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PRELIMINARY RESULTS FOR ESTIMATING THE BACKSIDE HEAT LOSSES OF A COMPOSITE PANEL

A. F. Emery
Department of Mechanical Engineering
University of Washington
Seattle, WA 98195-2600
Ph: 206-543-5338 emery@u.washington.edu

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Abstract

The procedure for the estimation of heat losses from a composite panel that must be known in order to optimize repairs is described. Many papers for estimating parameters describe either simulated experiments or experiments conducted under very controlled situations and the results based upon models of the experiment are usually favorable [1,2]. In contrast when experiments are conducted in the field or under adverse conditions, even when the system is a simple one and amenable to modeling, the estimation can be unexpectedly difficult. The paper describes experiments to estimate the heat losses from the back side of a composite panel undergoing repairs and the modeling of the system. Although the temperatures based on the estimated parameters successfully match the measured steady state temperatures, the model does not accurately predict the transient behavior, raising questions about its ability to determine the magnitude of the observed heat losses and, more importantly, what must be done to improve the model.

Introduction

Repairing composite panels is a multi-step process: 1) an area much larger than the damaged area is defined and the composite is scarfed out; 2) a patch is manufactured that will fit in the removed area; 3) the patch is emplaced and heated to a prescribed temperature; 4) the patch is maintained at that temperature until bonding of the patch and the remaining material has occurred. The scarfed region and the patch are depicted in Figure 1. In order to assure a strong bond, the angle tends to be small, of the order of 5 degrees. Hence the lateral dimensions of the patch are usually large with respect to the lateral dimensions of the damage. It is often the case that the repair is made without removing the panel from its operational site and the conditions or structure behind the panel are not well defined. Even if the details of the supporting structure are known, their thermal characteristics may not be. As a consequence when the patch is heated there may be areas where there are large heat losses from the back side and areas of smaller heat losses and the temperature of the patch will vary considerably spatially. If this occurs bonding will be degraded in the cool regions and damage will occur in the overheated regions.

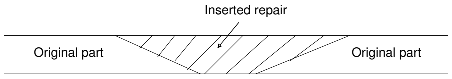

Figure 1: Depiction of a Scarfed Joint

Heating may be provided by focused infrared irradiation or by an electric blanket. Because of the need to provide a defined spatial variation of heat, only the electric blanket is practical. The blanket must be designed to accommodate the heat losses and the question is how to determine what they are. Since the backside of the panel is usually not accessible, the most practical way is to place thermocouples on the front surface of the panel and to take infrared thermograms of the blanket surface. The heat transfer from the panel to the underlying structure can be characterized by back side thermal conductances that expressed in terms of convective heat transfer to the local air.

The experiment

A square panel, made of carbon fiber, had several stringers located on its underside as shown in Figure 2. These stringers will connect to the supporting structure and are the cause of both overheating because of the insulating effect of the trapped air and increased heat losses to the supporting structure. The upper panel surface and the sides of the stringers are 2.54 mm thick, the slightly thicker sections where the stringer attaches to the panel are 4.4 mm thick, the stringer depth is approximately 3.5 cm and the heating blanker is 1.52 mm thick. The panel is symmetric about a line through the thermocouple 9. Thermocouple were placed on the surfaces as indicated. An electrical heating blanket was placed on the upper surface and heat applied until the system came to equilibrium. The blanket was then quickly removed and the panel allowed to cool.

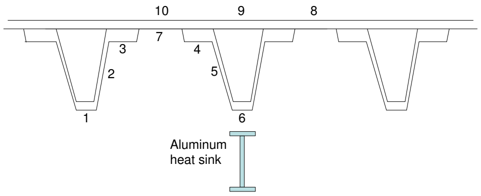

Figure 2: Schematic of the panel showing thermocouple placement

Three different experiment were performed

A) The panel was placed on an insulating base. Because the panel is slightly curved, only the left and right stringers touch the base and the air under the panel was essentially quiescent. Because the outboard stringers touched the base, there was an increased heat loss from the panel in this region.

