COMPARING TRANSIENT SIMULATION WITH THERMOGRAPHY TIME SERIES

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ABSTRACT

Thermography is an emerging technology used by construction professionals focused upon the thermal and condition performance of buildings. However, the interpretation of thermal images is difficult and often misinterpreted. This paper reports on initial work that compares thermographic images from relatively simple experimental setups with transient models of the same experiment. Thermographic images were obtained from a FLIR ThermaCam S65 while simulation was undertaken using the Voltra transient heat transfer program. The work highlights some of the inherent problems with interpreting thermal images of actual buildings, and suggests how these comparisons can provid a better understanding of real-life material performance.

INTRODUCTION

In 2010, the European Union published legislation aimed at significantly reducing the energy use of buildings, which at present are for approximately 40% of the total EU energy consumption (European Union, 2010). This has given significant impetus to improvements in construction and material standards as new and existing buildings endeavour to become more energy efficient than they were in the past.

As more ambitious targets, such as the UK's aim of 80% reduction in carbon emissions by 2050 (DECC, 2011) are unveiled, more stringent building standards have been introduced to help achieve them. Part L of the England and Wales Building Regulations sets out a number of standards dealing with the *conservation of fuel and power in buildings* (HM Government, 2010), including standards related to the thermal transmission of the building fabric and CO_2 emissions. The underlying basis for the assessment of the thermal building performance in these standards is typically a semi-stationary heat flow calculation.

Within this context, building professionals are starting to address the existing building stock. They employ various approaches to assess actual buildings and to identify defects, such as visual inspection and long-term measurement. This work is highly relevant as most of the built environment remains in use for a long time, resulting in a significant impact on overall energy use and/or carbon emissions. However, it takes place in a completely different context, where heat flows are changing dynamically due to continuous changes in weather and operational conditions, where often construction details are unknown, and defects are prevalent. Although calculating the thermal performance of a building based on steady state conditions is useful for assessing design conditions, it is not suitable to assess the actual condition and performance of a real building envelope. Conditions such as moisture in walls or heat stored within thermally massive building components (Hart, 1990) can change the material properties on a dynamic basis, which in the case of moisture in walls, could damage (Mumovic et al., 2006) and reduce the overall performance for a given construction system.

Thermography is an emerging technology used by construction professionals as a non-destructive tool focused upon the thermal and condition performance of buildings (UKTA, 2007). A thermal camera detects infrared (IR) radiation, which is emitted from the surface of an object and converts this into a thermal image (Hart, 1990). Thermographers generally record IR data as single instantaneous images. This aligns with a stationary perception of buildings, where temperatures can be used to assess heat flows. Unfortunately, this leaves the potential for misinterpretation. Transient conditions such as

thermal mass and dampening effects are not always visible in instantaneous thermal images (Pearson, 2011) due to time scales for such environmental changes. Some thermal cameras also have the ability to record movie sequences and time-lapse images. This affords the thermographer the ability to observe the change of thermal surface conditions of the structure over a prolonged period (Drollett, 2001). However, the normal approach in building surveying practice is to use single images, which represent only one point in time.

This paper reports on initial work that is part of a research project, which seeks to develop a deeper understanding of thermographic images of buildings, including the relation between single time-frame images and the on-going transient heat-flow process where indoor and outdoor environmental conditions are in constant flux.

OBJECTIVE

Before embarking on the studies of real buildings, which come with complex multi-layered and three-dimensional envelopes that behave dynamically within a constantly changing environment, this paper studies the dynamic behaviour of simple monolithic material samples.

It aims to compare time-lapse thermographic images of four material samples with simulated transient models of the same experiment to observe a correlation between the results. This will help to build an understanding for transient thermographic and simulative investigation, and will then form the basis for future investigations into more complex situations including building case studies.

The use of transient simulation software presents opportunities to observe heat flow through the layers of the model and these layers can reveal hidden components for further investigation. This is in contrast to thermography, which can only assess the surface of an object. At the same time, modelling rests on a number of assumptions, with thermal camera readings pointing out issues that might need further development.

METHODOLOGY

In order to begin comparing transient thermography with simulation, a relatively simple experiment was devised, which enables sample materials to warm up over a period of time and results compared between the two experiments.

