Infrared for Detection of Exterior Wall Moisture and Delamination: A Case Study and Comparison to FEA Predictions

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ABSTRACT

An 80-year-old building, stucco over terra cotta, was surveyed for moisture from the exterior. Solar loading was used to detect suspect areas. The results and basis of the IR are discussed. Physical probing is still in progress, but some results are available. A comparison of the results to heat transfer simulation of the system using FEA is also presented.

Keywords: building thermography, moisture, delamination, heat transfer analysis, FEA, prediction, simulation

BACKGROUND

Kleinfeld Technical Services, Inc. was retained to provide a survey of the exterior of a building that had a history of water problems in the walls. The survey was carried out in August. The building is located in the Greater New York metropolitan area. It is approximately 80 years old, of stucco over terra cotta construction. It is sufficiently isolated from neighboring buildings and other obstructions that nearly all walls receive direct sun, at least in the summer. Solar loading was therefore used to drive the transients necessary to detect moisture in the exterior walls. A series of scans of the outside was made over two testing days, covering a time period from before sunrise through to early evening. Areas were scanned over the day, but not all areas were scanned through the entire day. Weather on the two testing days was similar, with fairly clear skies, low wind, and moderate air temperatures in the 70s to 80s.

A selection of images from one part of the building is presented along with some sample images from other areas of the building. Findings included areas suspect for moisture and some areas suspect for delamination. Additionally, clear evidence of filled-in windows, of which the owners were not aware, was found.

THERMAL BEHAVIOR OF WALLS

Surface thermal anomalies will be caused by structural and moisture conditions. In warm season conditions, the exterior wall can be expected to be warmer than the interior. The following discussion is based on that scenario.

Over a daily cycle of solar heating and air temperature-driven heating during the day and convective and radiational cooling at night, the surface of the facade will respond in a manner indicative of and caused by its condition and underlying materials. During solar exposure, starting from a cool nighttime state, areas that are thermally better connected to the interior, that is, not well insulated, will warm more slowly. Similarly, those areas with higher thermal mass, such as trapped water, will also warm more slowly. Areas that are not well connected, such as those over disbonds or delaminations, will be unable to dissipate the applied heat as readily and will warm more quickly and to a greater degree than the "normal" areas. The reverse behavior will be observed during a cooling phase: wet areas or areas that draw more readily from the interior will stay warmer, and disbonded areas will cool more rapidly.

The wet areas and the poorly insulated areas will tend to behave similarly. The ends of interior walls and of floors are clear examples of the poorly insulated areas. It is necessary to make some judgments of areas that are suspect solely on their thermal behavior: whether the indicators are structurally driven; i.e., caused by walls, floors, penetration headers, etc.; or if there is evidence of moisture in the walls. Often the location and comparison to similar locations should suffice. Information about the construction of the building, if available, will be helpful. In situ testing for moisture content at locations identified by IR is advisable. The areas that are suspect for delamination have less uncertainty. The other possible causes for the higher temperature signature on heating and the lower temperature signature on cooling are variations in surface condition, such as dirt or paint color that would affect the amount of solar energy absorbed and radiant energy re-emitted.

IR Results

The building that was examined had balconies that shaded portions of the walls. As a result, the IR images generally have too broad a temperature range for a single presentation of the image to be used to examine both the exposed and shaded areas. Only the exposed areas are shown here. They present a clearer result than the shaded areas, because they have more extreme loading.

In general, IR images that were taken near dawn for reference show the ends of the walls and floors as warmer than the bulk of the facade. Other warm areas in these images include the surroundings of the windows, doors, and air conditioner sleeves. Under the heating regime caused by solar and convective loading during the day, the images reverse. The wall and floor ends become the cooler areas, compared to the bulk of the wall. The areas around the penetrations are also cooler.

Field Results

Figure 1 shows a typical finding, presented in different palettes and temperature spans for clarity and accompanied by a photo of the area. The image at the bottom with a wider temperature range shows three measurement areas indicating the temperatures for the apparently normal, wet, and delaminated areas. The temperatures are approximate, as explained above. The delaminated area is saturated hot.

