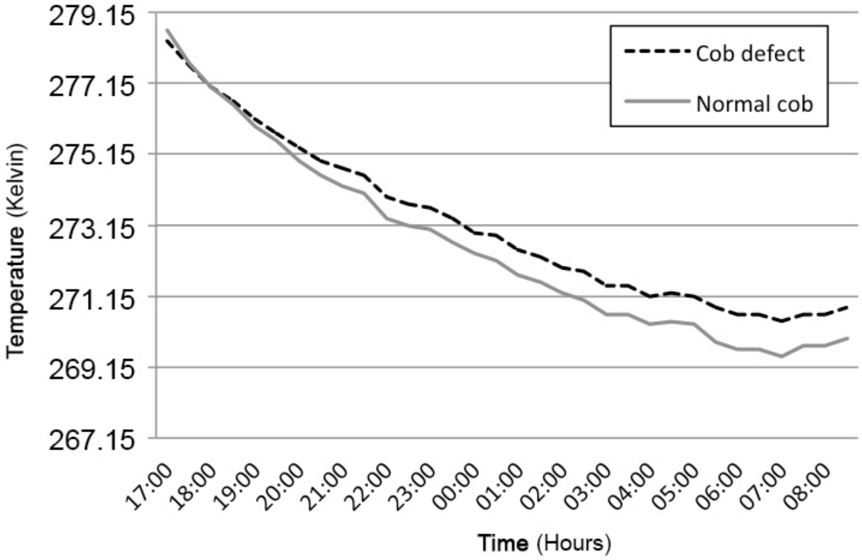

Figure 8. Graph showing temperature difference between normal cob and cob warm patch (defect).

