

MODELING OF HEAT TRANSFER IN A MULTI-LAYERED SYSTEM FOR INFRARED INSPECTION OF A BUILDING WALL

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Abstract

Infrared inspection of concrete walls and other building components has been explored for its potential applications in energy conservation and defect characterization. Infrared thermography, or IRT, provides not only fast temperature measurement for a given area but also images of sub-surface anomalies. The accuracy of temperature measurements and thus the thermal contrast of the acquired images can be greatly affected by the ambient conditions. The objective of this research is to analyze the heat transfer in a multi-layered system simulating a building wall. Finite difference formulation and finite element analyses were both used for modeling this transient heat problem. Initial results showed that both numerical models were in agreement with the experimental results of IRT. The time to maximum thermal contrast increases as the depth of internal void from the surface of the concrete increases.

1. Introduction

Infrared thermography, or IRT, is an effective tool for fast and qualitative inspection of the state of a structure. IRT is also a very powerful technique that quantifies the thermal field on a target surface. Emerging applications of IRT in civil engineering include the detection of subsurface flaws in FRP laminates bonded to concrete [1], the characterization of temperature distribution of fresh and recently cast concrete [2], and examination of moisture and other anomaly in building walls [3, 4]. The accuracy of temperature measurements using IRT and thus the thermal images acquired can be affected by the ambient conditions. The objective of the current research is to analyze the heat transfer in a multi-layered system simulating a building wall. Finite difference formulation and finite element analyses were both used for modeling this transient heat problem.

2. Experimental program

Three specimens were constructed to investigate the heat transfer of a multi-layered wall, as shown in Figures 1 and 2. The first specimen was made of concrete and contained internal voids, as reported elsewhere [4]. The second specimen is composed of a gypsum layer and a concrete layer.

The third specimen has a wedge opening between the concrete layer and the gypsum layer. The heating surface of each specimen is 80cmX80cm. The four sides of each specimen are surrounded by foam for heat insulation. These specimens were heated with halogen lamps for 5, 10, or 60 minutes. Contact measurement of temperature was taken from three thermal couples. The thermal images were captured using an infrared camera after the halogen lamps had been removed. The infrared camera, NEC TH7102, is sensitive to the wavelength of 8 to 14 μ m. The minimum temperature difference detectable is 0.1 $^{\circ}$ C.