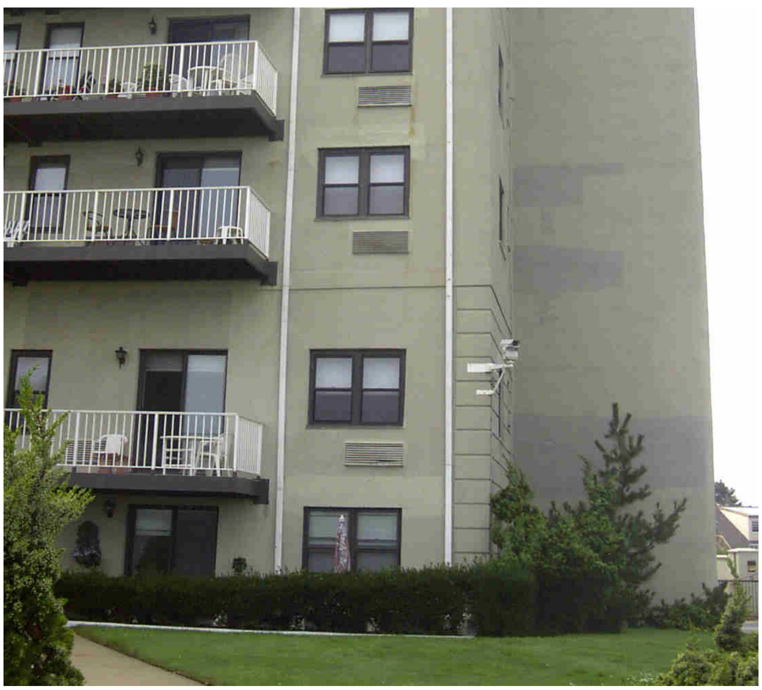


Figure 1A. Photo of wall section

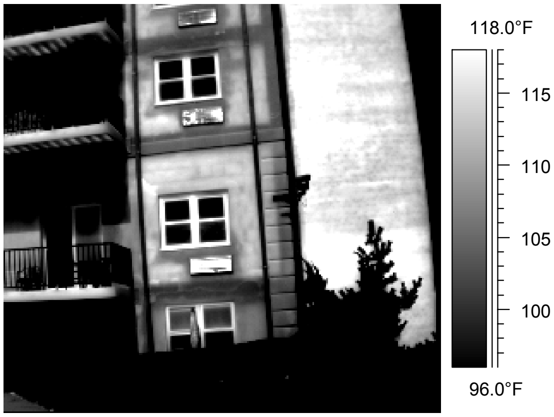


Figure 1B. Gray scale IR image.
8/20/2003, 10:48:28 a.m. EDT

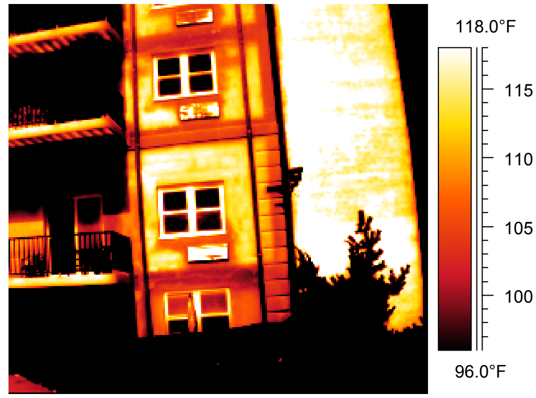
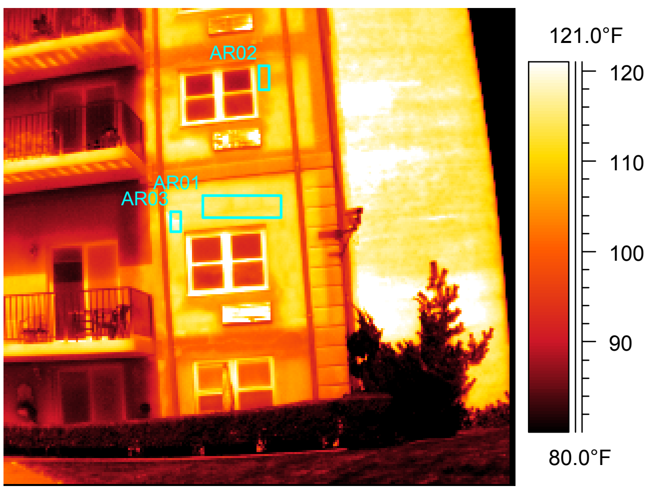


Figure 1C. Same image in glowbow palette



Label	*Value*
AR01 : max	*115.7°F*
AR01 : min	*110.0°F*
AR01 : avg	*113.0°F*
AR02 : max	*107.2°F*
AR02 : min	*103.1°F*
AR02 : avg	*104.3°F*
AR03 : max	*>122.0°F*
AR03 : min	*113.8°F*
AR03 : avg	*>116.8°F*

AR01 is a normal wall; AR02 is a suspect wet wall; and AR03 is suspect delaminated.

Figure 1D. Same image in glowbow palette, with wider temperature span and suspicious areas marked

Following this area over time, from pre-dawn to the last image taken at 10:48 a.m. EDT, Figure 2 shows how the temperatures evolve. The images are not on a common temperature scale. The pre-dawn image clearly shows the reversal of relative hot and cold areas from the later images, especially at the floor-to-wall connections.

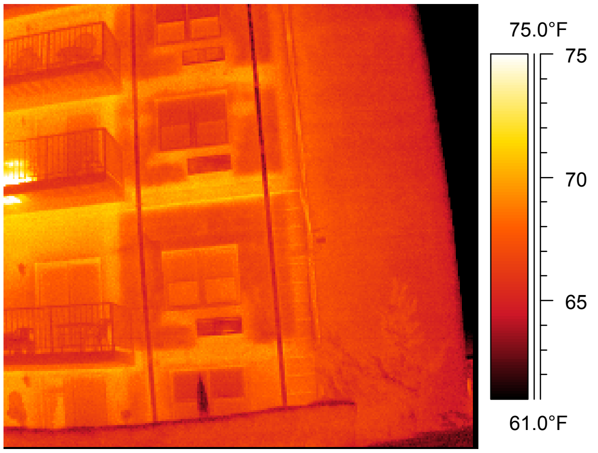


Figure 2A. Dawn image showing the ends of the floors and the suspect wet areas as warmer than the dry wall. 8/20/2003, 6:01:49 a.m.

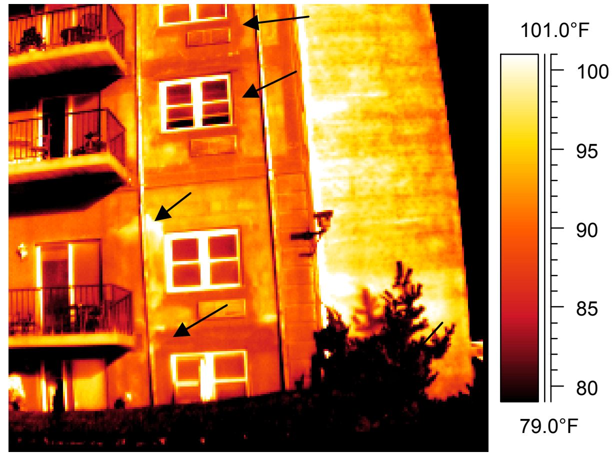


Figure 2B. SE elevation already receiving sun and warming. Problem areas have become visible, as shown by the arrows. 7:50:28 a.m.

