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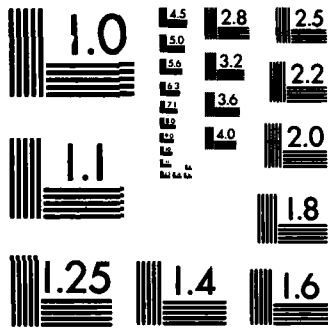
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STUDIES OF ADVANCED AND  
COMPOSITE STRUCTURES

Lawrence W. Rehfield  
School of Aerospace Engineering  
Georgia Institute of Technology  
Atlanta, Georgia 30332



Final Scientific Report  
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<p>This final report summarizes the objectives and accomplishments of the three tasks pursued during a one year grant from AFOSR to continue ongoing research in 1) development of new bending and buckling theories for beams and plates, oriented toward composite structures, 2) experimental investigation of the effects of delamination on structural response of composite panels, and 3) damage tolerance of isogrid composite structure, a stiffening concept that employs a repetitive equilateral triangular pattern of ribs. Papers, reports, and</p>										

presentations resulting from this research are listed. In Task 1 a new theory of bending is developed including effects of transverse shear strain, transverse normal strain, and section warping. Included are a dynamic theory for planar bending of homogeneous beams, static theory for homogeneous plates, buckling theory for homogeneous columns, planar bending theory of composite laminates, theory for laminated plates, and a theory for bending and buckling of stiffened plates. Task 2 investigates structural consequences of delamination using a series of quasi-isotropic symmetric ply layup composite panels with single delaminated zones between the central plies, all delaminations of the same size (ten percent of the panel area) but all of different shapes. Experiments conducted include nondestructive compressive buckling, three and four point bend, and free-free and clamped vibration. Absolute effects of delaminated zones of the size studied are not large, and delamination zone shape is not a significant parameter. Task 3 investigates the damage tolerance of continuous filament composite isogrid, developed by McDonnell Douglas, by cutting grid ribs at nodal sites, simulating the observed failure mode in bending. The panels are tested nondestructively as clamped wide columns to assess buckling resistance degradation with increasing damage. Flexural vibration tests are also conducted at each damage level. The results demonstrate that this type of structure is very tolerant to damage.

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## INTRODUCTION

The work described herein was performed at the School of Aerospace Engineering, Georgia Institute of Technology during the period 15 November 1980 - 31 December 1981. Professor Lawrence W. Rehfield was the Principal Investigator. The research is divided into three tasks. Task 1 is "Theory and Analysis of Advanced Structures". It is concerned with the continued development and application of new theories of structural behavior which include effects that are especially important to composite structures.

Task 2, "Failure Processes in Compression For Composites", focuses on the structural consequences of delamination in composite laminates. Task 3 addresses experimental methodology for the evaluation of advanced structural concepts. Particular emphasis has been placed upon the study of damage tolerance in continuous filament composite structures.

For convenience, this report contains a separate section devoted to each task. The original research program was defined for performance over a two year period. Consequently, some topics selected for investigation require additional study and the work will continue under another grant.

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MATTHEW J. REYER  
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## TASK 1: THEORY AND ANALYSIS OF ADVANCED STRUCTURES

### Objectives

The objectives of this research task were: (1) to continue to develop new theories of structural behavior with improved predictive capability, (2) to validate the theories in systematic ways, and (3) to apply them to generic problems for which new insight is needed. The direction of the work is oriented toward structures constructed of modern composite materials. Classical theories ignore three effects which are significant for certain geometries and stiffness characteristics - - -transverse shear strain, transverse normal strain and section warping. The new theories include these effects in an appropriate manner which still retains the simplicity of an engineering approach.

### Accomplishments

The work has progressed from statics to dynamics to buckling in terms of applications and from planar bending to plates to laminates in terms of structural complexity. The following specific accomplishments were achieved since the research began:

- (1) An improved dynamic version of the theory for planar bending of homogeneous structures has been developed, validated and presented at the recent AIAA SDM Conference in Atlanta<sup>1</sup>.
- (2) A paper on the static theory of planar bending has been written and accepted for publication in the AIAA Journal<sup>2</sup>.
- (3) A static theory for homogeneous plates has been developed and validated in comparative studies with exact solutions and other engineering theoretical predictions. The results were presented at the AIAA SDM Conference in Atlanta<sup>3</sup>. A manuscript has been prepared and submitted to the AIAA Journal<sup>4</sup>.