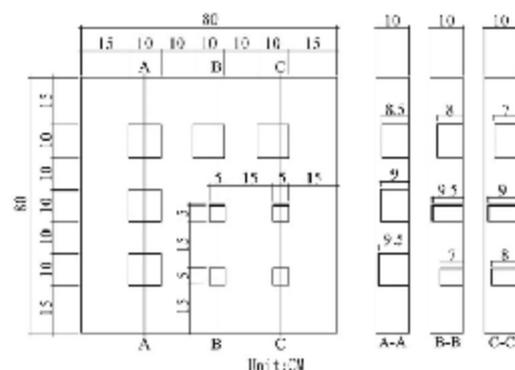


Figure 1: Geometry and dimensions of the first specimen with air voids

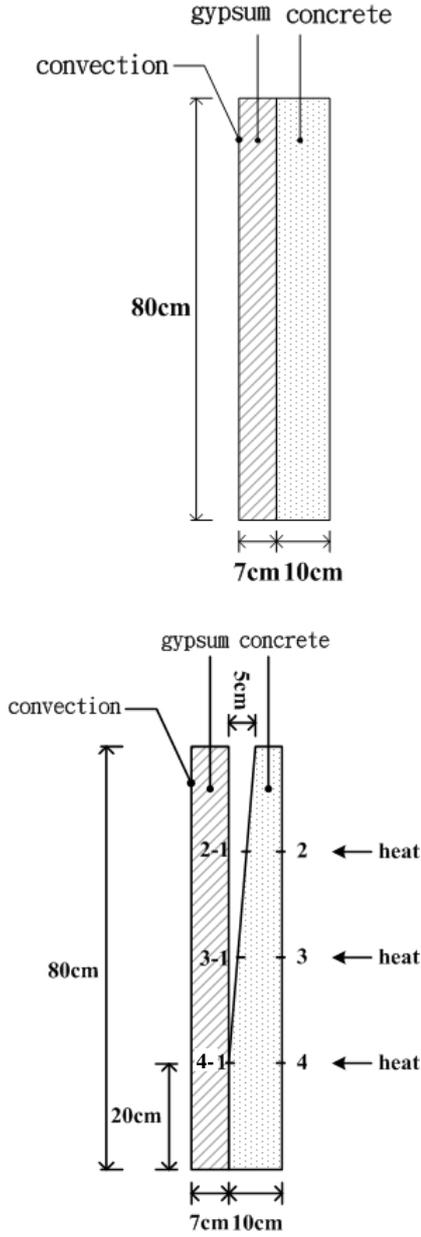


Figure 2: Cross sections of the second (top) and third (bottom) specimens. The heating surface is 80cmX80cm

3. Methods of analysis

The transient heat equation for a large plate is given as

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = r c \frac{\partial T}{\partial t} \quad (1)$$

In one-dimensional analysis, discretization based on the classical finite difference method [5] is given as

$$\frac{T_{m+1}^r + T_{m-1}^r - 2T_m^r}{(\Delta x)^2} = \frac{rC}{k} \frac{T_m^{r+1} - T_m^r}{\Delta t} \quad (2)$$

where T_m^r temperature at node m and the p th time step; k thermal conductivity; ρ density; C specific heat capacity and $\Delta \tau$ size of time step.

The temperature variation at the boundary of wall is calculated using the relation,

$$k \frac{T_{m-1}^r - T_m^r}{\Delta x} + \sigma \epsilon \left[(T_\infty)^4 - (T_m^r)^4 \right] - h(T_m^r - T_\infty) = rC \frac{\Delta x}{2} \frac{T_m^{r+1} - T_m^r}{\Delta t} \quad (3)$$

where T_∞ ambient temperature; σ Stephan-Boltzmann constant; ϵ thermal emissivity and h convection coefficient.

The temperature variation across the interface of layers A and B inside a wall is computed using the relation,

$$k_A \frac{T_{m-1}^r - T_m^r}{\Delta x} + k_B \frac{T_{m+1}^r - T_m^r}{\Delta x} = r_A \cdot C_A \cdot \frac{\Delta x}{2} \cdot \frac{T_m^{r+1} - T_m^r}{\Delta t} + r_B \cdot C_B \cdot \frac{\Delta x}{2} \cdot \frac{T_m^{r+1} - T_m^r}{\Delta t} \quad (4)$$

The equations are solved simultaneously to obtain the temperature at different positions at each time step.

In two-dimensional analysis, numerical stability of finite difference became more difficult. The finite element method was used instead. The element used is a four-node plane element with a mesh size of 5mm. The numerical simulation is executed using the transient thermal analysis provided by the software package ANSYS. Uniform heat flux is applied to the right-hand side and convection is allowed at the left-hand side of the specimens, as shown in Figure 2. Adiabatic boundaries are assumed at the top and bottom of the specimens, in agreement with the foam insulation in the experiment.

4. Discussion

Temperature reduction, ΔT , is calculated based on the following formula,

$$\Delta T = T(\tau + d\tau) - T(2\tau) \quad (4)$$

where τ heating time.

The cooling time is very close to τ . For example, τ is 600 seconds in Figures 3, 4, and 5. The measurements were taken at points 2, 3, and 4, as shown in Figure 2. The cooling process starts

shortly after the heating lamps are removed (time accounted for by $d\tau$). The temperature recording proceeds to 1200 seconds. Using contact measurement as a reference, the temperature reduction obtained by IRT is off by 2.4K or less. However, the two-dimensional finite element analysis needs to be modified. Currently the results of the finite element model are 1.0 to 3.4K higher than those of the contact measurement, as shown in Tables 1 and 2.