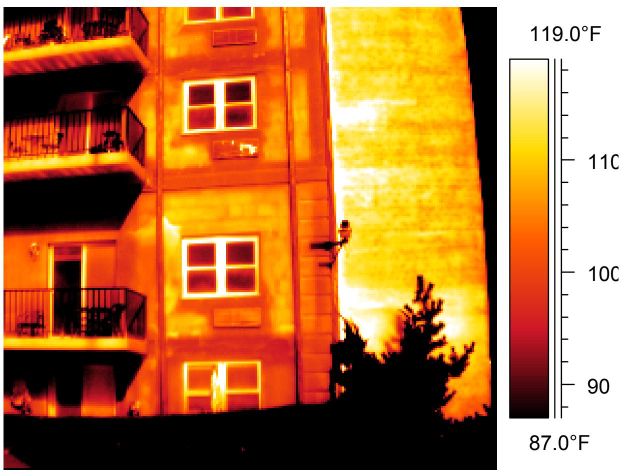


Figure 2C. 9:06:52 a.m.

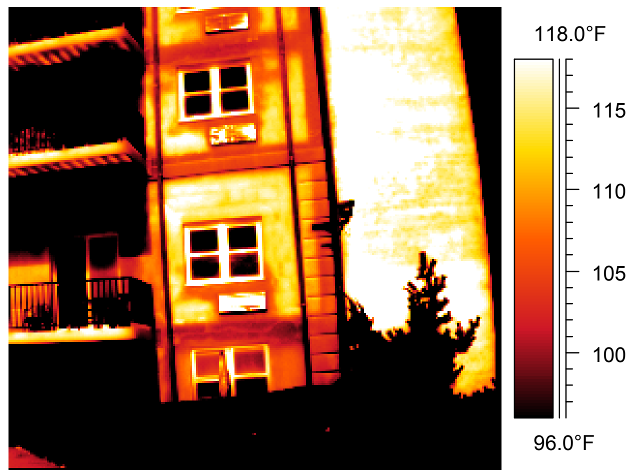


Figure 2D. 10:48:28 a.m.

A few additional IR images are presented in Figure 3, showing some features of interest. Photos of probes done on various parts of the building, based on the IR work, are also shown.

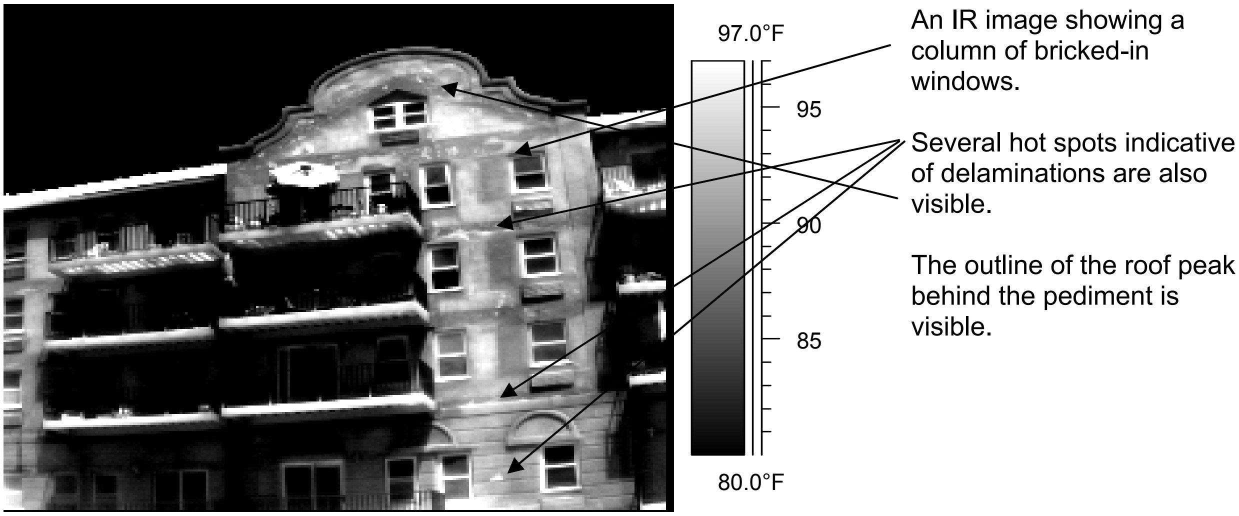


Figure 3A. Features of interest on one area of the building. 8/12/2003, 12:53:37 p.m.

