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NASA LeRC/AKRON UNIVERSITY GRADUATE COOPERATIVE FELLOWSHIP PROGRAM AND GRADUATE STUDENT RESEARCHERS PROGRAM

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October 1983

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16. Abstract
On june 1, 1980, the University of Akron and the NASA Lewis Research Center (LeRC) established a Graduate Cooperative Fellowship Program in the specialized areas of Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization, in order to promote and develop requisite technologies in these areas of engine technology. The objectives of this program were consistent with those of the NASA Engine Structur Program in which graduate students of the University of Akron have participate by conducting research at Lewis. This report is the second oh this grant and summarizes the second and third year research effort, which included the participation of five graduate students where each student selected one of the above areas as his special field of interest. Each student was required spend 30 percent of his educational training time at the NASA Lewis Research Center and the balance at the University of Akron. His course work was judiciously selected and tailored to prepare him for research work in his field of interest. A research topic was selected for each student while in residence at the NASA Lewis Research Center, which was approved by the faculty of the University of Akron as his thesis topic for a Master's and/or a Ph.D. degree.

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SECTION 1

SUMMARY

On June 1, 1980, The University of Akron and the NASA Lewis Research Center (LeRC) established a Graduate Cooperative Fellowship Program in the specialized areas of Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization, in order to promote and develop requisite technologies in these areas of engine technology. The objectives of this program were consistent with those of the NASA Graduate Student Researchers Program in which graduate strudents of The University of Akron have participated by conducting research at Lewis.

The first year effort included the participation of six graduate students, and their research accomplishments were reported in the October 1981 report, Report Number NASA CR-167943, NAUFP 202-1. The efforts of the second and third year of the program are included in this report. Each year involved the participation of five students where each student selected one of the above areas as his special field of interest.

Each student was required to spend 30 percent of his educational training time at the NASA LeRC and the balance at The University of Akron. His course work was judiciously selected and tailored to prepare him for research work in his field of interest. A research topic was selected for each student while in residence at the NASA LeRC, which was approved by the faculty of The University of Akron as his thesis topic for a Master's and/or a Ph.D. degree.

The objectives of the second and third year efforts were successfully completed and all the students were enthusiastic about the scope of the program. The idea of working together with NASA engineers on highly specialized areas of Aerospace Technology was very beneficial to the program participants, and it provided to them the required motivation to make these areas their special field of interest. The problems encountered in carrying out the objectives of the program were rather insignificant compared to the benefits obtained.

TABLE OF CONTENTS

FORWARD

This report presents the work performed on the "NASA LeRC/Akron University Graduate Cooperative Fellowship Program", NASA Grant NAG 3-50, June 1, 1981 to May 31, 1983, "Graduate Student Researchers Program", NASA Grants NGT 36-001-800 and NGT 36-001-801, September 1, 1981 to August 31, 1983, with Dr. C.C. Chamis, NASA Lewis Research Center, as Project Manager. This is the second in a series of reports regarding the program and status of these educational grants. The Principal Investigators and Directors for Grant NAG 3-50 are Drs. Demeter G. Fertis and Andrew L. Simon; for Grant NGT 36-001-800 is Dr. Demeter G. Fertis, and for Grant NGT 36-001-801 is Dr. T.Y. Chang - all of the University of Akron.

SECTION 2

INTRODUCTION AND OBJECTIVES

On June 1, 1980, under Grant Number NAG3-50, the University of Akron and the NASA Lewis Research Center established a Graduate Cooperative Fellowship Program in order to achieve common objectives in certain areas of aerospace research and engineering. The broad areas of specialization under this program were concentrated on Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization.

The accomplishments of the first year effort which included the participation of six selected graduate students that did research in the research areas stated above, have been presented in the October, 1981 report under the title "NASA LeRC/Akron University Graduate Cooperative Fellowship Program and Graduate Student Researchers Program", Report Number NASA CR-167943 NAUFP 202-1. The accomplishments of the second and third year efforts are presented in this report. A brief discussion regarding the purpose and objectives of the program is also included in this section of this report.

The research work and training in the above four areas of specialization is intended to promote efforts towards the solution of problems related to aircraft engines. The general purpose is to develop the requisite methodology to solve linear and nonlinear problems associated with the static and dynamic analysis of rotating machinery, understand better their static and dynamic behavior, and develop better understanding regarding the interaction between the rotating and nonrotating parts of the engine. Research and training of this nature could result into imporved engine designs with improved engine efficiencies and lower fuel consumption.

A specific purpose of the program was that linear and nonlinear structural engine problems be investigated by developing solution strategies and interactive computational methods whereby the man and computer could communicate directly in making analysis decisions. Representative examples include modifying structural models, changing material parameters, selecting analysis options, and coupling with interactive graphical display for pre- and post-processing capability.

These research efforts will include the development of optimization techniques and methodology for the analysis of structural components made up of advanced materials, including composites that are subjected to various types of engine loads and performance constraints. This will require better understanding and more accurate determination of the mechanical properties of composite materials and their dependence to the various variations in processing procedures.

Through this program, NASA is expected to broaden the base for new ideas to develop in these areas of specialization, and bring fresh inspiration in the solution of complex problems of propulsion systems by increasing the availability of young talent for immediate employment in the aerospace industry. It will also provide a mechanism for assistance to senior government researchers in the identification and solution of such complex problems. The University of Akron is also benefiting from this fellowship program by having the opportunity to provide greater depths to its graduate programs, and by attracting high quality students to the University who will concentrate their efforts on current research needs. The students participating in this program have the opportunity to fully utilize the teaching and research expertise of the University community and the technical expertise of the NASA Lewis Research Center.

The Graduate Fellowship Program is organized and administered in a way that is expected to produce optimum results for both NASA and the University of Akron. The students who are participating in this program are selected on a competitive basis and they are under the tutelage of University of Akron faculty and Adjunct Professors appointed from NASA personnel. They are expected to complete a Master's and/or a Doctoral degree. Each student spends about 30 percent of his educational training time at NASA and the balance at the University of Akron. His coursework is judiciously selected and tailored to fit the requirements of his field of specialty.

His residency at the NASA Lewis Research Center consists of suitable continuous time intervals, usually during the summer months and/or during the four week Christmas recess, followed by a suitable parttime residency during school semester periods. In this manner the fellowship student maintains continuous contact with both institutions during the whole educational period required for his graduate degree. During his NASA residency he performs research work on a problem of his choice that is selected from a group of problems that are of interest to NASA and also related to the general areas of specialization duscussed earlier. A Master's and /or a Doctoral thesis is expected to be completed as a result of this research work. The graduate degree is awarded to the student when the academic requirements at the University of Akron, as well as his NASA residency, are completed.

The NASA LeRC/Akron University Graduate Cooperative Fellowship Program is also coordinated with the Graduate Student Researchers Program that is established by NASA and administered by the University Affairs Office of NASA Headquarters in Washington, D.C. Graduate students of the University of Akron were selected to participate in this program with Lewis Research Center as the NASA Host Center.

Under this program the graduate students are selected by the individual NASA Host Center on the basis of their academic qualifications, the quality of the proposed research program and its relevance to NASA interests and needs, the student's utilization of research facilities at the NASA Center, and the availability of the student at a NASA Center for a sufficient time to accomplish the defined research. These requirements are similar in principle to those established by the NASA LeRC/Akron University Graduate Cooperative Fellowship Program and, therefore, the objectives of these two programs are served better by coordinating their graduate educational activities, training and availability of the student to the NASA Center to accomplish his defined research.

The students receiving support under these two graduate programs are not under any formal obligation to the Government of the United States, but the objectives of these programs are very well served by encouraging the students to actively pursue research or teaching in aeronautics, space science, or space technology after completion of their graduate studies.

SECTION 3

PROGRAM PARTICIPANTS

During the first year of the two programs, six graduate students were selected to participate in these programs. Four of the students were supported by the NASA LeRC/Akron University Graduate Cooperative Fellowship Program and the other two by the Graduate Student Researchers Program. The accomplishments of these six students are reported in detail in the October, 1981 report, and reference of this report is given in the second paragraph of Section (2) of this report.

The second and third year efforts included the participation of seven graduate students who were selected as discussed in Section (2). Six of these students were supported by the NASA LeRC/Akron University Graduate Cooperative Fellowship Program and one by the Graduate Student Researchers Program. A brief description of the interests and research objectives for the five students is given below in alphabetical order. The research work of the remaining two students is completed and it will be published as separate NASA reports.

3-1. RITO ALVAREZ, completed the degree Bachelor of Science in Civil Engineering (B.S.C.E.) at Youngstown State University and the degree Master of Science in Civil Engineering (M.S.C.E.) at the same university. At the University of Akron, under the NASA LeRC/Akron University Graduate Cooperative Program, he is pursuing graduate work leading to the Ph.D. degree in Engineering. His area of specialization is Optimization, and his research topic, "Structural Optimization of a Variable Cross Section Cantilever Beam", involves a cantilever beam of varying circular cross section and the development of a computer program that utilizes an optimization technique by which the selected design variables are optimized in such a way that makes the weight of the beam a minimum. The ultimate purpose of this work is to develop the method to the extent that it can be applied to blades.

3-2. STEVE ARNOLD obtained a Bachelor of Science in Civil Engineering (B.S.C.E.) degree from the University of Akron, and he is now working toward completion of the degree Master of Science in Civil Engineering (M.S.C.E.) at the same university under the NASA LeRC/Akron University Graduate Cooperative Program. His area of specialization is "Computational Mechanics", and his Master's thesis research deals with the development of a standard pre- and post-processor which can interact dynamically with a finite element code in such a way, as to produce a model which will be consistent with the given loading or deflection states at any given time. The title of this research is "A Study of Mesh Refinement Criteria Based on Typical Finite Element Output" and the main objective of this project is to develop a computer program that can incorporate such capabilities.

