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FINITE ELEMENT MODELING OF TRANSIENT THERMOGRAPHY INSPECTION OF COMPOSITE MATERIALS

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Introduction

The objective of this project was to model the transient thermal behavior of composite materials with defects for thermographic inspection. Thermography is one of the key techniques available today for non-destructive evaluation (NDE) of materials or performing quality assurance for manufacturing process. It is non-invasive and non-contacting. A relatively large area can be inspected at one shot. Furthermore, the data can be easily stored as digital thermal images for further analysis and retrieval. To inspect materials for defects and imperfection in ambient temperature, a very short burst of heat can be introduced to one of the surfaces or slow heating of the side opposite to the side being observed. Due to the interruption of the heat flow through the defects, the thermal images will reveal the defective area by contrasting against the surrounding good materials. This technique is called transient thermography, pulse video thermography, or thermal wave imaging. A schematic diagram of a typical transient thermography inspection system is shown in Figure 1.

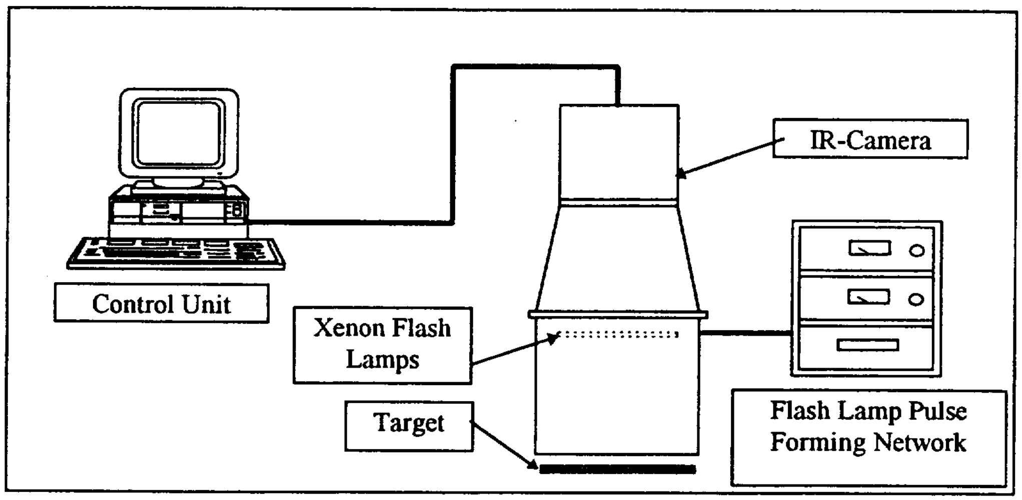

Figure 1. A Typical Transient Thermography System

Thermography is being used to inspect void, debond, impact damage, and porosity in composite materials at NASA Marshall Space Flight Center and is the standard inspection method for the ET Composite Nose Cone. It has been shown that most of the defects and imperfection can be detected. However, the current method of inspection using thermography technique is more of an art than a practical scientific and engineering approach. The success rate of determining the defect location and defect type is largely depend on the experience of the person who operates thermography system and performs the inspection. The operator has to try different type of heat source, different duration of its application time, as well as experimenting with the thermal image acquisition time and interval during the inspection process. Furthermore, the complexity of the lay-up and structure of composites makes it more difficult to determine the optimal operating condition for revealing the defects.

In order to develop an optimal thermography inspection procedure, we must understand the thermal behavior inside the material subjected to transient heat in order to interpret the thermal images correctly. Fabrication of finite element models of characteristic defects in composite materials subjected to transient heat will enable the development of appropriate procedure for thermography inspection. Design of phantom defects could be modeled and behavior characterized prior to physically building these test parts. Since production of phantom test parts can be very time consuming and laborious, it is important to design good representative defects. Phantom defects frequently will not function as expected. Additionally, methods of thermography could be modeled and compared based upon the FEA modeling without performing the test.

Finite Element Modeling

Finite element method is a very powerful numerical tool that is widely used in the industry for stress, dynamic, and thermal analyses of structure and materials including composites. The finite element models constructed include composites with square and circular debond and void in various depths. Finite element modeling and analysis were performed on Pentium type computers using the COSMOS/M FEA package. This FEA software contains static, dynamic, and thermal modules that allow both linear and nonlinear analyses. The results of the finite element analysis showed that the models of composite panels with void or debond can effectively reveal the temperature distribution at any time step.

All finite element models were generated for a composite panel with a $[\pm 0/90]_s$ laminate geometry. The thickness of the panel is 0.61 mm. The area of the panel under consideration for all models is 38x 38 mm. Quarter symmetry was considered in modeling the panel. The element used is the 8-node isoparametric solid element (brick element). Each ply is one element thick. The duration of the time under investigation is 0.1 seconds. The time step used is 0.001 sec. The heat flux applied to the top surface of the model is 2800 kw/m^2 for the first 0.004 seconds with a total energy of 11.2 kJ/m^2. The coefficient of natural convection applied to the bottom surface is 58.9 w/m^2-°C. The initial temperature is 24 °C. The composite panel used for constructing the model has a density of 1.492 g/cc and a specific heat of 1.269 J/kg-°C. The thermal conductivity is calculated to be 2.272 along the fiber direction and 0.194 w/m-°C in the directions perpendicular to the fiber and through the thickness.