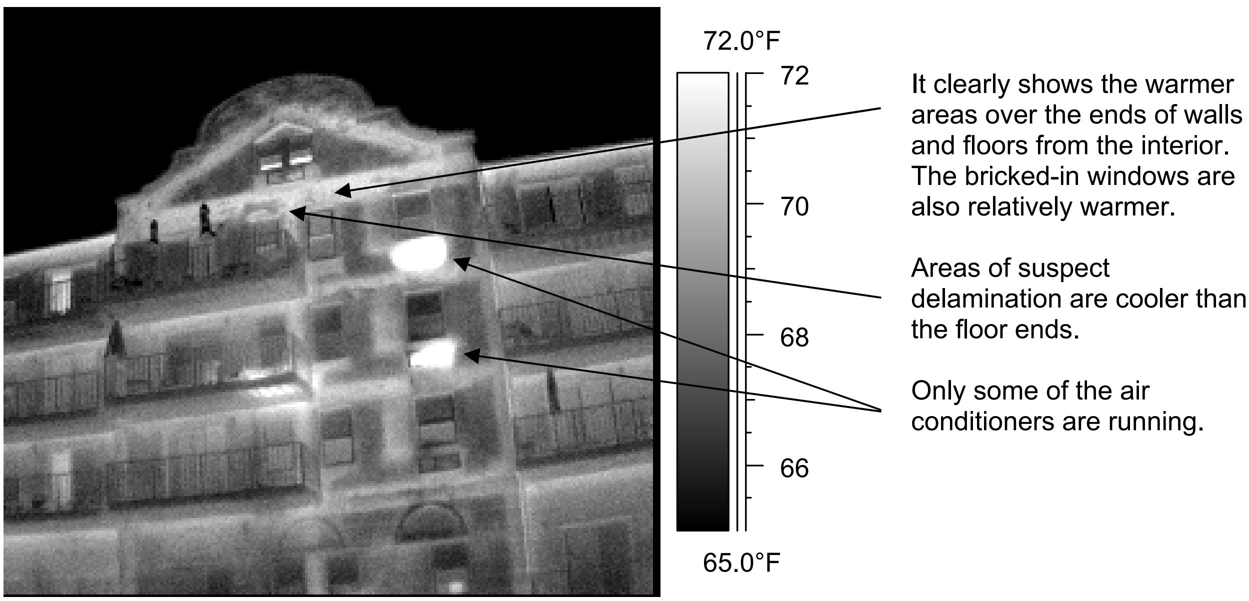


Figure 3B. An image similar to the one above, but taken at dawn. 8/20/2003, 6:14:56 a.m.

Figure 4. Photos after opening the wall. Note the rusted condition of the steel.

This type of IR survey is qualitative. It does not require temperature measurement. However, in order to compare the field results with the heat transfer calculations, some temperature measurement from the field is necessary. This becomes somewhat problematic for at least two reasons. First, not all the data necessary for temperature measurement was taken in the field. For example, no emissivity or sky temperatures were actually measured. Second, the IR camera and analysis software used, a FLIR ThermaCAM® 390, does not do well in measuring temperatures outdoors. Much of the ambient or background temperature for a wall, especially at higher floors, is the sky temperature; or if it is in sunlight, solar temperature. A clear sky, even in the daytime, but especially at night, can have temperatures below what can be calculated by or even entered into the IR camera. The difficulty is compounded by the fact that the background temperature is an uncertain mix of the sky temperature and the temperature of the ground and other surroundings. Nevertheless, some approximate values for the building temperatures were derived for this comparison.

HEAT TRANSFER ANALYSIS AND FEA

Finite element analysis (FEA) is a numerical method for performing steady state and transient engineering calculations. I have used it for heat transfer calculations related to IR thermography applications. The temperatures that we, as thermographers, observe or measure are the results of heat transfer in the objects we examine. By modeling the system in question, in this case the wall and its surroundings, we can predict its behavior in its surroundings. The predictions can then be used to provide guidance in picking the conditions for performing the IR, to provide explanation of what is found, and to improve our efficiency and effectiveness as thermographers.

As thermographers, we see the surface of the building walls. The heat transfer that affects that surface temperature occurs as conduction, convection, and radiation. The interchange of the wall or other system with its surroundings is described as boundary conditions (BCs) and is used in the heat transfer calculations, whether performed by FEA or other methods, to relate the system (the wall) to the rest of the world.
In the modeling, conduction of heat through the wall's components is handled by specification of the shape, size, material, and connectivity of the wall's components. The convection boundary conditions occur at the exterior face of the wall, between it and the ambient air; and at the interior face of the wall, between it and the interior air. An assumed constant interior air temperature of 70°F was used throughout. A time-dependent outside air temperature was assumed, based on the limited field data that was taken. Radiation similarly occurs between the surroundings and the exterior and interior surfaces. Since the interior surface temperature and the interior surroundings are at similar temperatures, the radiation BC for the interior was neglected. The surroundings for the exterior wall's radiation BC were taken as the sky, for which temperatures were assumed as a function of time. In addition, the impact of the sun on the wall was taken as a heat flux that varied with time. Values for this solar loading were obtained from ASHRAE [1], based on the time of year, the latitude, and the orientation of the wall. Changes in the solar loading BC would be made for changes in any of these factors. All of the assumptions in the selection of BCs were reasonable, but, since they are assumptions, their values are not certain, and they will affect the final results.

Details of the wall construction were also assumed and considerably simplified. Literature values for some of the components' material properties were not directly available, so values for "similar" materials were substituted. In addition, the simulation uses assumed values for the amount and location of the water in the wall and for the location and size of the delamination. A value of 20% contained water was assumed for the stucco layer of the wet wall area. An air-filled gap of 0.25” thickness was assumed for the delamination. While all assumed values were selected to be as reasonable as possible, they are not necessarily accurate. This will affect the level of agreement between the simulation and the actual wall’s behavior.

FEA / Heat Transfer Analysis Results

The model used for the analysis is shown in Figure 5. The three types of areas, sound or dry wall, wet wall, and delaminated wall, were combined in a single model to save time and to also allow an estimate of the interchange between their thermal signatures. The pink layer is stucco, the dark gray is the terra cotta, and the light gray is interior plaster. The delaminated area also has a thin layer of air between the stucco and the terra cotta, shown in blue. The face dimensions of each section are 4 inches square. The stucco is 1 inch thick; the terracotta is 6 inches thick, except where it was trimmed to 5.75 inches to allow for the air gap without “bulging” the wall; and the plaster is 2 inches thick. The wet area was treated as having 20% water added to the stucco. The properties of the stucco were adjusted by adding 0.20 times the material property of the water to that of the stucco. This was done for density, specific heat, and thermal conductivity. The reasoning used was that the water would fill in spaces in the stucco’s matrix. This would directly increase the density and specific heat. Similarly, the water would create a parallel path for heat flow, essentially by displacing air; so it would add conductivity to the stucco.