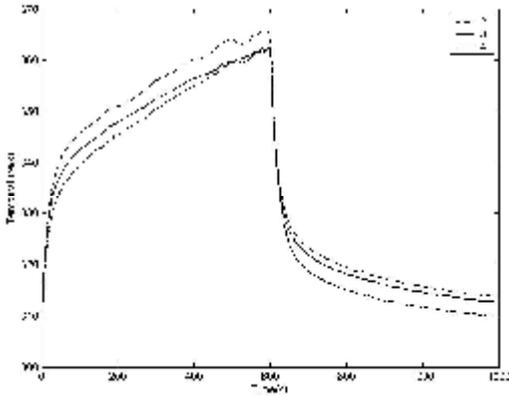


Figure 3: Contact measurements at the surface of the 3rd specimen

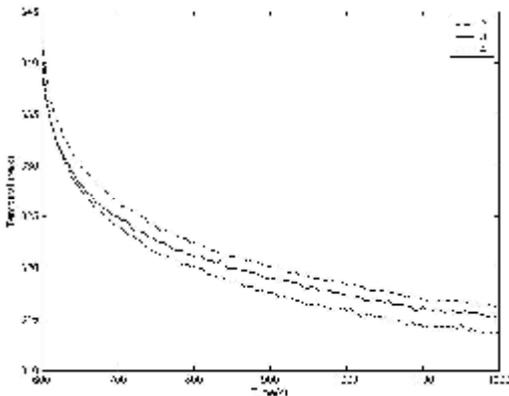


Figure 4: IRT Temperature measurements at the surface of the 3rd specimen

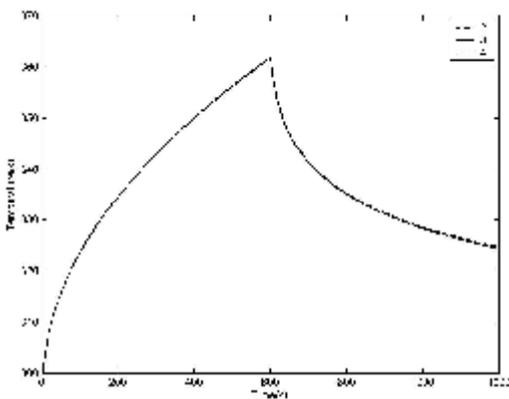


Figure 5: 2-D finite element modeling of temperature variation at the surface of the 3rd specimen

Table 1: Temperature reduction ΔT at the surface of the 2nd specimen. Measurement was taken at the center of the heating surface. $\tau = 600s$

Contact measurement	28.8K
IRT	31.2K
2-D finite element	36.2K

Table 2: Temperature reduction ΔT at the surface of the 3rd specimen. $\tau = 600s$ and $d\tau = 10s$

Measurement point	2	3	4
Contact measurement	25.4K	25.8K	28.5K
IRT	27.1K	25.5K	28.4K
2-D finite element	28.8K	29.2K	29.1K

The time to maximum thermal contrast obtained from IRT tends to be less than that predicted by both numerical models. Based on the results of one- and two-dimensional analysis, time to maximum thermal contrast increases as the depth of internal defects increases. This is confirmed by the measurements using IRT. Table 3 lists the time to maximum contrast obtained using IRT and both numerical models.

Table 3: Time to maximum thermal contrast at the surface of the 1st specimen ($\tau = 300s$)

Depth of void	IRT	1-D finite difference	2-D finite element
0.5cm	5~6min	5~6min	9~10min
1.0cm	6~7min	8~9min	13~14min
1.5cm	7~8min	12~13min	17~18min
2.0cm	10~11min	16~17min	22~23min
3.0cm	13~14min	23~24min	35~36min

5. Summary and Conclusion

Finite difference formulation and finite element analysis were both used to model the heat transfer in a multi-layered wall system. Initial results showed that both numerical models were in agreement with the experimental results of IRT.

The time to maximum thermal contrast increases as the depth of internal void from the surface of the concrete increases. However, the numerical models do not perform well in predicting the temperature field at the surface of a multi-layer wall. Further study will focus on the following,

- I Verify the initial boundary conditions at the wall surface. The assumption of uniform heat flux will be compared with the measurements using heat flux meters.

- I Include the heat convection at the front surface of the wall specimens in the finite element model. The amount of heat loss to the ambient may be significant at the end of heating process.

- I Improve the numerical stability of the two-dimensional finite difference model.

6. References

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