Figure 2 shows the result from the finite elment analysis of the panel with a square debond between the 2nd and the 3rd plies. The size of the debond is 12.7 x 12.7 mm. This figure shows the temperature distribution at time step of 25 which is corresponding to 25 msec after firing the flash lamps. As can be seen from the temperature distribution in the figure, more heat is transferred along fiber direction in the top ply. The maximum temperature difference at the top surface is about 3.3 °C. The temperature on the top reaches equilibrium after about 40 msec. Two more FE models with square debond were built. One has a 5 x 5 element disbond (quarter symetry) between the 1st and the 2nd layers, another has a disbond between the 3rd and the 4th layers. Prior to building these two models, a study of the effect of the size and mesh density of the model on the resulting temperature distribution has been conducted. It has been determined that a 15 x 15 element model with convection defined only on one surface would produce similar results to a 30 x 30 element model or a 15 x 15 element model with convection defined on the top and bottom surfaces.

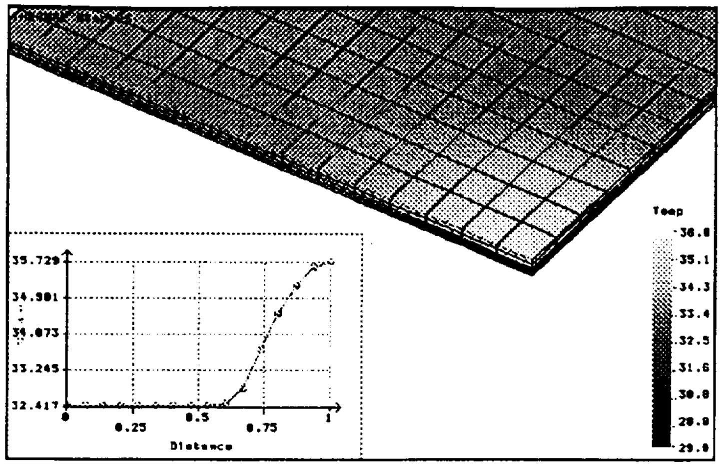

Figure 2. Plot of the FEA results of the panel with a square debond in the mid-plane

The effect of heat flux modeling has also been studied. A model of two heat flux curves has been created in Excel. The first curve, a square curve, was used to model the first series of finite element models. The second curve were created to generate the next series of finite element models. Figure 3 shows the two heat flux time curves. The goal in creating these heat flux curves was to more accurately model the flash lamp while keeping a similar area under the modified curve to the square curve. The results show that the effect of different time curve is minimal.

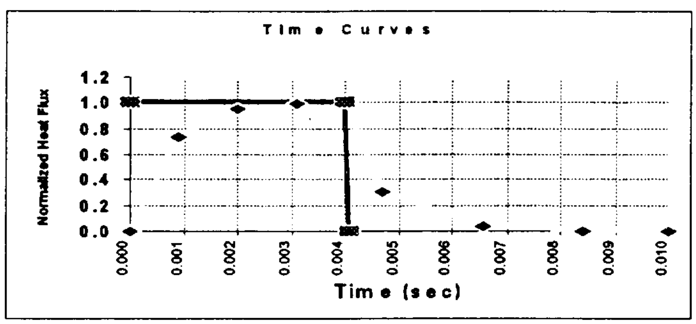

Figure 3. Heat flux time curves

A new model of a composite panel with a square defect at the mid-plane was constructed in SI units. The results from finite element analysis was compared to that from the thermogrphy inspection. The 305 mm square panel has three 12.7 mm square phantom defects fabricated at the mid-plane. The materials used are Teflon tape, backing film, and vacuum bag paper. The temperature profiles at several time steps were compared to the thermal images of the phantom defects. The ranges of temperature are very similar. Since the timing and profile of the heat pulse from the xenon lamps are still unknown, exact comparison is not possible. More information is needed to model the heat flux in order to determine the optimal environment for transient thermography inspection. The thermal images of the panel is shown in Figure 4.

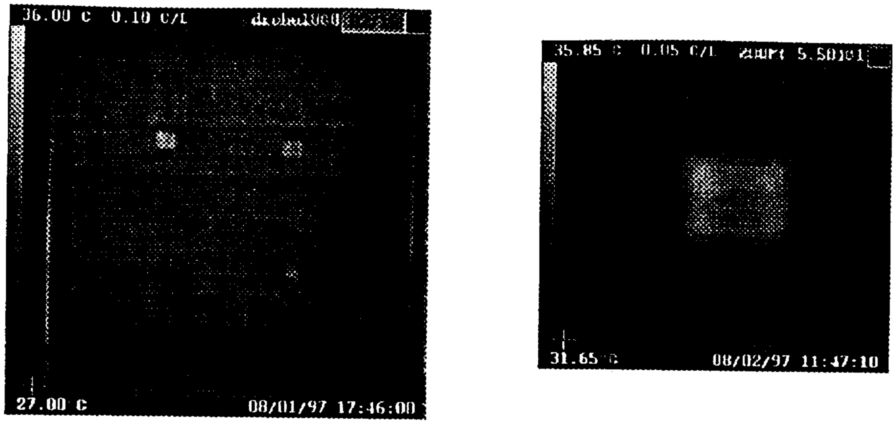

Figure 4. Thermal images of the panel

Conclusions

Several finite element models of defects such as debond and void have been developed for composite panels subjected to transient thermography inspection. Since the exact nature of the heat generated from the flash lamps is unknown, direct comparison between FEA and experimental results is not possible. However, some similarity of the results has been observed. The shape of the time curve that simulates the heat flux from the flash lamps has minimal effect on the temperature profiles. Double the number of flash lamps could increase the contrast of thermal image and define the shape of defect better.

Heat flux from the flash lamps need to be measured. Build database of thermal properties for composites. Model composite structures. Establish proper procedure that could provide the optimal thermal inspection environment by analyzing the FEA results. Model impact damage and porosity.