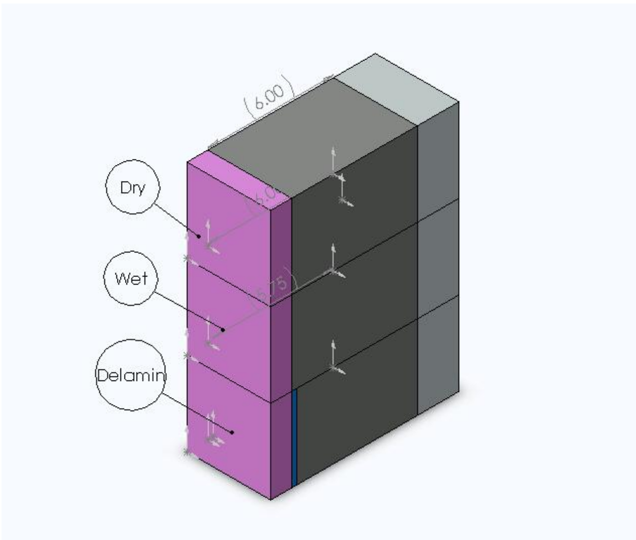


Figure 5. Model for FEA analysis

A typical graphical image result from the FEA modeling is shown in Figure 6. The case shown is for 10:00 a.m. EST. The model result is shown in an isometric view, including the "interior" of the wall. This is information that would not be available in the field, since only the face of the wall is actually visible. Temperature data from the center of each 4 x 4 face section was taken from the FEA results and plotted. It gives the temperature history of the sound, wet, and delaminated areas over a 24-hour cycle. By comparing them, the contrast between the areas can be derived, which is important in terms of being able to detect the anomaly with an IR camera.

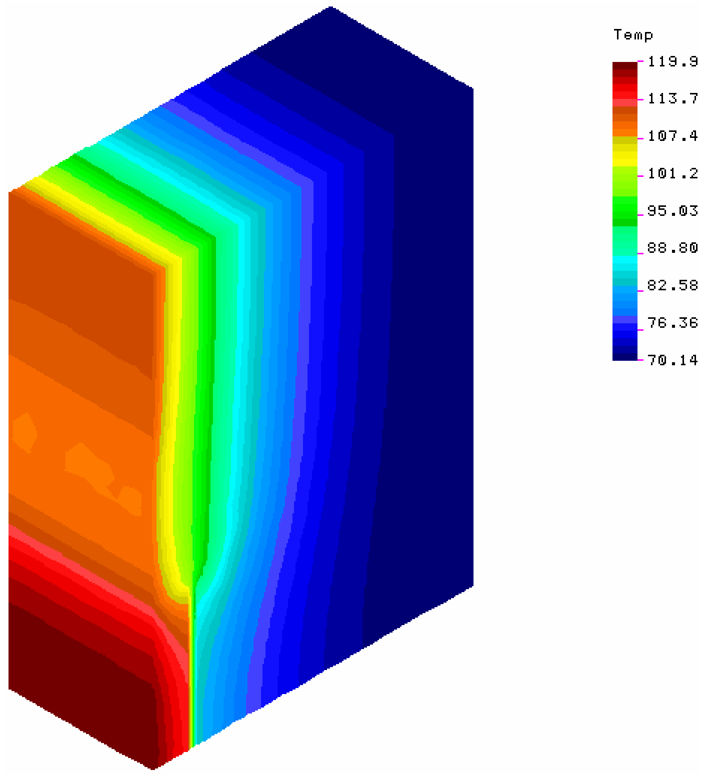


Figure 6. FEA modeling graphical image for 10 a.m. EST

Figure 7 shows the predicted thermal history of the three sections along with data taken from the IR images. The behavior of the three sections is similar to each other, but note the following differences. The peak temperatures, occurring around 10:30 a.m. EST, are in the order expected: the delaminated area is hottest, and the wet area is coolest. Furthermore, the nighttime temperatures are in reversed order, with the delaminated area coolest and the wet area warmest. The swing or range of temperature is least for the wet area and greatest for the delaminated area. This is consistent with our understanding of how the wall interacts with its surroundings. The available data for the section of wall shown above in the IR images is plotted on the same graph as oversized data markers, along with data from a second section of the building with the same SE orientation. There is good agreement, especially considering the number of assumptions that were made, in the values of the temperatures, the trend of the temperatures, and the relative order of the temperatures.

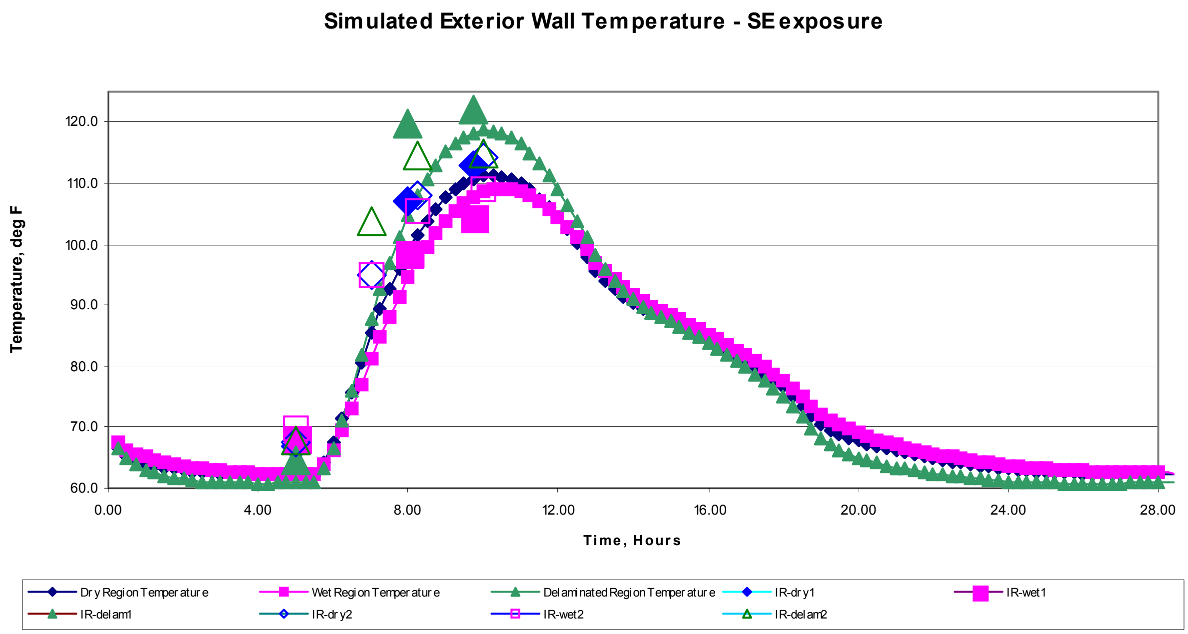


Figure 7. Predicted exterior surface temperature vs. time for various wall sections

