1996

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

FINITE ELEMENT MODELING OF THE THERMOGRAPHIC INSPECTION FOR COMPOSITE MATERIALS

Prepared By: Ronald B. Bucinell, Ph.D., P.E.

Academic Rank: Assistant Professor

Institution and Department: Union College, Schenectady, NY 12308
Department of Mechanical Engineering

NASA/MSFC:

Laboratory:	Materials and Processes	Materials and Processes
Division:	Nonmetallic Materials and Processes	Engineering Physics
Branch:	Polymers and Composites	NDE and Tribology

MSFC Colleague: Alan T. Nettles, Ph.D. Sam Russell, Ph.D., P.E.

INTRODUCTION

The need for safe, lightweight, less expensive, and more reliable launch vehicle components is being driven by the competitiveness of the commercial launch market. The United States has lost 2/3 of the commercial lunch market to Europe. As low cost Russian and Chinese vehicles become available, the US market share could be reduced even further. This international climate is driving the Single Stage To Orbit program at NASA. The goal of this program is to reduce the cost per pound of payload by a factor of 10. This will be accomplished with a totally reusable launch vehicle designed for low-cost aircraft-like operations. Achieving this goal will require more efficient use of materials. Composite materials can provide this program with the material and structural efficiencies needed to stay competitive in the international launch market place.

In satellite systems the high specific properties, design flexibility, improved corrosion and wear resistance, increased fatigue life, and low coefficient of thermal expansion that are characteristic of composite materials can all be used to improve the overall satellite performance. Some of the satellites that may be able to take advantage of these performance characteristics are the Tethered Satellite Systems (TOSCIFER, AIRSEDS, TSS2, SEDS!, and SEDS2), AXAF, GRO, and the next generation Hubble Space Telescope. These materials can also be utilized in projects at the NASA/MSFC Space Optics Technology and Systems Center of Excellence.

The successful implementation of composite materials requires accurate performance characterization. The performance of composite materials is dependent on the constituent materials selected, material structural geometry, and the fabrication process. Flaws can form in composite materials as a result of the fabrication process, handling in the manufacturing environment, and exposure in the service environment to anomalous activity. Often these flaws show no indication on the surface of the material while having the potential of substantially degrading the integrity of the composite structure. For this reason it is important to have available inspection techniques that can reliably detect sub-surface defects such as inter-ply disbonds, inter-ply cracks, porosity, and density changes caused by variations in fiber volume content.

Many non-destructive evaluation techniques (NDE) are capable of detecting sub-surface flaws in composite materials. These include shearography, video image correlation, ultrasonic, acoustic emissions, and X-ray. The difficulty with most of these techniques is that they are time consuming and often difficult to apply to full scale structures. An NDE technique that appears to have the capability to quickly and easily detect flaws in composite structure is thermography [1,2]. This technique use heat to detect flaws. Heat is applied to the surface of a structure with the use of a heat lamp or heat gun. A thermographic camera is then pointed at the surface and records the surface temperature as the composite structure cools. Flaws in the material will cause the thermal-mechanical material response to change. Thus, the surface over an area where a flaw is present will cool differently than regions where flaws do not exist. Figure 1 is an illustration of a thermographic image of composite tubes that have service damage present.

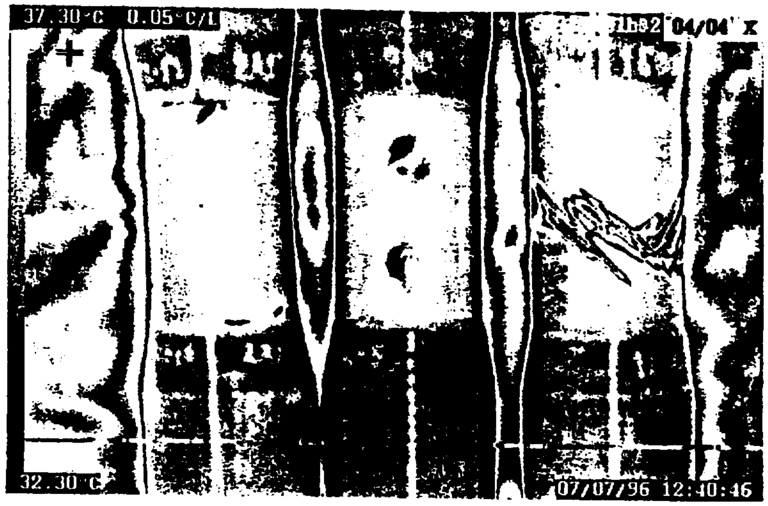

Figure 1: Thermographic images of 2" diameter composite tubes with defects.