3-3. JAMES J. BENEKOS has completed a Bachelor of Science in Civil Engineering (B.S.C.E.) from the University of Pittsburgh and he is now completing the Master's of Science in Civil Engineering (M.S.C.E.) degree at the University of Akron under the NASA LeRC/Akron University Graduate Cooperative Program. His Master's thesis research topic, "Dynamic Response of Fibrous Composites", includes testing of certain composite material specimens to determine specific material properties and compare the results with theoretically expected values. The tested specimens were made out of laminates which were constructed from graphite fibers and PR288 epoxy resin matrix refered to as AS/E. His area of specialization is "Structural Dynamics".

3-4. RONALD R. CARNEY obtained the degree Bachelor of Science in Electrical Engineering (B.S.E.E.) from the University of Akron, and he is now working towards completing the degree Master of Science in Electrical Engineering (M.S.E.E.) at the same university under the NASA LeRC/Akron University Graduate Cooperative Program. His area of specialization is "Experimental Mechanics", and his thesis research topic, "A Graphics Subsystem Retrofit Design for the Bladed-Disk Data Acquisition System", deals with the design of a graphics subsystem to be added to the Bladed-Disk Data Acquisition System (BDDAS) which was developed by the NASA Lewis Research Center. This addition of graphics viewing modes was to be accomplished without substantial modification of the existing BDDAS as much as possible, and, by using equipment and parts available in stock at LeRC.

3-5. JOHN J. CARUSO has completed the Bachelor of Science degree in Civil Engineering (B.S.C.E.) at the University of Akron and he is currently working towards completion of the degree Master of Science in Civil Engineering (M.S.C.E.) at the same university under the support of NASA LeRC/Akron University Graduate Cooperative Fellowship Program. His area os specialization is "Mechanics of Composite Materials", and his thesis research topic, "Fiber Epoxy Composites", deals with Finite Element analysis methods to determine mechanical and thermal properties of composite materials. Graphic capabilities of computer codes were also utilized to generate plots of the deformed and undeformed shapes of the finite element model.

SECTION 4

RESEARCH PROBLEM DESCRIPTIONS AND RESULTS

The research work of each program participant is briefly discussed in this section and it is listed in the alphabetical order of the last name of the participants. The discussion of each research includes background information and objectives of the research, development and research results, and selected bibliography regarding the research. It should be pointed out, however, that the research work of the participants may not have yet been completed, and therefore a brief discussion of the work completed to this date of the report is included in this section. The complete work of each participant will be reported in detail as a separate NASA report when it is completed.

4-1. STRUCTURAL OPTIMIZATION OF A VARIABLE CROSS SECTION CANTILEVER BEAM.

Researcher: Rito Alvarez

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center
Dr. Demeter G. Fertis, the University of Akron

BACKGROUND AND OBJECTIVES

This problem includes a preliminary study of a cantilever beam of variable circular cross section along its length. Its end diameters DB and DT, Fig. (1), and its constant wall thickness t, are the design variables which are to be optimized for a given load condition. The design variables are illustrated in Fig. (1), and the selected load conditions involving a uniformly distributed load and a point load are shown in Figs. (2a) and (2b), respectively.

The objective of the research is to develop a FORTRAN program which will incorporate an optimization technique where the design variables are optimized in such a way which makes the weight of the beam a minimum. The design variables are determined by satisfying a number of constraint equations which are used to maximize the beam's flexural stress, the deflection at the free end, critical buckling, and its fundamental natural frequency.

The analysis of the problem will be initially confined to isotropic materials and small deformation theory. for the load cases indicated in Fig. (2), the material properties for structural steel, aluminum, tungsten, and graphite will be used in the analysis. As soon as these materials are analyzed and the basic theory is well developed, the methodology will be extended to include the analysis of composite materials.

Further extension of the work will include the analysis of a turbine blade. The work will be extended by using again the cantilever beam concept but with a varying elliptical cross section along its length. The loading will be dynamic and the elastic properties of composite materials will be mainly considered.

DEVELOPMENT AND RESULTS

The optimization procedure used in determining the design variables is the penalty function method.[1] Equation (1) below, which is known as the interior feasible method, is written as

$$PE = W + PC \sum_{i=1}^{N} (1/Gi)^2 \tag{1}$$

where

PE = objective function

W = weight equation to minimize

Gi = the constraint equations - one for each constraint

PC = penalty constant

$PC \sum_{i=1}^{N} (1/Gi)^2$ = penalty function

The problem requires that Eq. (1) be minimized, which is done by solving sequentially a series of optimization problems. The parameter PC will be quite large initially, and it will gradually be reduced as the optimization process continues. It should be noted that as PC approaches zero the unconstrained problem for PE approaches the constrained problem W (weight equation). Because PC is sequentially reduced, this method has been called SUMT (Sequential Unconstrained Minimization Technique).

The optimization technique used for determining the design variables is known as the least-pTH algorithm.[2] Unlike other techniques, such as the steepest-descent, the least-pTH algorithm is written for a specific type of problem, thus making it usually more efficient. It assumes that the objective function is of a particular form. This assumption is not very restrictive, but it can drastically improve the rate of convergence. Eq. (2) expresses the objective function in a series from with each term raised to an even positive power of p. That is

$$E\,(x) = \sum_{i=1}^{M} e_i(x)^p = e_1(x_1,\ x_2,\ x_3,\ldots)^p + e_2(x_1,\ x_2,\ x_3,\ldots)^p + \ldots$$

$$+\ e_M(x_1,\ x_2,\ x_3,\ldots)^p \tag{2}$$

To minimize the function E(x), the gradient of E(x) must be zero. That is;

$$\nabla E(x) = \sum_{i=1}^{M} P\ e_i(x)^{p-1}\ \frac{de_i}{dx_k} = 0 \tag{3}$$

Equation (3) will be made zero by iteration and a proper selection of the parameter change for x_1, x_2, x_3,.... Initially $\nabla E(x)$ will not be zero, but by iterating the gradient may be made as close to zero as desired, thus obtaining the values of x_1, x_2, x_3, ..., which will minimize E(x).

That is, we set each term in Eq. (1) to the following terms in Eq. (2):

$$e_1\ (x_1,\ x_2,\ x_3,\ldots) = W \text{ (weight equation)}$$

Then

$$\sum_{i=2}^{M} e_i(x_1,\ x_2,\ x_3,\ldots) = \sum_{i=1}^{N} (PC/Gi)^2$$

Thus as PC gradually approaches zero during the iteration process, $E(x)$ approaches $e_1(x_1,\ x_2,\ x_3,\ldots)$ which is the minimum weight of the structure. The final values x_1, x_2, and x_3 which corresponds to DB, DR and R, respectively, will satisfy all the constraint equations.

To elaborate more on the constraint equations G(i), we can derive both the geometric constraint and the behavior variable constraint equations for each of the load cases previously mentioned. Figure (3) shows the geometric constraint equations only. The three geometric equations are described here as follows:

$$20.0 - DB \geq 0 \quad (4)$$

$$0.5 - DR \geq 0 \quad (5)$$

$$DR - 2R \geq 0 \quad (6)$$

$$R - 0.05 \geq 0 \quad (7)$$

where

DB = Diameter at the fixed end.

DR = DT/DB, Ratio of tip diameter to diameter at the fixed end.

R = t/DB, Ratio of wall thickness to fixed end diameter.

The next four equations deal with the behavior variables;

$$STRBL - STRB \geq 0 \quad (8)$$

$$DEFL - DEF \geq 0 \quad (9)$$

$$STRCBL - STRCB \geq 0 \quad (10)$$

$$FREQL - FREQ \geq 0 \quad (11)$$

where

STRBL = Allowable bending stress.

STRB = Bending stress formula

DEFL = Maximum allowable deflection at the free end.

DEF = Deflection equation

STRCBL = Critical buckling stress limit

STRCB = Critical buckling stress

FREQL = Frequency limit

FREQ = Fundamental frequency equation

The flexure formula was used to determine STRB, that is;

$$S = Mc/Ix$$

where

Ix = variable moment of inertia

M = maximum moment

c = variable diameter/2

The deflection equation DEF was derived using the curvature formula;

$$\frac{d^2W}{dx^2} = \frac{M}{EI_x}$$

where

E = modulus of elasticity

Rayleigh quotient[3] was used in deriving both the critical buckling and frequency equations. The buckling equation is

$$P_{CR} = [E\int_0^H I_x(\frac{d^2W_1}{dX^2})^2 d_x]/[\int_0^H (\frac{dW_1}{dX})^2 dx]$$

and the frequency equation is

$$(FREQ)^2 = [E \int_0^H I_x (\frac{d^2W_1}{dX^2})^2 dx]/[\rho_M \int_0^H A(x) W_2^2 dx]$$

where $W_1(X)$ and $W_2(X)$ are approximate deflection equations which satisfy the kinematic boundary conditions.

The bending stress, deflection, buckling stress, and frequency for the point load case only are as follows;

Case I: Point load

$$STRB = 4\ P\ D_B(1+ax)(x-H)/\{\pi RD_B^4[(1+ax-R)^3 + (1+ax-R)R^2]\}$$

$$DEF = (k/R)[V\ Tan^{-1}(\frac{V}{R}) - \frac{R}{2} Log(V^2+R^2)] - k\ (1+aH-R)[\frac{1}{2\ R^2}\{V\ Log(\frac{V^2}{V^2+R^2})$$
$$-2R\ Tan^{-1}\ (\frac{V}{R})\}] + C_1V + C_2$$

$$STRCB = [E\ I_{FE}\ K_1]/[8\ \pi\ RD_B^2\ (1-R)]$$

$$FREQ = (2.2919/\pi)(D\ /H^2) \quad (Eg/\rho_W)K_2$$

where

a = slope coefficient

v = variable distance along beam

c_1, c_2 = constants of intergration

I_{FE} = inertia at fixed end

K, K_1, K_2, = coefficients that are determined in derivations

The above equations for critical buckling and fundamental frequency were also used in the uniform loading case.

