NASA-CR-202645

[illegible]

CR-407

# Final Technical Report

for

# The Development of Computational Techniques for the Nonlinear Analysis of Composite Structures at High Temperature

NASA Grant Number
NCC3-248

Grant Duration
January 13, 1992 to March 1, 1995

Theo G. Keith, Jr.
Distinguished University Professor
&
Thomas E. Wilt
Senior Research Associate

Department of Mechanical, Industrial and Manufacturing Engineering
University of Toledo
Toledo, Ohio 43606

November 1996

# Development Of Computational Techniques For The Nonlinear Analysis Of Composite Structures At High Temperatures

## Objectives and Scope of Proposed Research

The primary objective of this research project was to develop robust and efficient computational tools for deformation and life analysis techniques. This task encompassed many topics, namely, development of viscoplastic continuum models, the associated numerical integration techniques, suitable micromechanics models/methods, and coupled deformation and damage algorithms. Some of these topics resulted in the development of stand-alone computer codes, some of which have been disseminated to industry. In addition, the work preformed under this grant served to bring together the results of various other research projects and was the beginning of the establishment of a concise framework for complete deformation and life analysis capabilities at NASA Lewis.

Since this research project was to develop computational techniques for composite structures, the work was involved with model/methods which can be applied to composite structures on both microscale and macroscale levels. The macroscale analysis pertains to the development and implementation of continuum-based deformation and damage models. The research involving damage focused on the development of a fully coupled finite element damage evolution scheme. These items were developed in the context of an in-house finite element code STARS, as well as in the form of "user subroutines" to be used with the commercial finite element code MARC.

The microscale analysis utilized Aboudi's Generalized Method of Cells, (GMC) micromechanics model as well as finite element models of similar composite architectures, i.e., square and hexagonal fiber pack models. Comparisons have been made in terms of both longitudinal and transverse deformation predictions and the microstress states in the fiber/matrix constituents. The accuracy of the GMC micromechanics model were assessed in terms of its damage evolution predictions as compared to the damage evolution predicted in an equivalent finite element micromechanics analysis.

## Research Accomplishments

Under the heading of computational tools are two catagories into which the present research work maybe divided: 1) finite element based computer algorithms and 2) stand-alone computer codes. The work in both of these catagories will be briefly reviewed in the following.

Considering that the challenging structural analysis tasks in the area of aeronautics require the use of the finite element method, it is essential that any new developements in deformation and life (damage) analysis be adaptable to finite element software. This may take the form of small, in-house, finite element codes available from academia which provide complete access to the source code of the finite element program. By having in effect unlimited access to the code allows the implementation of complex algorithms such as those required for life analysis. The result will be a small finite code with specific capablities tailored to the required analysis tasks, for example, high temperature viscoplastic deformation and life analysis. But, such small codes are unattractive to industry. Industry prefers more verstile commercial finite element codes such as MARC, ABAQUS, etc. which have a variety of analysis capabilities. What is of interest to industry is the ability to use some of the material models developed at NASA Lewis within those commercial codes. Thus, implementing as much of the work as possible through user subroutines provided in these codes is necessary.

## Finite Element Analysis

With the above discussion in mind, the finite element work preformed under this research project has focused on developing an in-house finite element code while simultaneoulsy writing user subroutines for commercial finite element codes. MARC is the nonlinear finite element code predominately in use at NASA Lewis. As a result, algorithms were written in the form of the user subroutine HYPELA. These different HYPELA models are available for use by both NASA Lewis MARC users and industry. Specific details will be presented below.

One area of research has involved the development of implicit integration algorithms for the viscoplastic constitutive models. A fully implicit backward Euler integration algorithm developed by Wilt andSaleeb has been implemented into the HYPELA subroutine for MARC. This implementation then served as a *template* for other viscoplastic model implementations into HYPELA. That is, Robinson's creep model and a form of the Bodner-Partom model, each using a simple explicit forward Euler integration scheme, have been written as HYPELA subroutines.As a result, experience and standardizaton has been obtained in implementing viscoplastic models into the HYPELA format thus making future model implementation a relatively straightforward task.