- (4) An elementary buckling theory for homogeneous columns, the first step toward a nonlinear, large deflection theory, has been developed, validated and applied to estimate hygrothermal degradation in resin matrix composite columns<sup>5</sup>.
- (5) A theory for planar bending of composite laminates has been developed and is undergoing validation. This work will be presented at the upcoming Symposium on Advances and Trends in Structural and Solid Mechanics<sup>6</sup>.
- (6) A theory for laminated plates is under development. Progress is tied to the completion of the planar bending case, item (5) above. This work is incomplete.
- (7) A comprehensive theory for bending and buckling of stiffened plates has been developed and applied. It is aimed at stylus woven stiffened composite configurations of the type manufactured by McDonnell Douglas Corporation. For these types of structures, nonclassical effects are predicted to be significant in parameter ranges of practical interest. This is in complete accord with conclusions drawn from earlier experimental findings on composite isogrid structures. This work will be presented at the 24th Israel Conference on Aviation and Astronautics and published in a special volume of the Israel Journal of Technology<sup>7</sup>.

Major emphasis has been given to this task. The work has a unique character. It is believed it will impact directly modeling technology for composite structures in the future.

## TASK 2: FAILURE PROCESSES IN COMPRESSION FOR COMPOSITES

### Objective

Compressive failure processes are poorly understood for composites. More efficient utilization of these materials requires the acquisition of both understanding and predictive capability. The objective of this task is to determine the structural consequences of delamination. Laminated composite panels with prescribed areas of delamination have been manufactured by Lockheed Georgia Company. These were subjected to nondestructive buckling and vibration tests.

### Accomplishments

The panel specimens have been designed with a quasi-isotropic symmetric ply layup with a single delaminated zone between the central plies. The delaminated area is ten percent of the panel area, which is thought to be an upper limit to the size encountered in service between inspections. The total area of delamination has been held fixed, but different rectangular shaped delamination zones have been manufactured into the panels. This permits the influence of shape as well as size of the delaminated zone to be studied in a systematic way. Buckling and vibration behavior are overall panel responses, so their sensitivity to prescribed delaminations is the fundamental issue being addressed.

The following experiments have been conducted on a flaw-free control panel and three panels with distinct delamination patterns:

- (1) Nondestructive compressive buckling tests with clamped loaded edges and both free and simply supported unloaded edges;
- (2) Three and four point bend tests;
- (3) Free-free vibration experiments to determine natural modes and frequencies up to 400 Hz;

- (4) Vibration experiments with two opposite edges clamped to provide boundary conditions comparable to the wide column buckling tests.

The findings from the above experiments are outlined below.

- (1) All the test data are consistent and indicate similar trends.
- (2) Absolute effects of delaminated zones of the size studied are not large.
- (3) Delaminated zone shape is not a dominant characteristic.
- (4) One panel, which was manufactured with a delaminated zone, performed as if perfect in spite of the fact that the delamination is verified by C-scan ultrasonic inspection.

The last finding has been repeatedly confirmed by experiments of all types. It is the most significant practical result to emerge from the study to date. It demonstrates that extensive defects can exist which have no structural significance.

Prior to publication of the results, a finite element simulation of the delaminated panels will be made in an effort to predict the observed findings. This work is, therefore, incomplete and will be continued under another grant. A "work in progress" presentation<sup>8</sup> is planned for the upcoming AIAA SDM Conference.

### TASK 3: EXPERIMENTAL EVALUATION OF ADVANCED STRUCTURAL CONCEPTS

#### Objective

Originally this task was intended to develop test methods appropriate to the element level of scale and complexity for advanced structural concepts. While it retained this scope, the emphasis was given to a direction different from that originally proposed. The focus has been upon damage tolerance of continuous filament composite stiffened structures. A complete testing methodology has been developed and implemented which serves as a model for this type of study.

#### Accomplishments

The search for efficient, light-weight aerospace structural concepts is a continuing process. One promising concept is isogrid. It is a stiffening concept that employs a repetitive equilateral triangular pattern of ribs. The name "isogrid" is derived from the fact that the triangular grid exhibits isotropic properties in a gross or overall sense.

Continuous filament composite isogrid (CFCI) is a type of construction developed by McDonnell Douglas Astronautics Company - St. Louis. The ribs of the grid are constructed of continuous unidirectional fibers by using a weaving process. It combines synergistically the efficiency of a stiffened structure with the superior properties of a composite material system in a manner consistent with automated manufacturing technology. The gridwork provides a multiplicity of load paths. Due to its highly redundant nature, it is expected that this construction will be tolerant to damage.

