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Volume 168

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Rivka Gilat • Leslie Banks-Sills

Advances in Mathematical Modeling and Experimental Methods for Materials and Structures

The Jacob Aboudi Volume

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Foreword

This volume is dedicated to Jacob Aboudi, a fine scientist who has made seminal contributions in applied mechanics. The papers presented here reflect the appreciation of many of Jacob's colleagues. A publication list following this introduction provides an indication of his distinguished academic career, currently in its fifth decade, and the breadth of his knowledge. His papers consistently demonstrate originality, innovation and diligence. This list uncovers the methodical work of a dedicated researcher whose achievements established him as a leading authority in the area of mathematical modeling of the behavior of heterogeneous materials, the area which became known as homogenization theory.

Starting in 1981, Jacob established a micromechanical model known as the Method of Cells (MOC) which evolved into the Generalized Method of Cells (GMC) that predicts the macroscopic response of composite materials as a function of the properties, volume fractions, shapes, and constitutive behavior of its constituents. The versatility of the model has been demonstrated to effectively incorporate various types of constituent material behavior (i.e., both coupled and uncoupled mechanical, thermal, electrical and magnetic effects). As a result of its potential in providing an efficient tool for the emerging field of multiscale analysis, the method gained increasing attention and became a subject for further research. In 1997, NASA presented Jacob with a certificate of recognition "for the creative development of exceptional scientific and technical contributions which have been determined to be of significant value in the advancement of the aerospace technology program of NASA entitled: MICROMECHANICAL ANALYSIS CODE with GENERALIZED METHOD of CELLS (MAC/GMC)".

Subsequently, the limited accuracy of GMC which results from neglecting coupling between normal and shear stresses led to his developing the High Fidelity

Generalized Method of Cells (HFGMC). Jacob continues to extend this method with incorporation of large deformations, constitutive laws for advanced constituent materials and an improved numerical formulation.

The publication list also reflects Jacob's contributions in other areas including wave propagation, fracture mechanics, contact problems and applied numerical solutions of partial differential equations.

Of course, the publication list cannot provide any indication of Jacob's character and interests, such as his love of history. In this regard, those who have had the pleasure to collaborate with him can attest to his integrity, collegiality, sound judgment and ability to give advice on a wide spectrum of issues. He is skilled at effectively clarifying complex concepts for students, is dedicated to his graduate students, and has contributed to the academic community in numerous ways.

Jacob Aboudi was born in 1935 in Baghdad, and emigrated to Israel in 1951. After graduating in 1961 with a B.Sc. degree in Applied Mathematics from Tel Aviv University, Jacob taught in the same department while pursuing advanced studies at the Weizmann Institute of Science. The latter institution awarded him M.Sc. and Ph.D degrees in 1964 and 1968, respectively, both in Applied Mathematics. Jacob was then hired as a Lecturer at Tel Aviv University, first in the Department of Environmental Sciences and then in the Faculty of Engineering where he became a Professor in 1980. He served 8 years as the head of the Department of Solid Mechanics, Materials and Structures, 6 years as the Dean of the Faculty of Engineering and participated in many University and Faculty Committees. Jacob was the incumbent of the Diane and Arthur Belfer Chair of Mechanics and Biomechanics for 13 years.

Jacob has spent sabbatical leaves and extended visits abroad at the University of Strathclyde, UK, Northwestern University, Virginia Polytechnic Institute and State University, the University of Virginia, and at NASA Glenn Research Center, Cleveland, all in the USA.

With this volume, we wish to express our profound respect and admiration of Jacob Aboudi.

Rivka Gilat and Leslie Banks-Sills

Contents

Publications by Jacob Aboudi

Books

1. (1991) Mechanics of composite materials – A unified micromechanical approach. Elsevier, Amsterdam
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Aboudi's Micromechanics Theories Applied to Multiscale Analysis of Composites

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Abstract NASA Glenn Research Center in Cleveland, OH has worked with Professor Jacob Aboudi since 1992 to develop and implement his micromechanics theories into a user-friendly software suite. This effort has resulted in the publicly available Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC) software, along with the coupling of the code with finite element analysis and structural sizing software for multiscale analysis of composite structures. This chapter outlines these methods, discusses why Aboudi's methods are ideal for use in multiscale analyses, and briefly describes three recent multiscale composite analysis examples involving (i) creep of a woven ceramic matrix composite (CMC), (ii) damage/failure of a polymer matrix composite (PMC) T-stiffened panel, and (iii) damage/failure of notched PMC laminated plates.