Figure 8 presents the contrast of the anomalous areas to the dry area. Note that the peak differences occur at different times: approximately 8:00 a.m. EST for the wet area and 9:30 a.m. EST for the delaminated area. These times are also different from the peak temperature times, which occur at 10:30 a.m. for all three areas. The temperature assumptions made about the ambient air and sky temperatures primarily cause the unevenness in the curves, especially visible in the contrast curves, and most particularly in the afternoon and early evening. The shoulder in the curves in late afternoon is also caused by the solar flux not being symmetrical with time for the southeastern exposure that was both simulated and measured.

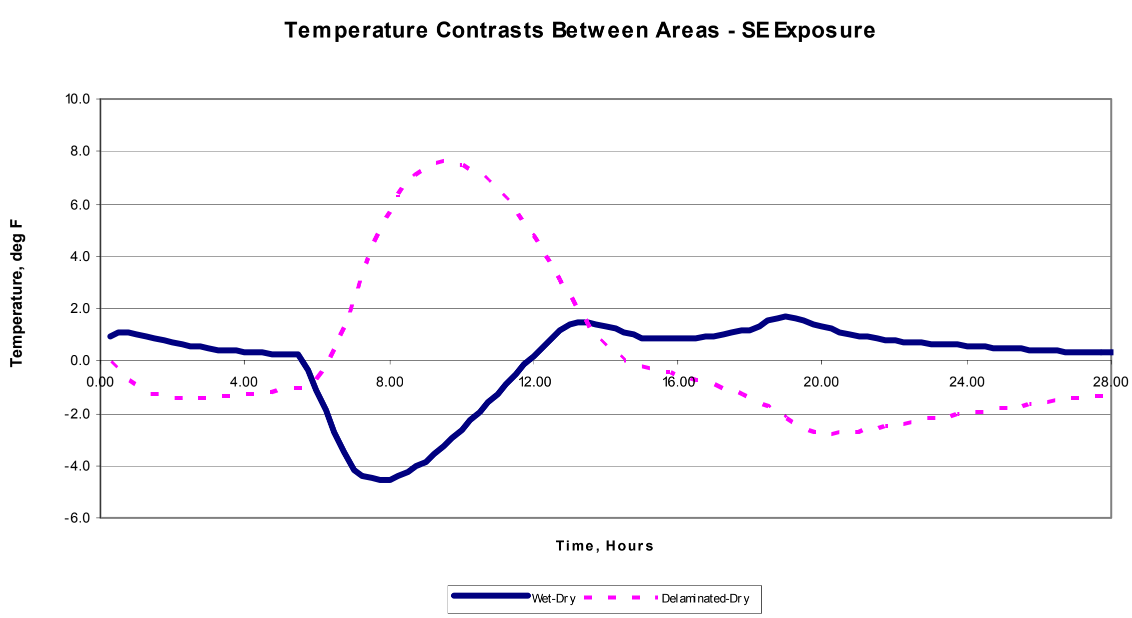


Figure 8. Temperature contrast vs. time for modeled anomalous areas to dry area. Wet-to-dry is solid line; delaminated-to-dry is dashed line.

This behavior can also be seen in the FEA images. A series of images, for the SE exposure, is presented in Figure 9, for times corresponding to the IR image series shown in Figure 1.

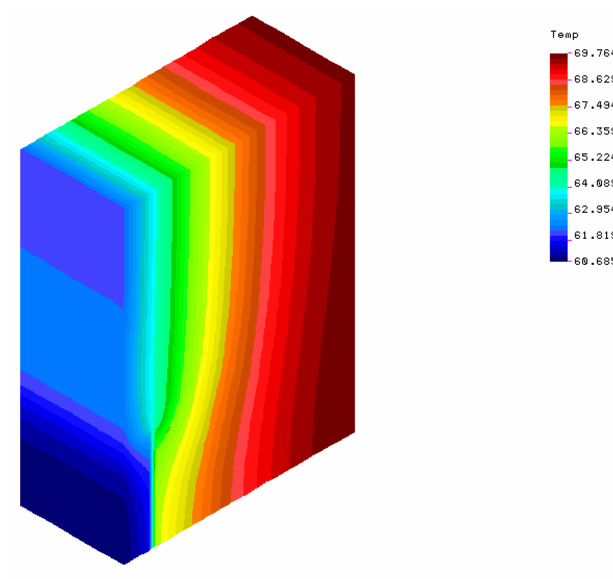


Figure 9A. Delaminated area is coolest; wet area is warmest.