Since isogrid is a stiffening concept, a stiffness critical application, buckling under uniaxial compression, is considered. In flexural strength tests of beam

specimens containing a single backbone rib, the bending failure originates at the tension surface of the backbone rib near a node. If the skin is in compression, the rib fracture propagates throughout the rib depth to the rib/skin interface. Further damage to the specimen is in the form of rib/skin disbonding. Based upon this failure mode, damage to the grid ribs at nodal sites has been introduced in order to study damage tolerance of the structure in this stiffness-critical application. Information on systematically damaged specimen behavior is the only reliable means of assessing damage tolerance.

The observed failure mode in bending is simulated on the panels by cutting grid ribs at nodal sites. The panels are tested nondestructively as clamped wide columns with buckling loads determined by a stiffness plotting technique. Degradation of buckling resistance is determined by progressively damaging lengthwise ribs and retesting the panels. Strains at selected rib sites are measured at each damage level to ascertain the redistribution of stresses. Also, flexural vibration tests are conducted at each damage level to assess the frequency reduction. A finite element analysis provides satisfactory correlation with test data. The results demonstrate that this type of structure is very tolerant to damage.

Preliminary results have been presented in Tokyo<sup>9</sup> and at the AIAA SDM Conference in Atlanta<sup>10</sup>. An overview was presented at the DOD/NASA Composites Meeting in Dayton<sup>11</sup>. A complete presentation of the work will be given at the ASTM symposium in Williamsburg, Virginia and published in the proceedings<sup>12</sup>.

A key to damage tolerance is predicting degradation in performance accurately. If this cannot be done reliably, then exploitation of damage tolerance cannot occur. It appears from this work that a finite element simulation using SAP

IV provides a good model for predicting the stiffness-related behavior of the structure. The study also suggests the feasibility of using CFCI structures in foreign object damage prone applications.

## PAPERS, REPORTS AND PRESENTATIONS

1. Rehfield, L.W., and Murthy, P.L.N., "Structural Dynamics of Beams: A New Theory and Applications," AIAA Paper 81-0625-CP, presented at the 1981 AIAA Dynamics Specialists Conference, Atlanta, Georgia, April, 1981.
2. Rehfield, L.W., and Murthy, P.L.N., "Toward a New Engineering Theory of Bending: Fundamentals," to appear in the AIAA Journal, 1982.
3. Rehfield, L.W., and Valisetty, R.R., "Bending of Plates: A Refined Theory and Comparative Study," AIAA Paper 81-0476-CP, presented at the 22nd AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Atlanta, Georgia, April, 1981.
4. Rehfield, L.W., and Valisetty, R.R., "A Comprehensive Theory for Plates: Statics," submitted to the AIAA Journal.
5. Murthy, P.L.N., and Rehfield, L.W., "A New Engineering Theory of Planar Bending and Applications," AFOSR Scientific Report (Number to be assigned.), February 1982.
6. Rehfield, L.W., and Valisetty, R.R., "A Comprehensive Theory for Planar Bending of Composite Laminates," to be presented at the Symposium on Advances and Trends in Structural and Solid Mechanics, Washington, D.C., October 4-7, 1982 and published in the Journal of Computers and Structures.
7. Yehezkely, O., and Rehfield, L.W., "A New, Comprehensive Theory for Bending and Buckling of Stiffened Plates," presented at the 24th Israel Annual Conference on Aviation and Astronautics and to appear in the Israel Journal of Technology.
8. Reddy, A.D., Widman, C.G., and Rehfield, L.W., "Influence of Prescribed Delaminations on Stiffness Controlled Behavior of Composite Laminates," Work in Progress Session, AIAA 23rd SDM Conference, New Orleans, May 1982.

9. Rehfield, L.W., and Reddy, A.D., "Damage Tolerance of Continuous Filament Composite Structure: A Preliminary Assessment," presented at the Japan-United States Conference on Composite Materials: Mechanics, Mechanical Properties and Fabrication, Tokyo, Japan, January, 1981. Proceedings to be published.
10. Rehfield, L.W., and Reddy, A.D., "Damage Tolerance of Continuous Filament Composite Isogrid Structure," Work in Progress Session, presented at the 22nd AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Atlanta, Georgia, April, 1981.
11. Rehfield, L.W., and Reddy, A.D., "Damage Tolerance of Continuous Filament Isogrid Structures," DOD/NASA Mechanics of Composites Review, Dayton, Ohio, October 28-30, 1981.
12. Reddy, A.D., Rehfield, L.W., Haag, R.S., and Widman, C.G., "Compressive Buckling Behavior of Graphite/Epoxy Isogrid Wide Columns with Progressive Damage," presented at the ASTM Symposium on Compression Testing of Homogeneous Materials and Composites, March 11, 1982. To appear in Compression Testing of Homogeneous Materials and Composites, an ASTM STP Volume, 1982.

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