B) The entire panel was suspended with room air allowed to circulate below the panel.

C) The panel was suspended and the heat sink was attached to the bottom of the center stringer. Air could circulate about the underside of the panel and around the heat sink.

Thermogram temperatures were measured with a calibrated infrared camera with a resolution of 0.1C and type J and K thermocouples were read with a calibrated data logger with a resolution of 0.5C. The thermocouples were calibrated in a reference bath over the range of 0 to 200C to an accuracy of better than 0.5C. While the emissivity of the heating blanket and the composite material was not measured, assuming that both behaved as black surfaces, the thermograms taken with both at room temperature agreed with the thermocouples to within 0.5C. Although in practice, it unlikely that underside thermocouples can be used, they were installed to gather sufficient data to confirm the numerical model that was used to determine the sensitivity of the surface temperature measurements to estimate the heat losses.

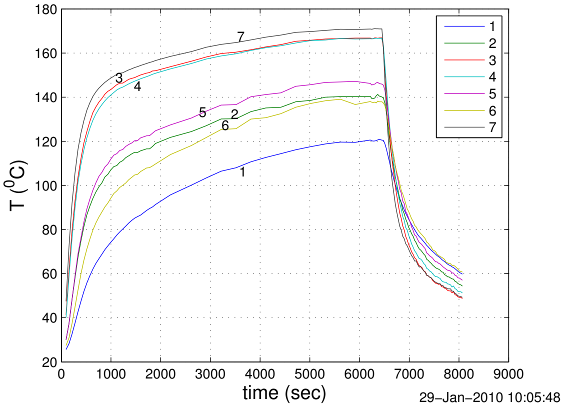

Figure 3a Test A No surface thermocouples

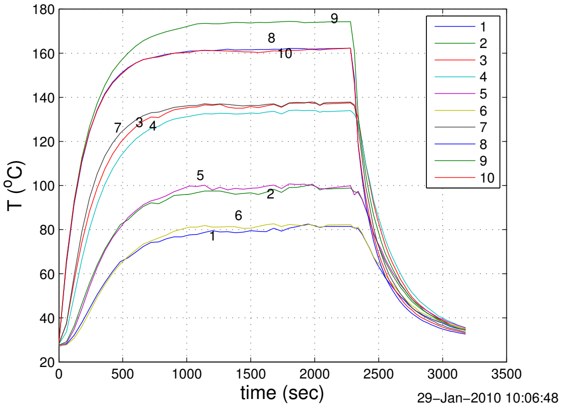

Figure 3b Test B Panel suspended with air allowed to circulate beneath it

Figure 3a-3c show the time history of the three experiments. Test A displayed a curious history. It is speculated that the underside air was originally quiescent until a small circulatory free convection flow was established. The two side stringers were in contact with the massive base and conducted heat to it giving a maximum temperature less than that observed in tests B and C. Test C showed a reduced maximum temperature because of the enhanced heat loss to the aluminum heat sink.

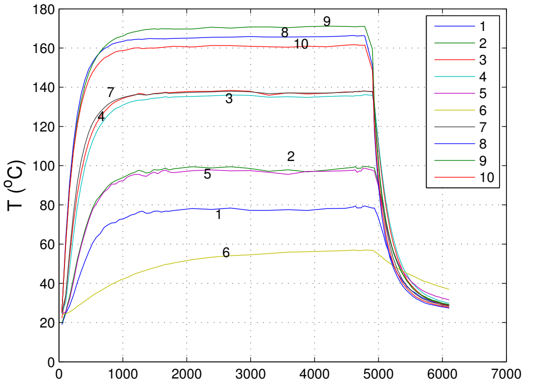

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Figure 3c Test C Panel with
a heat sink attached

Figure 4 compares the difference in the surface temperature of the blanket determined from the infrared thermogram between surface points directly above thermocouples 9 and 10 and the difference between these two surface temperatures.