Once the optimization program is operational, the results, that is fixed end diameter, tip diameter, wall thickness and weight of the beam, will be tabulated as a function of the load cases. For example, in the case of the point load, P will be incremented from a small value until one of the geometric constraints is validated. Additional information can be also obtained by gradually reducing the wall thickness for given load values, which will lead to analyzing a structural element with large deflection and linear material properties.

FUTURE DEVELOPMENT

Optimization techniques provide a very important tool in structural design. The method presented here can be used to analyze a variety of structural problems. Additional research on the subject will include the analysis of a cantilever beam with a variable elliptical cross-section. The material properties would be that of an uni-directional composite, where the density of the composite will be the design variable. New equations will then be developed for frequency, stresses and deflection. Each of these equations will become a function of load, variable geometry and density.

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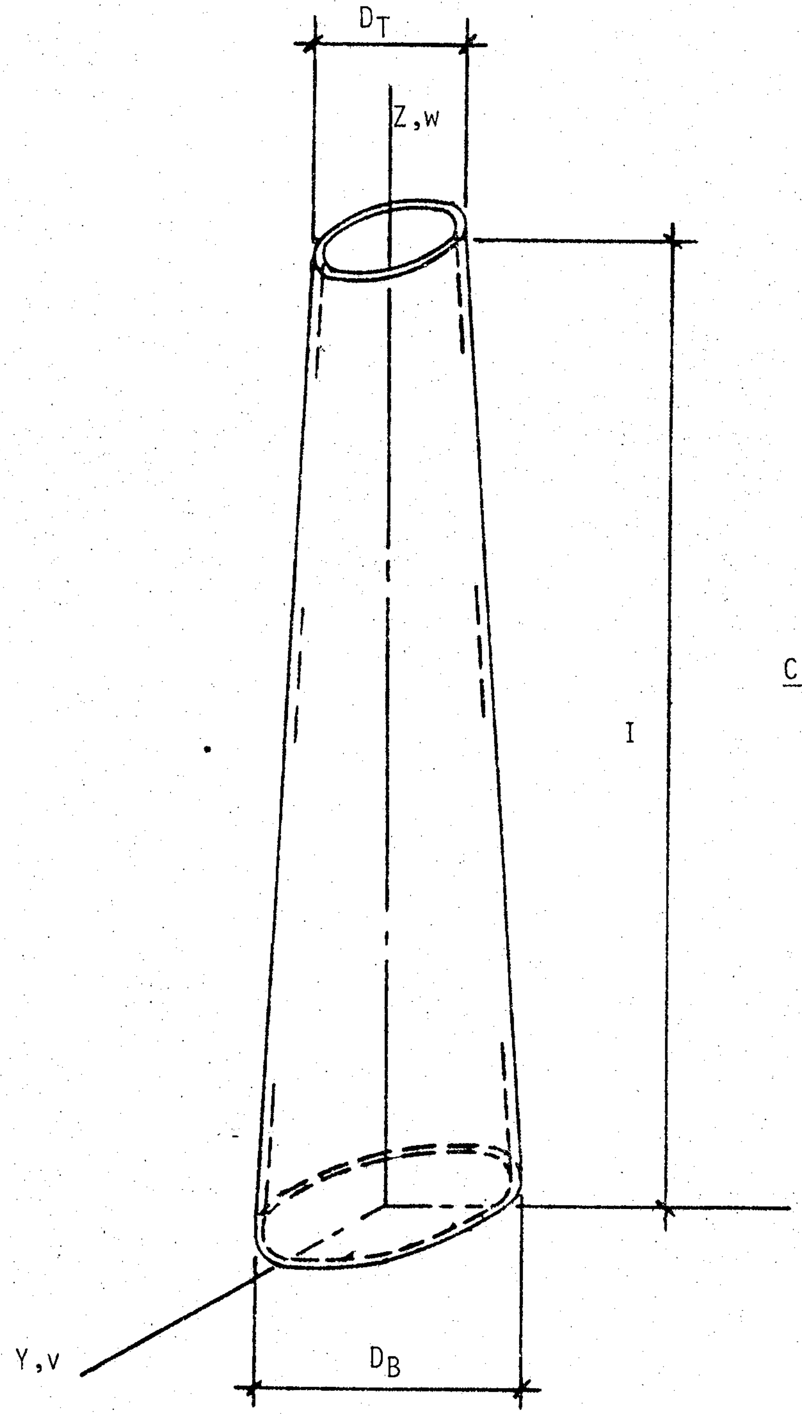
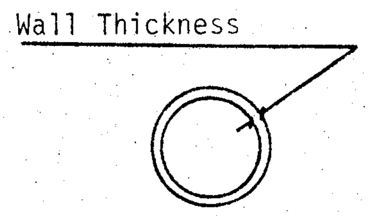
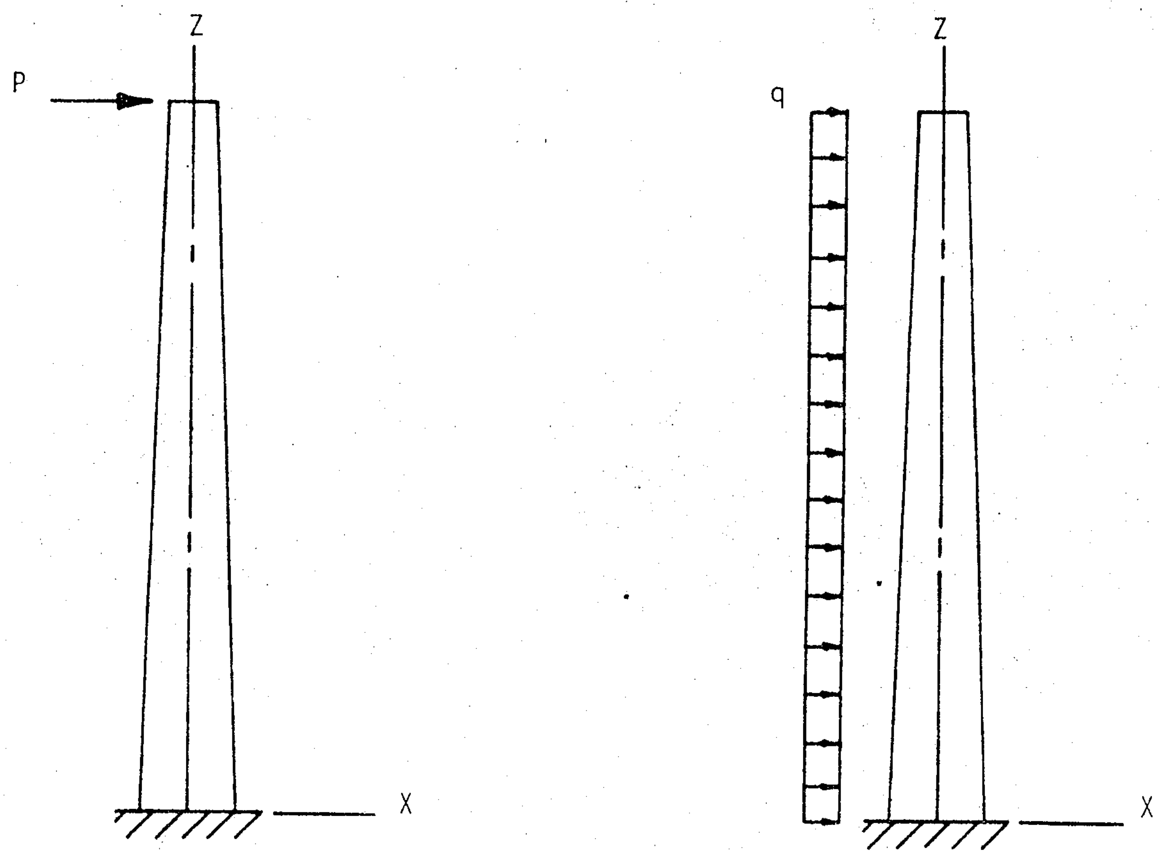




CIRCULAR CROSS SECT.

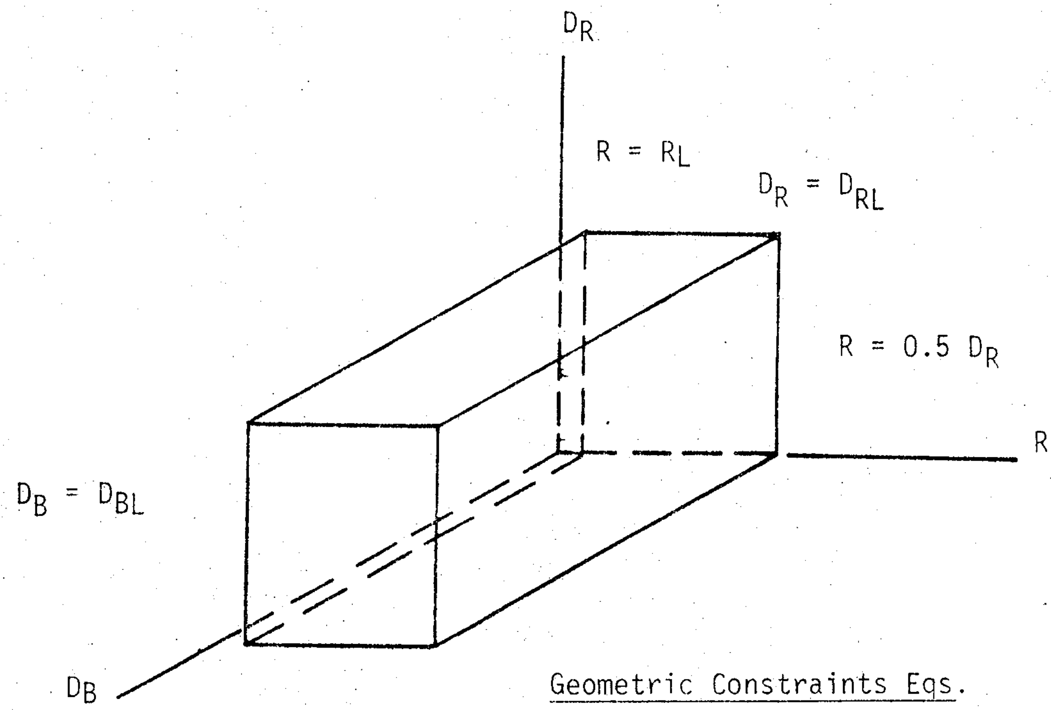
FIGURE 1.



a. Point Load

b. Uniform Loading

FIGURE 2.