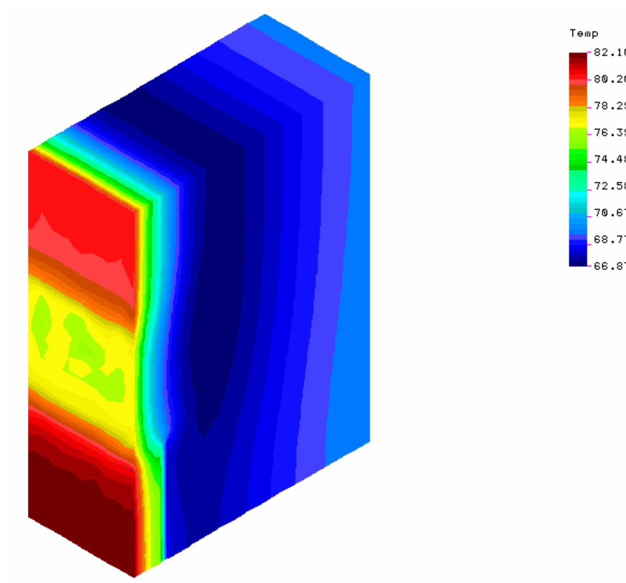


Figure 9B. Delaminated area is warmest; wet area is coolest. The inability of heat to get through the air gap can be seen, as can the hold-up of heat by the water in the wet stucco. 7:45 a.m. EDT

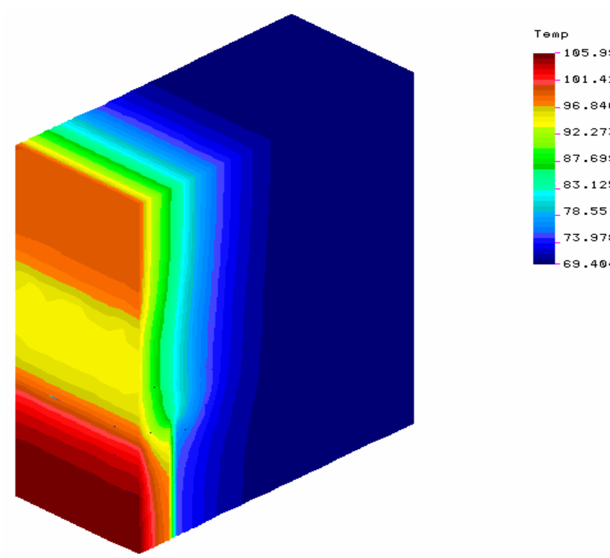


Figure 9C. Same order as Figure 9B. 9:00 a.m. EDT

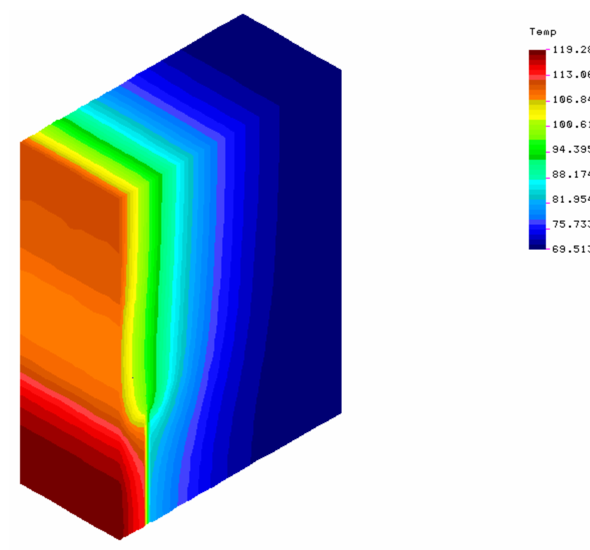


Figure 9D. Wet and dry areas are getting closer as the entire face of the wall is warming up. 10:45 a.m. EDT

Once the model is developed in the FEA software, it is a comparatively simple and short effort to evaluate the impact of different conditions. For example, the expected temperature history and contrasts for a different orientation of the wall can be evaluated by changing the solar flux BC to match the new orientation and re-running the model. Figures 10 and 11 present the results for a western facing wall. Note how the timing of the peaks has shifted to later in the day. The maximum values are also slightly higher. This is due to the combined effects of the solar loading and convective heating from the ambient air. The relative behavior of the three types of wall area, dry, wet, and delaminated, remains the same.