In Figure 1 the thermographic image of the tube on the far left is indicating that damage is present near the top end-tab. The center tube was impacted and the dark spots indicate the impact sites. The right side tube has been cyclically loaded to a level below the life of the tube. Damage is present in the mid-section of the tube. There is no indication on the surface of these tubes that any damage exists. Although these images indicate that damage is present, they do not provide a description of the damage that would allow an engineer to determine if the damage has compromised the integrity of the structure.

To help explore the capability of the thermographic technique a finite element model was developed to study the flow of heat through composite materials so that the thermographic images can be better interpreted. Some of the issues that the model can help to resolve include the sensivity of the technique to various types of material defects such as inter-ply disbonds, intra-ply cracking, porosity, and density changes. Modeling can help define the bounds of the technique and optimize the use of the technique.

In the remainder of this report the effort to thermo-mechancially model the thermography process will be discussed. First the material properties and physical parameters used in the model will be explained. This will be followed by a detailed discussion of finite element model used. Finally, the result of the model will be summarized along with recommendations for future work.

MATERIAL PROPERTIES AND PHYSICAL PARAMETERS

The governing equation for conduction heat transfer is as follows.

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \cdot \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \cdot \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \cdot \frac{\partial T}{\partial z}\right) \quad (1)$$

In Equation (1) T is temperature, t is time, ρ is material density, c is specific heat, and k is thermal conductivity in the respective directions. From this equation it is clear that the density, specific heat, and thermal conductivity need to be calculated for the composite structure under consideration in order to model the transient heat transfer problem.

Measured values of the thermal properties for the composite were not available so the material properties were predicted using micromechanics. The composite under consideration is made of HMS fiber (like IM7) and 977-2 matrix in a $[\pm 25/90]_s$ laminate geometry. This geometry is chosen because it represents a typical rocket motor analog geometry. The lamina or ply level properties are calculated using a spherical inclusion model based on the differential scheme [3,4,5]. The laminate properties are not computed because each ply of the laminate is modeled separately in the finite element model. The thermal-mechanical lamina properties for the material under consideration are summarized in Table 1.

Table 1: Predicted thermal-mechanical properties for the HMS/977-2, lamina

Elastic Modulus lb/in^2		Shear Modulus lb/in^2		Poisson's Ratio	
E_{11}	$32.6(10^6)$	G_{12}	$0.770(10^6)$	ν_{12}	0.414
E_{22}	$0.874(10^6)$	G_{13}	$0.277(10^6)$	ν_{13}	0.576
E_{33}	$0.874(10^6)$	G_{23}	$0.770(10^6)$	ν_{23}	0.414

Thermal Expansion 1/°F		Thermal Conductivity Btu/in-s-°F			
α_{11}	$-0.271(10^{-6})$	k_{11}	0.0304	c	0.3032 Btu/lb-°F
α_{22}	$14.7(10^{-6})$	k_{22}	0.00260		
α_{33}	$14.7(10^{-6})$	k_{33}	0.00260	ρ	0.0621 lb/in^2

When porosity is considered, voids are added to the matrix material using the spherical inclusion differential scheme. Then the lamina material properties are computed. For the case of 15% voids the fiber direction thermal conductivity is reduced by 14%, the transverse conductivity by 65%, the specific heat by 24%, and the density by 11%.

Besides the material properties the other parameter of importance to the development of this model are the heat flux input to the plate as a result of the heating of the surface and the natural convection off of the back side of the plate. In reality, the input heat flux is due to radiation. Since the emisivity of the material surface and the temperature of the heat lamps are unknown, a heat flux input is estimated that would create a 10° heating of the plate surface. This is the value observed in experiments. The value of the heat flux in the model is 0.5 Btu/in^2-°F. On the back surface of the plate natural convection takes the heat away. The coefficient for natural convection used is $2(10^{-5})$ Btu/s-in.

FINITE ELEMENT MODEL

A finite element model is used to investigate the transient heat transfer in an 8in by 8in composite plate with various types of flaws utilizing 8-node isoparametric brick elements. Each layer of the composite was one element thick. An 0.5in by 0.5in flaw was located in the center of the plate in the third ply from the top. Quarter symmetry was employed in the discretization. To avoid convergence problems the aspect ratio for each element was held to a maximum of 8 to 1. Time steps for the model are set to 0.001s up to 0.1s. The heat flux is applied to the top surface of the model for the first 0.01s and is then removed.

Figure 2 illustrate the result of the finite element analysis for the case of a 3 element by 3 element (0.24 in by 0.24 in) disbond was located between the second and third layers from the top. This figure represents the temperature distribution in the plate at 0.01s into the model. The temperature above the disbond is 10° warmer than the elements directly below the disbond. The temperature in the plate equilibrates at 0.05s into the model. This is not much different than what is observed in the experimental results.