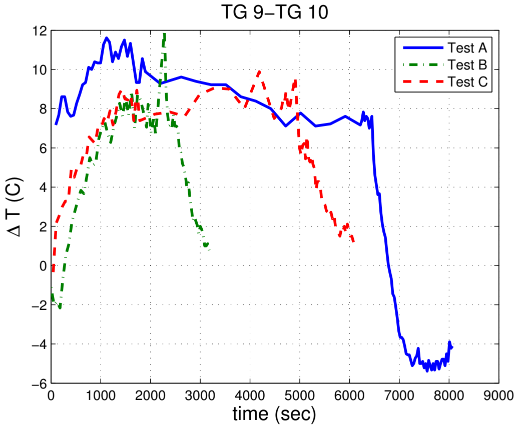

Figure 4a Difference in Blanket Surface Temperatures
Measured by the infrared thermogram
at points directly above thermocouples 9 and 10

A measure of the heat lost to the backside is the difference between the temperatures at thermocouples 4 and 5. This difference is a function of heat conducted down the inclined stringer piece to the bottom of the stringer. This is shown on Figure 4c. The differences between the tests is quite clear with Test C having the most heat conducted and Test A the least. A comparison of Figure 4a with 4b and 4c make it clear that it will not be possible to use heating blanket surface infrared measurements to estimate the existence of backside surface losses. On the other hand, the measurement of the panel surface temperatures appear to offer an acceptable approach.

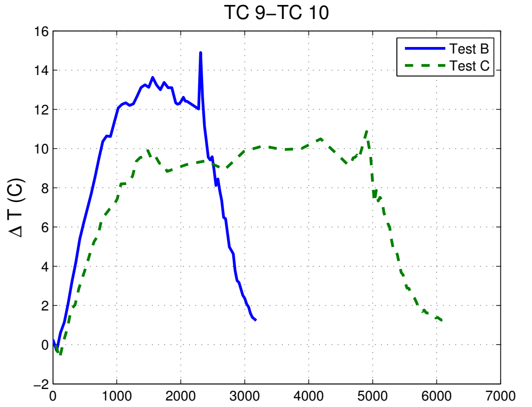

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Figure 4b Difference in Panel Surface Temperatures
at thermocouples 9 and 10

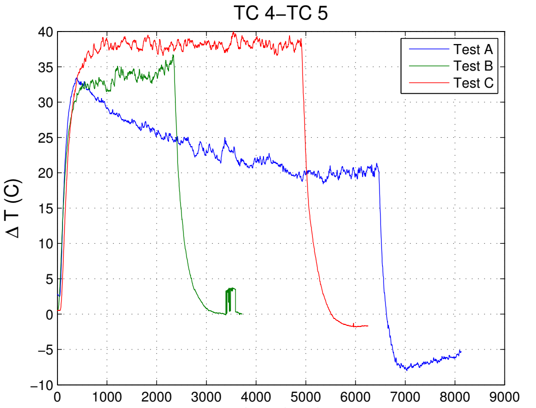

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Figure 4c Difference in temperatures at
thermocouples 4 and 5

Sensitivity of the measurements to backside loss

A finite element analysis of the panel was conducted using the multiphysics application, COMSOL [3]. The panel conductivity is strongly orthotropic with a lateral conductivity of 3.6 W/mC and a through the thickness conductivity of 0.52. The thinness of the panel causes the heat transfer in the vicinity of thermocouples 7 and 10 to be one dimensional while the low thermal conductivity of the air trapped in the stringer forces the heat to flow laterally to the edge of the stringer and then down the inclined piece. Because the air in the stringer and the ambient air under thermocouples 7 and 4 is hottest at the underside of the panel, there is very little free convection and the heat loss is primarily by radiation. Heat loss from the blanket surface and the panel surface after the blanket is removed is by radiation and free convection. The sensitivities to the upper side, h_t, and surface of the stringer, h_b, the effective convective heat transfer coefficients were determined using estimated radiative and free convection losses [4] and are shown in Figure 5. The non dimensional sensitivities are defined as

$$S(h_t) = h_t\frac{\partial T}{\partial h_t} \quad S(h_b) = h_b\frac{\partial T}{\partial h_t}$$

and have units of ^oC.