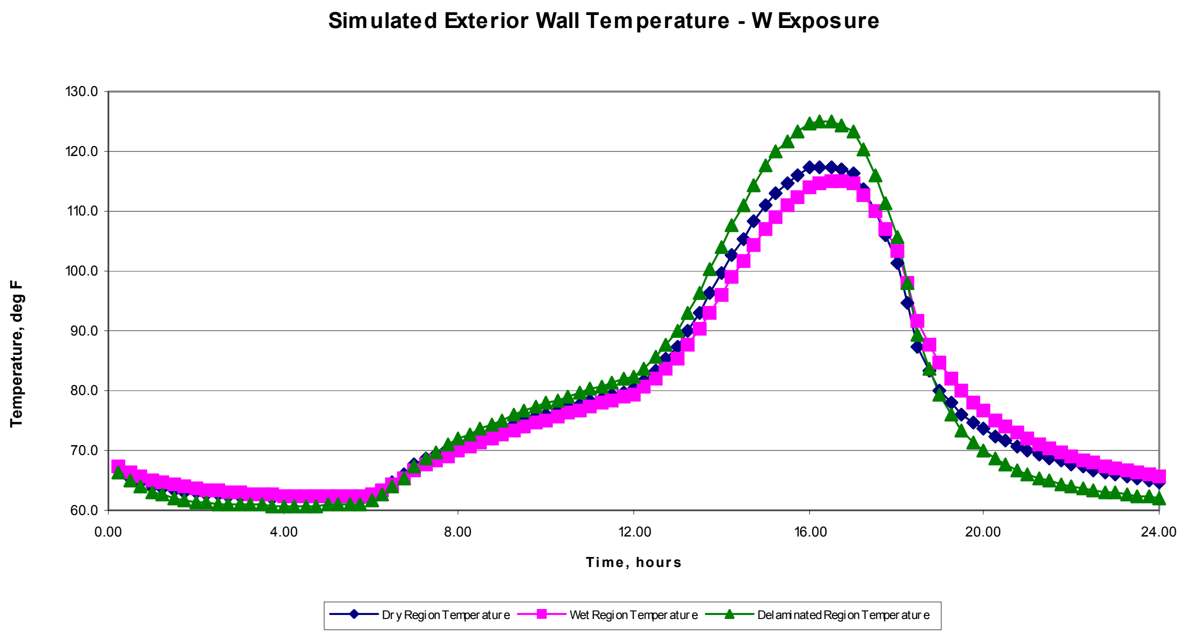
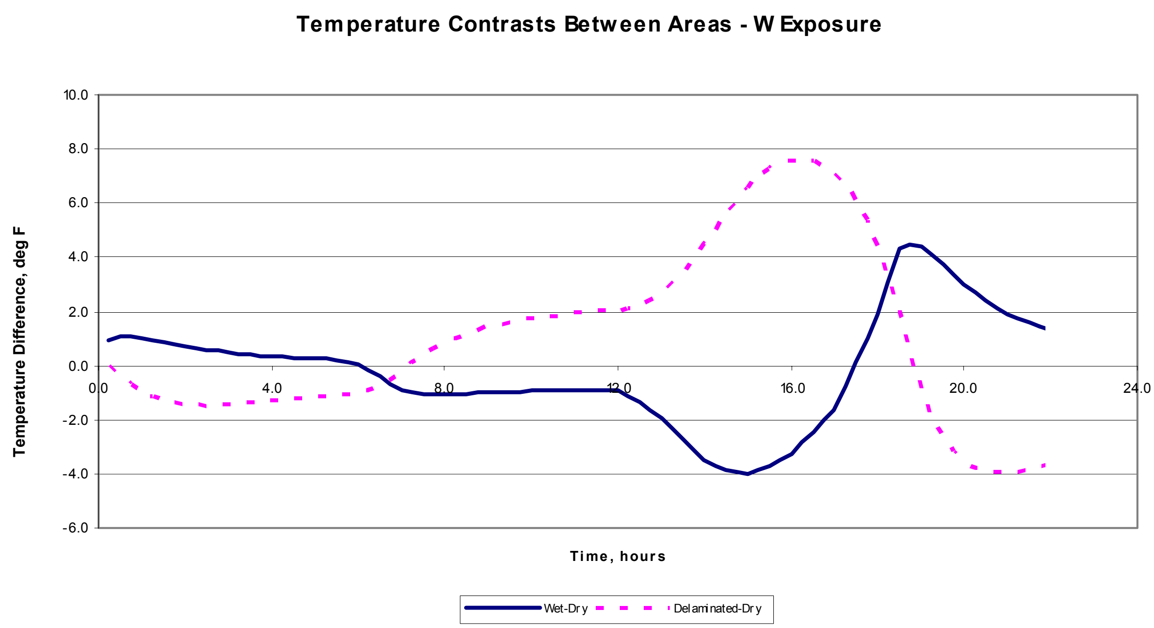


Figure 10. Simulated exterior wall temperatures for various elements



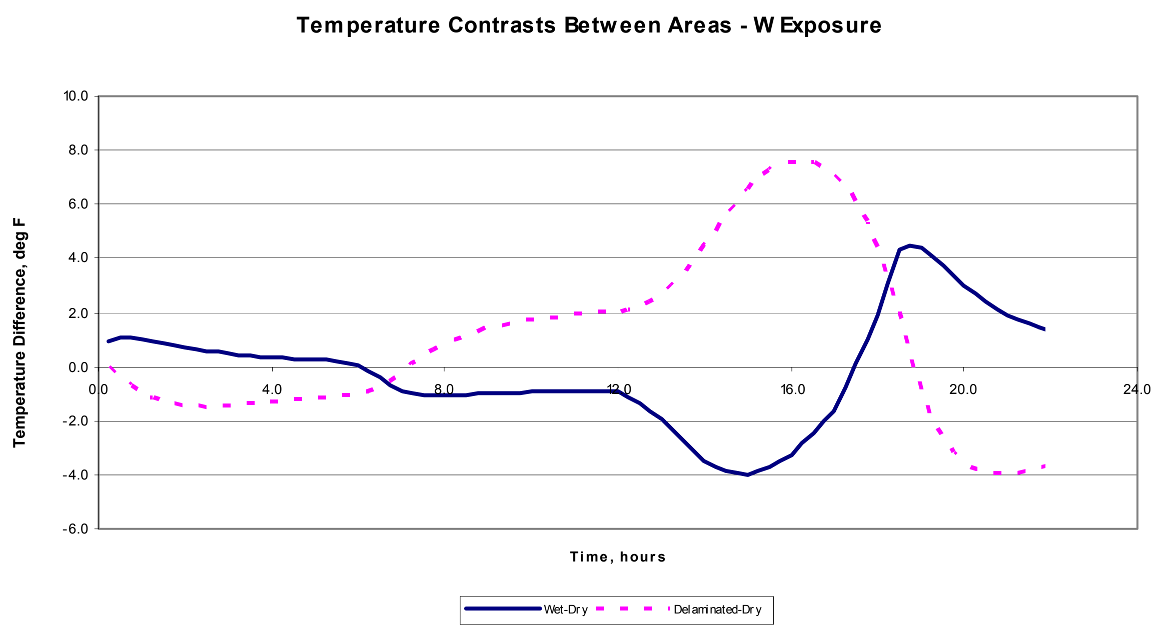


Figure 11. Modeled temperature contrast vs. time for wet-to-dry (solid) and delaminated-to-dry (dashed)

SUMMARY

The utility of IR for finding facade problems has been explained and demonstrated through examples from a building study. It includes the ability to locate suspect areas of moisture and delamination. The ability to model the behavior of the system, for either prediction or study, using FEA-based heat transfer analysis, was demonstrated. Excellent agreement between the simulated and actual results was obtained. The comprehensive nature of the results available from FEA modeling was also demonstrated. By using FEA in combination with IR, the time spent in the field can be reduced and made more effective, since the FEA results will highlight the times of peak detectability of features of interest.

REFERENCES

[1] *ASHRAE Handbook, Fundamentals*. I-P edition. 1993. Atlanta, GA: American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc.