N94-24454

1993

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

EVALUATION OF ADVANCED MATERIALS THROUGH EXPERIMENTAL MECHANICS AND MODELLING

Prepared By:	Yii-Ching Yang, Ph.D.
Academic Rank:	Assistant Professor
Institution and Department:	Tuskegee University Aerospace Science Engineering
MSFC Colleague:	Samuel Russell, Ph.D.
NASA/MSFC:	
Laboratory:	Material Processes
Division:	Engineering Physics
Branch:	Non-Destructive Evaluation

INTRODUCTION

Composite materials has been frequently used in aerospace vehicles. Very often it is inherited defects during the manufacture or damages during the construction and services. It becomes critical to understand the mechanical behavior of such composite structure before it can be further used. One good example of these composite structure is the cylindrical bottle of solid rocket motor case with accidental impact damages. Since the replacement of this cylindrical bottle is expensive, it is valuable to know how the damages affects the material, and how it can be repaired. To reach this goal, the damage must be characterized and the stress/strain field must be carefully analyzed.

First the damage area, due to impact, is surveyed and identified with a shearography technique which uses the principle of speckle shearing interferometry to measure displacement gradient(1). Within the damage area of a composite laminate, such as the bottle of solid rocket motor case, all layers are considered to be degraded. Once a lamina being degraded the stiffness as well as strength will be drastically decreased. It becomes a critical area of failure to the whole bottle. And hence the stress/strain field within and around a damage should be accurately evaluated for failure prediction.

To investigate the stress/strain field around damages a Hybrid-Numerical method which combines experimental measurement and finite element analysis is used. It is known the stress or strain at the singular point can not be accurately measured by an experimental technique. Nevertheless, if the location is far away from singular spot, the displacement can be found accurately. Since it reflects the true displacement field locally regardless the boundary conditions, it is an excellent input data for a finite element analysis to replace the usually assumed boundary conditions. Therefore, the Hybrid-Numerical method is chosen to avoid the difficulty and to take advantage of both experimental technique and finite element analysis.

Experimentally, the digital image correlation technique(2-4) is employed to measure the displacement field. It is done by comparing two digitized images, before and after loading. Numerically, the finite element program, ABAQUS (version 5.2)(5), is used to analyze the stress and strain field. It takes advantage of the high speed and huge memory size of modern supercomputer, CRAY Y-MP, at NASA Marshall Space Flight Center.

DIGITAL IMAGE CORRELATION

Digital image correlation is based on the comparison between two digital images. The system uses a standard CCD video camera attached to video digitizer card to acquire digital images. The digitizer transforms an image to a 512 x 512 set of numbers representing the image. Each number represents the intensity of light impinging on a small area of camera sensor, which is called a pixel. The value of each pixel ranges from 0 to 255 with the lowest value representing black, highest value representing white, and values in between representing different shades of gray. An image processing software in a personal computer is then used to compare subsets of numbers between the two digital images. To measure how well the subsets match, a correlation function is used. By minimizing the correlation factor, the values of displacement and strain at any location of image can then be determined.

FINITE ELEMENT ANALYSIS

Finite element analysis for stress/strain of a structure is based on the following equations of equilibrium:

$$[K]\ \{q\} = \{F\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [1]$$

It is resulted by minimizing the potential energy of the whole structure. Where {q}, {F}, and [K] represent nodal deformation, nodal loads, and structural stiffness matrices, respectively. Each member in {q} matrix is a degree of freedom. It is corresponding to a nodal force or moment in the same direction. For the static linear elastic problem, a degree of freedom is either unknown or known by fact or assumption. In the later case, the corresponding nodal force is unknown and to be solved as a reaction. In the Hybrid-Numerical approach, some parts of {q} matrix will be filled with the displacements measured by the digital image correlation besides the regular assumed boundary conditions. Providing the stiffness matrix of structures, [K], the unknowns in both {q} and {F} can be solved with a high speed computer.

The stiffness matrix of a structure, [K], is assembled from the stiffness matrices of element. Each member of [K] matrix relates a degree freedom to an associated nodal force or moment. The value of each member is determined by the geometry and the material properties of associated elements. Since composite laminates is used as examples, the stiffness matrix of each layer, [Q], must be first formed in the structural coordinates system, or loading directions. And the load-displacement relations is then constructed as the following form(6):

$$\begin{pmatrix} [A] & [B] \\ [B] & [D] \end{pmatrix} \cdot \begin{pmatrix} [\epsilon^o] \\ [k] \end{pmatrix} = \begin{pmatrix} [N] \\ [M] \end{pmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where [A], [B], and [D] are determined by integrating the stiffness of all layers. Using above equations as the constitute equations of thin shell elements, the stiffness matrix of elements made of composite laminate can be formed.