<u>Geometric Constraints Eqs.</u>

1. $D_{BL} - D_B > 0$
2. $D_{RL} - D_R > 0$
3. $D_R - 2R > 0$
4. $R - R_L > 0$

FIGURE 3 - FEASIBLE REGION WITHIN RECTANGULAR CUBE INCLUDING ADDITIONAL CONSTRAINT EQUATIONS

4-2. A STUDY OF MESH REFINEMENT CRITERIA BASED ON TYPICAL FINITE ELEMENT OUTPUT

Researcher: Steve Arnold

Research Supervisors: Dr. Murray S. Hirschbein, NASA Lewis Research Center
Dr. T. Y. Chang, University of Akron

BACKGROUND AND OBJECTIVES

Finite element analysis has evolved to such a state of the art, that today it is one of the main tools of a structural analyst. However, one major drawback to it's complete domination is the time and expense required in preparing extensive input data necessary for an application problem with complex geometry. Another is the difficulty associated with determining whether ones' problem has been correctly modeled. As a result, a great deal of time and money is being spent developing pre and post processing software to aid the engineer in both the preparation and interpretation of the input and output data associated with the various finite element (F.E.) codes, i.e. (NASTRAN, ADINA, NFAP, etc.).

The sophistication of preprocessing software necessary to generate the finite element mesh and asssociated load and boundary conditions has progressed to a satisfactory level. However, because of the heavy reliance upon intuition and experience, the development of postprocessing software capable of varifying the adequacy of a given mesh has developed at a slower rate. Ideally, one would desire a software package which could interact 'dynamically' with a given F.E. code assuring one of a properly refined mesh capable of capturing the primary responses of a structure at any given time. Such a code might be classified as an "Expert System" since an analyst would be insured of a correctly modeled problem, within the limits of the approximations made in F.E. analysis, whether or not he has expertise in the field. Presently, such a code is unattainable because of inadequate decision making criteria.

The need to ascertain a satisfactory criteria which would indicate the areas and/or levels of refinement has motivated this research project. Our primary objective is to study the feasibility of using typical F.E. output, such as displacements, strains, and stresses, in the form of gradients and variations, as criteria for mesh refinement.

The most sophisticated criteria proposed are those based on a-posteriori error estimates.[1] These procedures use the results of an analysis to estimate, in some selected norm, the total discretization errors throughout the domain of the problem. Our approach will follow this thrust, however the technique used to detect discretization errors will be more simplistic and heuristic in nature than the recent efforts being made in the area of grid optimization.

PROCEDURE

Our study has been conducted using NFAP, a nonlinear finite element analysis program developed at the University of Akron, under the direction of Dr. T. Y. Chang, and has been confined to the analysis of four linear plate bending problems, using both four and nine node plate elements. These four problems consisted of:

1. A cantilever beam, 1" x 12" x 1/4" subjected to a concentrated point load located at its end.
2. A simply supported square plate, 6" x 6" x 1/4", subjected to a concentrated point load located at its center.
3. A simply supported rectangular plate, 6" x 12" x 1/4", subjected to a concentrated point load off center, (x = 3", y = 9.0").
4. A simply supported rectangular plate, 6" x 12" x 1/4", subjected to two concentrated point loads, three inches apart, forming a couple (twist moment).

Concentrated point loads were chosen because of their severity and analogy to hot spots, plastic hinges, and other regions where high stresses may occur.

Originally, all problems were analyzed using a course mesh. Subsequent analysis consisted of densifying each successive mesh by a factor of two. This procedure was employed for both four and nine noded elements. In addition, the 4 noded square plate problem was modeled using a different refinement technique consisting of progressively denser regions, again by a factor of two, centering around the load. This type of grid enrichment scheme was chosen for several reasons.

1. It is one of the most common forms.
2. It insures that the new elements will not become elongated.

3. It provides for an accurate error estimation.

A program has been developed to calculate the various nodal field quantities such as displacements, stresses, strains and strain energy density; and their associated gradients and variations. The ability of these gradients and variations to detect discritization errors will be the basis of our refinement criteria.

The above mentioned code can easily be expanded to encompass other fields such as centroids, integration points and the like, along with any combination thereof. We have chosen to examine nodal point quantities initially for several reasons.

1. They are the locations at which all information is transferred to and from connecting elements.
2. Their position can be maintained throughout the refinement process, thus allowing for an accurate error estimation between each successive refinement.
3. Their familiarity with the user community.

Gradients and variations will be defined as follows:

$$\text{Grad}(i) = [P(n) - P(i)]/\Delta R$$

where

P(n) - is a reference field (nodal) point
P(i) - are the neighbouring points
ΔR - is the distance between P(n) and P(i)

$$\text{Var}(i) = [P(\max) - P(\min)]/\ P\max$$

where

P(max) = maximum point value between the reference and current surrounding point.
P(min) = minimum point value between the reference and current surrounding point.

NOTE: the surrounding nodes include all the associated nodes belonging to the elements which have common to them the reference node.

Prior to calculating the gradients and variations, point properties must be evaluated. Since we are concerned with nodal field properties, displacements can be obtained directly from the F.E. output, whereas stresses, strains and strain energy density must be interpolated from the nearest surrounding integration points. The interpolation scheme we have employed is one introduced by Wilson.

Basically, it is a weighted averaging technique using the inverse distance between a reference point and the surrounding points as a weighing factor.

$$f_k = \frac{\sum_{i=1}^{M} W_i P_i}{\sum_{i=1}^{M} W_i}$$

$W(i) = 1/d(i)$

$d(i)$ = distance between point k and i

M = number of neighbouring points

During our investigation of the cantilever beam and square plate problems, the various nodal properties have remained in their directional components, i.e., x,y,z,; because of symmetry considerations. However, when examining the rectangular plate problems, we consider the properties in their principal directions. Currently, we are in the process of graphically displaying the gradients and variations for each property with respect to chosen lines of interest in the hopes of establishing a pattern or relationship between each successive refinement.

RESULTS

Presently, only some general trends have appeared.

1. The loading and boundary conditions of each problem will dictate what pattern the gradients and variations will assume.
2. If the analysis was performed correctly, a pattern must emerge for a given problem, i.e., proper order of integration, element formulation, etc.
3. Similar patterns have been established for stress, strain and strain energy density therefore we need only consider one of the three properties.
4. Both linear and quadratic elements produce similar patterns.

Under certain circumstances following the gradient and variation patterns leads one, correctly so, toward mesh refinement even after the examination of the displacement and stress profiles have indicated convergence.

CONCLUSIONS

After examining the preliminary results it is believed that by using gradients and variations, of typical Finite Element output, it might be possible to develop a viable criteria for mesh refinement. This criteria would possess the following advantages and disadvantages.

Advantages

1. Conceptially and computationally simplistic.
2. Problem independent at least from the stand point that each problem will establish its own patterns.
3. Element independent.
4. Independent of refinement technique, assuming an accurate error estimation can be made.

Disadvantages

1. Iterative solution.
2. Limited refinement per iteration cycle.
3. Mesh produced is not optimized thus possibly requiring additional iterations.
4. Patterns may be complex and hard to identify.

4-3. DYNAMIC RESPONSE OF FIBROUS COMPOSITES

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Researcher Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center
Dr. Demeter G. Fertis, University of Akron

BACKGROUND AND OBJECTIVES

The primary purpose of this research is to physically test certain composite material specimens to determine specific material properties which will be compared with theoretically expected values. In addition, the logarithmic decrement is calculated in order to determine the effects of hysteresis damping.

The use of fibrous composites as a structural material has been gaining popularity in the recent years. A great deal of work, both theoretical and experimental, has been already performed for these composites. However, one area in which more research work is needed deals with the dynamic response of fibrous composites. Once the dynamic properties for such materials are determined, the structure, or a structural component, can be analyzed and designed for dynamic loadings.

Due to the inherent nature of composites, the material properties of a composite made up from the same constituents will vary according to the way the laminate is constructed from the plies of the constituents. Therefore, a laminate made up of the same constituents would have different values for each material property, which are dependent upon the way the laminar is constructed. On this basis, testing will be required for each laminar to obtain an empirical value for each material property of a laminar.

DEVELOPMENT AND RESULTS

The MFCA computer program was developed at NASA Lewis Research Center to predict the properties of any laminate when the properties of the constituent materials and the laminate geometry are given. Several common constituent materials have been incorporated into this computer program, including those materials that are used in the tests of this research. The laminar geometry consists of the number of plies in the laminate and the angular orientation of each ply with respect to an arbitrary 0 axis.

Two laminates made out from graphite fibers and PR288 epoxy resin matrix, referred to as AS/E, were tested in this research. The first laminate, referred to as pseudo-isotropic, is made up of eight plies with the fiber orientation of the plies with respect to the longitudinal axis (Fig. 1) being 45^o, -45^o, 0^o, 90^o, 90^o, 0^o, -45^o and 45^o, as shown in Fig. (1b). The other laminate is refered to as the blade-like laminate (Fig. 1c).

All specimens used to test the pseudo-isotropic laminate were cut from a single 12" x 18" plate. Similarly, all specimens for the blade-like laminate were cut from a single 12" x 18" plate. Care was taken to insure that the 0^o axis from the original plate(s) was maintained in each specimen.

Three specimen types with a set of three replicates for each test were required from each laminate plate: an impact specimen having a longitudinal axis parallel to the 0^o-ply axis of the laminate, Fig (2a), a tensile specimen with the 0^o axis of the laminate parallel to the load axis, Fig (2b), and a tensile specimen with the 0^o axis of the laminate perpendicular to the load axis, Fig. (2c). An impact specimen with its longitudinal axis perpendicular to the 0^o axis was not made because of limited quantity of each laminate.