The experiment consisted of a physical model, which was replicated in Voltra software; for further details see details below. Materials were chosen that are representative of materials commonly found in UK buildings. The materials used in this experiment were:

- Brick
- Concrete Block
- Delabolle (Cornish) Slate
- Sanded softwood

Physical thermography experiment

Thin slices of the sample materials were positioned within a purpose built timber frame, which allowed the materials to be uniformly heated from behind with a 31W electric heating mat and copper plate to ensure even distribution as shown in figure 1 below. This would provide a sufficient temperature difference across the samples as required for thermographic investigations (BSi, 1999).
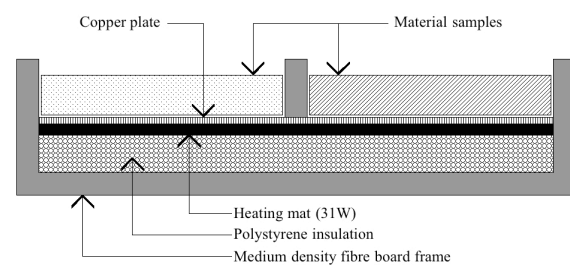
Figure 1 Section through the test board

In order to minimise any adverse environmental conditions that the building materials commonly face, the experiments were conducted in a semi-controlled internal environment, i.e. a room held at constant temperature of roughly 16°C.

Initially all the material samples were at a stable temperature in the 15 – 17°C range. The heating mat was then switched on, providing a continuous power of 31W during the experiment, and a series of thermal images were recorded every 5 minutes to record the warming up of the materials. After a period of four hours, the heating mat was turned off and left for a further hour to record the cooling down of the materials.

A FLIR ThermaCam S65 with a built-in 36mm lens, last calibrated by the UK's National Physical Laboratory in December 2010 across the temperature range of -5 to 100°C, was positioned 500mm from the test board. The internal temperature was recorded at 16°C with a relative humidity of 60% and a reflected apparent temperature of 17°C. To minimise the impact of reflected IR radiation from other sources, the test board was angled slightly so that the IR radiation from the camera (and operator) would not be reflected in the materials, and a fabric curtain was used to cover other potential sources of reflected IR radiation.

Figure 2 Photo of the experimental setup, thermocouples and IR camera

To analyse the samples using the IR camera, a box measurement tool was used for each material, to obtain an average temperature over the area of the box, which was close to (but not over) the area covered by the duct tape.

In addition, thermocouples were attached to the surface of each material with insulation tape to measure the actual surface temperatures (figure 2). To aid the accuracy of the thermocouples, heat sink compound was used between the surface and the tip of the K-type thermocouple.

Each material had its emissivity measured in accordance with the FLIR measurement procedure (FLIR, 2011). These were recorded and inputted into the *QuickReport* analysis software (FLIR, 2009)

The emissivities recorded for each material were:
- Brick (emissivity 0.97)
- Concrete Block (emissivity 0.98)
- Delabolle Slate (emissivity 0.86)
- Sanded softwood (emissivity 0.95)

The dimensions of the samples were 100 x125mm. Each had a thickness of 20mm, apart from the slate, which had a thickness of 5mm. These dimensions are based on practical considerations, with brick, concrete and wood cut to a relatively thin slice, whereas the slate was provided with the thickness given.

Where the first experiment observed the heat transfer through naturally dry materials, a second identical experiment was undertaken using the same materials, which had been moistened for an hour.

Simulated experiment

The environmental modelling software that was chosen for the simulation experiment was the Voltra simulation program from Physibel (Physibel, 2005). Voltra was selected because it is capable of transient analysis for material and construction details in 3D. It is one of very few 3D, transient cold bridge analysis tools presently available (US Department of Energy 2011).

Within Voltra, the test board and materials were modelled to match the experimental setup (figure 3). To simulate the heating mat turning on and off, a step function was set for the power output from the 31W mat. This step function was then applied to a series of node boundary conditions that had been evenly spaced within the heating mat layer on the model to provide a uniform distribution of heat.

Output nodes were positioned centrally at the surface of each material in order to record the temperature outputs from each material.

The simulation was then run for the same heating up and cooling time steps as the physical experiments and temperature readings were made every 5 minutes in line with the physical recordings.