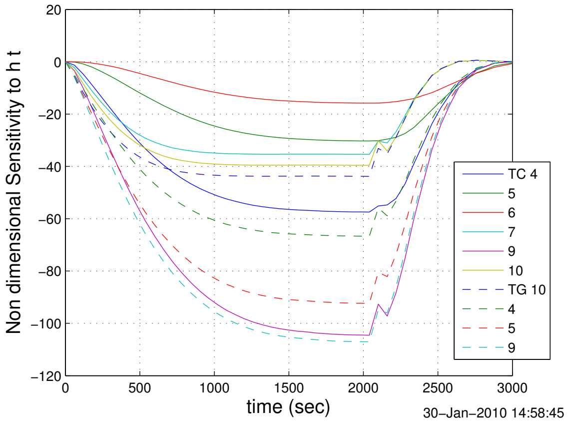


Figure 5a Sensitivity to top surface coefficient h_t (solid lines represent temperatures measured by thermocouples, dashed lines represent temperatures measured on the top of the blanket using infrared thermograms)

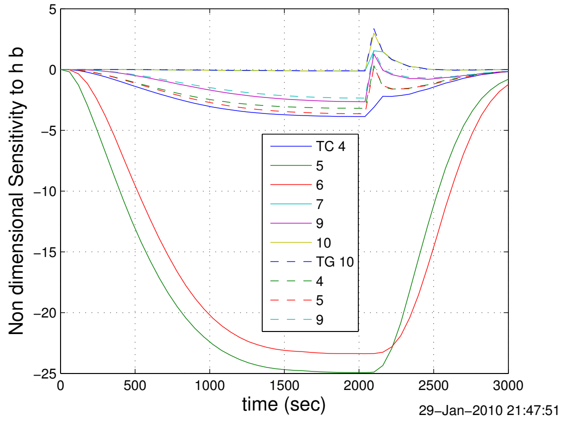


Figure 5b Sensitivity to back side coefficient h_b

As expected, temperatures measured closest to the upper surface have the highest sensitivity to h_t and those measured near the base of the stringer are most sensitive to h_b. Figure 5c displays the sensitivities of the temperatures at thermocouples 9 and 10 and thermogram measurements directly above these points. Because of the thinness of the panel, the heat transfer and temperatures away from the stringer, thermocouple 10, are representative of 1D flow and are insensitive to losses from the stringer.

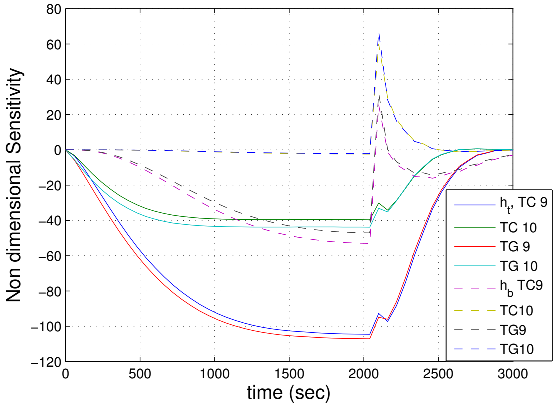


Figure 5c Sensitivity of T(9) and T(10) to top and backside coefficients (the sensitivities to h_b are multiplied by 20)

At this point it appears that

1) the temperatures on the surface of the heating blanket are so weakly sensitive to heat losses from the stringer as indicated by the predicted sensitivities and the nearly identical $TG_9 - TG_{10}$ seen on figure 4a that their measurement is likely to be of little value.
2) temperatures measured on the upper surface of the panel are weakly sensitive to h_b, as compared to h_t and it will require further experimentation to determine if they will suffice.