A fatigue damage algorithm was developed and implemented into the finite element code MARC using not only the HYPELA subroutine but other provided user subroutines as well. The algorithm was developed based on the fatigue damage model developed by Arnold and Kruch. This newly developed algorithm now provides for fully coupled deformation and damage analysis capabilities within the context of the finite element method. The algorithm has been applied to composite structures on both the macroscale and the microscale and this work was presented at the 1993 HITEMP conference. The presentation was well received and was considered noteworthy among those representing industry.

Finally with regards to the above micromechanics models, the Generalized Method of Cells (GMC) model has been implemented into the finite element code MARC using user subroutines. This was done so as to allow comparsions in computing time of a finite element analysis using continuum-based macro models versus the micromechanics models. Some preliminary results have been obtained and will appear in some forthcoming publications.

As stated in the opening paragraph of this section, the development of an alternative to commercial finite element codes is necessary for a variety of reasons. One reason is that it provides access to the complete finite element FORTRAN source code. This is desirable and required since some of the work requires significant modifications to the codes general solution algorithm and in some cases the overall code organization. It was found that trying to work within HYPELA, in MARC for example, imposes far too many constraints and makes certain implementation overly complex and sometimes not possible.

Thus, development of the in-house STructural Analysis Research Software (STARS) finite element code was undertaken. Work with STARS has consisted of implementing the implicit integration schemes for viscoplastic material models, the generalized Method of Cells (GMC) micromechanics double periodicty model, coupled fatigue-damage algorithm. In addition, some reorganization and maintanence of the code has been preformed. The STARS code also serves a second vital role to NASA Lewis and that is it serves as a vehicle for transfering work performed under a grant with the University of Akron to develop integration schmes for viscoplastic models. Again, close contact has been kept with Professor A. F. Saleeb at the University of Akron with regards to incorporating their work into STARS.

## Stand-Alone Codes

As mentioned, in addition to finite element based algorithms, stand-alone computer codes are useful for a variety of tasks. For example: constitutive model development and characterization of the model for a specific material system, study of material behavior, material fabrication process simulation, micromechanics of composite materials, etc. As a result, several stand-alone analysis codes have been developed during this research project.

First is the Inelastic Deformation Analysis Code (IDAC). This code is based upon work of Arnold. Work with this code involved rather extensive modifications to the original computer code, which consisted of extending the code to full multiaxial stress/strain state capabilities, which, in turn, required substantial changes to the internal memory scheme. Also, the code was complete reorganized into a modular format which makes understanding the code easier and facilitates the implementation of future modifications. The option for either interactive or batch mode improved load history inputand improved post-processing of generated results of the full thermomechanical analysis capabilities and an improved resident materials database have all been added to IDAC. A variety of viscoplastic models have been added, including the Generalized Viscoplastic Potential Structure (GVIPS) model which was developed during this research project using IDAC. The code was also restructured so as to allow greater user flexibility for using IDAC for viscoplastic model characterization and was used extensively for this purpose when characterizing the GVIPS model for the TIMETAL21S material system. The concept of developing a code to automate this model characterization process influenced some of the reorganization of IDAC so that it may be used as the basis for such a code in the future.

A second code, which is a subset of IDAC, has been developed. The Micromechanics Analysis Code (MAC) contains Aboudi's Generalized Method of Cells (GMC) models for double and triple periodic composite modeling capabilities. MAC has been designed for the analysis of composites which have different fiber architectures. A set of new RepresentativeVolume Elements (RVE's) was developed and incorporated into MAC. The results of this phase of this research project wil be presented at this year's HITEMP conferenc. Professor Aboudi has been working with NASA Lewis on another grant through the University of Virginia. Close contact has been kept with Professor Aboudi for his feedback with regards to the development of MAC and so as to allow the latest improvements to the Generalized Method of Cells to be incorporated in to the present research work. In discussions with Professor Aboudi, it is believed that no other software presently exists that has the Generalized Method of Cells linked with the capabalities of MAC. As a result, a user manual has been completed for MAC thus making MAC available to industry or anyone who desires to use it.