Variation and analysis process

The comparison between the thermography experiment and the Voltra simulation was carried out twice: once under typical dry conditions, and once where the material has been made wet. This was done in order to test the generic assumption that thermal imaging of buildings should not take place during when the materials are wet. This yields the following experiments:
- DIR – Dry InfraRed (Physical experiment)
- WIR - Wet InfraRed (Physical experiment)
- DV – Dry Volta Experiment (Simulation)
- WV – Wet Voltra Experiment (Simulation)

Following this approach data was collected (both images and numerical data). The numerical data was then plotted within graphs to illustrate the warming up and cooling down phases of the material samples.
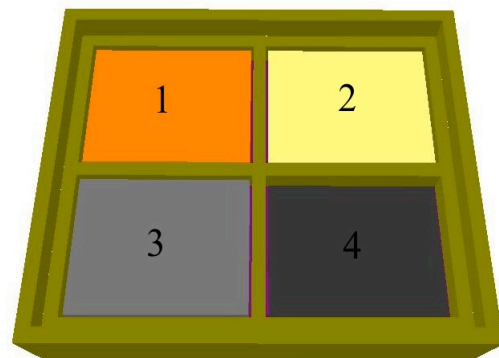
1. Brick, 2. Softwood, 3. Concrete block, 4. Delabolle slate

RESULTS

The dry experiment was undertaken initially and provided an indication of the thermal performance for each material sample. The samples were left for 20 minutes, before being warmed up for four hours and left to cool down for a further hour. Figure 4 shows the dry IR camera survey (DIR) data for the material samples over this experimental period.
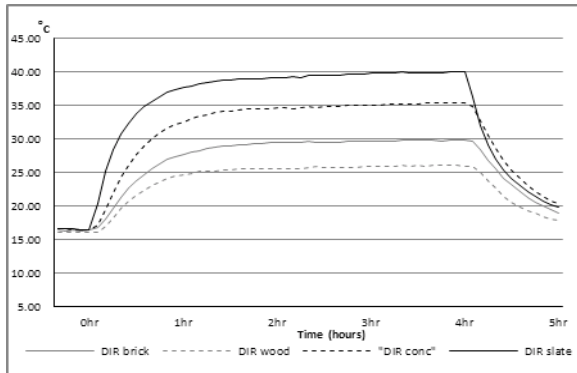

Figure 4 Dry experiment, IR camera apparent surface temperature

Figure 4 also shows the difference in performance between the four material samples.

Thermocouple data also recorded surface temperatures for each material sample, which were consistent with the IR data.

Following the DIR experiment, the same setup and test parameters were modelled and simulated within Voltra to compare with the IR camera results.

Table 1 shows the material properties that were used within the dry Voltra (DV) experiment. Properties for each material were sourced from data contained within the Voltra software, engineering toolbox website (engineering toolbox, undated) and from a BEPAC research report (Clarke, 1990).

The specific properties, thermal conductivity, density and thermal capacity for each material were chosen in order to best allow a comparison to the DIR experiment.

Table 1 Material properties used in Voltra

	Thermal conduc.	Mat. density	Specif. heat capaci.
Material samples	W/mK	kg/m^3	J/kgK
Brick	0.340	2403	1050
Softwood	0.180	700	1600
Concrete block	1.000	1400	1000
Slate	1.500	2700	1000
Test board			
Fibreboard	0.070	250	1700
Heating mat	25.000	7850	480
Polystyrene	0.035	25	1400
Copper plate	401.000	8930	390

Figure 5 Comparison between Voltra and IR camera image data. Measured temperatures given for each material square. Time periods: A – 0 minutes. B – 40 minutes. C – 100 minutes. D – 280 minutes

The internal room environment was also modelled within Voltra, with a boundary temperature of 16°C and surface heat transfer coefficient of 17.5W/m^{2}K. Again, the heat transfer coefficient parameter was adjusted several times before a situation arose that emulated the physical experiment.

Figure 5 illustrates a selection of key time stages of visual data within Voltra and captured with the IR camera. Although the colour coding representing the temperature gradient is different between the two, (the ability to directly match the colour coding is limited by the thermographic software and the limited pallet available from the simulation software), there is a visual correlation between the experiments. This correlation was further investigated through the production of graphs.