1 Introduction

The use of advanced composites (PMCs, CMCs, metal matrix composites (MMCs)) provides benefits in the design of advanced lightweight, high temperature, structural systems because they provide increased specific properties (e.g., strength to density ratio) in comparison to their monolithic counterparts. To fully realize the benefits offered by these materials, however, experimentally verified, computationally efficient, multiscale design and analysis tools must be developed for the advanced multiphased materials of interest. Furthermore, in order to assist both the structural analyst in designing *with* these materials and the materials scientist in designing/developing *the* materials[1], these tools must encompass the various levels of scale for composite analysis, see Fig. 1.

[1] The structural engineer's perspective relates to the design of structures with given materials whereas the materials scientist's concern is how to design a material for a given application. Clearly, the two perspectives are not mutually exclusive.

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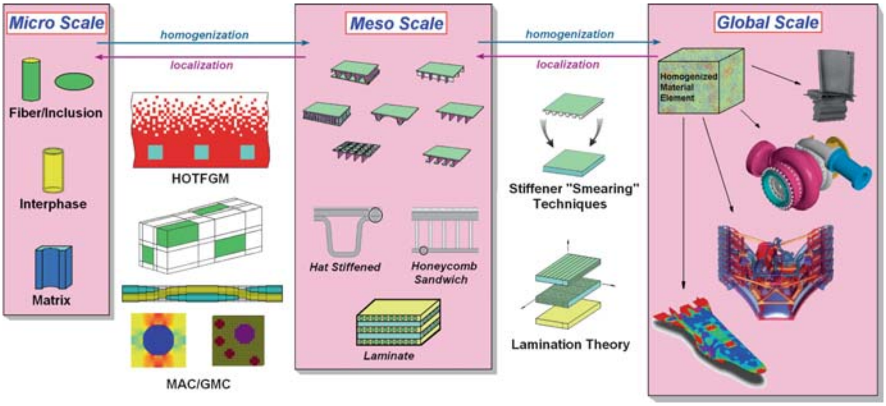

Fig. 1 Illustration of associated levels of scale for composite analysis

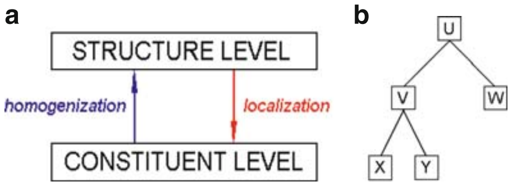

Fig. 2 (**a**) Homogenization provides the ability to determine structure level properties from constituent level properties while localization provides the ability to determine constituent level responses from structure level results. (**b**) Example tree diagram

These scales are the micro scale (constituent level), the meso scale (laminate/composite and/or stiffened panel level) and the macro scale (global/structure level), and they progress from left to right in Fig. 1. One traverses (transcends (moves right) or descends (moves left)) these scales using homogenization and localization techniques, respectively (Figs. 1 and 2a); where a homogenization technique provides the properties or response of a "*structure*" (higher level) given the properties or response of the structure's "*constituents*" (lower scale). Conversely, localization techniques provide the response of the constituents given the response of the structure. Figure 2b illustrates the interaction of homogenization and localization techniques, in that during a multi-scale analysis, a particular stage in the analysis procedure can function on both levels simultaneously.[2] For example, for the process of homogenizing the stages represented by X and Y to obtain

[2] This is also illustrated in Fig. 1 where, for example, the global scale has subscales (components) within it (i.e., vehicle – engine – turbopump – blade) and the mesoscale has subcomponents (stiffened panel – laminate – ply).

properties for the stage represented by V, X and Y form the constituent level while V is on the structure level. However, for the process of homogenizing V and W to obtain properties for U, V is now on the constituent level (as is W). Obviously, the ability to homogenize and localize accurately requires a sophisticated theory that relates the geometric and material characteristics of structure and constituents.