However as illustrated in Figure 4c, the heat losses, as suggested by the temperature difference $T_4 - T_5$, in the three tests differed by -40% and +15% from the nominal (Test B) and we have not tested situations in which the differences are more marked, particularly increased heat losses that are likely to be observed in actual situations where there are substantial supporting structures.

A model was constructed with variable heat transfer coefficients on each of the areas associated with the thermocouples, i.e., h_{top}, $h7$, $h4$, $h5$ and $h6$. Each of these h values included the effect of radiation. Using standard inverse techniques [5] these values were adjusted until the steady state temperatures just before the blanket was removed matched the experimental values. Table 1 lists the root mean squared difference between the measured and estimated temperatures, h_{top}, $h7$ and the

Behavior of the Model

Test	root mean difference (C)	h_{top} (W/m^{2}C)	$h7$ (W/m^{2}C)	q stringer base (W)	q stringer (W)
A	0.405	19.43	5.36	0.43	10.06
B	0.507	22.57	8.94	1.99	15.12
C	0.348	23.60	8.37	7.31	14.75

heat lost from the stringer. As expected the top surface h value and the value of $h7$ are roughly the same for all three tests, $h7$ is the lowest for test A in which the air under the panel appeared to insulate the panel while it is very much the same for tests B and C where the air was free to circulate. Although the predicted heat loss from the bottom of the stringer shows an increase for Test C over Test B, the combined loss from the side and bottom are nearly the same for both tests. The model is reasonably good in yielding estimated values of h that match the measured steady state temperatures to an acceptable degree.

Model Performance

In practice one will not have access to back side temperatures as was done in the experiment. These temperatures were measured to see if in fact we could model the results of the experiment. Figure 6 compares the experimental and modeled temperatures for Test B. Although excellent matches are obtained at steady state, it is seen that the model significantly lags the experimental results at early times but leads it during the cool down.

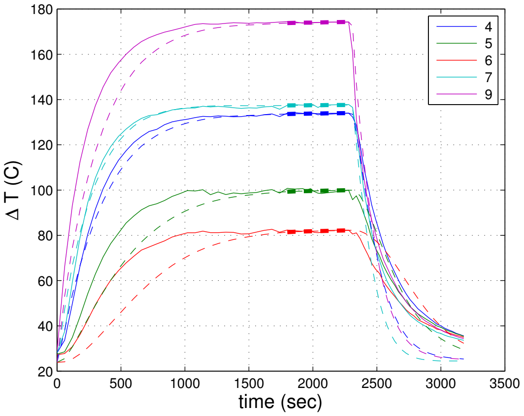


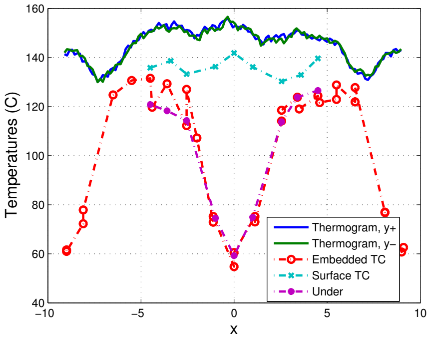
Figure 6 Comparison of Measured and Modeled Temperatures for Test B (solid lines are experimental dashed lines are simulation)

Now it is hard to reconcile how a model can display a longer time constant during heating up and a shorter time constant during cool down. An intense effort was expended to understand this effect. All of the properties of the model were allowed to vary, i.e., specific heats, densities, thermal conductivities, and even modeling the air in the stringer using CFD since during the cool down the temperature gradient reverses from that which exists during heating. Regardless of the efforts made, no model was successful in matching the entire thermal history of any of the three types of tests.