Four tests were conducted: a 0^o tensile test, a 90^o tensile test, a free vibration test, and an impact test. The 0^o test was performed on the specimen type shown in Fig. (2b). The 90^o or transverse tensile test was performed on specimens of the type shown in Fig. (2c). The free vibration and impact tests were performed on specimens of the type shown in Fig. (2a).

The material properties that are determined from these tests are, the modulai of elasticity E_1 and E_2 for the 0^o and 90^o tensile tests, respectively, the Poisson's ratios ν_{12} and ν_{21} for the 0^o and 90^o tests, respectively, and the modulus of elasticity E_{b1} for both the free vibration and impact tests. They are shown in Tables (1), (2) and (3).

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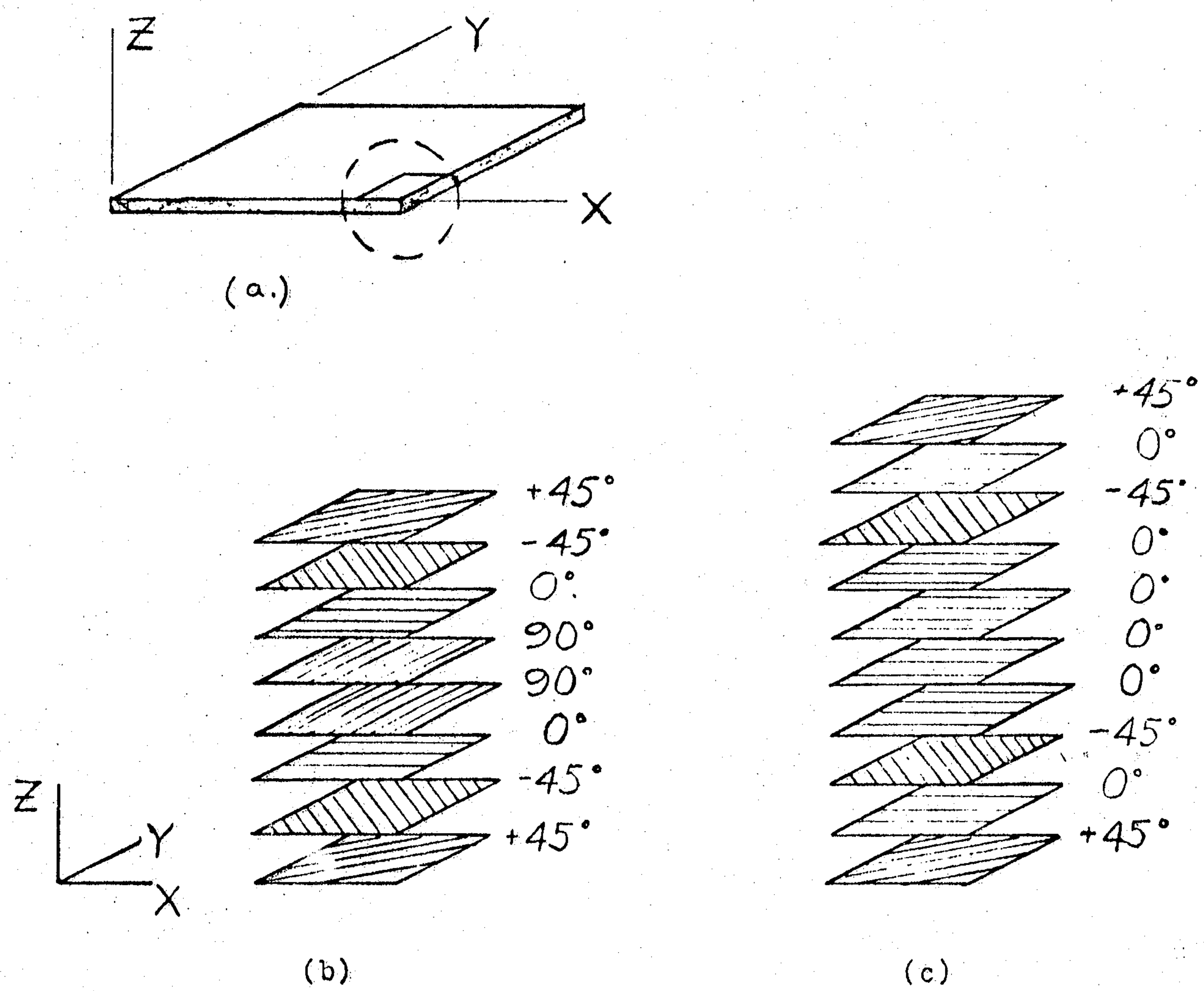

FIG. 1. PLY ORIENTATION OF LAMINATES. (a) LAMINATE. (b) PSUEDO-ISOTROPIC. (c) BLADE-LIKE.

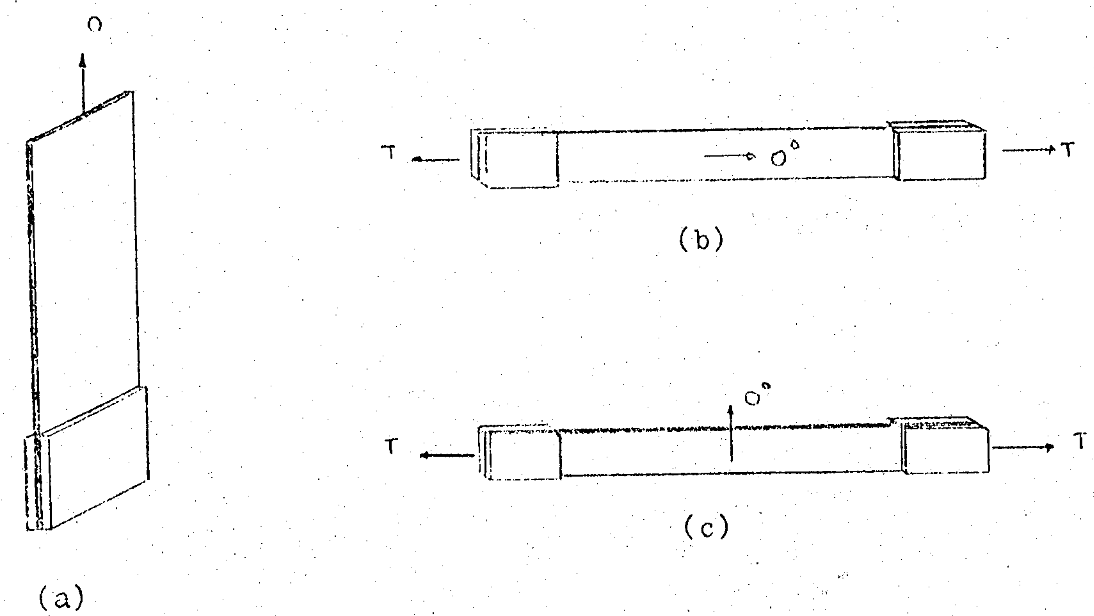

FIG. 2. (a)FREE VIBRATION AND IMPACT SPECIMEN. (b) 0° TENSILE SPECIMEN. (c) 90° TENSILE SPECIMEN.

TABLE 1 - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR PSEUDO-ISOTROPIC LAMINATE

PROPERTY	MEASURED	PREDICTED	% *
Modulus, 10^6 psi			
E_1	7.98	7.31	9.2
E_2	8.26	7.31	13.0
E_{b1} (free vibration test)	5.69	4.19	35.8
E_{b1} (impact test)	4.92	4.19	17.4
Poisson's Ratio			
ν_{12}	0.327	0.325	0.62
ν_{21}	0.335	0.325	3.1
Density, 10^2 lb/in^3			
ρ	5.68	5.70	0.35

* With respect to predicted values.

TABLE 2 - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR BLADE-LIKE LAMINATE

PROPERTY	MEASURED	PREDICTED	% *
Modulus, 10^6 psi			
E_1	16.0	12.2	31.1
E_2	2.48	3.25	23.7
E_{b1} (free vibration test)	8.58	8.25	4.0
E_{b1} (impact test)	8.88	8.25	7.6
Poisson's Ratio			
ν_{12}	0.732	0.614	19.1
ν_{21}	0.138	0.164	15.8
Density. 10^2 lb/in^3			
ρ	5.57	5.70	2.3

* With respect to predicted values.

TABLE 3 - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR BLADE-LIKE LAMINATE WITH REVISED PLY ORIENTATIONS

		PLY ORIENTATION WRT 0°			
		40°		35°	
Property	Measured	Predicted	%*	Predicted	%*
Modulus, 10^6 psi					
E_1	16.0	12.7	26.0	13.4	19.4
E_2	2.48	2.76	10.1	2.41	2.90
E_{b1} (free vibration test)	8.58	8.88	3.38	9.91	13.4
E_{b1} (impact test)	8.88	8.88	0.00	9.91	10.4
Poisson's Ratio					
ν_{12}	0.731	0.702	4.13	0.754	3.05
ν_{21}	0.138	0.152	9.21	0.136	1.47

* With respect to predicted values

4-4. A GRAPHICS SUBSYSTEM RETROFIT DESIGN FOR THE BLADED-DISK DATA ACQUISITION SYSTEM

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Research Supervisors: Mr. Louis J. Kiraly, NASA Lewis Research Center
Dr. John T. Welsh, University of Akron

BACKGROUND AND OBJECTIVES

The National Aeronautics and Space Administration at the LeRC (Lewis Research Center), has developed a data acquisition system that is capable of recording the detailed motion of vibrating blades on bladed-disk assemblies. This data acquisition system, called the BDDAS (Bladed-Disk Data Acquisition System) in this report, represents a new and unique capability in data collection for gas turbine engines. In the past, data collection on bladed-disk assemblies was accomplished by the use of strain gauges. In order to obtain detailed motion, at least one and if not more, strain gauges were required on every blade of the bladed-disk assembly. This technique presented many problems. Strain gauges are expensive and provide poor output in adverse conditions. Also, the number of strain gauges needed presently exceeds the capacity of available slip ring assemblies.[1] To overcome these problems the BDDAS was developed. The BDDAS takes data from optical probes around the circumference of a casing that shrouds the bladed-disk assembly. Each optical probe acquires its data by bouncing a light beam off the end of a blade.