4.2 Building 2, Study 2: External time-lapse study

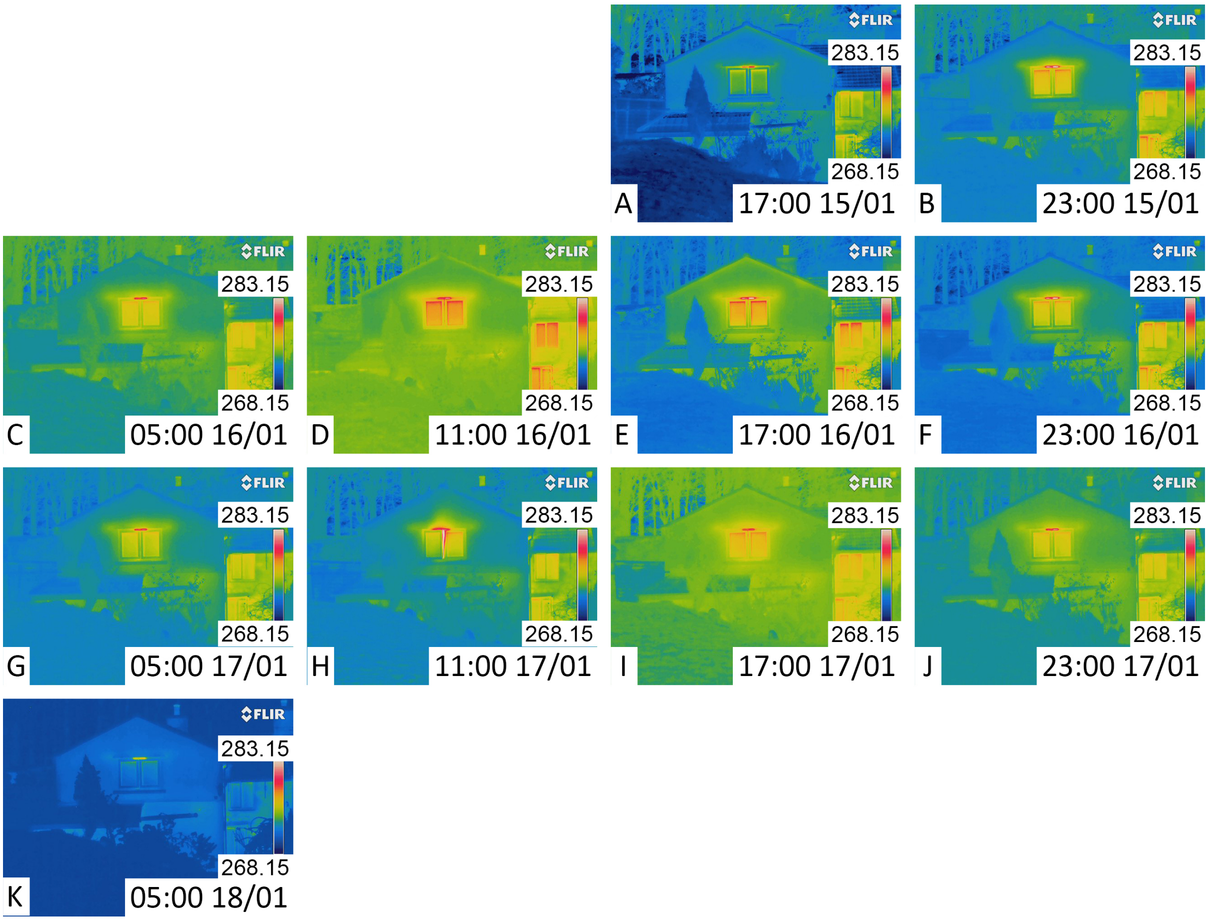

Figure 9. Top left to bottom right (A-K). Study 2. Displayed every 360-minute image only (every 12th image).

From figures 9A-K, several areas of interest can be observed, including differences in surface temperature between the original stonewall construction (back right of images) and the newer rendered concrete block, cavity wall extension (foreground building). Above the window of the extension, a warmer patch was identified, which marks the location of a lintel. Within this patch was an even warmer feature (6.0K greater than the average surrounding wall temperature), which shows internal heat escaping through air leakage from a trickle vent.

Recorded at 17:00 over three days, figures 9A, E & I illustrate qualitatively how thermal patterns appeared to fluctuate from day-to-day during study 2. Measured apparent temperatures recorded at this time fluctuated from 273.25K to 274.95K. In order to minimise the effects of thermal mass from the day before, generic wisdom states that building thermography should be conducted in the morning, before sunrise [11, 42], yet further comparisons between figures 9C, G & K recorded at

05:00 over three days again show discrepancies with measured apparent temperatures ranging from 272.05K to 274.25K. At both 17:00 and 05:00 time intervals, a temperature difference of about 2.0K was experienced over three days.

4.3 Building 1, Study 3: Internal time-lapse study

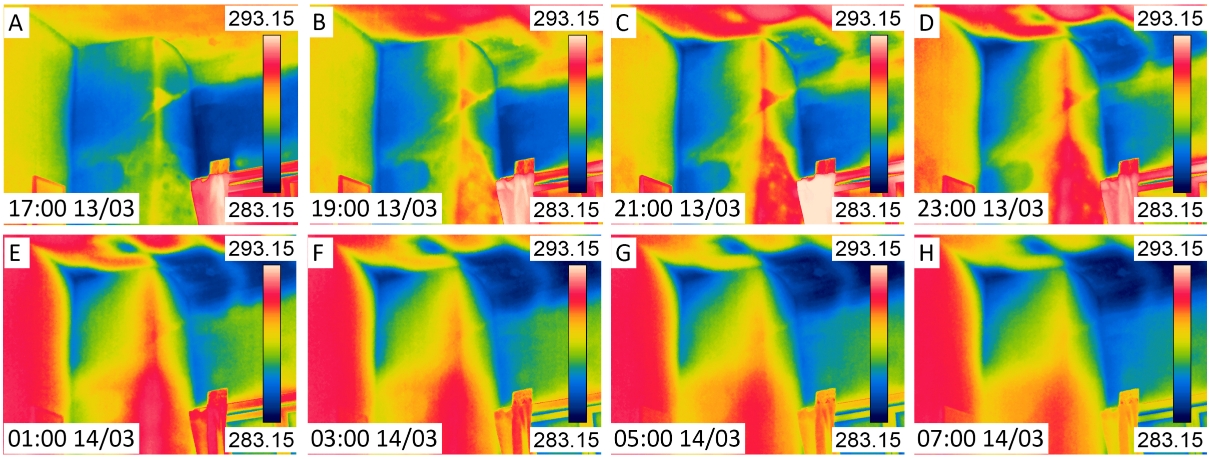

Figure 10. Top left to bottom right (A-H). Study 3. Displayed every 120-minute image only (every 4th image).