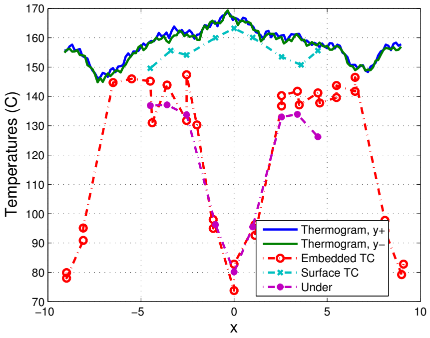
Improved Experiments

Although we were able to match temperatures during steady state, the estimated properties varied considerably from test to test even though efforts were made to ensure constant and equal environmental conditions for all tests. Further experiments were carried out with thermocouples embedded in the thin upper surface of the panel, in the stringers, and surface thermocouples were placed on the lower exposed surface and on the upper surface between the panel and the heating blanket. The air under the panel was quiescent. Several experiments were repeated, but no improvement in the simulation was achieved.

However, careful comparison of the thermograms and the surface thermocouples temperatures suggested that there was contact resistance between the heating blanket and the panel, even though the blanket is dense and heavy and when hot appears to deform sufficiently to give good thermal contact with the panel. It was conjectured that the thermocouple wires caused thin air layers to be formed adjacent to the wires. The blanket was then covered with a thin sheet of plastic and a vacuum pulled between the plastic and the blanket. Atmospheric pressure then forced the blanket into intimate contact with the panel. In addition, several tests were conducted with thermal paste applied to the panel between the surface thermocouple wires. Figures 7 and 8 compare the temperatures in terms of the distance from the center of the central stringer. With no vacuum, during heating the thermogram showed that the top surface of the heater was substantially hotter than the interface between the blanket and the panel as measured by the surface thermocouples. Looking down on the panel the surface thermocouple wires extended from the edge of the panel to approximately the middle of the panel in the y direction. Two scans are shown for the thermograms, one positioned on a line about 4 cm ahead of the thermocouple junctions, y^+, and one on a line about 4 cm behind the junction, y^-. This was done since it was questioned that if the thermocouple wires caused tunnels of air to exist, these tunnels might extend ahead of the wires. The figures show that there is no difference in the thermogram scans, i.e., if there are air tunnels they extend ahead of the ends of the thermocouple wires. A computation of the temperature distribution expected during heating indicated that at steady state that the surface temperatures should exceed the temperatures on the upper surface of the heater for reasonable values of surface heat transfer coefficients. This is clearly not the case as shown in Figure 7.



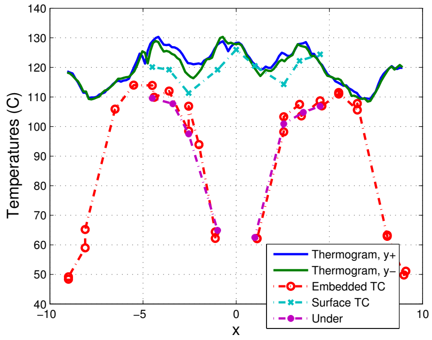
7a: during heating



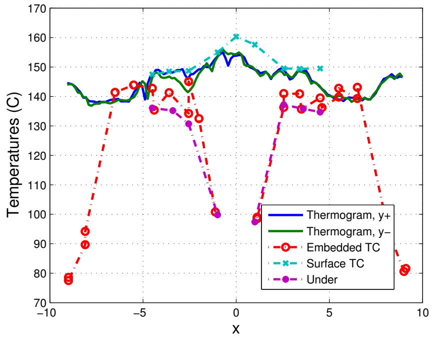
7a: at steady state

Figure 7a Temperature Profiles for a heating blanket simply placed on the panel (under refers to surface TC on the underside)

Figure 8 displays the corresponding temperature profiles when a vacuum is applied. As expected, at steady state the surface temperatures exceed that of the upper surface of the heating blanket.