The BDDAS can record large amounts of data in a very short period of time, approximately 400,000 data points in 70 milliseconds.[1] Presently the only means of analyzing this data is by Fast Fourier Transform techniques which is done off line. Since there is no real-time mode giving information about the bladed-disk assembly the operator has to guess when the best time would be to collect data. Along with the real-time mode, LeRC recognizes the need for a post-processing visual mode that allows viewing of detailed blade motion as a supplement to Fast Fourier Transform analyzer frequency output. Accordingly, the author was requested to design a graphics subsystem to be added to the BDDAS. This addition of graphics viewing modes was to be accomplished without substantial modification of the existing BDDAS, and using equipment and parts available in stock at LeRC, as far as possible.

DEVELOPMENT

The graphics subsystem retrofit design can be divided into three parts (1) hardware, (2) firmware, and (3) software. The hardware consists of a special purpose bit-slice computer that is interfaced with the BDDAS. The computer acts as a translator that can combine data from three different I/O ports with preprogrammed data to form coordinates for a CRT plotting system. The architecture of the computer is based on the AMD 2900 series of bit-slice components. This is a microprogrammed controlled architecture. The advantage, of using microcode, is the ease in which the bit-slice computer can be adapted to changes in the BDDAS.

In addition to the bit-slice computer, special firmware will be loaded into a PROM on each microcomputer of the BDDAS. This firmware will provide synchronous organization to the BDDAS microcomputers, which, were originally designed to operate asynchronously. The organization is required to eliminate bus contention to the bit-slice computer by the microcomputers. Also, the microcomputers can record and output data to the bit-slice computer at a rate which exceeds the bus bandwidth. This implies that some data reduction technique must be implemented. An algorithm has been designed to accomplish data reduction and is included in the firmware. Finally, the firmware will contain a post-processing mode. The post-processing mode will organize the microcomputers so that data, which has been down loaded by the host computer, will arrive at the bit-slice computer in a predetermined format.

The last part of the retrofit design will include the flow charting of software for the host computer (HP-1000). This software will include the initialization for both the bit-slice computer and the BDDAS microcomputers. The initialization for the bit-slice computer will consist of background screen data, normalized blade positions for each blade of the bladed-disk assembly, and the order in which blade data will arrive off the buses. The initialization for the BDDAS microcomputers will consist of a designation of one microcomputer to start bus transmission, algorithm parameters to determine which blade data will be transmitted on to the buses, and the order this data will be transmitted. In addition to initialization, the software will provide a sorting algorithm for detailed data that will be used in the post-processing mode.

BLOCK DIAGRAM DESCRIPTION

Figure 1 shows the block diagram of the present BDDAS system. This figure shows the basic interconnection between the major system components. The spin rig holds the bladed-disk assembly and the optical probes. The spin rig is connected to the microcomputer rack by way of 96 coaxial cables. Each cable links one optical probe with a corresponding microcomputer. The microcomputer rack holds the 96 microcomputers and permits them to record and store the data from the optical probes in parallel and asynchronously. The data that is stored in the volatile memory of the microcomputer rack is then transferred to the HP-1000 by way of the 16 bit parallel port after data collection is complete. The HP-1000 stores the data on disk in a format which corresponds to the format of the Fast Fourier Transform analyzer. The disk can be removed and transported to the Fast Fourier Transform analyzer for frequency analysis.

Figure 2 shows the addition of the graphics subsystem hardware to the BDDAS. The hardware includes the bit-slice computer, HP 1350A graphics translator, and the oscilloscope display. The bit-slice computer is connected to the microcomputer rack through the command bus and the three data buses A, B, and C. The bit-slice computer acts like a BDDAS microcomputer and receives its commands from the HP-1000 through the command bus. The blade data from the optical probe is transferred to the bit-slice computer, from the microcomputers, through the three data buses. The data is then manipulated by the bit-slice computer to a format which is acceptable to the HP 1350A graphics translator. The data is transferred to the graphics translator through a high speed, 500 MHZ, 16 bit parallel port. The graphics translator takes digital data stored in its memory and converts it to analog data. The analog data consists of three channels X, Y, and Z. The X and Y channels provide the signal that creates the coordinates of a blade position. The Z channel allows for intensity modulation of the display to maintain a constant brightness independently of the number of blades displayed. The analog channels are connected to an oscilloscope display device which provides the visual interface. Figure 3 shows a typical display that could be seen on the oscilloscope. Two other figures have been included for the interested reader, which are Figures 4 and 5. Figure 4 shows the detailed bus architecture of the microcomputer rack and Figure 5 shows the detailed block diagram of the bit-slice computer.

SUMMARY

The addition of the bit-slice computer, the graphics translator and the oscilloscope display constitutes the graphics subsystem hardware. The complete graphics subsystem retrofit design consists of the above hardware, the PROM firmware, and the HP-1000 software flow charts.

One of the primary goals was to provide this design with little modification of the BDDAS and use as many in-house components as possible and still provide an acceptable graphics display. The author feels that these goals will be met.

Much of the research for this design is completed and the writing of the thesis is in progress. What remains is the coding of algorithms and the component design of the bit-slice computer. The present projection for the completion of this thesis is in the summer of 1983.

In the future, the author expects to build this system and present a paper on the results of the working design.

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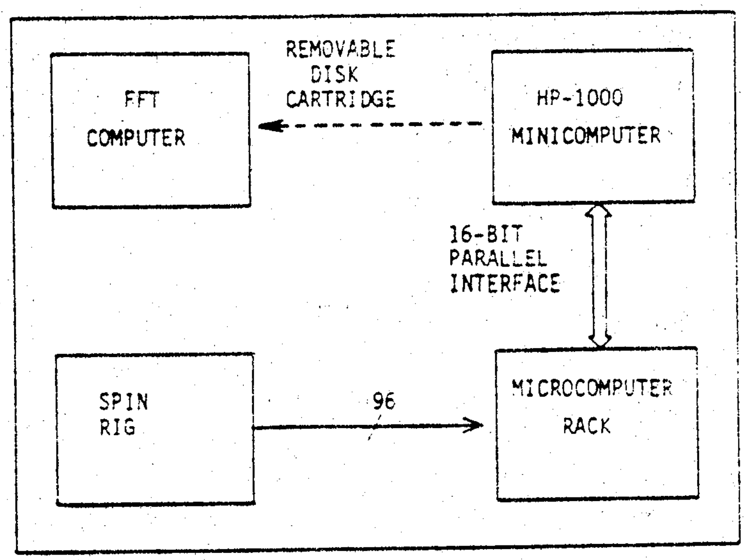