Numerous homogenization techniques (micromechanical models) exist that can provide effective composite properties to a finite element package. These range from the simplest analytical approximations (i.e., Voigt/Reuss) to more accurate yet involved methods (e.g., concentric cylinder assemblage, Mori-Tanaka, Eshelby, and Aboudi's generalized method of cells) to finally, fully numerical methods that are the most general and accurate yet computationally intense (e.g., finite element, boundary element, Fourier series). Each has its realm of applicability and advantages, however, many are unable to admit general user defined deformation and damage/failure constitutive models for the various constituents (i.e., fiber or matrix) thus limiting their ultimate usefulness, especially for high temperature analysis where nonlinear, time-dependent behavior is often exhibited.

An alternative approach to micromechanics involves fully characterizing the composite material or laminate experimentally, which has the advantage of capturing the in-situ response of the constituents perfectly. However, such full characterization for all applicable temperatures and configurations (e.g., fiber volume fractions, tow spacings, etc.) can be expensive, and composites are almost always anisotropic on this scale. Thus some properties needed as input for finite element models can be virtually impossible to measure, and development of realistic models that capture the nonlinear multiaxial deformation and failure can be challenging (due to the anisotropy). Clearly, the physics of deformation and failure occur on the micro scale (and below), and, by modeling the physics at the micro scale, models for the monolithic, often isotropic, constituents can be employed.

Recently, a comprehensive and versatile micromechanics analysis computer code, known as MAC/GMC [7], has been developed at NASA Glenn Research Center based on Aboudi's well-known micromechanics theories [1–5]. FEAMAC (the coupling of MAC/GMC with the finite element analysis framework through user subroutines) and HyperMAC (the coupling of MAC/GMC with the commercial structural sizing software known as HyperSizer [10]) have begun to address the truly multiscale framework depicted in Fig. 1. This software suite, known collectively as ImMAC, provides a wide range of capabilities for modeling continuous, discontinuous, woven, and smart (piezo-electo-magnetic) composites. Libraries of nonlinear deformation, damage, failure, and fiber/matrix debonding models, continuous and discontinuous repeating unit cells, and material properties are provided, and the software is available from NASA Glenn.

2 Analysis Tools Based on Aboudi's Theories

2.1 Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC)

In developing an analytical tool that can serve both materials scientists and structural analysts, the employed methods must admit physics-based deformation and life models on the scale of the constituents and be capable of accurately predicting the macro composite response. This enables materials scientists to investigate the effects of deformation/damage mechanisms on the scale where they occur and make changes to develop new materials. From the structural analyst standpoint, the methods must be accurate, efficient, and compatible with structural finite element models. A number of models presently exist that can fulfill certain aspects of the aforementioned requirements. However, there are very few working models that are both computationally efficient and sufficiently accurate both at the micro and macro scales. It is the authors' position that Aboudi's micromechanics theories – the method of cells [1], the generalized method of cells (GMC) [2, 13], and high-fidelity GMC (HFGMC) [5] – are unique in this regard.

Aboudi's theories are capable of predicting the response of both continuous and discontinuous multi-phase composites with arbitrary internal microstructures and reinforcement shapes. They are continuum-based micromechanics models that provide efficient, closed-form expressions for the macroscopic composite response in terms of the properties, size, shape, distribution, and response of the individual constituents or phases that make up the material. Perhaps most importantly, Aboudi's theories admit physics-based viscoplastic deformation and arbitrary damage/life models for each constituent due to their ability to localize to the subcell level, providing full multiaxial stress and strain fields throughout the constituent materials. For these reasons, Aboudi's micromechanics theories were selected as the basis for NASA Glenn's MAC/GMC software. MAC/GMC provides industry, academia, and government engineers and materials scientists with a comprehensive, computationally efficient, user-friendly micromechanics analysis tool that can easily and accurately design/analyze multi-phase (composite) materials/structures for a given application. The distinction between HFGMC and GMC is that, through the use of an assumed higher-order local displacement field, HFGMC provides improved local field accuracy. However, HFGMC is more computationally intensive as it requires solution of a greater number of equations to fully discriminate its more accurate local fields. Two review papers documenting the application of GMC and HFGMC by various researchers were presented by Aboudi [3, 4]. MAC/GMC includes both theories and can thus be thought of as a variable-fidelity tool.

It should be noted that MAC/GMC includes capabilities for traditional constituent materials as well as thermo-electro-magnetic materials and shape memory alloys (so-called "smart" materials). The code also includes a multiscale classical lamination theory module, wherein Aboudi's micromechanics theories are employed at each integration point in each ply, see Fig. 3a. Thus, once lamination