To explore the effects of moisture within the selected materials, a second physical experiment was conducted once the material samples had been moistened for an hour. The data from this wet IR experiment (WIR) was then plotted along side the data for the DIR and DV experiments, so that comparisons between the three could be made. Figures 6, 7, 8 and 9 show DIR, WIR and DV data for each sample and also include the dry thermocouple (DT) and wet thermocouple (WT) data for each sample, which was recorded as a check of the IR data.
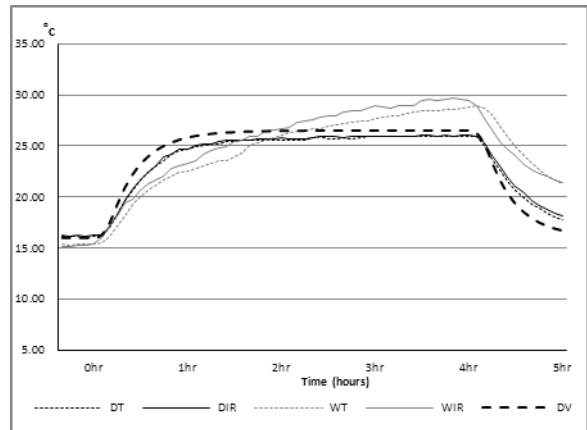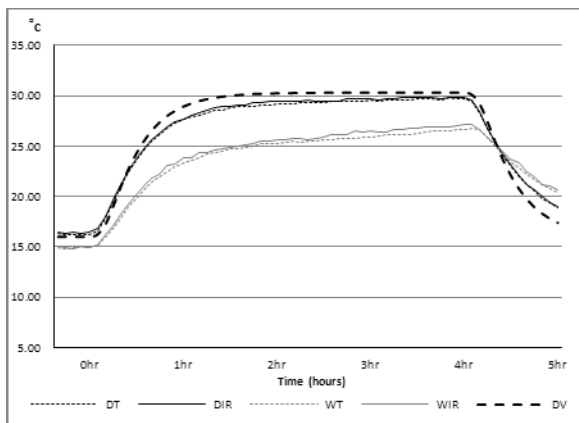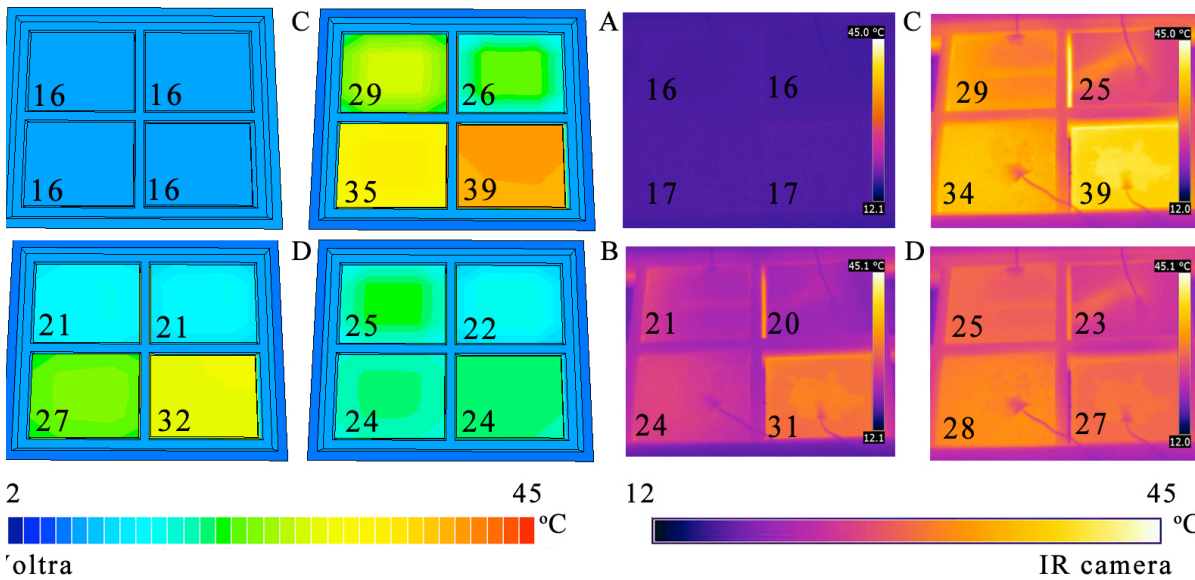