FIGURE 1 - BODAS BLOCK DIAGRAM

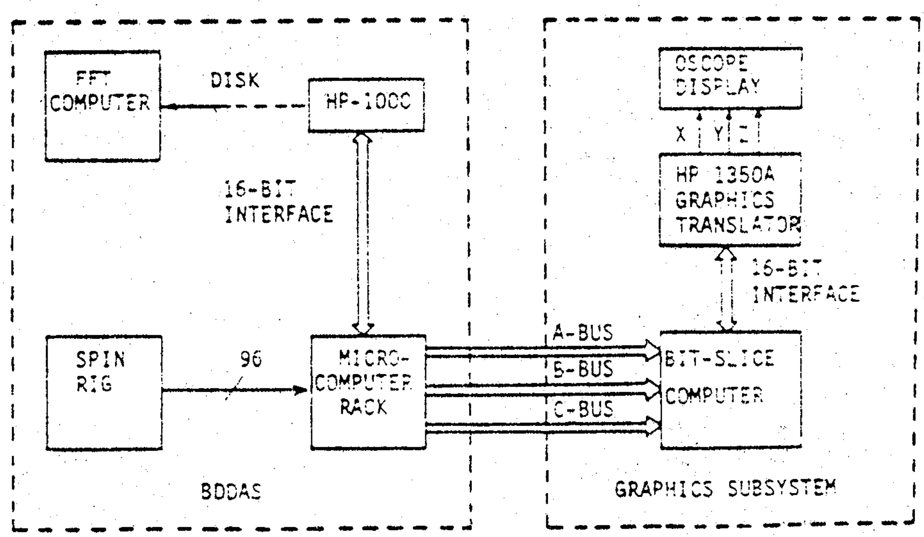


FIGURE 2 - GRAPHICS SUBSYSTEM RETROFIT

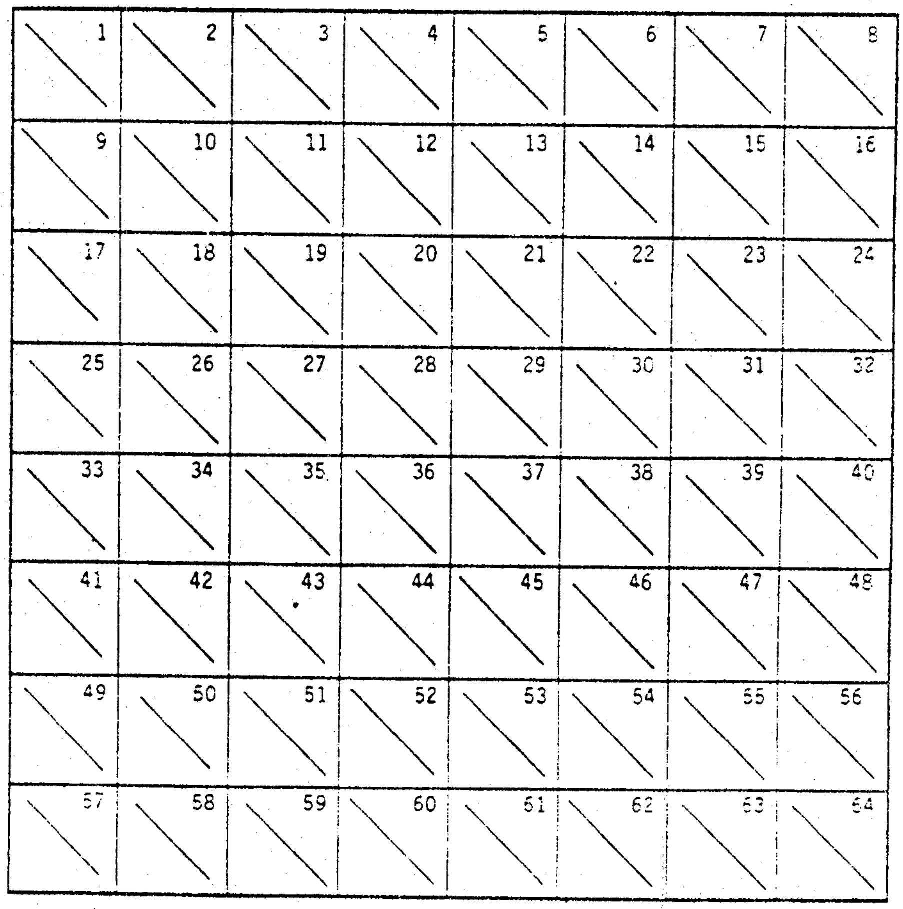


FIGURE 3 - TYPICAL OSCILLOSCOPE DISPLAY

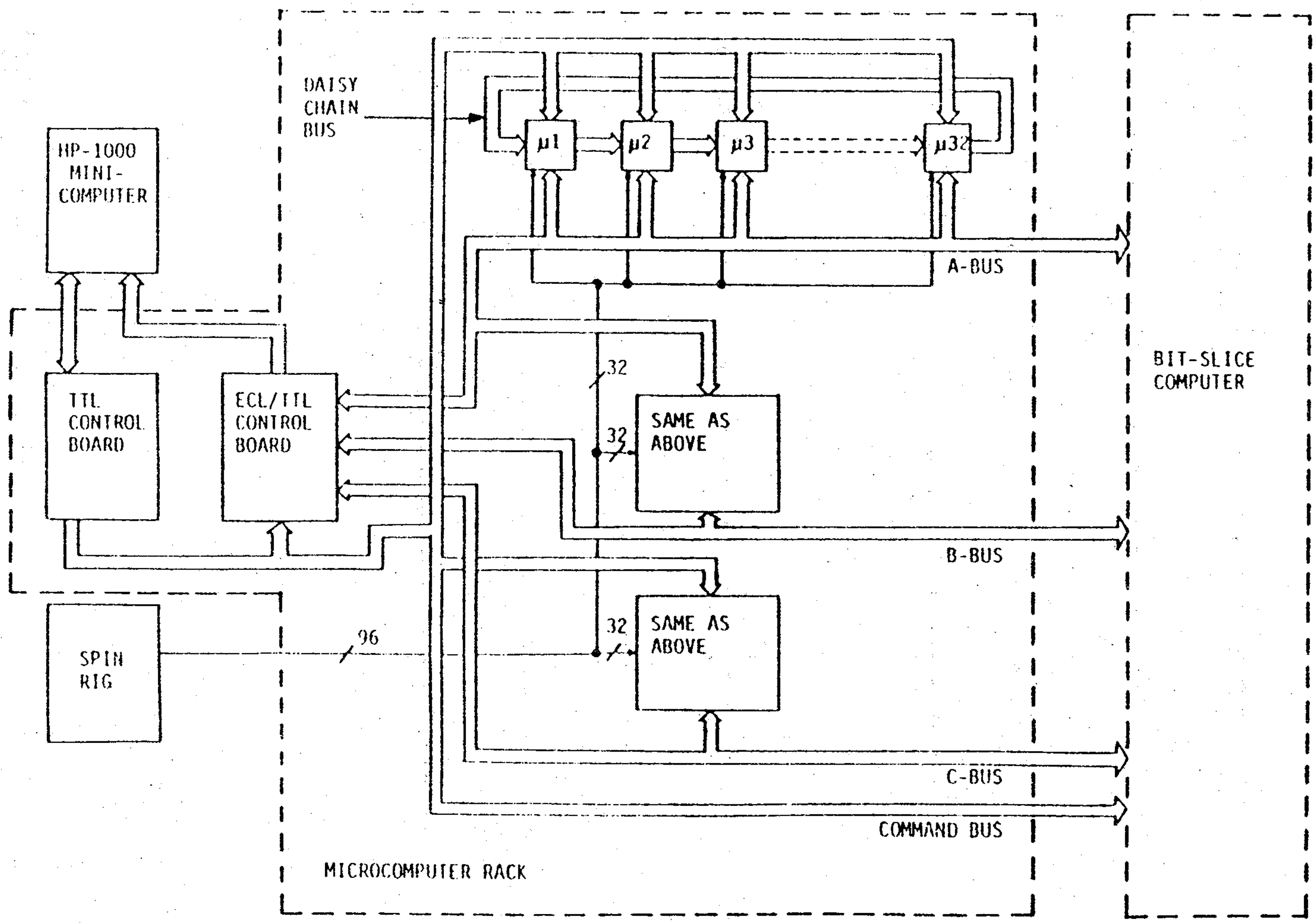


FIGURE 4 - DETAILED BUS ARCHITECTURE OF THE BODAS

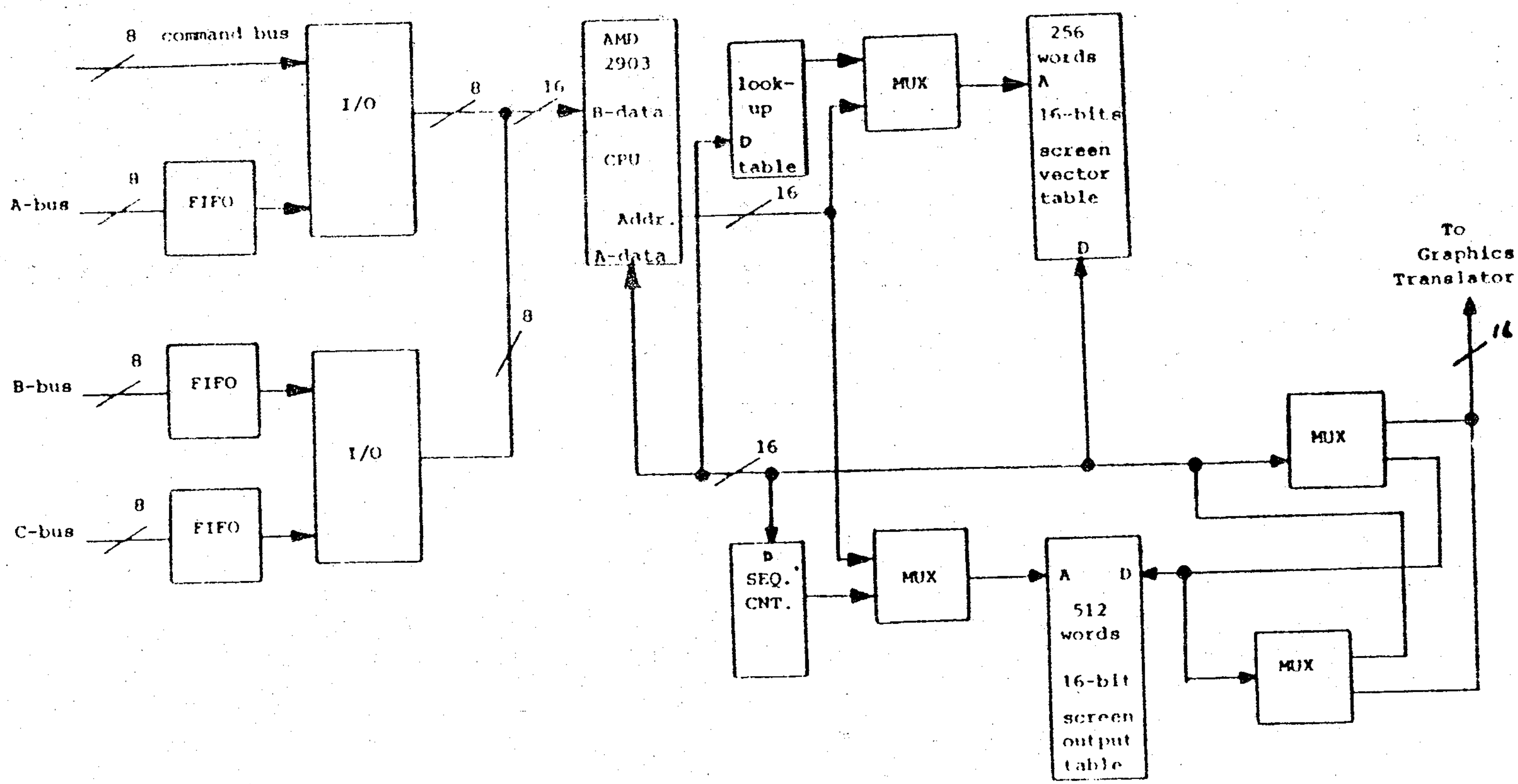


FIGURE 5 - BIT-SLICE GRAPHICS COMPUTER BLOCK DIAGRAM

4-5. FIBER EPOXY COMPOSITES

Researcher: John J. Caruso
Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center
Dr. T. Y. Chang, The University of Akron

BACKGROUND AND OBJECTIVES

The purpose of this research project is to obtain and document information on composite material property predictions. The analysis is conducted using two finite element codes and the composites micromechanics equations.

Two general purpose finite element computer codes are used on two different computer systems. Specifically, COSMIC NASTRAN is used on a UNIVAC 1100 system and MSG NASTRAN is used on a CRAY 1-S system. The graphics capabilities of each computer code is utilized to generate plots of the undeformed and deformed shapes of the finite element model.

Boundary conditions are implemented so as to model those assumptions made in the derivation of the micromechanics equations. In this way one can make a direct comparison between the micromechanics equations and the finite element results.