Qualitative interest included noticing unidentified features that were seen as bright markings within the cob. These patterns were clearly visible at the start of the investigation (figures 10A–C), though diminished in clarity as the survey proceeded throughout the night, before becoming completely indistinguishable by the end (figure 10H). Above the window was a patch of solid brick walling that appeared cooler than the adjacent cob. Above the brick was a patch located within a corner of the eaves and which appeared even cooler than the brick and other parts of the eaves.

4.4 Temporal resolution exploration

Seeking to investigate the most appropriate temporal resolutions for time-lapse thermography, a series of movies were created of the case studies at different temporal resolutions. The movies used for this analysis can be observed in gif format. Movie: 1 (Building 1, study 1, 30min temporal resolution), 2, 4 & 5 (Building 2, study 2, 20, 120 & 360min temporal resolutions) and 3 (Building 1, study 3, 30min temporal resolution) (Insert links to movie files) uploaded to the Elsevier website. These time-lapse recordings have been processed in the following way. Initially, the movie sequences consisted of each recorded frame, giving the full 20 or 30-minute temporal resolution. To begin with, these were reviewed using qualitative analysis techniques [43], including target signature, target symmetry and target comparison. From this investigation, it became apparent that some images in the sequence were very similar to subsequent images. This is best observed through movie 2, which shows a 20-minute temporal resolution for building 2. In this movie, very little colour change over the concrete block cavity wall between images was discernible. Seeking to address this, further movies at longer temporal resolutions were created for building 2, which included 120 (movie 4) and 360-minute (movie 5) intervals. At 120-minute intervals, the colour change between surface temperatures was much more discernible than at 20-minute intervals, while at 360-minute intervals the spacing did not appear to offer any greater contrast than the 120-minute temporal resolution.

Following qualitative analysis, quantitative analysis was used to measure the change in target apparent surface temperature between images. Figure 11 shows a thermal transect graph, which was plotted for the cob and stone portions of study 1. The apparent surface temperature difference between 30-minute spaced images for the cob gave an average of 0.3K, while for the stonewalling the temperature difference was 0.2K. At 120-minute intervals, the average apparent temperature difference for the cob was 1.2K and for the stone, 0.8K (figure 11).

Comparing the measured apparent surface temperatures of different constructions at 60-minute image intervals, the average temperature differences between images were:

- Cob (study 1): 0.5K
- Stone (study 1): 0.4K
- Concrete block cavity wall (study 2): 0.2K