This stiffness matrix of elements can be different depending on the material properties of individual element. In this study, a degraded material has been assumed to the damage areas. The elastic constants related to the transversal direction of a degraded lamina is assumed to be decreased by a degradation factor. By Using these constants the load-displacement relations of damaged lamina can be found, and hence the stiffness matrix of damaged elements.

FAILURE ANALYSIS

As it has been described, the above combination of experimental technique and finite element analysis will provide a more accurate results of stress and strain in the singular zone. Assuming the composite materials responds linearly under a set of given load, the output stress from finite element analysis can be used to predict the loading level of lamina and laminate failure. The Tsai-Wu Tensor Theory(7) is chosen to determine the stress level of failure since it is mostly adopted for a polymer composite lamina. According to this theory a lamina will have initial crack in polymer matrix, and hence degraded if its stress state fail to satisfy the following inequality:

$$F_{ij}\ \sigma_i\sigma_j \quad + \quad F_i\sigma_j \quad < \quad 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad [3]$$

Furthermore, since the linear elasticity has been assumed, the ratio of the stress state at failure to that under the given load, R, can be calculated with the following equation:

$$(F_{ij}\sigma_i\sigma_j)\ R^2 \quad + \quad (F_i\sigma_i)\ R \quad = \quad 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad [4]$$

This ratio can be interpreted as how many times of given load would cause a lamina to degrade. Once a lamina is degraded the stresses in every layer will be redistributed so that the next lamina may be degraded at a higher loading level. The loading level of that all laminae being degraded is referred as the Last Ply Failure of laminates. At this stage an intensive acoustic events of fiber breaking may be heard experimentally.

EXAMPLES AND CALCULATION

In this study the cylindrical rocket motor cases are investigated. They are cylindrical pressure vessels made of IM7/Epoxy with the winding layout of $[78.5/-78.5/0/0]_2$ from inside out. In which the 0 degree is referred to the circumferential direction. It is about 5.75 inches in diameter and 4 inches long (does not count both semispherical dome at ends). Every bottle has been subjected to a low speed impact test. They are three different impact energy levels, 3, 5, and 7 foot-pound applied at the middle of bottle and perpendicular to the composite laminate skin. The size of damage areas has been measured with shearography technique. It has been seen the smallest damage is scattered within 1"x1" area; and the highest is 3"x3". Based on the identified patten of damage, the associated elements in the finite element analysis are assigned to the degraded material group.

During the burst test of each pressure vessel, two images has been taken, one at free load and the other at 1000 psi pressure level. The calculation of digital image correlation runs over about 300 by 300 pixels. It covers an area of composite laminate about 1.90" by 1.61". The resulting displacements are then input as boundary in the finite element analysis. A mesh diagram with 20 by 20 rectangular thin shell elements is constructed. Using a computer code, ABAQUS, the stresses and strains of shell elements are calculated. And the stresses is then checked with Tsai-Wu Tensor Theory to predict the pressure level at the Last Ply Failure of cylindrical bottle skin. The preliminary results show it agrees with that of the acoustic observation.

REMARK AND FUTURE WORK

Due to the complexity of test and shortage of facility and manpower, only few pressure vessels have been bursted. Although the preliminary result shows promising, more vessels should be tested; and more analyses must be done before a firm conclusion can be reached. By then it may be better understood how an impact affects the rocket motor cases and how to repair it if necessary.

REFERENCES

1. Toh, S.L., Shang, H.M., Chaw, F.S., and Tay, C.J., "Flaw Detection in Composites Using Time-Average Shearography," Optics & Laser Technology, 23 (1991)
2. Peters, W.H. and Ranson, W.F., "Digital Imaging Techniques in Experimental Stress Analysis," Opt. Eng., 21 (1982) 427-431
3. Sutton, M.A., Cheng, M., Peters, W.H., Chao, Y.J., and McNeill, S.R., "Application of an Optimized Digital Correlation Method to Planar Deformation Analysis," Image and Vision Computing 4 (1986) 143-150
4. Bruck, H.A., McNeill, S.R., Sutton, M.A. and Peters, W.H., "Digital Image Correlation Using Newton-Raphson Method of Partial Differential Correction," Experimental Mechanics, 29 (1989) 261-267
5. ABAQUS version 5.2, Bibbitt, Karlsson & Sorensen, Inc. (1993)
6. Jones, R.M., Mechanics of Composite Materials, Mcgraw-Hill Book Company (1975)
7. Tsai, S.W., and Wu, E.M., "A General Theory of Strength for Anisotropic Materials," Journal of Composite Materials, January (1971) 58-80