Figure 7 Softwood material sample surface temperature

Figure 6 Brick material sample surface temperature

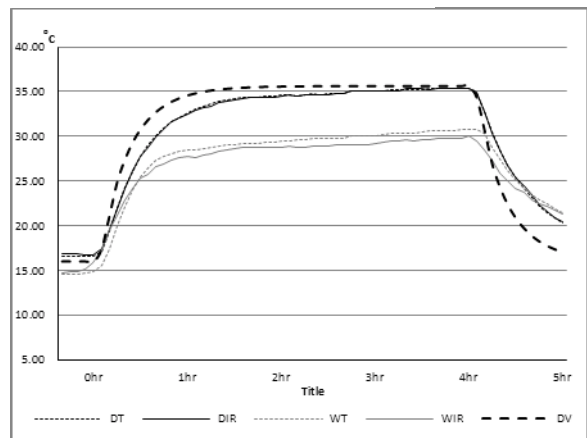*Figure 8 Concrete block material sample surface temperature*
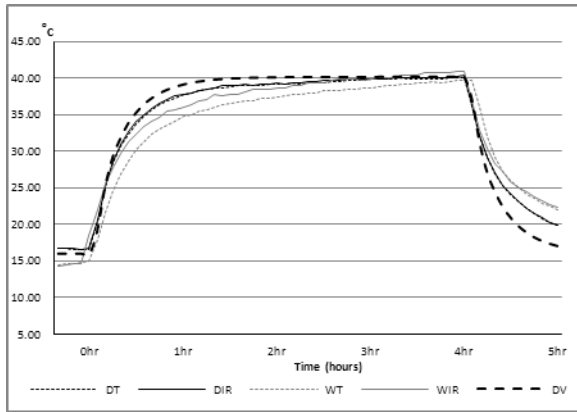
Figure 9 Delabolle slate material sample surface temperature

Knot shown as brighter

Figure 10 IR image of softwood material sample showing anomaly due to knot within the sample.

Comparing the DIR and DV results

Comparing figures 6, 7, 8 and 9, patterns within each experiment could be observed between the material samples. For each material the DV samples appeared to warm up at a faster rate during the initial heating phase than the DIR samples.

Once the DV sample had reached its highest temperature, it maintained this until the heating mat was turned off. The DIR samples however showed a small steady rise in temperature once they had past the initial rapid heating phase.

At the end of the 4-hour heating phase, the mat was turned off and a cooling period of an hour was recorded. This cooling phase showed that the DV samples cooled at a faster rate than the DIR samples.

The faster warming up and cooling phases for the DV samples suggest that some of the material and environmental properties used in Voltra may not correctly simulate the actual properties of the physical experiment. This observation highlights an issue when comparing real experimental data with software., The level of match between the experimental material and environmental properties with the software's possible choice of parameter values will need to be further investigated in light of these findings.

Another observation was related to the softwood timber sample. As the sample reached a higher temperature, the thermal image (figure 10) showed a brighter patch within the sample. This was actually a knot within the sample and would be difficult to accurately model within the software.
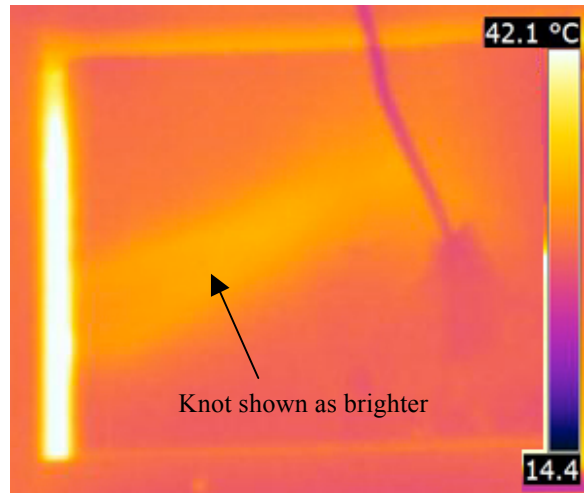
Comparing WIR with DIR results

Reviewing the data from the WIR experiment, it can be observed from figures 6, 7, 8 and 9 that when the samples were damp, the initial heating phase took longer than the DIR experiment. Actual results depend on the amount of water that is present in the sample, with brick and concrete showing a different pattern from wood and slate. Following this phase, the WIR samples showed a sharper rise in temperature over the 4-hour heating period than the DIR samples, this was due to the materials drying out over the heating period.

Brick (figure 6) and concrete block (figure 8) show a lower temperature over the duration of the heating phase for the WIR. It was observed that these materials were still damp at the end of the heating phase and account for this lower temperature.

Although having a longer initial heating phase, the WIR delabolle slate sample (figure 9) showed a temperature profile that ultimately matched the DIR data, which would suggest that the moisture on top of the slate had evaporated. Due to the impervious nature of slate, this would seem plausible.

The cooling down phases for all of the WIR samples was shorter, and had a steeper gradient, which would be expected from damp materials in comparison with their dry counterparts.