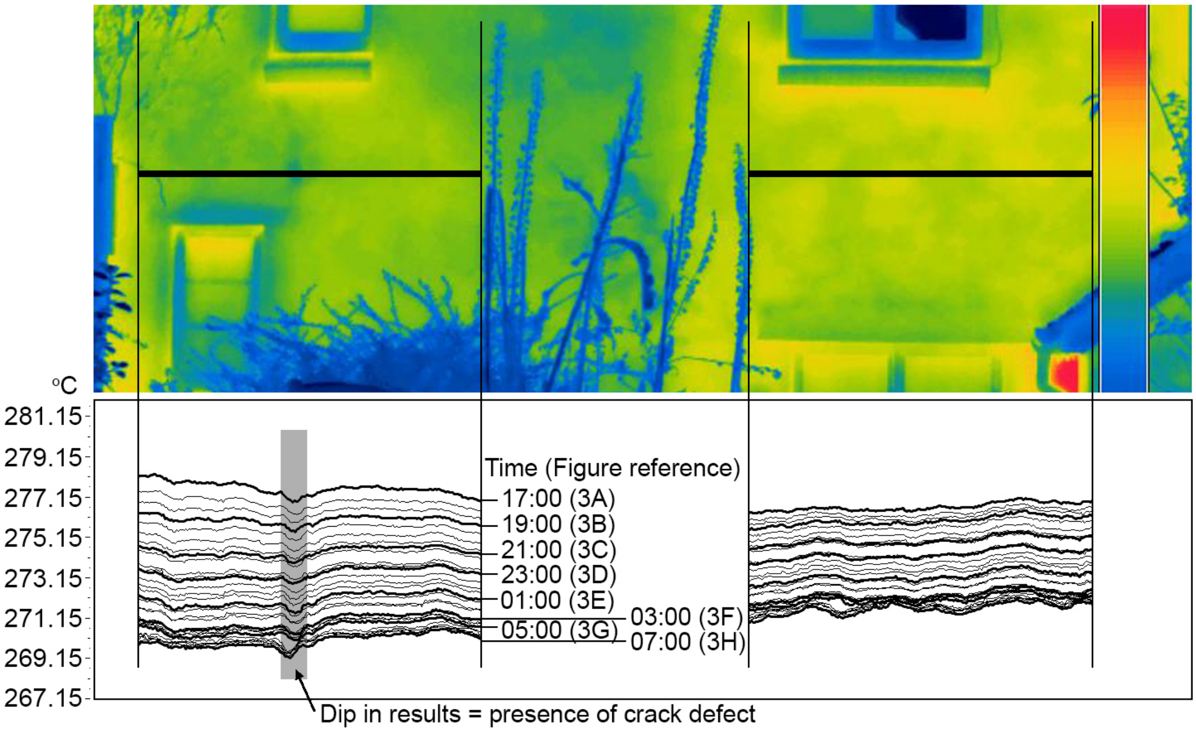

Figure 11. Graph showing thermal transects (taken along the two lines indicated in the thermal image above) plotted for each 30-minute interval thermal image for building 1. Bold lines highlight 120-minute image intervals and correlate with thermal images displayed through figures 6A – H. The grey block within the graph indicates the presence of the crack defect.

5. Discussion

Results shows that time-lapse thermography offers deeper insights into how unknown constructions might be behaving when compared with traditional analysis using thermal images taken at one single point in time. Once a better understanding of how a construction might be behaving (over time) is made, behavioural nuances can be factored in so potential defects become more straightforward to identify and diagnose. Observe study 1, where a warmer patch was identified within the cob walling (figure 8). In this specific case, delamination was identified through gentle tapping of the identified area, which gave a dull hollow sound. It was unclear whether moisture was present beneath the cement render, though Keefe [44] suggests a common failure with cob arises when moisture enters cavities behind cement render via hairline cracks (also observed in building 1). The temperature effects captured through the time-lapse thermography could result from the presence of moisture, because water holds a higher specific heat capacity than other common building materials and will retain heat longer than materials surrounding it [21].

Although the defects identified in study 1 might have been detected using single point in time thermography (following a reduction in thermal mass stored from the previous day), time-lapse thermography enables an assessment through image evolution. Such evolution can be seen in figure 8, which displays the increased temperature difference from approximately 0.1K at 17:00 to 1.0K at 08:00. Giving a time related enhancement of a static technique provides a greater insight into the size of a defect over time. Furthermore, viewing the time-lapse images in a motion sequence helps to qualitatively review the evolution of heat losses, which also indicates how materials respond to changes in transient conditions[1]. This extra layer of information is devoid from single point in time analysis.

Study 1 showed that the effects of solar gain presented a significant limitation to thermographic results. This corresponds with findings by Lehmann *et al*. [28], though largely depends on the elevation viewed, as study 2 was not subject to solar gain in the same way. Once stored, solar energy had been released (study 1), the heat flow from inside to outside became increasingly apparent, leading to a clearer picture of potential defects later in the investigation. Conversely, the internal investigation (study 3) presented clearer images at the start, prior to the introduction of artificial domestic heating. As the wall surfaces warmed up through domestic heating the heat appeared to dissipate through the construction and led to a reduction in image clarity. Had study 3 been undertaken using a single point in time methodology following a period of domestic heating, potential subsurface defects might have been missed or misinterpreted. It is therefore critical to consider the effects different heating sources might have on how a construction might behave, whether from previous solar irradiation or from internal appliances.

Work to develop a time-lapse thermography methodology has shown that there are more practical limitations to overcome externally than experienced within internal investigations. In particular, attention needs to be taken over the security, weather proofing, monitoring of environmental conditions and power supply for the thermal camera. In light of these key limitations and methods for overcoming these, the time and effort required to setup and maintain a time-lapse investigation for prolonged periods of time are quite considerable and might prove prohibitive for non-specialist

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[1] *This paper shows a small selection of the experiment images. All of the thermal images will be uploaded to the Energy and Buildings Journal website.*

commercial application. Also, it should be remembered that at distances of approximately 20m from the target surface, defects smaller than 41.6 x 41.6mm will have been missed. This is potentially significant since not only will small defects be missed, but the edges of detectable defects will not necessarily be accurate. For example, the assessment of the perceived crack in study 1 (figure 7) might not have been very accurate due to its width being less than 41.6mm.