A fatigue damage algorithm developed under this project has been implemented into a newer test version of MAC and coupled with the micromechanics models. This version of MAC will have the capability to perform life analysis on composites on the micromechanics level.

One note that pertains to both IDAC and MAC is that both codes were organized so as to allow the constitutive model subroutines written for either IDAC or MAC to be transferred to a finite element code with relative ease and minimal changes.

## Summary

An overview of the work accomplished under this cooperative research grant has been presented. The results of this work has been the development of a variety of computational tools for the analysis of composite structures. These tools take the form of stand-alone computer codes IDAC and MAC, user subroutines for the commercial finite element code MARC and the development of the in-house finite element code STARS.

The work may be summarized by two key points. First, the establishment a uniform computer code framework which will allow subroutines/algorithms developed for one code, to be transferred relatively easily to another code. All of the different codes, (IDAC, MAC, STARS) material model subroutines were organized in basically the same format, thus allowing interchanging of subroutines. In addition, the work at the University of Akron has also been written basically in this same framework, thus making transfer of that work to NASA Lewis much easier.

The second point is that this research project has served not only to perform new research, but to also tie together other research developments from other grants, such as the work in micromechanics under a grant with the university of Virginia. As a result, NASA Lewis now has significantly improved capabilities as applied to deformation and life analysis.

## Project Publications

T. E. Wilt and S. M. Arnold, "Micromechanics Analysis Code (MAC): User Guide: Version 1.0", NASA TM 106706, 1994.

S. M. Arnold, T. E. Wilt, M. J. Pindera, "Influence of Fiber Architecture on The Elastic and Inelastic Response of Metal Matrix Composites", NASA TM 106705, 1994.

S. M. Arnold, T. E. Wilt, M. J. Pindera, "Impact of Fiber Architecture on The Inelastic Response of Metal Matrix Composites Via The Generalized Method of Cells (GMC)", Proceedings of the 7th Annual HITEMP Review, October 1994.

T. E. Wilt and S. M. Arnold, "A Coupled/Uncoupled Deformation and Fatigue Damage Algorithm Utilizing the Finite Element Method", NASA TM 106526, March 1994.

S. M. Arnold, A. F. Saleeb, and T. E. Wilt, "A Modeling Investigation of Thermal and Strain Induced Recovery and Nonlinear Hardening in Potential Based Viscoplasticity", to appear in Journal of Engineering Materials and Technology.

T. E. Wilt and S. M. Arnold, "A Computationally-Coupled Deformation and Damage Finite Element Methodology", Proceedings of the 6th Annual HITEMP Review, October 25-27, 1993.

S. M. Arnold, T. E. Wilt, A. F. Saleeb, and M. G. Castelli, "An Investigation of Macro and Micromechanical Approaches For A Model MMC System", Proceedings of the 6th Annual HITEMP Review, October 25-27, 1993.

S. M. Arnold and T. E. Wilt, "A Deformation And Life Prediction Of A Circumferentially Reinforced SiC/Ti 15-3 Ring", ASME 10th Biennial Conference in Reliability, Stress Analysis and Failure Prevention, Albuquerque, New Mexico, Sept. 19-22, 1993.

S. M. Arnold, A. F. Saleeb, and T. E. Wilt, "A Modeling Investigation of Thermal And Strain Induced Recovery and Nonlinear Hardening in Potential Based Viscoplasticity", NASA TM 106122, March 1993.

S. M. Arnold and T. E. Wilt, "Influence of Engineered Interfaces on Residual Stresses and Mechanical Response in Metal Matrix Composites", NASA TM 105438.