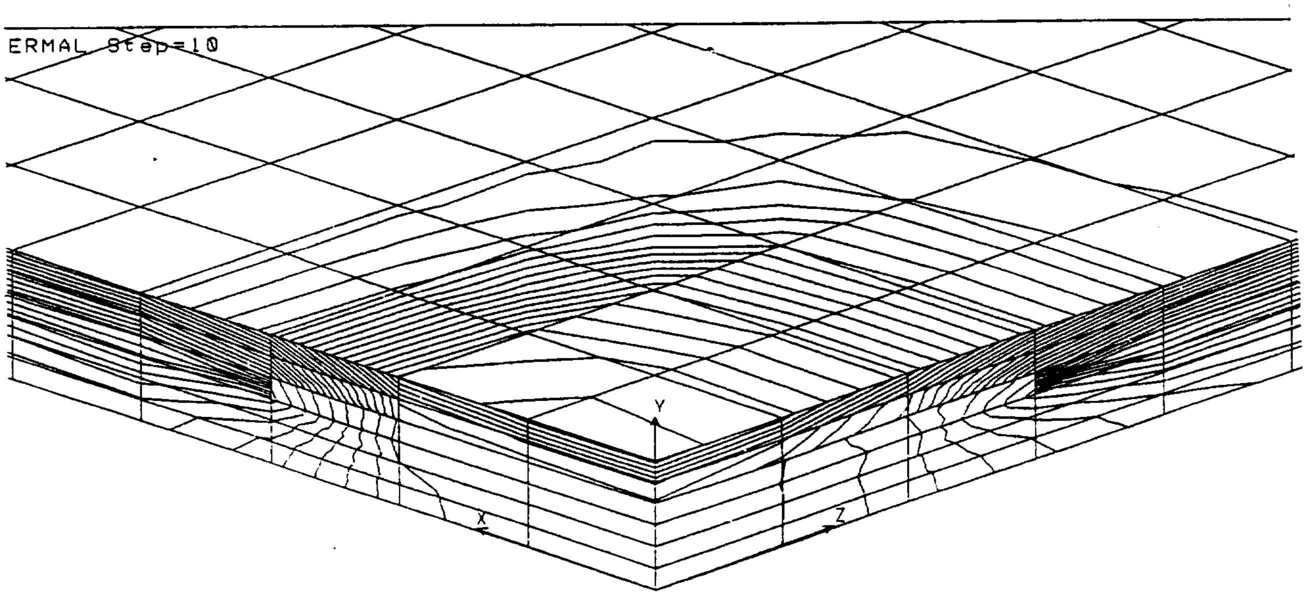

Figure 2: Finite element result for the case of a disbond between layers 2 and 3 at 10ms into the loading

The effect of porosity on the heat transfer is also modeled. Porosity as high as 15%, by volume, is added to the model in a 3 element by 3 element square in the third layer from the top of the plate. This model resulted in less than a 2° temperature gradient in the model.

RESULTS AND CONCLUSIONS

The finite element method has been shown to be a tool that can help investigators determine the meaning of thermographic images. Finite element models can also help to determine the bounds of the thermographic technique. Areas that the finite element method can assist investigators in are:

1) Determine the sensivity of the technique to transverse cracks, inclusions, and multiple flaws,
2) Developing a methodology for using thermography to determine the depth of flaws,
3) Evaluating the effects of forced convection on enhancing the thermographic results, and
4) Determine plate thickness bound in which the technique is valid.

If the finite element technique is going to be used to model the behavior of a specific plate, the emisivity of the composites surface, energy imparted by the heating system, and accurate material properties will have to be identified.

It is recommended that the investigation of the thermographic process using the finite element technique be continued so that a deeper understanding of the meaning of the thermographic images can be developed

REFERENCES

1 Winfree, W.P., James, P.H., "Thermographic Detection of Disbonds," *proceedings of the 35th ISA International Instrumentation Symposium*, Pg. 183-188, 1989

2 Bouvier, C.G., "Investigating Variables in Thermographic Composite Inspections," *Materials Evaluation*, (May 1995), pp 544-551.

3 McLaughlin, R., "A study of the Differential Scheme for Composite Materials, " *International Journal of Engineering Science*, 15(1997), pp. 237-244.

4 Boucher, S., "On the effective moduli of isotropic two-phase elastic composites," *Journal of Composite Materials*, 8(1974), pp. 82-89

5 Christensen, R.M., *Mechanics of Composite Materials*, John Wiley & Sons, New York, 1979.