With regards to the selection of temporal resolution for time-lapse analysis, results from the three studies showed that a greater accuracy in surface temperature difference (lower temperature differences between consecutive images) was gained from shorter temporal resolutions. Whilst a high degree of temperature accuracy, such as a difference of 0.2K between image intervals, might be required for quantitative analysis, for qualitative analysis such low differences were not visually discernible. Instead, temporal resolutions that gave approximately a 1.0K surface temperature difference between images seemed more appropriate.

Temperature variations between each of the observed construction types tended to be greater or smaller when viewed at the same temporal resolution. This suggests that the temporal resolution selected will largely depend on the type of construction being monitored, where, for example, more modern and highly insulated constructions will show less heat flow (from inside to outside) compared with older solid masonry constructions.

Further analysis of temporal resolutions showed that apparent surface temperature differences between consecutive images could fluctuate significantly, as seen through the thermal transect in figure 11. For example, temperature differences between 60-minute image intervals for the cob in study 1 started at 1.4K between 17:00 and 18:00 before ending at 0.2K between 07:00 and 08:00 the following morning. This result was most likely due to transient changes in environmental conditions, such as the thermal mass experienced in study 1. The impact of this is significant because if a temperature difference of no greater than 1.0K is desired between consecutive images, then a temporal resolution shorter than 60-minutes might be required to ensure that all temperature differences are below 1.0K.

This work has demonstrated how environmental conditions and building properties can fluctuate over multiple days (study 2), giving a surface temperature difference of about 2.0K between images recorded at identical times over three days. This was as a result of transient environmental conditions such as air temperature, precipitation and cloud cover, which had an impact on the apparent surface temperature results during the entire study period. Consequently, if thermography were conducted externally on just one of these days, the results would be different to that undertaken on another day. This, therefore, questions the ability to obtain accurate results from relatively short time-lapse investigations and particularly from single point in time images, indeed Biddulph *et al.* [45] recommend in situ investigations of at least 3 days for better estimation of u-values using heat flux sensors. Therefore, if quantitative analysis using time-lapse thermography were to be pursued, it would be advisable to conduct investigations over at least 3 days before taking averages from the results and drawing conclusions on how environmental conditions are impacting the results.

6. Conclusions

This paper has explored the practical application of time-lapse thermography for building defect detection. Contrasting time-lapse thermography with traditional single-moment-in-time methodologies, it was evident that although traditional studies might be useful in capturing particular defects at one moment in time, this methodology is often constrained by physical limitations, such as reflected radiation and the interaction between transient weather conditions and materials (solar gain and moisture). This makes the process of formulating assumptions related to defect behaviour or thermal transmittance using single-point-in-time images particularly challenging. Passive time-lapse thermography, however, has been shown through this paper to enable the evolution of heat loss to be observed and thus better understood.

Through the application of time-lapse thermography, a methodology for such an investigation has been developed in this paper. This addresses practical limitations, comprising of safety and security concerns, spatial resolution / FOV limitations resulting from camera distance to object surface, unwelcome foreground objects, difficulties observing front elevations and challenges involved with supplying continual power to the thermal camera.

The work also investigated the different temporal resolutions required for time-lapse analysis of different building constructions. Qualitative analysis of the time-lapse movies recorded at 20–30 minute image intervals showed that some images in the sequence were visually identical to others, not helping to discern variations within thermal patterns. These studies found that the apparent temperature difference between consecutive images varied with construction type, indicating that no single temporal resolution would fit all circumstances. Because assumptions are sometimes made on constructions, it seemed appropriate that the thermal camera should capture images over a short time frame using temporal resolutions of less than 30 minute intervals, before analysing and reducing the temporal resolution depending on initial results. Quantitative analysis, such as U-value determination, might require more accurate / lower temperature differences between images compared with qualitative analysis, and may therefore require shorter temporal resolutions.

On-going work is currently reviewing the use of time-lapse thermography for quantitative analysis, and specifically the determination of U-values, through work that combines in-situ observations with observations made in a controlled environment (hot/cold box set-up).

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