Attempts were made to try and simulate the WIR experiment within Voltra. Material properties were adjusted to replicate the moisture within the samples, however it was assumed that over the duration of the WIR experiment that the samples material properties would be constantly changing as they dried out from their initial damp state, and that certain parts of each sample would dry out differently.

CIBSE applications Manual, AM11: 1998 describes this variance in material thermophysical properties as a source of uncertainty within modelling software, and this did indeed prove to be a limiting factor within the Voltra software, which was unable to replicate the drying out conditions, and therefore ruled out this proposed experiment.

CONCLUSION

This paper presents a comparison of simulation efforts with the results of time-lapse thermographic images. In both cases four simple material samples where heated and both warm-up and cool-down behaviour was observed. This comparison was undertaken in order to better understand thermal images, and is stage one in a broader project that looks at identifying the performance – and potential defects – in actual buildings.

The results demonstrate how undertaking simulation in combination with thermography might help thermographers and building designers to better understand the complex behaviour of building fabric, even for simple monolithic material samples under known conditions.

From the perspective of a thermographer, the level of information that can be gained from thermal images is important. Much of the industry perceives thermography as a 'relative' tool (Pearson, 2011), observing colour gradients through the IR camera and using their experience and best judgement to interpret what they are seeing. However, the work presented here hints that it might be possible to use thermography to quantify thermal behaviour far better than this, especially if coupled with simulation expertise.

The experiments presented highlight the difficulties in selecting accurate parametric data to enable precise analysis. Not only in terms of environmental conditions, but also in relation to material properties, which could have anomalies such as fractures or areas of non-homogeneousness within them, such as the softwood sample in this experiment (figure 10).

Furthermore, since difficulties were encountered when selecting parametric data for this relatively simple experiment, a larger scale real life building would present more issues related to refining parameters for circumstances where there will likely be multi-layer elements.

In relation to effective thermographic work using thermal cameras to conduct comparable experiments alongside simulations will enhance the understanding of the thermal processes and assumptions underlying both approaches.

From the perspective of transient analysis, this study demonstrates the importance for longitudinal investigation of material behaviour over a prolonged period, where there are changing conditions. The thermographic experiments in this study proved successful in demonstrating the transient heat flow from both the dry and wet samples.

Voltra proved useful in simulating and assessing the heat flow through the dry samples, and presents a strong case for undertaking transient simulation of materials and constructions for analysis and design.

The actual software used in this work appeared less able to simulate dynamically changing conditions such as the wet experiment, where moisture had a non-stationary impact on the materials properties. Other transient thermal analysis software such as WUFI could offer an alternative. In this context, it is worth noting that other dynamic environmental conditions such as thermal mass changing under moisture content might also present difficulties for transient simulation.

Overall, this study demonstrated that although it is difficult to model a real life situation, doing so presents great benefits to better understanding the performance of a material or building fabric, when used in combination with measurements such as thermography.

Caution should be urged when scaling this experiment up to real life building examples, since other parameters might begin to feature that are not present in semi-controlled conditions. Conditions such as changes in occupancy and weather might combine in a cocktail of parameters that have an impact over a multi-layer structure.

It is this precautionary warning that makes such transient analysis through thermography and simulation even more important. Specifically for construction professionals, if they are to gain a deeper understanding of the thermal performance for their buildings, this is particularly important, since more common design based 'steady state' fabric analysis belies the real life performance of the building during frequently changing environmental conditions. Therefore this work has the opportunity to raise awareness of transient analysis and some of the methods available to observe and understand this.

FUTURE WORK

Having reviewed the outcomes from this study, there are a number of areas for potential further investigation that this wider project might follow.

The relatively simple experiments undertaken for this study have proved to be very useful for determining

base-line calibration data for single layer samples that can be used in future work. Additionally this experiment has also provided a methodology, which could be replicated for multi-layer material build-ups using a similar experimental procedure.

Another area of future work would be through scaling up these experiments to observe transient effects on real life construction case studies as discussed in the conclusion.

Where this study looked at using the Voltra transient simulation software for comparing with thermal data, it would be useful to compare with other, similar, software. In particular it would be useful to identify whether there is a transient simulation tool currently available, which is able to observe transient environmental conditions such as moisture or thermal mass in walls. Other forms of software might include 'Therm' (Lawrence Berkeley National Laboratory, 2012) or 'MATLAB' (Mathworks, 2012).

ACKNOWLEDGEMENT

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