8a: during heating



8b: at steady state

Figure 8 Temperature Profiles for a heating blanket under vacuum

Simulations were done with the temperatures obtained with vacuum and a typical result is shown in Figure 9. The simulation was based upon radiation from the bottom of the panel (because air could not flow under the panel, the hot surface prevents any free convection) and both free convection and radiation from the top surface of the blanket. With the vacuum applied, the blanket could not be removed after steady state was achieved, so the cooling profiles are slightly different than shown for the previous tests. Estimations of the surface convective coefficients were based upon thermogram temperatures alone, surface temperatures alone, thermogram and surface temperatures, and with all temperatures. All methods agreed to within 10%. Figure 9 shows only the thermogram (TG) and surface temperatures (STC) since these are the only ones practically available in a real test. The convective coefficients were evaluated using only the steady state temperatures because of the lagging behavior during heating and uncertainty about the specific heat of both the panel and the blanket. Table 2 lists the values and the rms error.

Table 2
Estimated values of h_t
from Steady State Temperatures

Data	h_{top}	rms (C)
TG	11.0	1.9
STC	10.3	0.7
TG+STC	10.7	2.2

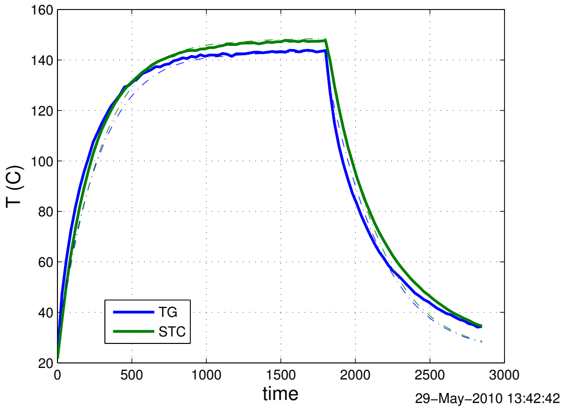


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Figure 9 Temperature Profiles for a heating blanket under vacuum

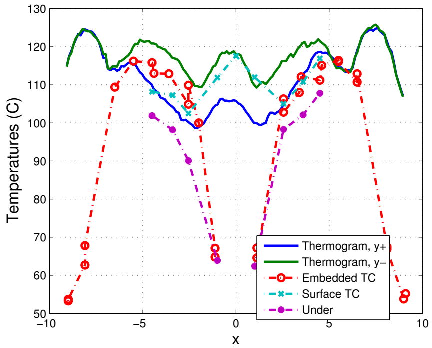
The agreement between the simulation and the experiments is markedly improved, although the model still seems to lag during heating and lead during cooling. Using the convective coefficients and solving for an effective specific heat gave the values shown in Table 3.

Table 3
Effective Specific Heat
in terms of original values

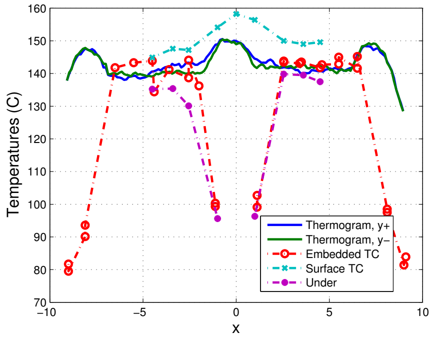
Test	heating	cooling
no paste	85%	103%
paste	106%	105%
conditioned paste	89%	105%

Estimates are based upon three vacuum tests: 1) vacuum only, no thermal paste, 2) vacuum with thermal paste, 3) a repeat of 2 after the paste has been conditioned by a test. The thermograms showed that the paste had a dramatic effect during both heating and cooling and that it was not possible to observe any difference between the test using the first application of the paste and the repeat test. However, fitting the model to the data suggested that the conditioning of the paste did have a substantial effect with the estimated specific heat of tests 1 and 3 being similar, while test 2 gave a substantially larger estimate of the specific heat. Strangely, all three tests gave the same effective specific heat during cooling and this was always greater than our initial estimate and that found to be applicable during heating. We do not understand why the corrections for heating and cooling differ.