DEVELOPMENT AND RESULTS

The finite element model chosen for this research project was one used in a previous investigation which involved the analysis of a metal matrix composite system. Results from this investigation gave good comparisons of mechanical and thermal properties as predicted from finite element analysis with those predicted by micromechanics equations. It should be noted that the fiber matrix modulus ratio (EF/EM) for this analysis is 2. It will be explained later why this fact is so important.

The model consists of 125 nodes and 96 elements (6-and 8-node brick elements). It has a depth of .012 in., a width of .01254 in., and a height of .01254 in.

The model was analyzed first using COSMIC NASTRAN. Separate cases were investigated for different applied loads and boundary conditions.

Resulting nodal deflections and constraint forces were tabulated. The analysis was repeated for various combinations of fiber/matrix ratio (EF/EM).

The average mechanical and thermal properties for the composite are calculated using the composite micromechanics equations shown in Figs. (1) and (2). The average properties determined from the finite element analysis are compared with those values obtained from the micromechanics equations. Typical results for boron epoxy (kf = .466) are shown in Fig. (3). Generally, the results of the finite element analysis are in poor agreement with the results determined from the micromechanics equations.

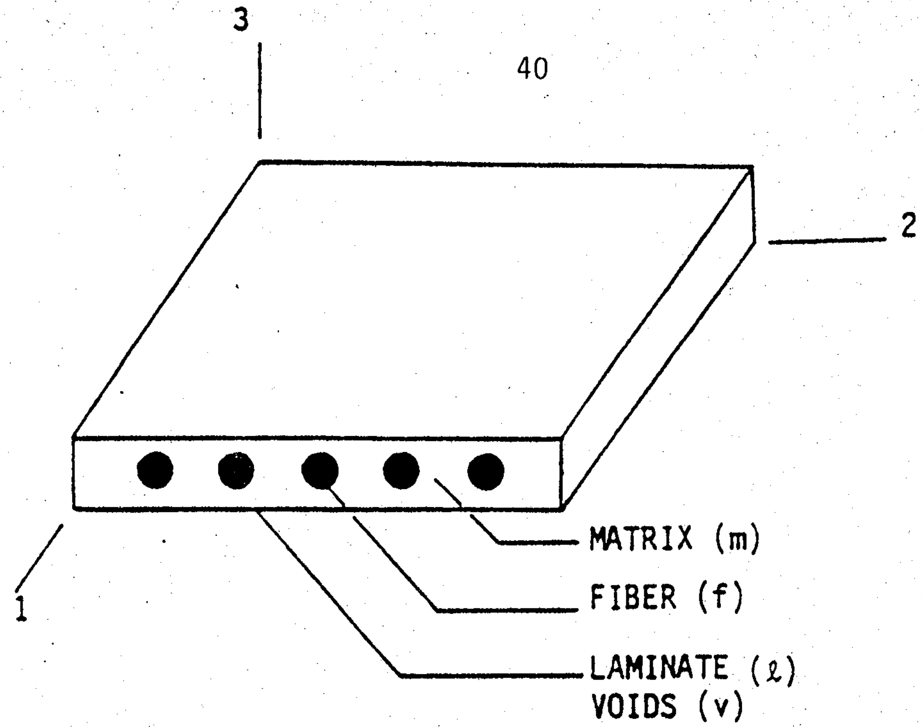
Results obtained from the initial finite element analysis indicated a problem with the mesh. It appears that changing the fiber/matrix ratio to a larger value causes this model to be inadequate. It is mentioned above how important the fiber/matrix ratio is. This ratio indicates the stiffness of the fiber to that of the matrix. When this ratio is large the mesh density must increase and a different technique may have to be used to model the boundary conditions.

As a result, a refined model is generated. The new model consists of 245 nodes and 192 elements (8- and 6-node solid elements).

With further analysis it became obvious that the boundary conditions did not adequately model those assumptions made in the derivation of the micromechanics equations. In order to satisfy compatibility, separate cases are investigated for different applied deflections and boundary conditions. Resulting nodal forces and constraint forces are generated by the finite element program.

The mechanical and thermal properties are calculated from the finite element analysis. The properties are compared to those calculated from the micromechanics equations.

Future work will involve the use of finite element substructuring to better represent the physical assumptions on which the composite micromechanics theory is based. Results of these efforts will be used to validate the composite micromechanics theory and equations.



Longitudinal Modulus: $E_{\ell 11} = k_F E_{f11} + k_m E_m$

Transverse Modulus:

$$E_{\ell 22} = \frac{E_m}{1 - \sqrt{k_f}\,(1 - E_m/E_{f22})} = E_{\ell 33}$$

Shear Modulus:

$$G_{\ell 12} = \frac{G_m}{1 - \sqrt{k_f}\,(1 - G_m/G_{f12})} = G_{\ell 13}$$

Shear Modulus:

$$G_{\ell 23} = \frac{G_m}{1 - \sqrt{k_f}\,(1 - G_m/G_{f23})}$$

Poisson's Ratio:

$$\nu_{\ell 12} = k_f\,\nu_{f12} + k_m \nu_m = \nu_{\ell 13}$$

Poisson's Ratio:

$$\nu_{\ell 23} = \frac{E_{\ell 22}}{2\,G_{\ell 23}} - 1$$

FIG. 1 - COMPOSITE MICROMECHANICS MECHANICAL PROPERTIES

Longitudinal Conductivity:

$$K_{\ell 11} = k_f K_{f11} + k_m K_m$$

Transverse Conductivity:

$$K_{\ell 22} - (1 - k_f K_m + \frac{K_m \; k_f}{1 - k_f (1 - K_m / K_{f22})} = K_{\ell 33}$$

For Voids:

$$K_m = (1 - k_v) \; K_m + \frac{K_m \; K_v}{1 - k_v \; (1 - K_m / K_v)}$$

Longitudinal Thermal
Coeff. of Expansion:

$$\alpha_{\ell 11} = \frac{k_f \; \alpha_{f11} \; E_{f11} + K_m \; \alpha_m \; E_m}{E_{\ell 11}}$$

Transverse Thermal
Coeff. of Expansion:

$$\alpha_{\ell 22} = \alpha_{f22} \; k_f + (1 - k_f)(1 + k_f \nu_m E_m / E_{\ell 11}) \alpha_m$$

Longitudinal Diffusivity:

$$D_{111} = (1 - k_f) \; D_m$$

Transverse Diffusivity:

$$D_{122} = (1 - k_f) \; D_m - D_{133}$$

Longituuinal Moisture
Coeff. of Expansion:

$$\beta_{111} = \beta_m \; (1 - k_f) \; E_m / E_{111}$$

Transverse Moisture
Coeff. of Expansion:

$$\beta_{122} = \beta_m \; (1 - k_f) \; 1 + \frac{k_f \; (1 - k_f) E_m}{k_f E_{122} + (1 - k_f) E_m} = \beta_{133}$$

FIGURE 2 - COMPOSITE MICROMECHANICS THERMAL AND HYGRO PROPERTIES

Property	Micromechanics Equation	Nastran Results
Longitudinal Modulus ($\times 10^6$ PSI)	$E_{\ell 11} = 27.4$	$E_x = 27.5$
Transverse Modulus ($\times 10^6$ PSI)	$E_{\ell 22} = E_{\ell 33} = 2.30$	$E_z = 2.61$
Shear Modulus ($\times 10^6$ PSI)	$G_{\ell 22} = G_{\ell 13} = .856$	$G_{xy} = .849$
Shear Modulus ($\times 10^6$ PSI)	$G_{\ell 23} = .515$	$G_{yz} = 1.02$
Poisson's Ratio	$\nu_{\ell 12} = .280$	$\nu_{xy} = .272$
Poisson's Ratio	$\nu_{\ell 23} = .372$	$\nu_{xy} = .404$
Longitudinal Thermal Expansion Coefficient ($\times 10^6$ in./in. - °F)	$\alpha_{\ell 11} = 3.34$	$\alpha_x = 4.14$
Transverse Thermal Expansion Coefficient ($\times 10^6$ in./in. - °F)	$\alpha_{\ell 22} = \alpha_{\ell 33} = 18.6$	$\alpha_y = \alpha_z = 26.6$

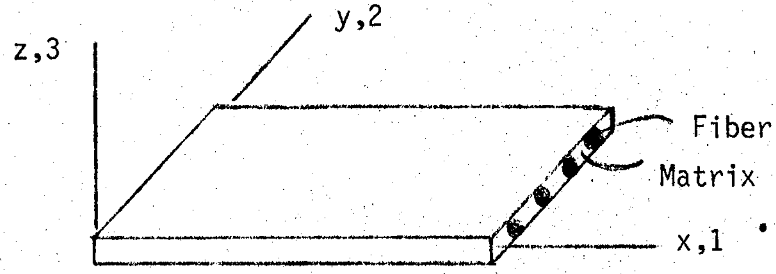


FIGURE 3 - COMPARISON OF MICROMECHANICS PREDICTIONS WITH NASTRAN TEST MODEL RESULTS

SECTION 5

CONCLUSIONS

The second and third year efforts regarding the "NASA LeRC/Akron University Graduate Cooperative Fellowship Program" and the NASA "Graduate Student Researcher Program" have been carried through successfully and with minor discrepancies. The participating M.S. and Ph.D. students were very pleased with both quality and purpose of the program, and they were very enthusiastic in doing research in the specified areas of the program. The opportunity for the students to work with NASA engineers and also be exposed to the great facilities of the NASA Lewis Research Center was received with great enthusiasm.

The student researchers of both programs have selected research topics from the four areas of specialization which they made it as their thesis topic. The finished research product was published as an official NASA report and it was distributed throughout the country according to the NASA rules. The students liked their research topics, the results were excellent, and the majority of them have expressed strong interest to make their selected area as their life long area of interest and become experts.

The program has attracted well-qualified students to undertake such complex engine structural and dynamics problems, and their effort was concentrated on problem areas where research work and development are needed. The problems encountered are considered to be minor compared to the benefits obtained.

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