Figure 10 for the test with vacuum and paste showed that the thermogram scans ahead and behind the thermocouple junctions gave quite different temperatures during heating and cooling but that the difference is minimal at steady state. The scan behind the junction, labeled y^- is over the paste while that labeled y^+ is over the un pasted region.



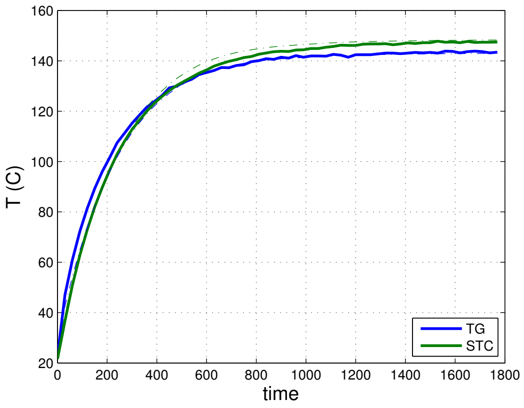
10a: during heating



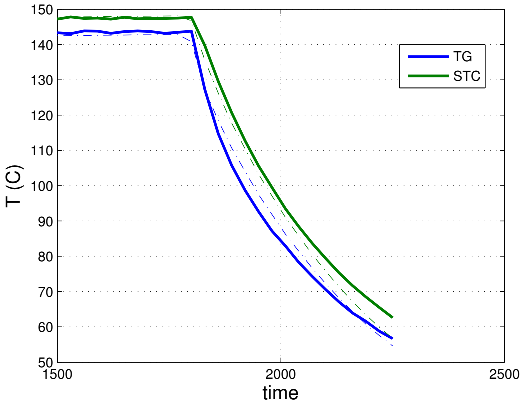
10b: at steady state

Figure 10 Temperature Profiles for a heating blanket under vacuum with paste

Figures 11 show the agreement between the simulation and the data for the vacuum test with no paste with the specific heat adjusted according to Table 3.



11a: during heating



11b: during cooling

Figure 11 Temperature Profiles for a heating blanket under vacuum

Conclusions

In contrast to many experiments performed in laboratories with well defined conditions using material with known thermal properties, tests such as those described here are more representative of what happens in field tests. In estimating heat losses for a repair, thermocouples cannot be embedded in the panel nor placed on the under (inaccessible) side of the repair, forcing one to rely upon thermographic data and surface mounted thermocouples. The application of vacuum resolved most of the problems, but the use of a thermal paste is questionable its properties are ill defined. The simulations with the properties estimated using only the thermographic and surface thermocouples are quite satisfactory, although it is clear that one must carry the test through to steady state, i.e., transient data are inadequate to estimate h without knowing the specific heat, and that the extremely rapid reduction in temperature during the cooling leads to thermal conditions that are not easily modeled. Regardless of the properties estimated, the problem is a classic ill conditioned inverse problem as evidenced by the low sensitivities to the heat loss from the bottom of the stringer and to the thermal capacity during cooling. The tests were intended to show the effect of heat losses from the bottom of the stringers, but the composite conductivity is so small that very little heat was lost from these regions and the sensitivities were unusually small. Further tests will be conducted with active cooling applied to the bottom of the stringers to be more representative of the losses expected to occur during repair.

On the basis of the measured temperatures at steady state, in the absence of the vacuum the suspected air layers were judged to be of the order of 0.2 mm thick. Since this would give a thermal resistance approximately equal to that of the composite panel and of the heating blanket it is clear that care must be taken to ensure that such pockets do no exist. Application of paste is questionable because little is known of its effective specific heat, particularly as a function of temperature, and because it has such a strong effect during the heating and cooling. It was both surprising and discouraging that these air layers not only affected the inverse problem, but lead to a system so ill conditioned that estimating parameters was extremely difficult.

Acknowledgments

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